Seismic Sounding of Shallow Depths

By H. HEDSTRÖM and R. KOLLERT, Stockholm[1]

(Manuscript received 14 October 1949)

Abstract

After a short review of the development of "artificial seismology" a description is given of the modern field procedure when using the seismic refraction method for measuring of small depths, of the order of only a few meters. A small portable instrument equipment used for this purpose is described. The theoretical and physical basis for the seismic exploration method is briefly discussed, and by an example it is shown that laboratory tests on rock samples can be used to calculate the transmission velocity of seismic waves. Some examples are given on the use of the seismic refraction method for civil engineering work. It is also related how the small portable instrument equipment previously described was used to measure the thickness of a glacier by means of the seismic reflection method. Repeated reflections (reverberations) were obtained and the smallest depth accurately determined in this way was 96 m.

The science of seismology, which dates back to the middle of the eighteenth century, developed into a science in the modern sense during the last decades of last century, when instruments of sufficient sensitivity, damping, and so on, had been developed for registration of earth tremors. About the turn of the century a complete theory had been developed for the transmission of seismic waves through the earth. (WIECHERT and ZÖPPRITZ 1907, WIECHERT 1910.)

From the studies of seismograms obtained during earthquakes the seismologists have generally assumed the existence of three main horizontal discontinuity surfaces in the earth's interior, at depths of about 30, at 1,000 and 2,900 km, respectively. (Attempts have also been made to subdivide the region between 30 and 2900 km depth in 6 "concentric shells", each with its characteristic transmission velocity of the seismic waves.) The first discontinuity surface, known as the *Mohorovičić Discontinuity*, is considered to be the contact surface between the "crystalline" crust of the earth and the underlying "vitreous" silicate shell, which has a thickness of some 950 km. At the depth 1000 km one has the upper surface of a thick sulphide-oxide shell which reaches down to a depth of 2,900 km, where it rests on the nickel-iron core of the earth.

In a recent paper by L. MINTROP (1949) the author says: "It has been much easier for the seismologists to determine the core of the earth at a depth of about 2,900 km than any interface between two formations with different wave velocities within the crust of the earth." However, in 1947 the depth to the "Peridotite layer", with a wave velocity of 8.1 km/sec was determined to be 27 ± 3 km, from seismograms obtained at the great explosion of 4,000 tons of munitions on Heligoland (18.4.1947), in 19 stations with distances up to 608 km from the explosion. No deeper discontinuities were reported at the time. From a study of seismograms from this explosion and from a number of earthquakes and also from previous observations by leading geophysicists, MINTROP now arrives

[1] AB Elektrisk Malmletning.

at the following "stratigraphy" for the uppermost part of the earth's crust. (V-longitudinal = velocity of dilatational waves; V-transversal = velocity of distorsional waves.)

Depth km	V-long. km/sec	V-transv. km/sec	Rock
0— 4	3.5	2.0	Sediments
4—13	5.2	2.9	Granite
13—28	6.5	3.6	Basalts
Mohorovičič Discontinuity			
28— 57	8.1	4.5	Peridotite
57—110	9.2	5.0	Pyroxenite?
110—118	7.0	—	(Plastic layer)
118—170	11.0	6.2	?
170—183	16.3	8.8	?
183—230	ca. 9.0	ca. 5.0	Alternatingly plastic and solid formations

Experimental study on "artificial" earthquakes were first taken up about 100 years ago (MALLET 1851). Buried gunpowder charges were detonated, and the resulting elastic vibrations set up in ground were picked up at a distance by means of rather primitive "seismoscopes". It was observed that different rock formations were characterized by different velocities for the seismic waves, although accurate determinations of the velocities could not be obtained. H. L. ABBOT was the first observer to take advantage, in 1876, of the exploding of a large dynamite charge (25 tons) to measure the transmission velocities of seismic waves near the earth's surface (ABBOT 1878). Seismoscopes were set up at distances from 8 to 19 km. Unfortunately the results of the measurements were rather poor because the sensitivity of the seismoscopes was too low. Some more experimental work was done up to about 1900, when it was first recognized that the seismometers would have to be much more sensitive than previously assumed in order to register the first weak pulse to arrive, before the arrival of later pulses of high amplitude.

In the first decade of the present century it gradually became clear that there might be some practical and commercial use for "artificial" seismology. WIECHERT's above mentioned paper of 1910 marked a turning point. In an article the same year MINTROP made references to practical uses of the method, and in 1914 J. WILIP in an article wrote:

"Up to the present it has not been possible to quite accurately determine the hodograph (travelling time curve) of the seismic rays for shorter distances, and the topmost layers of the earth's crust. However, it is the very characteristics of the vibrations of the topmost layers of the earth's crust which could be of great practical importance in that they may give us information about those parts of the earth's crust in which mining operations are carried on" (WILIP 1914).

In 1919 MINTROP applied for a patent in Germany covering the use of "refraction profiling" for determining the depth and type of subsurface formations. Exploration work with this *"refraction method"* was first carried out in North Sweden by MINTROP and his associates in 1922. In the following year the method was introduced for oil prospecting work in Mexico and 1924 in U.S.A., on the Gulf Coast, where it promptly led to the discovery of a number of oil fields during the next few years. In 1929 the number of "refraction seismographs" at work in U.S.A. had already risen to 175.

