Seismic Surveying Methods, Equipment And Costs In New York State

FRANCIS R. IRVING
Senior Engineering Geologist, Bureau of Soil Mechanics
New York State Department of Public Works

Seismic surveys for highway location, design, estimate and construction purposes have been conducted since 1948. Since 1956, two complete parties have been continuously engaged in these operations throughout each year, winter and summer.

This paper describes the methods and equipment used in performing seismic surveys for highway engineering purposes. Also included are the total and unit costs involved in maintaining the parties and equipment and conducting the surveys.

•THE Bureau of Soil Mechanics of the New York State Department of Public Works has been utilizing geophysical methods of exploration in its highway, bridge, and building design and construction programs since 1948. In the beginning both the seismic refraction and electrical resistivity methods were tried. However, it was soon found that, with few exceptions, the seismic refraction method gave better answers to the engineering problems involved. At present, electrical resistivity surveys are used by the Bureau primarily as an aid in locating buried aquifers for subsurface water supplies at various state institutions and facilities.

More recently the shallow reflection method, using high-resolution seismic systems has been tried by the Bureau on some special problems. Further equipment development will undoubtedly increase the usefulness of this method; however, the refraction method is still the best approach to the average engineering problems that are encountered in New York State. This is due in part to the complex geology in the areas where most of the seismic work is carried out.

Seismic survey data are utilized by the Department primarily for design and estimate purposes. All subsurface information, including seismic data, is made available for the inspection of the bidders prior to letting. Such data are considered extremely important in preparing bids because New York State excavation specifications are on an unclassified basis.

The first seismic investigations made by the Bureau were conducted by Paul H. Bird, at that time the only engineering geologist employed by the Department. He quickly proved the worth of the method to the Department. Gradually, additional personnel, mainly geology graduates, were hired under technician titles to assist with the field operations. Because there were no permanent positions in the Department for additional geologists and, therefore, practically no chance for advancement, the personnel turnover was very high. Despite this, the Bureau maintained two crews in the field during much of the time between 1950 and 1956. Six permanent engineering geology positions were added to the Bureau's roster in late 1956. This immediately minimized the geologic personnel retention problems. Two seismic parties, composed of engineering geologists and laborers have been in the field constantly since that time.

At present, the engineering geology staff of the Bureau consists of one associate, one senior, four assistant and six junior engineering geologists. As many as eight of these men may be engaged in the seismic program at one time.

Paper sponsored by Committee on Surveying, Mapping and Classification of Soils and presented at the 43rd Annual Meeting.

METHOD

The theory of the seismic refraction method is simple and straightforward. It follows the laws and principles of optical geometry; that is:

1. Snell's Law: The sine of the angle of incidence is to the sine of the angle of refraction as the velocity in the first media is to the velocity in the second media.
2. Fermat's Principle: The shortest time path between two points is in accordance with Snell's Law.
3. Huygen's Principle: Each point on a wave front may be considered as a source of new wavelets which travel outward in the direction of propagation.

The interrelation of these statements is best illustrated in wave front diagrams. The construction of wave front diagrams for a series of special problems is one of the first steps used by the Bureau in familiarizing new employees with the seismic method.

The application of the refraction method consists of recording the time that it takes the seismic pulse from an energy source to arrive at successive stations, generally in a straight line with the origin point. A time-distance plot of these arrival times is then made, which gives velocities and angular relationships which are used in calculating depth. Certain inferences regarding the material underlying the seismic line may be drawn from the velocities.

For the method to work, certain physical requirements should exist in the area being investigated: (a) successively deeper layers should have successively higher velocities; (b) each layer must have a certain minimum velocity to thickness ratio in relation to the velocity to thickness ratio of the overlying layer and the velocity of the underlying layer in order to show up on the plot of first arrivals; and (c) velocities should remain constant laterally over the length of the seismic spread. Practical considerations make it evident that these conditions are often violated, especially in Pleistocene ice contact deposits. However, the wavelengths of frequencies that can propagate in natural earth materials are long enough so that minor deviations from the theoretical can be tolerated. Larger deviations from the theoretical case often show on the seismogram, giving valuable, if negative, information. For instance, in the first problem, a velocity inversion will often show up as a "skip" in the time-distance curve. This is a clear indication that a low velocity layer exists beneath a relatively thin high velocity layer. In granular materials, an inversion could mean a clay layer with the possibility of a perched water table. Considerable additional information can be gained in these cases by using record characteristics as well as the arrival times. The second and third problems are more instrumental than anything else, since their final solution depends on secondary breaks.

