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SUBSURFACE GEOPHYSICAL METHODS USED TO DEFINE GEOMETRICAL OR STRUCTURAL CHARACTERISTICS

METHODES GEOPHYSIQUES DE SUBSURFACE, EMPLOYEES DE FACON PARAMETRIQUE OU STRUCTURALE

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Introduction

Site investigation techniques may be divided into two categories, destructive and non-destructive. Destructive techniques are those which, by their execution, in some way change the nature of the ground that they are investigating. Thus for example, plate bearing tests at the bottom of a shaft test ground influenced by the excavation of the shaft rather than undisturbed ground. Non-destructive techniques examine the ground without permanently altering its characteristics and are generally of an observational or geophysical nature.

Geophysical techniques fall into two main streams. In the first values of naturally occurring phenomena, such as gravity, magnetism or telluric currents, are measured with great accuracy, for values anomalous within general trends will reflect local geological conditions, In the second stream fall methods in which some form of signal is passed into the ground and changes or responses to the signal, resulting from geological conditions, are observed. Seismic and geo-electric techniques are the best known of this second group.

The causes of geophysical variations lie in the physical properties of the ground, such as elasticity, density, iron content and electrical conductivity. Some geological materials may be distinguished by these properties and thus the presence and boundaries of bodies of these materials may be determined by geophysical methods. The first and "traditional" use of geophysics in engineering geology was to determine boundary conditions. These techniques are now well known and are continually improving as the result of improved instrumentation and techniques of data analysis concomitant with general advances in electronics and computer sciences.

If geophysical anomalies caused by material properties allowed definition of geological bodies the idea soon came that material or mass properties might be assessed by studying the geophysical characteristics of known and defined geological bodies. One of the first applications of this idea was the concept of "rippability" determined by seismic velocity measurements on known rock materials. It was determined that particular lithologies had velocity signatures for fresh massive materials; as this material became weathered or fractured then velocities decreased and the ease of excavation increased. It was but a small step to tie velocity readings to lithologies to determine material excavatability using particular digging machinery. This somewhat simplistic but very practical approach has, despite its limitations and hazards, been in use for some two decades and is still a valuable aid to the assessment of rock mass "quality" with regard to excavation.

Since the days of the introduction of rippability geophysics has been often used as an aid to the assessment of mass quality with regard to a particular engineering process, the advantage being that the total mass can be examined as a whole. Mass "quality" can result from the combination of a variety of physical and structural properties. Should sufficient knowledge be available of some of these properties as the result of sampling and testing, then it may be possible to deduce other properties by processing the combined geophysical and testing data. The goal of such work is the determination of mass properties such as the deformability of foundation ground. The papers received for this symposium serve as a measuring staff indicating progress in the techniques of using geophysical methods in the assessment of material and mass quality and properties.

Review of the papers submitted

The 34 papers received may be divided into groups, defined by the geophysical method employed, in order to assess the relative popularity of the methods. The histogram given in Fig. 1 gives the percentages of methods employed in the works described in the papers. It is clear that the seismic geophysics method, in one form or another, is by far the most popular, followed by electrical resistivity and thence by a newcomer to the field of engineering geophysics, georadar. What was particularly significant for the author was that over 20 per cent of the papers dealt with the use of several methods in combination. However, it was also interesting to note that perhaps only eight of the papers submitted might be regarded as precisely relevant to the title of the topic.

Sixteen of the papers dealt only with seismic geophysics. Of these the determination of moduli of deformation was discussed by Aikäs, Lovén and Särkkä and of the dynamic properties of foundation rocks by Bruce, Wightman and Brown. Rock mass quality was assessed by Cosma by cross-hole measurements and thence mapping velocity densities of P and S waves. A method was proposed by Bolle for determining changes in weathering with depth by the analysis of seismic velocities while Fabre, Gamond, Giraud and Thouvenout have examined seismic velocity anisotropy in rocks with regard to rock fabric, structure and *in situ* stresses.