The seismic *"reflection method"*, which is in principle similar to the marine echo sounding, has been worked out, from the beginning, in U.S.A., where a patent for the method was applied for in 1919 by J. C. KARCHER. At first comparatively little work was done with this method and technical progress was slow. About 1930, however, the method was definitely established and by 1937 there were between 225 and 250 "reflection crews" working in U.S.A., as against 4 in 1929.

Last year (1948) the number of seismic crews operating in U.S.A. was estimated at about 450, corresponding to an annual expenditure for "artificial seismology" of the order of 100 million dollars.

In Sweden the refraction method was first used in Västerbotten (ore prospecting purposes) in 1922, later on, 1938—40, in Scania for large-scale structure mapping of the Cretaceous sediments in that region, and from 1941 also for civil engineering purposes. For the seismic refraction work in Scania the distances between shot point and seismometers were of the order 300 m to 17 km and the largest depths determined generally under 5—6 overlying layers with successively higher wave velocity were

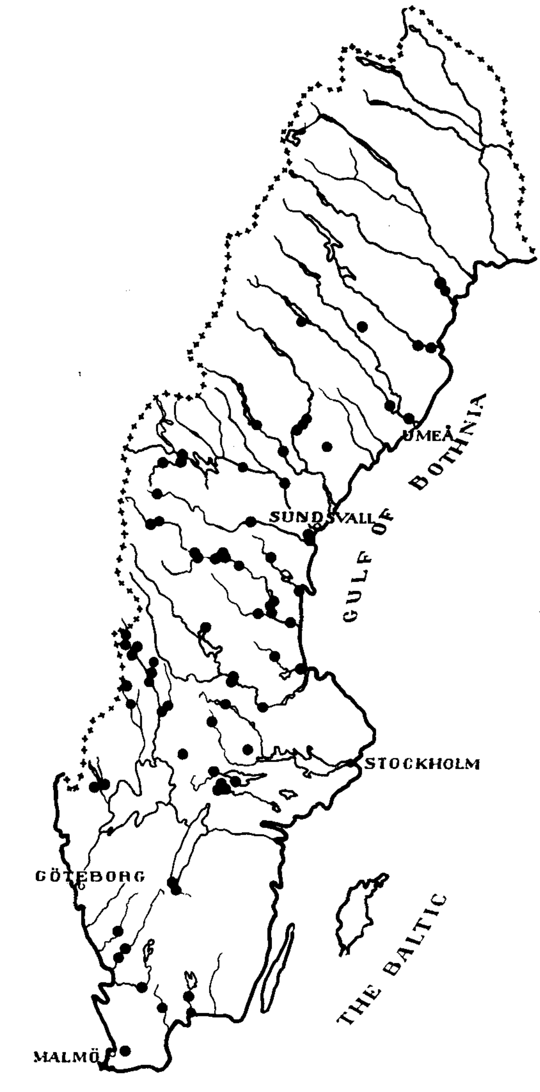

Fig. 1. Places in Sweden where the seismic method has been used for determination of depth-to-bedrock. In the two years 1947 and 1948 alone 51 contract jobs have been completed, resulting in 4,381 depth determinations, each one a substitute for a bore hole down to solid bedrock.

between 2,500—3,000 m, corresponding to the depth to the crystalline basement under the thick sedimentary cover in this part of the country. In this work, as well as in seismic reflection work carried out in the same area in the following years, the depths measured were thus still of the orders of kilometers or parts of kilometers. This is the case in all seismic exploration work in oil field terrain — the smallest depth that is said to have been measured by means of the seismic reflection method, is about 200 m, and generally the depths measured are of the order of 1,000—2,000 m.

In the above mentioned application of the refraction method for civil engineering purposes on the other hand, the depths involved are very often of the order of a few (2—3) meters only, and the depths will often change very quickly along a profile on the ground, necessitating a lot of careful detail work. Generally, the problem is to determine, rapidly, cheaply and accurately, the contour of a buried hard-rock surface under a cover of soil, sand and clay, glacial drift and hard moraine, which may vary in thickness from 1—80 m. In the last few years this work has reached considerable proportions, for Swedish conditions. The number of complete depth determinations of this work now totals about 8,000 (average depth to bedrock 12.1 m) divided on a number of contract jobs within Sweden, mostly in connection with water power projects. (Fig. 1.)

Field Procedure and Apparatus

In the above mentioned paper of 1910 WIECHERT described the principle of "refraction profiling" in the following way:

"The farther from the origin the earthquake waves are observed at the earth's surface, the deeper the rays have penetrated into the earth and the more of the assumed layers they have therefore traversed. If one therefore proceeds from the origin gradually in the distance, then initially only the first, later also the second, and then the third, and so on of the layers will come into action. One proceeds correspondingly with the computation. From the observations in the vicinity of the origin one draws conclusions first regarding the constants ... of the first layer ... The paths of all rays through this layer can then be calculated. From the paths of those rays which penetrate the first layer but remain close to it one draws conclusions regarding ... the second layer, and so on, in this manner."

This description fits very closely to the present practice of refraction profiling which is in civil engineering work carried out in the following manner.

Fig. 2. Seismic registration along a proposed tunnel line in central Sweden.