A basic rule followed by the Bureau of Soil Mechanics in applying the seismic method is to control everything possible at the field level. Precise systematic field work will eliminate many problems in interpretation. This means that all profiles, or seismic lines, must be reversed; i. e., shot at each end. Further, all reported shot points should be tied; i. e., common to two or more profiles.

One factor that can be controlled in the field is the effect of topographic irregularities. Any change in the general ground slope along the seismic line may result in ambiguous data. This does not mean that the data are useless, but it does mean that the topography must be accounted for in the interpretation of the data. Because topographic corrections in complex soil profiles are often difficult to make, it is better to lay out seismic lines so that changes in general ground slope are avoided wherever possible.

Another problem that can sometimes be controlled in the field is the velocity inversion caused by a thin layer of frozen ground. The wavelength of the lowest frequency that will propagate in a media is approximately equal to four times the thickness of that media. Briefly, the "skip" in the time-distance plot of Figure 1 is due to the fact that the relatively high frequency energy traveling in the high speed frozen ground dies out before the normal arrivals from the V_2 layer are due to arrive. At some previous point, the energy had diminished to the point where it could no longer sustain refractions down into the V_1 layer. It should be noted that as the frozen layer becomes

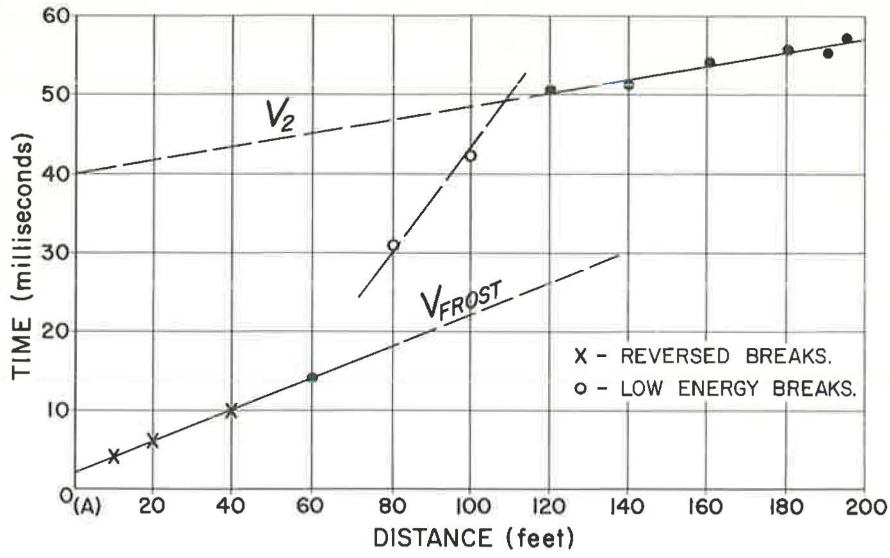

Figure 1. "Frost breaker" plot.

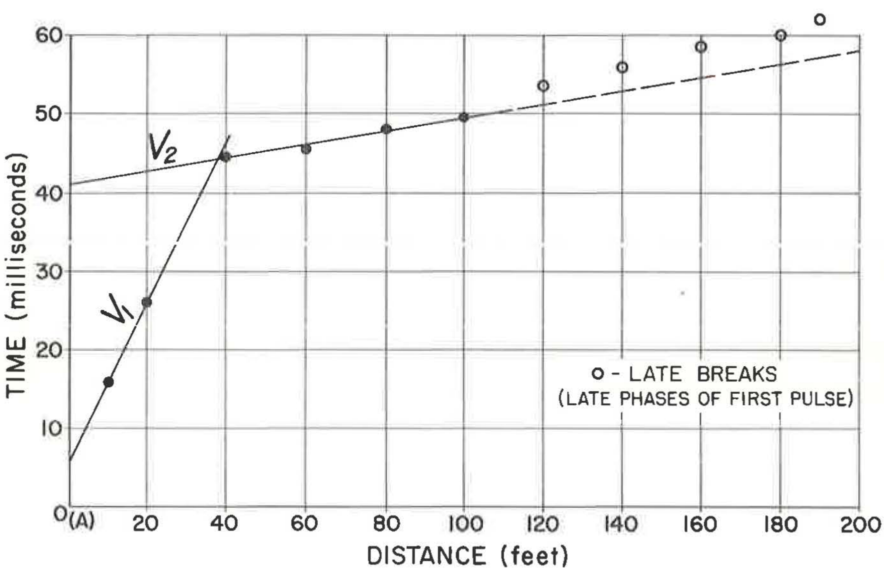

Figure 2. Small shot—following "frost breaker."