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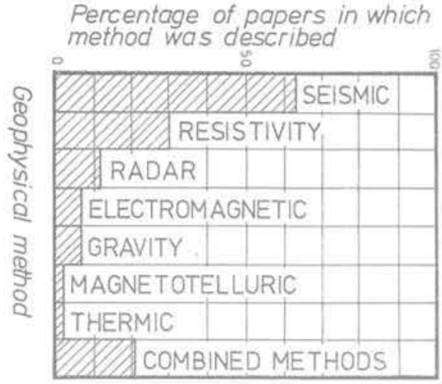

Fig. 1: Relative popularity of geophysical methods.

It is evident that the extending use of the seismic method owes much to improved instrumentation which in turn has allowed new techniques of application to be developed. A number of papers have mentioned new instrumentation but those in which it was of major importance were by Kobayashi, Yahiro, Kawamura, Ohta and Sugimoto in which a sonic 'crack detector' was described, by Carabelli and Superbo who described automatic generators for cross-hole measurements of P and S waves, and by Tonouchi, Sakayama and Imai who have given a refined technique for measuring S wave velocity in soft ground and thence related S wave velocities to other geotechnical parameters, in particular the N value derived from the standard penetration test.

The idea of correlating seismic parameters with geotechnical parameters has been extended by Zhang Baoshan and Lin Chopin who produced correlations between S wave velocities and geotechnical parameters (including N values) for tailings deposits.

Carabelli, Sampaolo and Superbo have described their application of sonic methods to the study of rocks, soils and concrete with particular mention of the use of spark transducer as a wave source. Rasolofosaon, Lagabrielle, Rat and du Mouza used spectral analysis of records generated by a hammer seismograph to give a guide to the properties of the layers investigated.

Tan, Yang and Loy have described a refraction survey in Singapore which aided the determination of sub-soil type and foundation conditions, while Haupt discussed the value of refraction surveys undertaken in connection with hydro-electric projects in Burundi.

Applications of seismic techniques underground were given by Bonvallet, Both, Peragallo, Pilet and Wojkowiak in connection with studies of mine pillar stability while the use of seismic methods to assist assessments of quarry face stability were discussed by Reymond.

An unusual and most interesting application of seismic techniques was described by Bely, Nazarov, Chebkasova and Chumachenko who have indicated how the measurement of seismic parameters may be used to help control construction of earth embankments and dams.

Only three of the papers dealt with electrical resistivity techniques as the prime investigation technique. Of these Lagabrielle and Lafont described a method of dragging an electrode array across the sea or river bed to undertake continuous apparent resistivity profiling while Barbier and Clement discussed their experience of the use of resistivity surveys to determine geological conditions for over 100 km of tunnels in southern France. A particularly interesting use of the resistivity method was described by Raso who has applied it to find and define field limits of steam cupolas in geothermal areas in Mexico.

The relatively new and certainly exiting radar techniques were the third most popular of those discussed in the papers. Of the two which dealt exclusively with radar Bjelm, Follin and Svensson discussed the various applications of georadar in Sweden while Ulriksen showed how computer processing of the recorded data may lead to the numerical evaluation of material properties.

Uses of electromagnetic techniques were discussed in the papers by Wang Weimin and by Deletie and Lemoine. In the former paper electromagnetic measurements made between boreholes were described as a means of locating such features as karst caves and abandoned mine workings. In the latter paper the use and advantages of airbourne electromagnetic techniques were discussed and contrasted with other methods as a method of engineering geological survey. Lagabrielle, Chevassu and Largillier examined the problems associated with the use of artificial magnetotelluric techniques in site survey with particular reference to the depth of investigation by these means.

The technique of measuring the strength of the earth's gravitational field to detect anomalies indicating the presence of underground cavities was described by Roques and Erling and illustrated by case histories related to railway construction. An unusual application of the gravity method was given by Bichara and Lakshmanan who, by modifying terrain correction proceedures, succeeded in assessing embankment bulk densities.

The remaining papers submitted in this topic dealt with the use of several geophysical methods in combination to resolve particular engineering geological methods in combination to resolve particular engineering geological problems. Thus Azimi, Desvarreux, Guerpillon and Keime attacked the very difficult problem of investigating very coarse grained soils which cannot be sampled, by a combination of seismic and resistivity geophyscis, aided by *in situ* density measurements and strength tests on reconstructed samples. Blinde, Hötzl and Merkler described their approach to the problem of determining underground water flow directions and possible injected grout takes in anisotropically jointed and disintegrated granite. Their study involved a combination of self potential measurements and surface, borehole and cross-hole seismic work to determine anisotropy in fissure systems.