A profile line is staked out on the ground and measured off from one end, where a shot point is planned for. Further shot points are placed in the points 30 m, 55 m, 70 m a.s.f. from the first shot point. The seismometers are then placed on the ground along the profile at intervals of 5 m. For best efficiency and good portability under average field conditions one uses generally 6 seismometers. The first seismometer set-up will therefore cover the section 0—30 m of the profile, with 2.5 m distance from the shot points to the nearest seismometers. Each seismometer is connected to the recording equipment by means of a two conductor cable of 200 m length. The recording equipment consists of a set of 6 amplifiers, a recorder with oscillographs, timing device and camera, and also equipment like shooting box, storage battery etc. From the recording apparatus two-conductor cables are layed out to the shot points at 0 and 30, but also to the shot points at 55, 80 and 105, and so on. After these preparations the shots (with 50—250 gr dynamite) in the shot points 0, 30, 55 and 80 are fired in rapid succession. Then the seismometers 1—5 are moved into the section between the shot points at 30 and 55 meters. Seismometer number 6, however, remains in its place and becomes number 1 in the new set up. The double record obtained in this station delivers the correction which has to be applied to the travel-times if the conditions

Fig. 3. Rope-way across a rapid, for the placing of explosive charges at the river bottom.

in a shot point should change between two successive shots. (The preceding shot might have aerated the soil, driven out the pore water etc.) Then the shots in 0, 30, 55, 80 and 105 are shot successively. The seismometers are now moved into the third profile section, except the one at 52.5 m, which stays where it is. The firing line to shot point 30 is moved to shot point 130 and shots are fired in 30, 55, 80, 105 and 130. This procedure is continued throughout the entire profile length.

For the planning of water power projects seismic depth-to-bedrock determinations often have to be carried out under lakes and rivers, and across rapids.

When one is working across fairly quiet waters, a long (up to 1 km) wire, also used as measuring tape, is stretched out along the profile line from bank to bank or between anchored boats. It is supported by small floats which keep it near the surface. Along this wire the work is carried out from small boats. In this case it is preferable to have seismometers in fixed positions on the bottom at the points 0, 30, 55 a.s.o. and to shoot in the points (at the lake bottom) corresponding to the seismometer positions of the above example.

When profiling across rapids one makes use of "travelling shotpoint", while the seismometers remain fixed at their stations on each bank of the river. Two wires are stretched

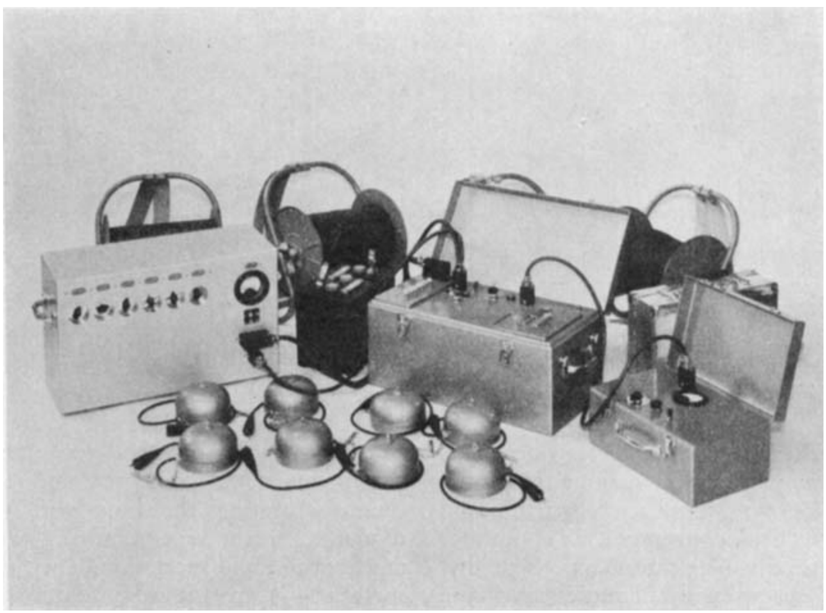

Fig. 4. Modern seismic equipment for depth-to-bedrock determinations. The heaviest piece weighs 53 pounds (24 kg), the total weight is 330 pounds (150 kg.). — In front 8 seismometers, at left behind seismometers the amplifier (for 6 "channels"), at right behind seismometers the recorder with oscillograph, timing device and camera, at extreme right the "fool-proofing" device for firing of shots and simultaneous starting of film in the recorder. In the background an accumulator battery, cable reels etc.

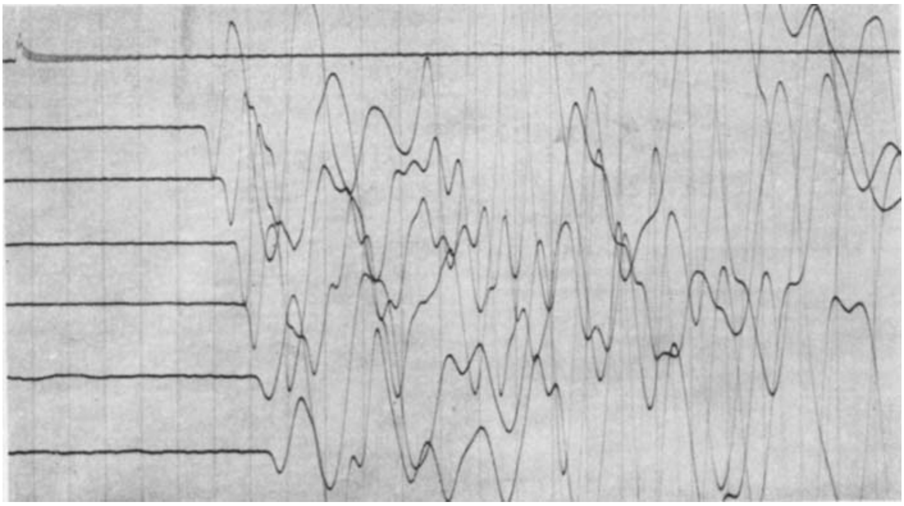

Fig. 5. Seismogram from a shot with a charge of 1 kg dynamite, recorded in stations which were 220 m to 320 m apart from the shot point.