thicker, the energy lasts longer and the "skip" diminishes and finally disappears leaving a normal looking record except for some reversed breaks. Reversed breaks near the origin are common in frozen ground due to the angle at which the wave front strikes the seismometers. Although this problem can be solved theoretically if all the velocities involved are known, this is seldom the case. Therefore, it is better to eliminate the problem wherever possible. One way to do this is to use two shots at every shot point. The first shot is a relatively large shallow one, generally 1 to 2 lb, placed just below the frozen layer in two or three closely spaced holes. This shot is used to break up

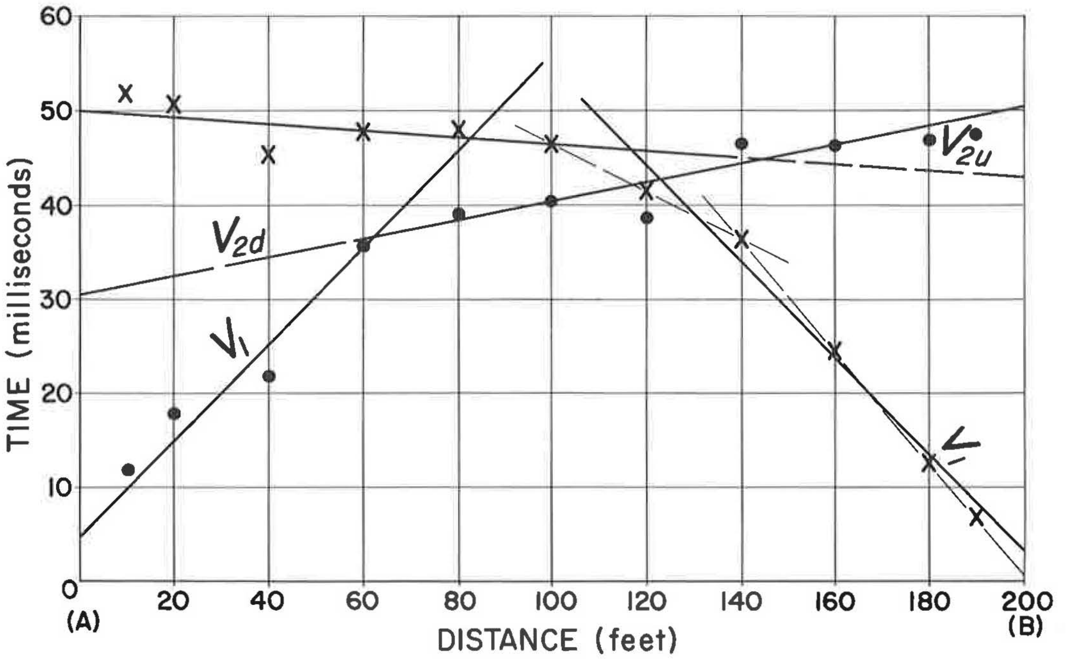

Figure 3. "Balance point" method.

