BULLETIN OF THE EARTHQUAKE
RESEARCH INSTITUTE
Vol. 45 (1967), pp. 727-738

38. *Experimental Study on Generation and Propagation of S-waves: III. Generation of SV-waves by means of a modified explosion source.*

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(Read October 25, 1966.—Received June 30, 1967.)

1. Introduction

Recent investigations on wave generation by means of explosions in bore-holes clarified that, in some cases, SV- and SH-waves as well as P-waves are produced simultaneously. The determination of underground structures has been tentatively carried out, using these S-waves, by a few workers.[1] However, most scientists are employing the information obtained by means of the simple detonation of explosives.

The appearance of the S-waves in usual seismic prospecting suggests to us that the seismic source in this case does not possess spherical symmetry, which is contrary to what has been believed. The energy partition rate of the S-waves to the P-waves and hence reliability of S-wave generation are closely related to the non-symmetry of the source. If we can give the explosive source a pertinent artificial modification, then we hope the S-waves produced will be stronger and more stable than in the past, and separation of the S-waves from the P-waves will become clearer.

In the previous paper[2] we tried, from this point of view, a preliminary experiment on the SV-generation by means of explosions in an iron pipe hung down in a bore-hole, we could estimate the S velocities to a depth of 30 m. The iron pipe, 150 cm in length, 7.5 cm in diameter and 0.3 cm in thickness, was used as a trial of the source control mentioned above.

At that time, however, a few defects were found in conducting the experiment: namely, lack of anti-knock strength of the iron pipe

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[1] T. HATAKEYAMA, *Butsuri-Tanko*, **19** (1966), 1-11, (in Japanese).
A. KUBOTERA and Y. OHTA, *Spec. Contr. Geophys. Inst., Kyoto Univ.*, **6** (1966), 267-279.

[2] Y. OHTA and E. SHIMA, *Bull. Earthq. Res. Inst.*, **45** (1966), 33-42.

and arrangements of shot points and seismometers.

This time we carried out similar experiments paying attention to the reinforcement of the iron pipe and improvement in technique. Consequently, we succeeded in disclosing the appropriate underground structure to 100 m in depth.

According to this method one can detect the existence of low velocity layers, since not only critically refracted waves, essential in the refraction method, but also direct waves from the source are taken into consideration. In addition, one need not prepare such a long spread of seismometers as in the past. We might say, therefore, that this method makes better use of the benefits of the usual refraction method and of velocity logging, developed in seismic exploration by use of the P-waves.

2. Experiment

(i) *Method*

This experiment was carried out at an agricultural field, Suibaramachi, Niigata Prefecture, situated at one end of the south-eastern part of Niigata plan, which is covered with heavy alluvial deposits composed of clay, sand and gravel.

Twenty-four horizontal seismometers having natural frequencies of 30 cps were set in a radial direction on the ground surface at intervals of 5 m from the epicenter to a distance of 120 m, and connected to the conventional recorder system (TI-8000), popular in seismic prospecting. In order to observe the absolute values of the events, a few three-component seismometers were employed. These auxiliary seismometers have responses proportional to the acceleration of the ground motion at frequencies from 0.3 to 30 cps.

The iron pipe, which was adapted to regulate the directivity of the force and hence to improve the amplitude ratio between S- and P-waves, was reinforced from 0.3 cm to 2.0 cm in thickness. After a proper amount of charge was placed in the central part of this pipe, this was slowly lowered down to the appointed depth in the bore-hole by use of a wire-rope (ultimate strength: 600 kg) and then fired (Fig. 1). It is desirable to have many shot points at different depths with this method. But to save time it was fired at intervals of 5 m from 5 m to 50 m in depth, and also at 60 m in depth. We also tried to obtain seismograms from the shots with and without the iron pipe, in order to ascertain the efficiency of usage of the pipe. A constant charge of dynamite, 20 g, was used throughout the experiment.