across the river at a distance of about two metres from each other. One wire serves to suspend the cables which connect the seismometers on the other side of the river with the recording equipment. On the other wire, which is actually an aerial rope-way, a device is mounted which can be drawn across the river by means of a light wire (fig. 3). The explosive charge (0.2—0.5 kg dynamite), weighted with a heavy piece of scrap iron or a stone, is fixed to this device and pulled out to a certain point along the profile. By a sudden pull in a "release" wire, a clamping device which holds the explosive charge lets go and the charge drops to the river bottom without appreciable off-drift. The charge is then detonated and the procedure is repeated in a point 5 m farther away along the traverse.

The seismometers referred to above pick up the ground vibrations caused by the explosions and transform them into electrical pulses. A seismometer belonging to the equipment shown in fig. 4 consists in principle of a permanent magnet, rigidly connected to the casing, and a moving armature which is suspended by springs. The vibrations cause changes of the air gap between magnet and armature, causing changes in the magnetic flux due to which a voltage is induced in the coil around the armature. This voltage is as high as 5 mV, measured over a load resistance of 500 ohms for vibrations of 40 c.p.s. of 0.001 mm amplitude. The seismometers are shaped like hemispheres with the center of gravity near the large flat bottom. Due to the "streamlined" shape the effect of wind noise is reduced to a minimum. The construction is waterproof and very solid, and clamping (arresting) of the seismometers is never required.

The amplifier mentioned above and shown in fig. 4 has 6 "channels", one for each working seismometer, in which the weak pulses from the seismometers are amplified (some 60,000 times) before they are delivered to the recorder. The amplification for each channel can easily be adjusted so that a suitable deflection is obtained on the corresponding oscillograph galvanometer (as can be observed on a ground glass window on the recorder.) The filament voltage for the amplifier unit — 6 volts — is delivered from a storage battery, the plate voltage from dry batteries.

The amplified pulses are photographically recorded on a fast moving photographic paper strip of 100 mm width (fig. 5). The recorder contains 7 galvanometers and all other means for photographic registration like light source and optical system, motor for paper transport and camera. It houses also a timing device of the shutter type (tuning fork with slotted diaphragms on the prongs) which projects time lines at intervals of 0.01 sec. on the record. One of the galvanometers is connected

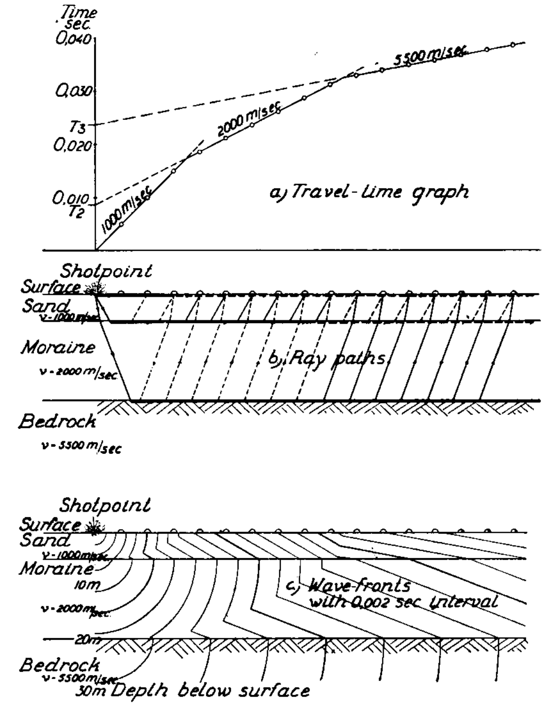

Fig. 6. Travel-time graph, ray path and wave front diagram calculated for a three 3-layer assumption.

to the shooting circuit and records the shot instant, the other 6 galvanometers register the vibrations picked up by the seismometers. The recording paper is transported by a D.C. motor, the speed of which is kept constant by a governor, which can be adjusted to a feed of 50 to 100 cm paper per second. Thus the time difference between shot instant and arrival of the impulses can be determined with an accuracy of better than one millisecond, depending upon the shape of the onset of the impulse. As a rule the travel time is read off with an accuracy of 0.2 milliseconds or better. The over-all amplification factor of the equipment, i.e. the ratio of the amplitude on the record to the amplitude of the ground vibrations is of the order of 4×10^6.

The sensitivity of the equipment is more than sufficient for refraction work on a large scale, where usually profiles of several kilometers' length are investigated. (The amplification will always have to be decreased until "the normal ground unrest" does not show up too much on the seismograms, and the size of the explosive charges used is then determined from this "permissible" amplification.) For work at which many short profiles have to be investigated, like at depth-to-bedrock determinations, several special features have been incorporated which facilitate the handling of the equipment and increase the efficiency. One of these arrangements is that the shot is automatically released by the camera at the instant when the recording paper has the proper speed and that recording is automatically stopped after a certain time. Another feature is the balanced shot circuit, resulting in transmission of the shot instant only, though the shot is fired via the same transmission line. Moreover the equipment is extremely portable. No part of it weighs more than 24 kg and the total weight, including cables and standard storage battery is about 150 kgs. The equipment can thus be transported by the normal working team generally consisting of 6 men, either on back or on simple transporting means like bicycle trailers or on sledges, depending on topography and season.