Sakayama, Hara and Imai combined radar and resistivity for soil exploration. Having noted the correspondence between radar reflector boundaries and resistivity boundaries, they found that by profiling using both techniques the combined data gave indications of the geotechnical nature of the sub-soil. Ballard, Cuénod and Jenni gave their experience in the use of surface resistivity, radar, sonar cross-hole and seismic refraction techniques in detecting karst cavities and other anomalous features under dam sites. They concluded that investigations of similar sites are best initiated by surface resistivity, refraction seismic and radar surveys to discover major anomalies, thence followed up by cross-hole radar between galleries to better define anomalies and completed by further seismic and radar work from galleries during the course of construction.

Gonzalez Villarreal and Fernandez Bollo employed, in their investigations for a 12 km long tunnel, both resistivity scanning and refraction seismic techniques to aid determination of the distribution of strata and groundwater. Armbruster and Merkler have examined the application of geophysical techniques to detect leakages through the sealing elements in earth dams. The utility of direct water and soil temperature measurements and surface temperature measurements by infra-red techniques was evaluated together with self-potential and resistivity geo-electric methods. Savich, Iliin, Ezersky and Kalinin undertook geophysical observations on rock foundations during the progress of dam construction and reservoir impounding. Changes were observed in seismic and geo-electric parameters.

Comment

The diversity of content of the excellent papers presented to this symposium displays the increasing variety of uses to which geophysics may be put within the field of engineering geology. The papers also appear to reveal a changing attitude to the employment of geophysical techniques. In the earliest days of the development of site investigation techniques in general the tendancy was to view geophysics as a low-cost substitute for boring, sampling and testing with the proviso that the results might be of limited accuracy and value. What now becomes clear is that geophysics offers the opportunity to measure mass properties and parameters which can be measured *by no other method* and must thus be considered as an investigation tool of an importance equal to that of the traditional methods.

Certain groups of papers struck the General Reporter as being harbingers of significant new trends which must develop in the future. The papers of Bely *et al.*, Savich *et al.* and Bichara and Lakshmanan deal with application of geophysical techniques which, with further development may be used as construction control methods which do not involve boring, sampling and testing. It is not impossible that, in some future time, geophysical parameters may be used to indicate that a construction has been undertaken satisfactorily, for example that an embankment made of a particular soil is compacted to specification.

It has been common in the past to compare and contrast geophysical methods so that in the eyes of some engineers they have been the victims of some geophysical competition in which all methods promised all things but some did it better than others. The papers which present the advantages of the use of several methods in combination should, it is hoped, bring engineers to recognise that geophysical techniques are but investigation tools which if used together can resolve problems which are insoluble by the application of one technique alone.

In the review of the papers submitted the author remarked that only a small number of the papers submitted were on subjects that fell within the scope of the topic. This was "Subsurface geophysics used parametrically to obtain characteristics other than geometrical or structural ones". In the author's view the strength of the geophysical method lies in the opportunity it affords to measure mass characteristics in contrast to the physical methods which test materials or, at best, just a small sample of the mass. One of the many mass characteristics are the boundaries within the mass between units of like geotechnical properties and structural defects or anomalies. Thus it is not possible to discuss mass characteristics obtained geophysically without including geometrical or structural factors. This may explain why many of the authors had difficulty in writing papers which dealt exactly with the title of the topic.

Two papers dealt with the assessment of mass anisotropy, one, by Blinde *et al.*, in relation to permeability and direction of water flow and the other, by Fabre *et al.*, examined the causes of velocity anisotropy. It seems to the author that the recognition of velocity anisotropy is particularly important and that the interpretation of this phenomenon may have some useful applications.