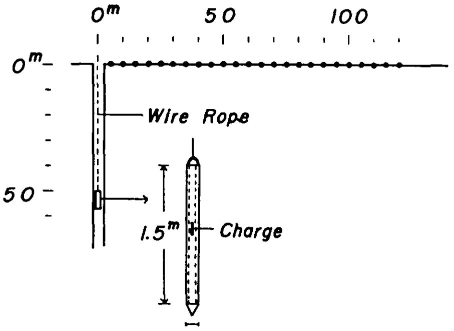

Fig. 1. Spread of seismometers and the iron pipe used to regulate the explosive seismic source.

(ii) *General view of seismograms*

In Fig. 2 the seismograms obtained at all shot points are compiled. This shows that the first arrivals of the P-waves and also the succeeding P phases are not so remarkable, being dissimilar to what is observed in the usual seismic prospecting. After weak P events passed, predominant phases having somewhat sharp onsets appeared. At the shot depth of 10 m, for example, these phases begin to appear markedly at about 100 m sec with an apparent velocity of 200 m/sec. The apparent velocity does not change so much in cases where the shot points are shallower than 20 m, but increases gradually with increasing shot depths. This suggests that the phases in question are the waves directly from the source. On the whole, the above mentioned features cannot be observed when the shot points are deeper than 40 m and the distances are far away from the epicenter. Here, the waves having a velocity of 600 m/sec. are the first arrived predominant phases: these must be the critically refracted waves.

The P-waves, observed in the shallow shots, fall off abruptly with increase in shot depths. And there are no noticeable phases after the phases with which we are concerned cease to exist. Thus we might say the seismograms obtained in this experiment are quite ideal.