Interpretation and calculation work

If energy is suddenly imparted to the ground, e.g. by a blast of explosives, a small fraction of the energy is transmitted away from the shot point in the form of elastic waves of longitudinal and transversal types. Their velocity of propagation is widely different in different geological formations, and seismic exploration methods as described above can therefore be used to identify geological formations hidden in the subsurface. Hereby in general use is made only of the longitudinal wave, the velocity of propagation of which in the encountered formations is found in the following way.

The time elapsed between the shot-instant and the arrival of the first pulse at each seismometer station is read off from the seismogram. This time is plotted as ordinate to the corresponding distance of the seismometer station from the shot-point. When these "plots" are connected, a broken line, a so-called travel-time graph is obtained (fig. 6). The first part, beginning in the origin, corresponds to pulses from direct waves through the first (= surface) layer and therefore the velocity of propagation in this layer $V_1 = dx/dy$. In the points on the next part of the travel-time graph, those waves which have penetrated to larger depth and travelled with high speed along the surface of the second layer and back to the surface have overtaken the waves in the first layer and are the first ones to arrive. The ratio dx/dy for this part of the travel-time graph gives the true value for the velocity of wave propagation V_2 in the second layer, provided that the interface is parallel to the surface (and an *apparent* velocity when this is not the case). For the determination of the true value V_2 one will therefore generally need travel-time graphs shot from both ends of the profile.

Some velocities of wave propagation which are usually encountered for soil types and rocks in Sweden are given in the following table.

Soil types and rocks	V in m/sec.
dry sand	300—500
glacial drift (boulders embedded in grit, sand. clay)	1,200—1,700
hard moraine	2,200—3,000
bedrock (granite, gneis)	5,000—5,500

The travel-time curves yield, however, also data from which the depth to the interfaces of the different layers can be calculated. As the geometry of the "ray path", corresponding to the shortest time of travel, is determined by the same principle which FERMAT developed for the propagation of light, the formulas for depth calculations are easily derived. For the simple case of 3 layers with interfaces parallel to the surface, as illustrated in fig. 6, the following relations give the travel-time for any station of the travel-time graph:

Section 1: $t_1 = \Delta/V_1$

Section 2: $t_2 = T_2 + \Delta/V_2 = 2\,h_1 \cos i_{12}/V_1 + \Delta/V_2$

Section 3: $t_3 = T_3 + \Delta/V_3 = 2\,h_1 \cos i_{13}/V_1 + 2\,h_2 \cos i_{23}/V_2 + \Delta/V_3$ a.s.o.

where t_1, t_2 and t_3 are the traveltimes for points in the three sections of the graph at any distance Δ from the shot point, T_2 and T_3 the time intercept on the ordinate in the shot point, V_1, V_2 and V_3 the true velocities in the corresponding layers, h_1 and h_2 the thickness of the first and second layer respectively and i the respective angles of total reflection. From these expressions, formulas for the thickness of the layers can be derived. Thus for the first layer we may write

$$T_2 = 2\,h_1 \cos i_{12}/V_1$$

and therefore

$$h_1 = \frac{V_1\,T_2}{2\cos i_{12}}, \text{ etc.}$$

An other type of formulas for depth calculations uses the distance x of the breaking points in the travel-time graph from the shot point. The corresponding expression of the depth h_1 to the first interface (= thickness of the first layer) is

$$h_1 = \frac{x}{2}\sqrt{\frac{V_2 - V_1}{V_2 + V_1}}$$

The depth formulas become rather complicated when dealing with several layers, especially when the interfaces are not parallel to the surface nor to each other. For these cases each computor usually has diagrams of his own construction in order to simplify the calculation operations. In many cases it will be still more convenient to evaluate the depths graphically by means of wave-front constructions according to HUYGENS principle. A description of this procedure will, however, carry too far for this paper and reference must be made to seismic literature. (ANSEL 1931, THORNBURGH 1930.)

The velocity of propagation of the elastic waves in the ground is directly related to the elastic constants of the geological formations penetrated by the waves. It can be shown mathematically that this velocity, for the longitudinal and the transversal waves, is given by the formulas:

$$V = \sqrt{\frac{G}{\varrho}}\sqrt{\frac{4 + E/G}{3 + E/G}} \text{ or } = \sqrt{\frac{k + \frac{4}{3}G}{\varrho}}$$

$$\text{and } v_{\text{trans}} = \sqrt{\frac{G}{\varrho}}$$

where

E = Young's modulus (stress-strain ratio for elongation or compression)

G = rigidity modulus (stress-strain ratio for change of shape e.g. twisting)

$\frac{1}{k}$ = compressibility (fractional change of volume per unit increase of hydrostatic pressure)

ϱ = specific gravity (volume weight)

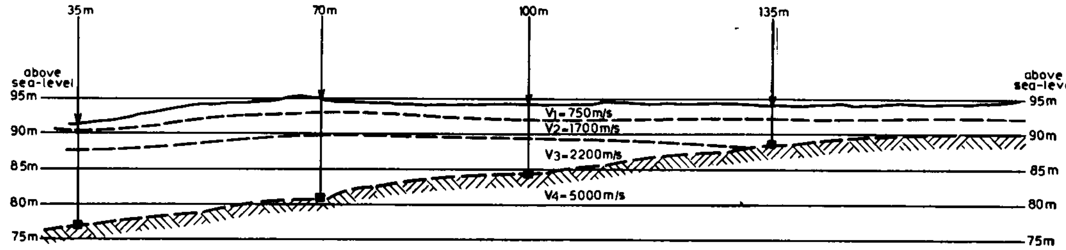

Fig. 7. Section showing bedrock profile and overburden layers as determined through a seismic investigation.

