18. A Note on Seismic Prospecting in Coal-Fields.

By Nobuji NASU,

Earthquake Research Institute.

(Read Nov. 20, 1941.—Received Dec. 20, 1941.)

The writer, before proceeding with this paper, wishes it to be clearly understood that neither seismic prospecting nor geophysical operations of any kind directly indicate the presence of oil or coal, nor measure their properties. All they can do is to indicate the character of the geologic formations that are associated with oil or coal. In the case of a coal field, neither its thickness, depth, nor the number of the coal seams themselves can be directly determined, but the general geologic formation of the coal-field, such as the thickness of the coal-bearing stratum and the presence of faults, are ascertained by the seismic method. The most important information available by this method is the structure of the coal-bearing stratum, that is, its thickness and the extent to which it is developed, which information enables us to form a rough idea of the coal that is hidden under the surveyed area.

In most of the coal-fields so far explored by us, it has been our experience that, as a rule, the coal-bearing strata underlie certain superficial low-speed layers of a young geological formation. In some fields, this low-speed layer was found to consist of two or more strata—a condition often noticed in drawing up the time-distance curves for the seismic waves. In other fields, there was no such overlying layer, the coal-bearing stratum being developed directly on the surface.

In our cases, all the coal bearing strata met with were rocks of Tertiary age, underlain by rocks of older age, the Cretaceous for example.

Practically speaking, to interpret a seismographic record of this kind is nothing but simple mathematics, by means of which the problem of multiple layers is solved. We assume a simple geologic formation in which the strata consist of several horizontal layers of thickness Z_0, Z_1, Z_2, etc., although in most cases, so far, there was no need, in field practice, to assume the presence of more than three layers, namely, the coal-bearing stratum and two other layers, one lying above and the other beneath this stratum. If this actually happens to be the case, the interpretation is much simpler than if otherwise.

The time-distance curve for such an ideal case as that just mentioned is shown in Fig. 1. We shall here introduce the term "delay time," so widely used at the present, and write down the times for the various wave paths shown in the same figure, namely,

$$T_0=\frac{x}{V_0}$$

$$T_1=\frac{x}{V_1}+2D_{01}$$

$$T_2=\frac{x}{V_2}+2D_{02}+2D_{12}$$

....

$$T_n=\frac{x}{V_n}+2D_{0n}+2D_{1n}+2D_{2n}+\ldots\ldots\ldots 2D_{(n-1)n} \tag{1}$$

In these expressions, the delay times are expressed by D, whence

$$D_{01}=\frac{Z_0\cos i_{01}}{V_0},\quad \text{etc.},$$

or

$$D_{mn}=\frac{Z_m\cos i_{mn}}{V_m}. \tag{2}$$

The delay time may be written in terms of the velocities, for example,

$$D_{01}=\frac{Z_0\sqrt{V_1^2-V_0^2}}{V_0V_1}$$

$$D_{mn}=\frac{Z_m\sqrt{V_m^2-V_n^2}}{V_mV_n} \tag{3}$$

For brevity, we shall use the notations

$$V_0V_1=P_{01}$$

$$V_mV_n=P_{mn}$$

and

$$\sqrt{V_1^2-V_0^2}=Q_{10}$$

$$\sqrt{V_m^2-V_n^2}=Q_{mn}, \tag{4}$$

whence expression (3) may be written

$$D_{01}=\frac{Z_0Q_{10}}{P_{10}}$$

$$D_{mn}=\frac{Z_mQ_{mn}}{P_{mn}}. \tag{5}$$

Thus, the general expression for the time taken by a ray to penetrate a layer is written by substituting the delay times in terms of the velocities from expression (5), namely,

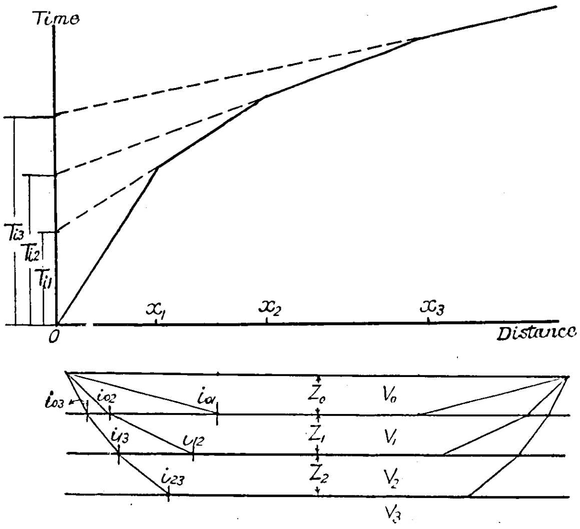

Fig. 1.

$$T_n = \frac{x}{V_n} + \frac{2Z_0 Q_{n0}}{P_{0n}} + \frac{2Z_1 Q_{n1}}{P_{1n}} + \cdots\cdots + \frac{2Z_{n-1} Q_{n(n-1)}}{P_{n(n-1)}}. \tag{6}$$

The intercept times are the values of T_1, which are given by putting $x=0$ in Eq. (1). These times can be determined graphically by projecting back the segments of the time-distance curves on the zero-distance axis, as shown in Fig. 1, in which the intercept times are designated as T_{i1}, T_{i2}, T_{i3}, etc.