Recent work in Delft by Hack (1982) has been concerned with the measurement of velocities in fan array traverses with a view to assessing the dominant directions of jointing or fracturing. One example of the results obtained is shown in fig. 2. In this case the fan shooting was done on a bench in an open-pit coal mine. The bench was underlain by a 1.7 m thick layer of siltstone, in turn underlain by shales and both horizontally bedded. Both strata were cut by two joint systems both vertical and striking in the directions 112° and 205° respectively. The traverses were undertaken using 12 channel equipment with geophones at 1.5 m spacing. The velocities shown in fig. 2 are those of the rock mass under a thin surface disturbed layer and showed marked peaks in traverse directions close to those of the strikes of the joints.

Various workers, of which Crampin (1977) and Garbin and Knopoff (1975) serve as examples, have developed approaches by which velocity anisotropy may be estimated if other geotechnical properties are known. The velocity variation estimated from their formulae is also shown in fig. 2 and there is some correspondence between this and the observed velocities. Similar results were obtained for other sites.

This study, together with others in the literature and those presented at this symposium clearly relates seismic anisotropy to anisotropy of mass properties. The measurement of such anisotropy is of importance as part of the site

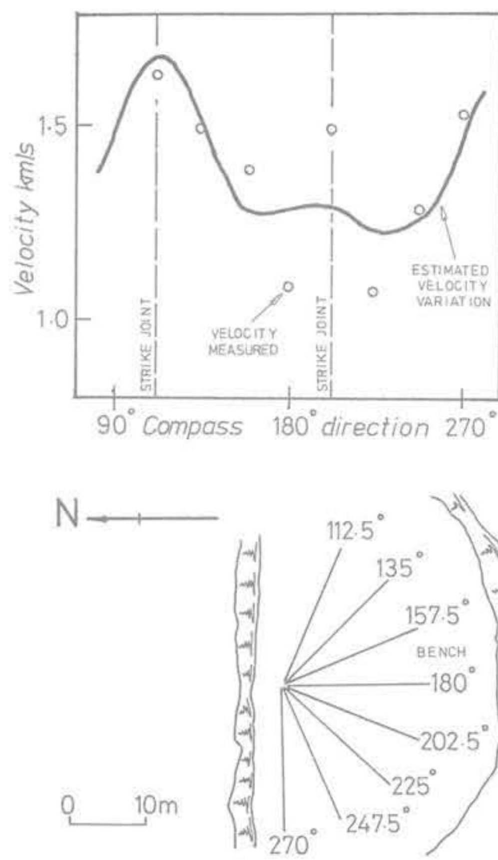

Fig. 2.: Variations in velocity determined by fan traverses on a bench of an open-pit coal mine near Leeds, England, contrasted with velocity variations estimated from observed geotechnical parameters following the theories of Crampin and others.

investigations for projects in which slopes are to be excavated or tunnels opened. In standard refraction surveys on rock masses, in which weathering is sometimes estimated by use of velocity measurements, it would seem sensible to incorporate fan shooting to assess whether velocity fall in a particular traverse direction is the result of weathering or of anisotropy due to discontinuities.

While immediate applications can be seen for the measurement of velocity anisotropy, anisotropy is also related to such factors as joint open-ness, degree of saturation and joint intensity. Measurements of wave attenuation indicate that this also is affected by mass anisotropy. The time seems thus ripe to put major research effort into developing a system of combined geotechnical and geophysical investigation which would quantify the parameters which determine rock mass anisotropy for this would surely offer great rewards, particularly in the field of rock excavation.

Some of the papers discussed the determination of the more conventional geotechnical properties of soils and rocks (such as density, elasticity etc.) by geophysical means. In Delft attempts have been made by Maris (1982) to see if there is any possibility of determining the relative density of sands with the aid of seismic measurements. Relative density is a measurement of the degree of compaction achieved by particular sands as the result of the way in which they were deposited and their subsequent geological history and thus gives an important guide as to how the sand will behave under a foundation load, in a slope or when subjected to an earthquake. Unfortunately it is very difficult to measure the relative density of sand samples with any great degree of confidence. Most relative density measurements are made using the standard penetration test proceedure which is also of somewhat doubtful accuracy because of the corrections which must be made. Another problem is that the tests in the borehole are made on a rather small 'sample' which may not be representative of a layer. If it were possible to assess relative density by, say, a cross-hole shooting proceedure between boreholes com bined perhaps with some form of testing on samples from these boreholes then this could be extremely useful.