Thus from the velocities measured in the field the elastic constants for the material of the "subsurface" can be calculated and conversely the velocities can be calculated when these constants are known. The elastic constants can be determined by laboratory tests on samples either by static or by dynamic methods. Static methods usually do not give accurate results on samples taken near the surface, (weathered, fractured), due to permanent "setting", or hysteresis phenomena, after the first application of the load, while the dynamic methods furnish satisfactory and reproducable results in most cases. Through IDE's method (1935, 1936), YOUNG's modulus is determined from the natural frequency of longitudinal vibrations in the length direction of a bar cut out of the material to be investigated, and for determination of the rigidity modulus the bar is brought into torsional vibrations. A comparison of the elastic constants as obtained by this method and as calculated from the velocities found in seismic field work will generally show good agreement.

As example may be cited an instance where drill cores from an exploration drill-hole in the southernmost part of Sweden were subjected to laboratory investigations. The method used for the tests was similar to IDE's above mentioned method, i.e. the test samples were subjected to vibrations of varying frequency, and a "spectrum" of resonance frequences was determined. In all 47 drill cores were tested, from depths between 328 and 1,097 m. From the elastic constants determined, and from the volume weights, the "velocity of sound" in each sample was determined. From these figures an average velocity for the longitudinal seismic wave between 330 and 1,100 m depth was determined. Further, the corresponding velocity down to a depth of 330 m had previously been determined through seismic work with the refraction method. The combination of these results gave an average velocity down to a depth of 1,100 m of 3,350 m/sec. Reflection work in the same area, with the reflection profiles extended comparatively far out from the shot point, had indicated a "vertical velocity" from a depth of about 1,250 m of 3,250 m/sec. In this same area reflections had been obtained at 0.772 sec., at 1.092 sec. and at 1.307 sec. Using the average velocity of 3,350 m/sec., the reflection time 0.772 sec. gave a depth to the reflecting surface of 1292 m. At a depth of 1,285 m the drill hole passed from a thick, sandy and porous formation into a clayey, harder formation of considerable thickness. No doubt this interface was the one that had caused the reflection at 0.772 sec. This goes to show that very good agreement can be obtained between field results and dynamic test results on samples in the laboratory.

Practical Results

The field procedure described above has been developed on the base of experience from the interpretation of tens of thousands of seismograms. It was soon found that travel-time graphs, obtained from shots at the end points of a profile of no greater length than necessary in order to reach the depth required, do not furnish sufficient data for a correct interpretation. One reason for this is that the velocities that are characteristic of the uppermost layers of the overburden often vary irregularly and quickly along the profile, due to variations in weathering and aerating. Other reasons are irregularly varying thickness, along the profile, of the different layers in the overburden, (fig. 7), and rough configuration of the bedrock surface (quickly changing depth along the profile). Therefore the investigation must furnish sufficient data to give a continuous record of the changes of velocity in the overburden layers and especially in the surface layer—where it may in places be as low as about 150 m/sec. due to aeration. It must also give continuous information regarding the configuration of the rock surface all along the profile, and especially underneath the shotpoints. The field technique described above is the result of these considerations. From this shooting scheme it follows that for each shot point a travel-time graph is obtained in each direction and of such a length that impulses from the bedrock surface are obtained over a sufficiently long distance. In that way the "bedrock-sections" of the travel-time graphs, shot in the same direction from two adjacent shot points, overlap each other for a certain distance. The same holds also for the sections of the travel-time graphs belonging to the deeper layers of the overburden. In this manner continuous observation of all layers is obtained all along the profile, thus facilitating the interpretation of the travel-time graphs. This shooting technique has proved to be satisfactory with regard to interpretation at the same time being very efficient.

On land a seismic crew, consisting of one observer and 6 helpers, covers on the average a profile length of about 150 m per day, corresponding to 750—900 m length of travel-time graphs per day. This involves recording of 25—30 shots for 5 to 6 seismometer set-ups. Under favourable conditions an efficiency has been reached of 400 m of profile, corresponding to 2000 m travel-time graphs per day, over several days in succession, with up to 60 shots per day. On lakes, about the same efficiency is usually reached at the cost of 1 or 2 more men who prepare the wire arrangement. In work across rapids usually one profile (of say 80—100 m length) is surveyed per day. In one such instance a seismic survey across a river was made with the object of determining the width of a shear zone that was expected to run along the center of the river. The investigation gave depths to bedrock in the center of the shallow river of some 50 feet, where it had previously been assumed that the bedrock was "outcropping". Subsequent drilling fully confirmed the picture obtained from the seismic work. The first two of these bore holes took five weeks to complete, each hole naturally giving the depth at one single point only. At the seismic investigation each traverse took only one day to complete, resulting in a complete bedrock profile across the river, and 5 such traverses could be measured at the cost of one single bore hole.