The thickness of the first layer is calculated by the formula for the case of a simple two-layer, namely,

$$Z_0 = \frac{T_{i1}}{2} \frac{P_{01}}{Q_{10}}, \tag{7}$$

Then since

$$T_{i2} = 2D_{01} + 2D_{12}$$
$$= \frac{2Z_0 Q_{20}}{P_{02}} + \frac{2Z_1 Q_{21}}{P_{12}}, \tag{8}$$

Z_1 is solved in terms of the previously determined value of Z_0 by

$$Z_1=\left(T_{i2}-\frac{2Z_0Q_{20}}{P_{02}}\right)\frac{P_{12}}{2Q_{21}}. \tag{9}$$

Generally speaking,

$$T_{in}=\frac{2Z_0Q_{n0}}{P_{0n}}+\frac{2Z_1Q_{n1}}{P_{1n}}+\ldots\ldots$$

$$+2\frac{Z_{n-1}Q_{n(n-1)}}{P_{(n-1)n}} \tag{10}$$

is solved for the thickness of the last penetrated bed Z_{n-1} by

$$Z_{n-1}=\frac{P_{n(n-1)}}{2Q_{n(n-1)}}\left(T_{in}-\frac{2Z_0Q_{n0}}{P_{0n}}-\frac{2Z_1Q_{n1}}{P_{1n}}-\ldots\ldots\right.$$

$$\left.-\frac{2Z_{n-2}Q_{n(n-2)}}{P_{(n-2)n}}\right) \tag{11}$$

Geologic conditions of the coal-fields.

The following examples are chosen from areas where the geologic sections included materials of very different lithologic character, with marked effects of the seismic wave.

(1) *A submarine coal-field in the Tyugoku district.*

The exploration was done on the sea over an area of 36 km². The measurements were made along five lines, the longest of which was 5·0 km. The result showed that the coal bearing stratum had a thickness of about 150 m, the bottom of which extended down to a depth of 300 m from the sea floor.

(2) *A coal-field in Hokkaido.*

Although, superficially, there was no direct indication here of the presence of coal, the first exploration made by the seismic method showed the presence of a thin stratum which was expected to be the coal bearing layer.

The second exploration, which was made over a larger area than in the first, showed the presence of a coal bearing stratum about 100 m thick, as the result of which a boring was made at a suitable point down to such a depth that it penetrated the coal bearing stratum, yielding coal from a number of seams in the layer, exactly as seismic prospecting had predicted.

In this field, the uppermost layer was loose soil, the second a sand layer about 130 m thick, and the third the coal bearing stratum (Tertiary age) about 150 m thick. Below this there lay a bed rock of Cretaceous age.

(3) *A coal-field in the Kyushu district.* (a)

Exploration was done on five main lines chosen on the field, these lines ranging between 4·35 km and 2·50 km. On the whole, the geologic and velocity conditions prevailing in this field were fairly regular, it being often possible to mark out clearly on the seismograph records the refracted waves that were propagated along the paths, penetrating various beds. The layers, however, were not ideally horizontal, there being considerable changes in their thickness, while in some places they were down-faulted to a certain extent.

(4) *A coal-field in the Kyusyu district.* (b)

In this coal-field, lying southwest of the preceding one, the thickness of the coal-bearing stratum was smaller than that in the preceding field (a), while in places the stratum thinned out or disappeared, the uppermost layer (soil) overlying directly a bed rock of Cretaceous age.

In this coal field, the exploration involved a somewhat smaller area than in the preceding field. Six lines of measurement were chosen, the longest of which was 2·0 km.

(5) *A submarine coal-field in the Kyusyu district.*

The sea was between 40 m and 20 m deep in this area. The longest line of measurement exceeded 8 km. Exploration showed that the Tertiary rock layer, the coal bearing stratum, was about 600 m thick, its bottom ranging in depth from 1100 m to 700 m from the sea floor. This coal bearing stratum was overlain by superficial soil about 300 m thick, maximum.

(6) *A coal field in the Kai district.*

The area of this coal-field was about 4 km^2, very small compared with the fields just mentioned.

The surface layer was a Pliocene conglomerate, containing thin seams of coal, underlain by quartz-porphyrite which geologists ascertained had intruded the conglomerate layer in the neighbourhood of this coal-field.

Exploring over a wide area, the geology of the underground proved very simple; a conglomerate layer of nearly uniform thickness of about 100 m overlay the bed rock.

The thickness and depth of the layers, the delay-time.

In calculating the thickness and the depth of the layers, as described in the foregoing pages, actual values of the wave velocities in the respective layers and the delay-times must be substituted in the formula. The mean velocities of the waves, the mean thicknesses of the layers that were obtained for the six coal-fields mentioned above, the calculated delay-times, and the critical distances will be found in the annexed Table.