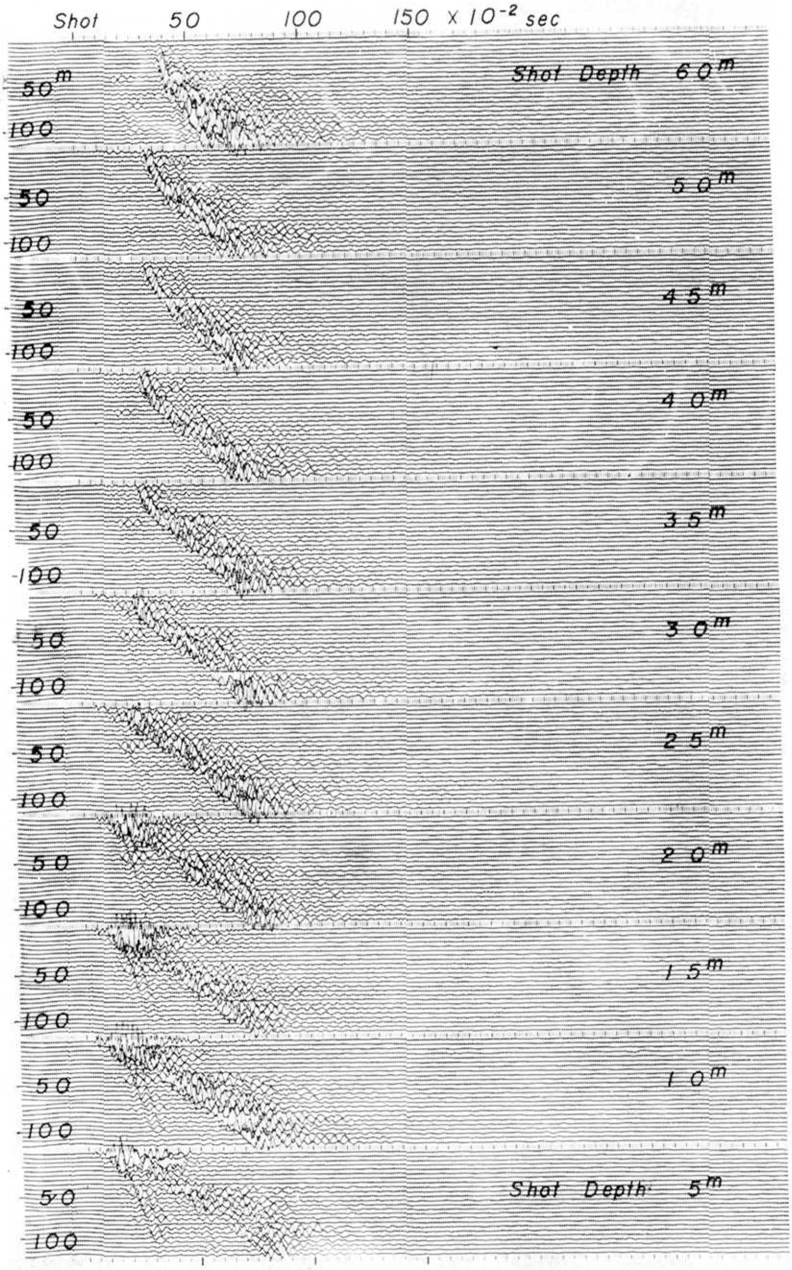

Fig. 2. General view of seismograms, with observations of all the shot depths compiled.

(iii) *Three-component observation*

To check whether the waves in question are the SV-waves or not, and, if so, to know the effect of the iron pipe on the improvement of the amplitude ratio between S- and P-waves, we carried out the following three-component observation by means of a direct recording system with no amplifier. With fixed conditions (shot depth: 30 m, charge size: 20 g, epicentral observational distance: 30 m), two detonations were made: one with the iron pipe, the other without, the latter corresponding to a conventional explosion. Seismograms are represented in Fig. 3.

The amplitudes due to the simple source are, as is expected, somewhat larger than those due to the modified source. The former amplitudes are reduced to one-third for convenience of comparison.

It is well known that the P-waves are, in general, most remarkable in the vertical component. The waves appearing in the time range from 60 m sec. to 120 m sec. must be essentially the P-waves. At a time of 26 m sec., the most predominant phases begin to start rather sharply. These are seen more clearly in the radial component. The seismometers installed radially on the ground surface are not sensitive to the P-waves traveling upwards. Circumstances are surely the same. The waves having the largest amplitude in the radial component, which are characteristic of the SV-waves, correspond exactly to the phases attracted in the seismograms illustrated in Fig. 2.

Attention is directed to another point. The iron pipe was introduced to regulate the source and to safely maintain the shot hole. To investigate the former effect, the following two points must be considered: onset of the SV-waves and separation of the SV-waves from the other waves. There is no doubt that the SV-waves are produced with and without the pipe. But, in detail, the SV-waves with the pipe appear somewhat solitary and hence, in comparison to the case without the pipe, the onsets are clearer.

In the transverse component a particular phase is found both with and without the pipe, but faint in the former and distinct in the latter. These must be the SH-waves (cf. Particle motion)[3]. The fact suggests to us that the iron pipe diminishes the tangential force acting along the hole in the neighbourhood of the shot point and consequently is effective.

The iron pipe was also useful because the shot hole, although unprotected, had been kept in good condition throughout the experiment.

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[3] Details of the SH-waves and Love waves produced by the explosion will be reported in another paper.