The accuracy of these seismic depth-to-bedrock determinations is largely dependent on local conditions in regard to the composition of the overburden and the configuration of the bedrock surface. The data collected from the field work described above are sufficient for an accurate interpretation. However, it goes without saying that a good deal of experience, and a sufficient knowledge of physics and geology, is required from the "interpreter" of the field results, if the best accuracy possible is to be obtained. In this calculation work it is necessary that the interpreter can at all times feel sure about the measurements made with the instrument equipment. With the equipment described above this is positively the case —as a result of criticism and suggestions from field crews it has been continually improved during 8 years of field work under partly very difficult conditions, until it is now considered "fool-proof".

From excavations made and drill holes put down after seismic depth-to-bedrock determinations in Sweden it has been found that the accuracy of the seismic depth determination can be put at about $\pm$ 10 % of the depth, or to $\pm$ 1 m at depths smaller than 10 m. In places with "normal" and fairly favourable conditions the difference between the seismic depths and the results of subsequent drilling usually is only a few decimeters. Where the bedrock surface has very strong relief, which often happens in Sweden, it must be kept in mind that the depth obtained from a seismic survey represents the average along a certain length of profile, while a drill hole gives the depth in one point only. In such a case a drill hole 10—15 m off the profile may show a depth that appreciably differs from the seismic figures along the profile.

Fig. 8 shows a typical case of a seismic depth-to-bedrock determination at a proposed dam site. The greatly increased demand for this type of seismic work in Sweden in the last few years shows that the method is now looked upon by Swedish civil engineers as a convenient and reliable tool for quick recon-

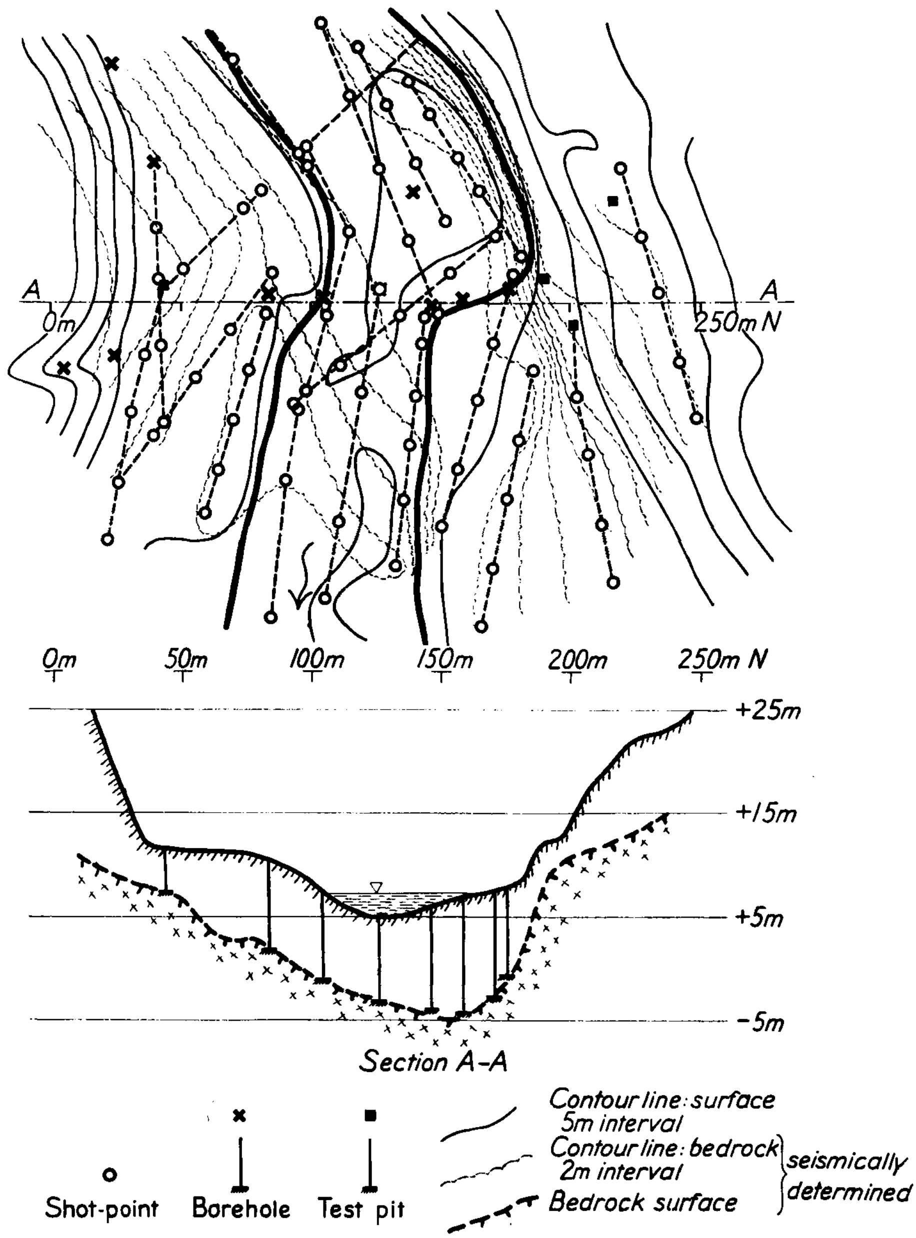

Fig. 8. Plan and section showing results of seismic investigation and of subsequent boring operations. Proposed dam site in northern Sweden.

naissance surveys of proposed sites for dams and tunnels.

The above equipment is now also being used for a very special purpose, namely for determination of the thickness of glaciers. The amplifier set shown in fig. 4, however, has then been replaced by an amplifier set with reflection amplifiers, including automatic gain control, variable filters and "mixing" (fig. 9).