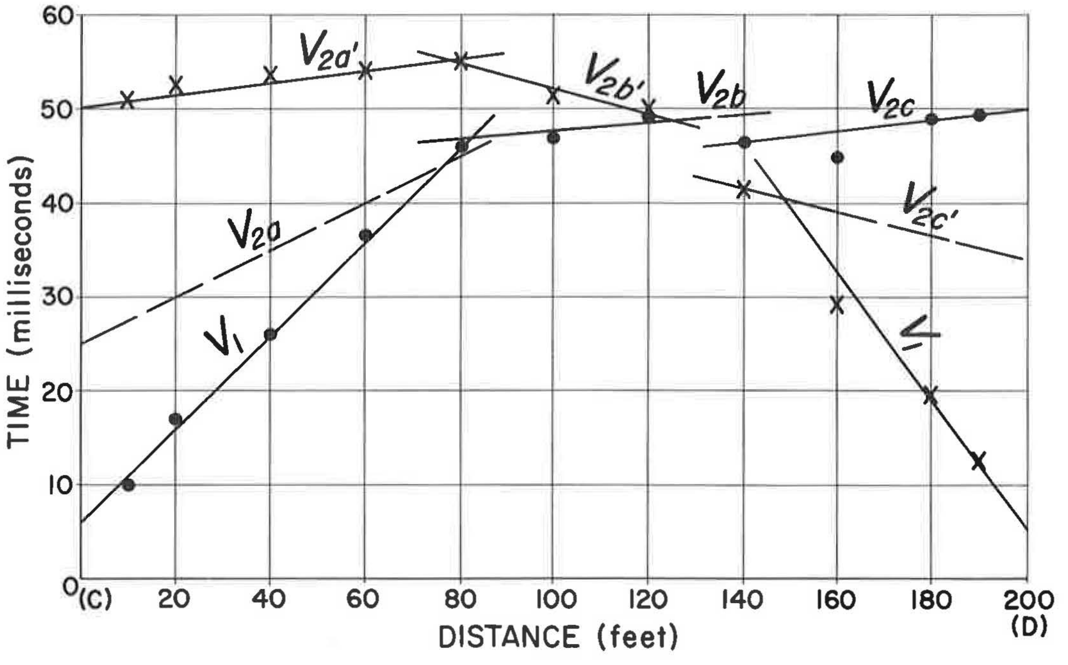

Figure 4. "Matched velocity" segments.

the frozen ground. The second charge is a very small one placed in the hole blown out by the first. The record from the first charge gives a valid rock line on the time-distance plot (Fig. 1), because, as long as the velocity of the rock, or whatever the second layer happens to be, is higher than the frozen ground velocity, the arrival times of the refracted wave will be affected by the frozen layer only on emerging. For thin frozen layers the effect on accuracy is negligible. The record from the second charge will usually give the surface velocity plus one or two arrivals on the rock line before the energy drops off (Fig. 2). Records from both charges may be combined to give a valid time-distance plot. Although this method is not feasible in some areas due to local culture or excessive thickness of frozen ground, it does permit seismic operations to continue in much of New York State during the winter months.

The reading of the seismic records is simply a matter of making the proper "picks" inasmuch as the cameras presently in use by the Bureau are equipped for two millisecond time lines. Good seismic breaks can be read to the nearest 0.5 millisecond. The actual drawing of the velocity line is done either by a balance point method or by a velocity segment method. Under the balance point method, readings that are late or early in one direction of a reversed profile are made late or early in the other direction (Fig. 3). If the relationship between the corresponding points on the reversed profile were not considered, the "B" end of Figure 3 could be misinterpreted as a three-layer problem, as shown by the dashed line. This system implies that the majority of the deviations are due to local near-surface differences. When this procedure will not fit the observed data, it usually means that the seismic interface will not fit an average line between the two shot points. Therefore, matching pairs of velocity segments are used. An example of this is shown in Figure 4, where the true velocity of V_2 may be determined from segments V_2b and V_2b^1 and the velocity of the segment V_2a found from the true velocity and the segment V_2a^1. Because V_2c is parallel to V_2b, V_2c' is drawn parallel to V_2b^1. One or the other of these methods combined with the information from the adjacent lines will usually give an unique solution. Statistical methods are used only when the record quality is very poor.

All computations done by the Bureau's seismic parties are based on theoretically correct formulas, most of which are dependent on "critical distance" (the distance from the origin at which the velocity lines intersect). These formulas are more accurate in practice than the time-intercept formulas (based on the time at which the extension of the velocity lines intersect the time axis). One reason for this is that small errors in reading the time intercept from the time-distance plot have a much greater effect on the calculated depth than do corresponding errors in reading the critical distance at the scales most commonly used in plotting shallow refraction data. For example, when $V_1 : V_2 = 1 : 2$, the effect on calculated depth of an error of one millisecond in reading the time intercept is equal to the effect of an error of almost 10 feet in reading the critical distance.

Constant charts and a mechanical calculator, which gives true velocity, mirage distance, constants, and dip angles, are used in the computations. Velocities are read directly from the time-distance plot simply by taking the number of feet traveled in 10 milliseconds and multiplying by 100 to obtain feet per second.

The actual plotting and calculating procedures are carried out in the field so that the best interpretation of the data can be made in the light of the local topographic and geologic conditions. The work sheets and report forms are reviewed in the main office of the Bureau before the final report is issued. Outcrop maps and geologic reports are submitted along with the seismic report wherever necessary.

EQUIPMENT

In general, it is the purpose of a seismic system to record the time that it takes a seismic pulse to travel from its origin to various recording stations along a governed path. In the shallow refraction method, we are primarily interested in the first pulse to reach any given station—i. e., the one that followed the shortest time path. There are certain criteria which are absolutely necessary to any seismic system:

1. It must have an accurate and easily read timing system.
2. It must have sufficient amplification so that the first pulse is recorded throughout the entire length of the seismic line (generally at least four times the depth of interest for control).
3. It should reproduce the incoming signals with a minimum of distortion and delay.
4. It should be rugged enough to withstand hard usage.