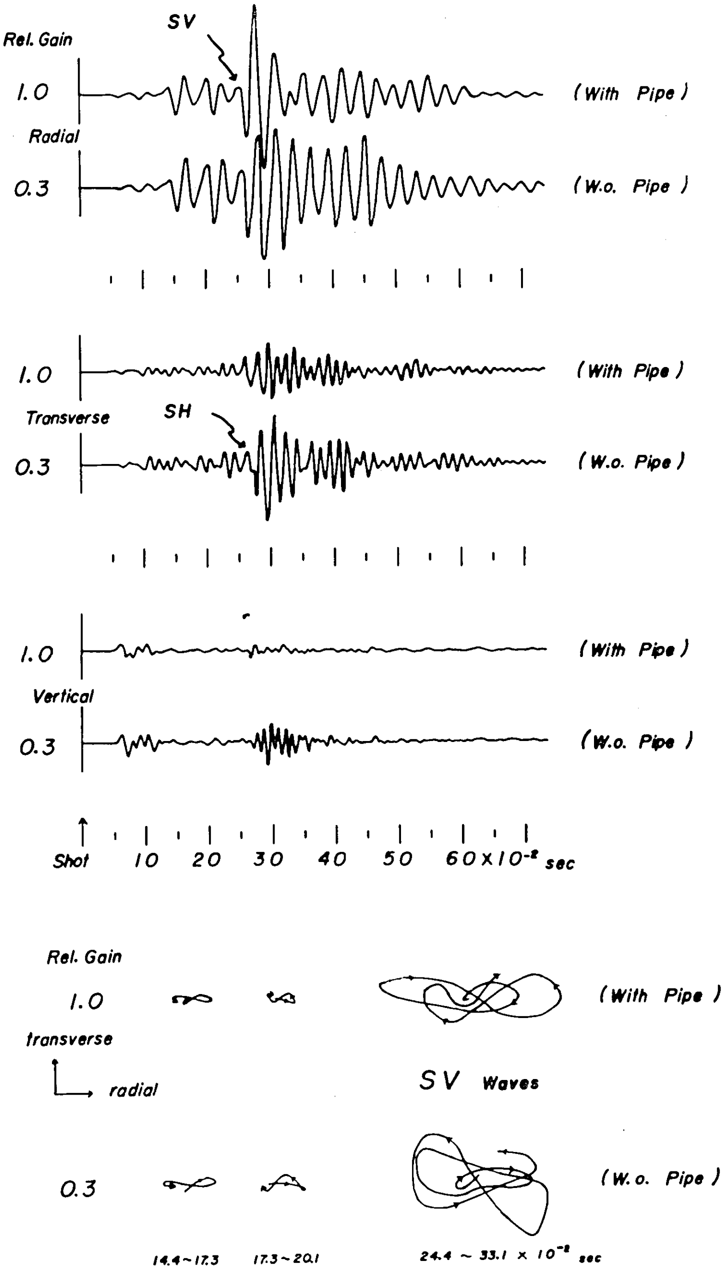

Fig. 3. Comparison of seismograms in three components and derived particle motions from the sources with and without the iron pipe.

3. Determination of underground structure

(i) *Readings and travel-time curves*

The readings are, in general, not such a difficult matter with the usual prospecting method of making use of the P-waves and their first arrivals. For the SV-waves circumstances are quite different, since we cannot remove the P-waves preceding the SV-waves. Also, in order to prevent the iron pipe and the shot hole from collapsing, we cannot place as much dynamite as was used in the P-wave generation.

It is inevitable, therefore, that the SV-onsets themselves are somewhat ambiguous, especially at the farther observation points. What is essential is not to misunderstand the general features of the structure, which will be derived finally.

For this purpose it is better to read the marked peaks or troughs having mutual correspondence at wider distances over the entire spread. The propriety of the derivations is confirmed by checking whether the readings from all the shot depths are, at any fixed observation point, in good order or not. Two examples in Fig. 4 indicate the readings obtained in this way.

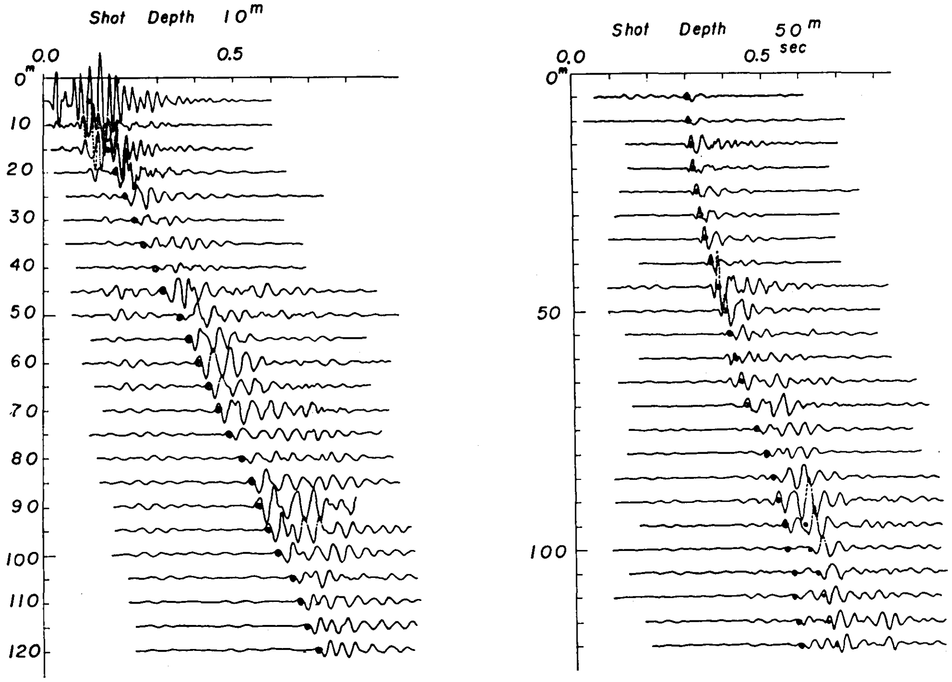

Fig. 4. Examples of enlarged seismograms and their reading points.

