In engineering geology and mineral prospecting we sometimes need to find the dynamic elastic constants of rocks and soils near the surface. These determinations are usually made by measuring the velocities of propagation of longitudinal and transverse elastic waves by seismic methods: the most detailed and accurate results are given by observations in boreholes. The best type of seismic borehole measurement is ultrasonic well logging, but this may be impossible at shallow depths owing to absorption of high-frequency vibrations in a loose medium. The shallow modification of seismic logging with three-component geophones pressed against the side of the hole is perhaps the most universal method of shallow seismic investigations, in the sense that it enables us to measure the velocities of propagation and amplitudes of the longitudinal and transverse waves in practically any ground conditions [1, 2].

Various methods are used to measure these speeds at shallow depths with borehole geophones: the most accurate results are provided by the transmission method, in which a small explosive charge and two geophones are installed at the same depth (in 8 holes), and the wave velocity is determined from the difference in the times of passage of the waves. However, this method requires many boreholes and observations, and may be unsuitable for routine use. The aim of this article is to describe and recommend a method which is suitable for general application, and which requires only a few relatively unskilled operatives. We will therefore consider the simplest method of borehole measurement - vertical seismic logging - and will consider its capabilities in investigations of the elastic characteristics of soils lying at depths of 100-200 m.

The use of boreholes in measuring the velocities of propagation of waves at shallow depths is made possible by the existence of self-propelled drilling rigs which can drill down to 150 m, and of cheap portable seismic equipment.

Long-interval measurements of elastic wave velocities at shallow depths are often made by means of inverted seismic logging [3], in which waves, generated by detonators placed in water-filled boreholes at various depths, are received by three-component geophones at the surface near the borehole. This method does not require special equipment, but it is less generally applicable than normal seismic logging: more will be said on this point below.

Vertical seismic logging consists of recording seismic pulses with receivers placed successively at various depths, beginning with the maximum. Horizontal impact of a hammer on an expanding anvil, or on a pile driven into the ground, creates longitudinal and transverse waves which can be detected at depths of up to 100-300 m, depending on the properties of the ground. Identification of these waves on three-component records is not very difficult, because if the point of excitation is sufficiently near to the borehole, the longitudinal wave is recorded only by the vertical seismograph, and the transverse wave only by the horizontal seismograph.

In vertical seismic logging, the rate of propagation of the waves is given by the slope of the travel-time curve - the curve giving the time of passage of the wave versus the depth of the instrument in the borehole. The usual accuracy of determination of the moment of arrival of the wave is millisecond, which means that the averaging base length of the travel-time curve must be 5-20 m (according to the measured speed). This imposes certain limits on the detail of the results obtained.

In shallow-depth seismic investigations, the results are markedly affected by inhomogeneities in the material due to gravitational consolidation, and by the dissipative properties of the medium. The first of these effects requires that variation in the wave velocity with depth be considered (which is not usually done in studies at depths of hundreds or thousands of meters), and the second requires consideration of the broadening of the wave pulse when measuring the moment of arrival of the wave at the seismographs.
From the viewpoint of propagation of elastic vibrations with wavelengths of meters of tens of meters, broken deposits and ledge rocks may be regarded as loose media, in which the wave velocity depends on the contact elasticity of the material. The depth dependence of the velocity of propagation of elastic waves in a loose medium has been studied theoretically [4, 5] on various assumptions about the nature of the contacts. However, all these cases (except for that of particles in elastic contact) are complex, and the corresponding calculations require a knowledge of quantities which cannot be determined experimentally. Since the elastic case does not give the velocity-depth \((v, z)\) curve observed in soils, it is obviously convenient to try to match the \(v(z)\) curves; this can be done by comparing the observed travel-time curves with curves calculated for various functions \(v(z)\). The contribution of the theory here is that it predicts a \(v(z)\) curve of the form

\[
v(z) = v_0 + kz^n
\]

Hence matching reduces to a choice of suitable values for \(k\) and \(n\).

It should be mentioned that it would be incorrect to represent all soils in the form of media with wave velocities which vary continuously with depth: in the case of loose water-laden soils the velocity of the longitudinal wave is mainly determined by the compressibility of water. It is thus approximately 1600 m/sec, and does not vary with depth until the contact elasticity becomes comparable with the elasticity of water. Strata with constant wave velocity can also occur in frozen soils.

The law of variation of wave velocity with depth was investigated by approximating the travel-time curves from borehole observations at various depths. A law of variation of velocity with depth was sought in the form

\[
v(z) = kz^n
\]

The coefficients \(k\) and \(n\) were determined by superposing various curves of the form

\[
l(z) = \frac{n-1}{n} \frac{1}{k} z^{\frac{n-1}{n}},
\]

plotted on transparent paper, on to the experimental travel-time curves.

We used more than a hundred measurements in sedimentary rocks (dolomites, sandstones, and limestones), and in water-laden and dry loose soils. These measurements were made by vertical seismic logging to depths of 100-300 m. They corresponded best with the theoretical curves for \(n = 3\). Only in the upper parts of the loose water-laden soils did the transverse waves match better with the curve for \(n = 2\). The ranges of variation of the coefficients \(k/n\) for various soils are given in the following table.

The quantity \(v_s\) in Eq. (1) corresponds to the velocity of propagation of a wave on the surface. Evaluation of the seismic-logging travel-time curves showed that the influence of the surface layer (in which direct velocity measurements are impossible) has the result that the origins of coordinates do not coincide in the experimental and theoretical graphs, but fall with approximately equal probability on either side. Thus inhomogeneity in the elastic properties of the upper layer conceals any effect of a nonzero surface velocity for wave propagation. Thus, we can assume that the surface wave velocity is zero. The velocity in the uppermost layer, where we cannot measure the time of arrival of the waves, is most correctly determined by taking the value of \(k_s\) which corresponds to the line joining the upper points of the travel-time curve with the origin.