This equipment has been put together for the Norwegian-Swedish-British Antarctic Expedition, which has just now started out. At

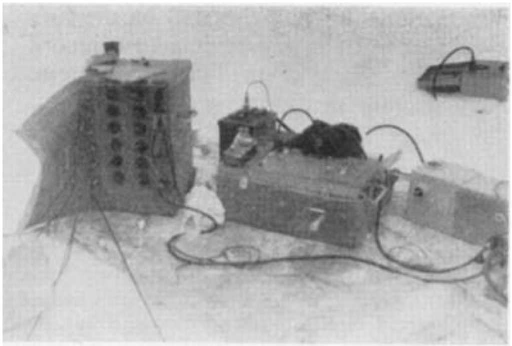

Fig. 9. Equipment used at the measurement on the main glacier of the Kebnekaise. At left the amplifier set with 6 reflection amplifiers, in the center the recorder with oscillograph, timing device and camera, at right the power unit and in the background an accumulator battery and the »fool-proofing» device for firing of shots with simultaneous starting of film in the recorder.

first a test was made on Hardangerjökul in Norway. From the experiences made during this test some modifications and special features have been included in the equipment and a final test has been made on the main glacier in the Kebnekaise mountains in North Sweden. One of the main objects with this test was to train the personnel of the above expedition in the handling of the instruments.

The equipment was sent by rail to Kiruna. From there part of the equipment was taken by airplane to Kebnekaise where it was dropped by means of parachutes. Other parts of the equipment were transported by motor car, boat and pack horse to the rim of the glacier, and from there transported on back and by sledge to the centre of the glacier. (Fig. 10.)

Where the ice was covered by 1—2 m of firn it was found that charges of 3—5 gr dynamite, exploded in drill holes at a depth of 1—2 m would give good reflections. Where the firn cover was very thick, charges of up to 60 gr of dynamite had to be used, fired in drill holes of 2—3 m depth. For refraction work, with profile lengths up to 600 m, it was found that charges of up to 1 kg dynamite had to be used, but that transmission of elastic vibrations to the firn could then easily be obtained if the charge was placed at the centre of a semi-spherical cavity in the firn surface, of about 1 m diameter.

From the refraction and reflection seismograms obtained from these measurements it was found that the velocity of transmission was 3450 m/sec. for the longitudinal waves and 1620 m/sec. for the transversal waves. Reflections were obtained for both types of waves. The optimal distance for these reflections seems to correspond to the largest possible angle of incidence, which of course must be smaller than the angle for total reflection for the interface between the ice and the bedrock underneath.

In one of the places tested, where the firn cover was fairly thin, reflections were obtained from both longitudinal and transversal waves. A calculation of the depth of the ice at this point gives for both reflections the same thickness of 96 m. One pronounced reverberation (repeated reflection) appears on all of the best records.

At another testing place, where the firn cover over the ice was evidently very thick, no transversal waves and no reverberations could be observed. Good reflections of longitudinal waves were obtained, however, and the depth evaluated from these reflections, and from the velocities determined by the refraction method, was 190 m. The probable reason for the absence of transversal waves in this case is that the firn has too small rigidity modulus to carry appreciable amplitudes of distorsional waves.

Although these tests on the main glacier of the Kebnekaise had only been planned as instrument check-ups and not as measurements

Fig. 10. Transport of the seismic equipment on the main glacier of the Kebnekaise.

of the thickness of the ice, their results are of considerable interest. They show that, by the use of modern equipment, ice thicknesses of less than 100 m can be measured by reflection shooting. As far as we know, these depth determinations (by R. TEGHOLM) on the Kebnekaise main glacier represent a new record in the determination of small depths by means of the reflection method.

REFERENCES

ABBOT, H. L., 1878: On the Velocity of Transmission of Earth Waves. *American Journal of Science and Arts*, Series 3, **15**, pp. 178—184, New Haven, Connecticut.

ANSEL, E. A., 1931: Das Impulsfeld der praktischen Seismik in graphischer Behandlung. *Erg. Hefte für angew. Geophysik* pp. 117—136.

IDE, JOHN M., 1935: Some Dynamic methods for Determination of Young's Modulus. *Rev. of Scient. instr.*, **6**, pp. 296—298.

— 1936: The Elastic Properties of Rocks: A Correlation of Theory and Experiment. *Proceedings National Academy of Science*, **22**, pp. 482—496.

MALLET, ROBERT, 1851: Second Report on the Facts of Earthquake Phenomena. *British Ass. for the Advancement of Science*, **21**, pp. 272—320, London.

MINTROP, L., 1949: On the Stratification of the Earth's Crust According to Seismic Studies of a Large Explosion and of Earthquakes. *Geophysics*, July, Number 3, pp. 321—336.

THORNBURGH, H. R., 1930: Wave-Front Diagrams in Seismic Interpretation. *Bull. of Am. Ass. of Petr. Geol.*, **14**, 2, pp. 185—200.

WIECHERT, E., 1910: Bestimmung des Weges der Erdbebenwellen im Erdinnern. *Physikalische Zeitschrift*, **11**, pp. 294—311.

WIECHERT, E. and ZÖPRITZ, K., 1907: Über Erdbebenwellen. *Nachrichten von der Königlichen Gesellschaft der Wissenschaften zu Göttingen*, pp. 415—549, Berlin.

WILIP, J., 1914: On an Artificial Earthquake Recorded at Pulkovo. *Proceedings of Permanent Central Seismic Commission*, **6**, 2 pp. 173—184.