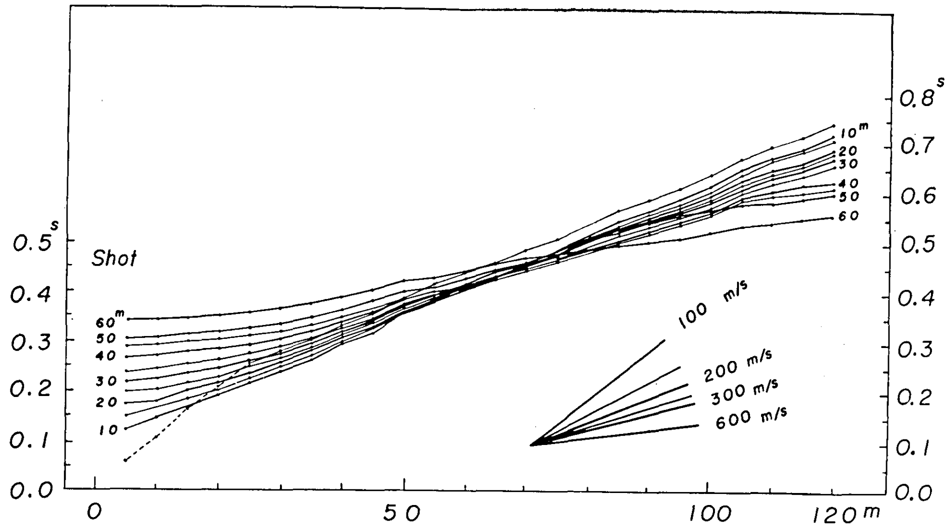

Fig. 5. Summary of travel-time curves obtained from the different shot depths.

Fig. 5 shows the summed up travel-time curves resulting from the different shot depths obtained by use of these readings. Except for the curve at a shot depth of 5 m, all the curves are situated in an orderly way in the form of a concave. These correspond to the travel-time curves for shot points deep under the ground surface. The gradient, $dT/d\Delta$, decreases as distance increases. Thus the deeper the shot points go the higher the velocities become. Nevertheless, circumstances are gradual.

On the other hand, the arrivals of the critically refracted waves are apparent when shots are fired at points deeper than 35 m. The highest velocity observed was 600 m/sec.

(ii) *Derivation of underground structure*

The travel time-curves cited above suggest that the experimental site is composed of layers with gradually increasing velocities down to the basemental layer of 600 m/sec., except for the very superficial surface layers, and that there is no indication of low velocity layers, such as first order discontinuities.

Now it is desirable to have shallow shot points to investigate the structure of the surface layer. However, the shallowest shot depth was only 5 m. So we inferred the derived velocities of 40 m/sec. for the 1st layer and of 125 m/sec. for the 2nd layer by the "hitting plate method", carried out along the same line of the site[4].

Other layers were determined as follows. At first, we estimated the velocity of the 3rd layer as 175 m/sec. by using the gradient of the curves at the shot depths of 5 m and 10 m. As is well known, the gradient due to the direct waves gives only the apparent velocity and not the true one. In general, it is easily understood that the difference between the true and apparent velocities is very small, if obtained at distances several times farther than the corresponding depths. The 3rd layer velocity, 175 m/sec., was determined by using the gradient at the distance from 30 to 50 m.

Next, to determine the thickness of this layer, we calculated the theoretical travel-time curves changing the thickness meter by meter, and searched for the most appropriate curve matching the observed one. Travel-times for the direct waves and the critically refracted waves were calculated. But when the change of velocity to the depth is gradual as it is in this field, the meaning of the critically refracted waves is somewhat ambiguous. In fact, it is difficult to distinguish between two waves on the records and therefore on the travel-time curves, since they appear at almost the same time range. Thus we adopted one of these waves according to circumstances. The same procedures were carried out down to the deepest describable layer. Final results and the comparison of observation to calculation are illustrated in Fig. 6.