Table 1. Wave velocity, thickness of the layer, intercept time, critical distance.

No.	District of the Coal-field.	Wave velocity (m/sec)	Mean thickness of the layer (m)	Intercept time (sec)	Critical distance (m)
(1)	Tyugoku (submarine)	$V_0=1520$ $V_1=2410$ $V_2=4800$	$Z_0=150$ $Z_1=150$	$T_{i1}=0{\cdot}153$ $T_{i2}=0{\cdot}295$	$x_1=630{\cdot}3$ $x_2=681{\cdot}6$
(2)	Hokkaido	$V_0=515$ $V_1=1320$ $V_2=2960$ $V_3=3660$	$Z_0=20$ $Z_1=130$ $Z_2=170$	$T_{i1}=0{\cdot}072$ $T_{i2}=0{\cdot}247$ $T_{i3}=0{\cdot}269$	$x_1=60{\cdot}4$ $x_2=425{\cdot}3$ $x_3=984{\cdot}9$
(3)	Kyusyu (a)	$V_0=1520$ $V_1=3000$ $V_2=4230$	$Z_0=210$ $Z_1=270$	$T_{i1}=0{\cdot}238$ $T_{i2}=0{\cdot}385$	$x_1=733{\cdot}7$ $x_2=1511{\cdot}5$
(4)	Kyusyu (b)	$V_0=1600$ $V_1=3200$ $V_2=4500$	$Z_0=130$ $Z_1=160$	$T_{i1}=0{\cdot}141$ $T_{i2}=0{\cdot}222$	$x_1=450{\cdot}3$ $x_2=902{\cdot}0$
(5)	Kyusyu (submarine)	$V_0=1400$ $V_1=3700$ $V_2=5400$	$Z_0=300$ $Z_1=600$	$T_{i1}=0{\cdot}397$ $T_{i2}=0{\cdot}650$	$x_1=893{\cdot}4$ $x_2=2977{\cdot}8$
(6)	Kai	$V_0=2330$ $V_1=4690$	$Z_0=100$	$T_{i1}=0{\cdot}075$	$x_1=344{\cdot}9$

In actual field practice, care must be taken in choosing suitable lengths for the lines of measurement, otherwise the refracted waves penetrating the deeper bed may be recorded much faster than the other waves associated with shallower refracting beds, the former waves being thus masked by the latter, resulting in possible failure to indicate the presence of the deeper bed. In actual coal-field exploration it is desirable to ascertain the thickness of the coal bearing stratum in detail, so that in every case the segments of the time-distance curves giving the velocity through the layer underlying the coal bearing stratum is most essential. In other words, if there were three layers, the first, second, and third, and the second one contains seams of coal, we extend the line of measurement to a distsnce greatly exceeding the critical distance at which the times of the waves refracted respectively at the first and second discontinuities become equal. Sometimes it must be extended so far as to become several times the critical distance. The Table enables determination of the measurement-line.

It must be borne in mind that the step-by-step calculation of Z_n or T_{in} is not very accurate, as small errors in each step tend to multiply and cumulate in computing the later steps, the calculation, besides, being applicable only to an area of very regular and simple geologic formation.

Lastly, since the refraction method may be applicable to areas of steep discontinuity, such as faults, which are often met with in the subterranean structures of coal fields, the methcd gives useful informa tion regarding the general geology of a coal-field, such as the thickness of the layers and their dips.

18. 炭田に於ける彈性波式探査法

地震研究所 那 須 信 治

炭田に於て實施する彈性波式探査法の目的は炭田の地質構造の全般的なものを知るにある．即ち挾炭層の存在する深さ，厚さ或はそれが斷層によつて落差を生じてゐるや否やを確かめるにある．筆者等の調査せる炭田に於ては挾炭層（第三紀層）は多くはこれより新しい岩石層に覆はれ，彈性波の傳播經路より考察すれば第一の速度不連續層がこれに相當する場合が多いやうである．但し或る地方では挾炭層の上部に二以上の層が存在することもあり，又直接地表に挾炭層の現はれてゐるところもある．

本論文に於ては從來調査せられたる結果の概略に就いて記しておいた．（詳細なことは諸種の事情により發表を差控えた）．

調査法の實用上に關する事項としては層の深さ及び厚さの求め方を記述し，實際上最も重要なる事項の一つとして測線の長さに關する事項．遮軸時間 (Intercept time)，臨界距離 (Critical distance) 等は實際の例によりこれを示し，一般炭田調査の參考とした．

彈性波の屈折法に於ては基盤が可成り急傾斜をなす場合でも又斷層によつて段違ひのある場合でもその形を求めることが出來るから斷層に屢々遭遇する炭田の調査に於ては專らこの方法による方がよい．

實際調査された炭田の例としては中國地方の1箇所（海底）北海道1箇所，九州3箇所（内海底1箇所）及び甲斐1箇所の6を選んだ．