The original equipment purchased by the Bureau was a three-trace seismic system, consisting of carbon granular seismometers, string galvanometers and a 35-mm movie camera. The system was insensitive and required a rather large explosive charge to investigate to nominal depths. It was slow because it had only three recording channels. The film records were also inconvenient to process.

Two Century 12-trace portable refraction sets were purchased in 1950. These sets used electromagnetic pickups, push-pull amplifiers, D'Arsonval type galvanometers and recorded on photographic paper. The timing system was a vibrator-controlled motor-driven disk which gave 10-millisecond time lines. These sets were used by the Bureau until 1958, when they were replaced by two Texas Instrument 12-trace high-resolution systems.

The high-resolution systems are very versatile because of their wide frequency response, filter selection and high gain. Recording is similar to Century. Each unit is equipped with a tuning fork-controlled motor-driven drum which places time lines across the paper every two milliseconds. These units are used with a variety of land and underwater seismometers.

A small self-contained 12-trace Electro-Tech Instrument which records on Polaroid film has recently been purchased for use where access is extremely difficult. This set, in combination with a Century camera modified to give two-millisecond time lines, will be used to instrument a third seismic party.

Transportation is a problem in many areas in which seismic survey work is done. For this reason, each seismic system of the Bureau is mounted in a special body built on a four-wheel drive Dodge "Power Wagon" WM 300 pickup truck equipped with a front end winch. The truck body is constructed so that it is always ready for operation. The instruments are mounted in a separate light, tight compartment which is entered by a door located on the side of the truck (Fig. 5). Photographic supplies, spare parts, drafting equipment, etc., are stored in built-in cabinets in this compartment. The cables, shot lines, digging tools, etc., are stored in shelves which are entered from the rear of the truck. The use of seismic cable extensions up to 1,000 feet in length makes it unnecessary to remove the equipment from the trucks, except in rare instances.

Figure 5. Seismic truck—door to instrument compartment is just forward of right rear fender.

TABLE 1

SUMMARY OF COST ANALYSIS (1962)

Factor	Value
Total cost, 1962[a] ($)	100,895
Production:	
No. of determinations[b]	2,489
No. of ELF (equivalent linear feet, depth)[c]	138,570
No. of determinations/day/party	5
No. of ELF/day/party	278
No. of stations/day/party	10
Unit cost ($)	
Per determination	40.50
Per ELF	0.728
To maintain each party/working day	202.000

[a] Including salaries, "fringe benefits," travel expenses, automotive expenses, supplies, parts repairs, and depreciation of seismic and vehicular equipment.
[b] A determination consists of an average of 2 "shots."
[c] The "equivalent linear feet, depth" for any determination is based on the number of feet that would have to be drilled to determine the depth to the surface of bedrock (usually depth to rock plus 10 feet into rock to differentiate from a boulder, or cut depth plus ten feet—whichever is less).

During the winter months, much of the work is done on snowshoes. Whenever it is necessary to remove the equipment from the trucks, it is mounted in special racks built on fiberglass "snow boats." These snow boats are pulled by a motorized toboggan.

Each party is also equipped with a six-passenger station wagon for transportation of personnel and supplies to and from the project. The seismic trucks are left in the project area until the seismic work is completed.

COST OF SEISMIC SURVEY OPERATIONS

The Bureau maintains accurate cost accounting records of its seismic survey operations. A summary of the cost analysis for 1962 is given in Table 1. Because the outcrop maps and geologic reports are considered as essential parts of the seismic program, no attempt has been made to separate the costs of the two phases.

CONCLUSIONS

Based on 15 years' experience with the seismic method of subsurface exploration for public works engineering purposes, it is the opinion of the Bureau of Soil Mechanics that the seismic method presents a rapid, economical, and satisfactory exploration tool, provided the following conditions are met:

1. Properly trained personnel of adequate experience are employed. It is the opinion of the Bureau that seismic survey and interpretation personnel have an engineering geology education and experience background.

2. The seismic instrumentation system is capable of faithfully and consistently recording arriving pulses. In general, simplified insensitive equipment will not consistently provide usable data within the range of depths that is of interest to the highway and building designer.

3. The method is used on problems to which it is suited. Each method of subsurface exploration has its limitations. The seismic method is no exception in this respect. It is, therefore, necessary for any user of seismic survey information to realize the limitations of the method and not attempt to apply the method to problems to which it is not adaptable.