A few remarks must be added. Four layers having the velocities of 200 m/sec., 225 m/sec., 250 m/sec., and 275 m/sec. respectively were conventionally introduced in place of a single layer in which the velocity changes continuously. It might be possible to construct another equivalent structure satisfying the observation data. Also a layer with the velocity of 350 m/sec. was introduced, because there is a noticeable later phase on the records when the shot depth is 50 m, though it is not so clear on the other records. The thickness must be very thin.

The correlation between the derived structure and the geology is excellent. The heavy layer composed of sand and sandy clay could have continuous characteristics. The gravel layer corresponds exactly to the layer with velocity of 600 m/sec. Though the boundary depths thus derived are deeper than the geological depths, this is perhaps due to the fact that we adopted somewhat delayed times compared with the onsets of the SV-waves.

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[4] N. KOBAYASHI and M. SAITO, *Read at Annual Meeting Seism. Soc. Japan,* Oct. 1966.

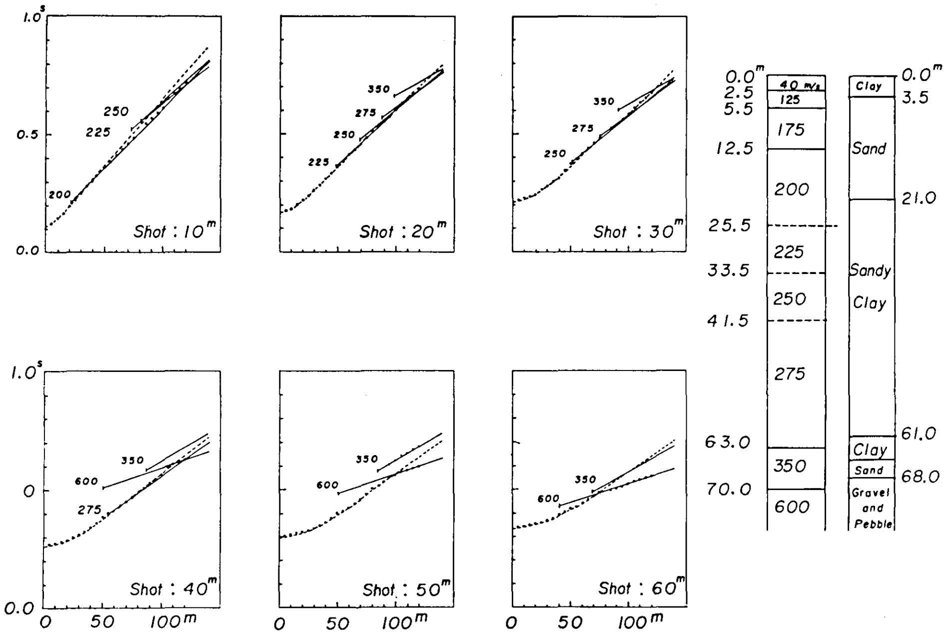

Fig. 6. Derived structure for S-waves and comparison of observations with calculations: solid circles show the readings, dotted curves and straight lines show the calculated travel-time curves for direct and critically refracted waves respectively.

If we assume, for example, that a layer having a velocity of 1000 m/sec. lies directly under the gravel layer, this boundary surface must be situated deeper than 80 m because there is no indication on the records obtained. Even in later phases we cannot recognize any velocities higher than 600 m/sec. The velocity distribution of the S-waves down to the depth corresponding nearly to the total length of the seismometer spread (120 m) was elucidated.

According to the preliminary report[5] carried out at the same experimental site, the P-wave velocities obtained are 500, 1600, 860, and 1250 m/sec. respectively from the top to the deeper portions; that is, there exists a low velocity layer for the P-waves. This discrepancy between P- and S-waves is probably due to the fact that the P-wave velocities are significantly affected by the extent of water content of the subsoils.

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5) T. TAKEUCHI et al, *Rep. Seism. Explor. Group Japan*, **41** (1966), 10-16, (in Japanese).