A very large number of tests were conducted on sands of various grain size distributions which were poured into the test tank and compacted to various relative densities. Velocities of compression waves were measured through the samples and increases in velocities were observed with increasing relative density and confining pressure on the sample, while velocities tended to decrease as the D_{50}/D_{10} ratio for the sand increased. The experiments were undertaken on dry sands and considerable difficulty was found in developing a uniformly reliable proceedure to assess sample relative density. However, relationships were seen to exist and one of these is put forward in fig. 3. This shows the relationship between velocity, D_{50}/D_{10} and relative density for dry sands under low confining pressures. It should be considered as but a very tentative approach to examine the possibilities that relationships might exist and is clearly not to be used in practice. However, it does illustrate the hope that by making cross-hole seismic measurements and measuring a geotechnical parameter on samples obtained from the boreholes it might be possible to assess relative densities of sand layers in a way that is more reliable than the methods presently available.

The actual relative density value is seldom used in foundation engineering calculations (except when considering liquefaction of sands under earthquake tremors) and correlations with bearing capacity are based on corrected 'N' values. It seems to the author that there would be merit in considering the possible substitution of seismically

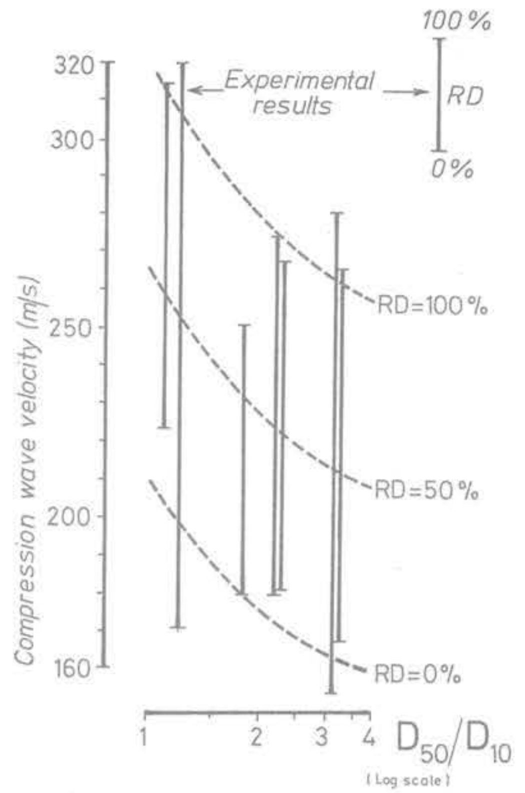

Fig. 3: Tentative relationshhip between P wave velocity D_{50}/D_{10} and Relative Density for dry fine to medium grained sands.

derived parameters for 'N' values in these correlations. The data presented by Tonouchi *et al.* in their paper suggests that this is not beyond the bounds of possibility.

The General Reporter believes that the status of geophysics in engineering geology has now reached the point that it must develop into one of the most important, if not the most important, techniques of investigation. The reasons for this are twofold. First is that it is the only method available of quantitatively assessing mass properties on the scale of the engineering work. Second we may note the tremendous and rapid advances which have been made in the last few years in micro-electronics and computer technology. These have had and will continue to have an increasing impact on the quality of acquisition of geophysical data and the depth and accuracy to which it may be interpreted. It is unlikely that the physical methods of investigation (the sampling, field and laboratory testing techniques) will equally advance.

We may speculate that within a relatively short time it may become normal to begin investigations with geological and geophysical work to be followed by boring, sampling and testing on selected locations, with the first two activities as the prime investigation activity. However, before this condition is reached engineering geologists and site investigators in general must become aware of the advantages of geophysical investigations and the geophysicists must be aware of the opportunities in the field of engineering for the application of their science. It is also necessary to consider the training of a new type of geotechnologist, the engineering geophysicist. This discipline would combine knowledge of the application and interpretation of appropriate geophysical techniques with basic knowledge of engineering geology and other earth sciences. People trained in this way would be a valuable addition to those who presently work in the field of earth sciences applied to engineering.

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