4. Discussions

The experiment on SV-wave generation was made more successful than that in the previous paper. But there still remain many problems to be disclosed in order to apply this method to the various fields. Let us consider a few points.

(i) *Better understanding of the usage of the iron pipe*

We could know the fact that the iron pipe regulates effectively the explosive source and therefore is useful in SV-wave generation. However, details of source mechanism are not yet so clear. Optimum length of the iron pipe and also appropriate charge size are unsolved.

We used a simple bore-hole without any protection, such as casing pipe in the shot hole, because we could easily have, in this experiment, a new hole whenever the previous one collapsed. But it is usually not possible to have such a good situation because of cost and time. In addition, one must consider that the shot holes are sometimes diverted to other purposes. To keep the holes in good condition during and after explosions is very important. This is another reason for using iron pipe. Is it enough to use iron pipe? In practice other protection, such as casing pipes made of chemical products or of iron, would be preferable. The significance of the iron pipe in question might be changed under such conditions. A more emphatic study on this situation is required.

(ii) *Shortening of the spread, and application to the complicated structure*

It is a general requirement in the field of seismic prospecting to increase the detectable depths at a prescribed spread. The velocity logging method has been developed for the P-waves, but this cannot be applied so directly to the S-waves. Much attention must be paid to this point, although the total length of the spread was greatly decreased in this experiment compared with what it was previously.

This time the site was assumed to be composed of parallel layerings. There are many exceptions and also situations are more complex. The first step in solving these problems is to install seismometer arrays on both sides of the shot hole. The low velocity layers and their derivings were overcome in this method, since one can prepare, as occasion demands, the records of which shot depths are in, above, and below the low velocity layers.

Acknowledgements

The field data reported here were obtained by the Seismic Exploration Group of Japan. The author wishes to express his sincere thanks to Prof. K. Iida of Nagoya University, the head member of the group. The author's thanks are also due to the technical experts of Japan Petroleum Exploration Company. The author wishes again to express his thanks to Dr. E. Shima for his kind discussions.

The numerical calculations were done by using the HITAC-5020 computer of the Tokyo University. Thanks are due to the members of the computation center.

Finally, the author acknowledges the assistance of Miss Y. Uemura for her kind help in the analysis of the data.

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38. S波の発生と伝播に関する実験的研究 Ⅲ
震源操作によるSV波の発生

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人工震源として用いる火薬爆発の際に発生する波動は必ずしも球対称的ではないとの考えがある．これを進めて，強制的に震源にある種の空間特性を与えるならば，この際現われる波動は一層非対称性を増し，従つて，S(SV)波の発生，SV波とP波の分離が一段と容易になるであろうとの観点から，今回の実験を行なつた．震源操作は，最も簡単なものとして，前論文同様に長さ150cmの鉄パイプを用いて，種々の深度で，この鉄パイプの中程で小量(20g)の火薬を爆発させ，発生する波動を把えた．ただし，パイプの肉厚は，前の経験から，一段と増し，これによつて全体の強度を上げるよう留意した．

今回は特にSV波に注目したため，地震計24成分(30cps)は全て測線方向の水平動を把えるように配置し，これを通常の地震探鉱器に接続した．一方，別に3cps加速度計3成分を置き1部同時観測をした．また，鉄パイプ内爆破効果の程度を知る目的で，鉄パイプあり，なしの場合の爆破を行ない両者を比較する記録を得た．

爆破は深度60mから浅い方へ5mないし10m間隔で行なつた．実験は，この点から，SV波による検層ともいえるはずである，P波による検層の場合とは，地震計・爆破点の位置関係が全く逆ではあるが．

結果は，Fig. 2にみるように，SV波のみがほとんど単独に出現する理想的な記録を得た．端念な読み取りに基づく走時曲線から，深度約100mに至るS波速度分布が得られた．これは地震計展開距離(120m)に匹敵する深さである．

他方，鉄パイプ利用は，SV波成分の相対的増加，従つて，P，S波分離の点で有効であることが確かめられた．また，爆破孔保持の点でも優れていることがわかつた．

最後に，複雑な地層への本方法の適用，今後の問題にも触れておいた．