The Use of Seismological Techniques to Determine the Physical Properties of Rock Bodies: Experimental Results and Recommendations for Future Work within the 'RADWASTE' Program

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by

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1. Introduction. A series of five reports presenting the results of seismological studies as part of the 'RADWASTE' program has recently been completed. A summary of the results and conclusions of each report has been given below. Recommendations and suggestions for future research have then been included in a separate section. Finally, I have described the additional information that should be obtained on the completion of those parts of the work that remain unfinished.

2. Results and Conclusions.

(i) Wright, C., and K. Langley, Estimates of Crack Density Parameters in Near-Surface Rocks from Laboratory Studies of Core Samples and In-Situ Seismic Velocity Measurements

O'Connell and Budiansky have derived a comprehensive theory of the elastic behaviour of cracked and porous solids. We have given a summary of those parts of their theory that are useful in the interpretation of seismic velocities, measured both in the laboratory and in the field, in terms of crack or fracture densities and fluid content. Numerical estimates of these crack parameters and their associated errors have been derived from both field and laboratory data. The results emphasize the importance of being able to measure reliable S wave velocities, and indicate that an accuracy of better than 2% in seismic velocity determinations is required. We suggest that 'saturated isobaric' rather than 'saturated isolated' conditions are appropriate for elastic wave propagation in situ or in the laboratory. The calculated crack density parameters lie in the range for which the spectrum of characteristic frequencies for transition from 'saturated isobaric' to 'saturated isolated' conditions depends on the inter-crack permeability. This suggests the intriguing possibility that the inter-crack permeability, which may be quite different from the gross permeability of the rock body, might ultimately be measured using seismological techniques.

(ii) Wright, C., and D.C. Kamineni, Predicted and Measured Seismic Velocities and Densities in Rock Samples from Chalk River, Ontario

The intrinsic or 'matrix' velocities of P waves in rock samples of gneiss and monzonite taken from a borehole at Chalk River, Ontario, were calculated from the modal analyses and estimates of mineral velocities given in the literature. These velocities are systematically higher by about 0.5 km/s than the velocities measured in the laboratory at 2.5 kb; they are probably better approximations to the intrinsic values because of residual porosity in the rock cores at 2.5 kb. The calculated intrinsic velocities and the measured densities are well correlated, and show a distinct layered structure that is also evident from petrological studies. The layering, however, is barely resolvable in the velocities measured at 2.5 kb, and is absent in other sets of measured velocities. A study of the correlations between various sets of seismic velocities and densities has demonstrated the inadequacy of the numerical and statistical methods that have previously been used in the interpretation of such data, and has shown the need for more accurate P wave borehole logs. In spite of the large scatter of the borehole log velocities, approximate crack density parameters estimated from them show a weak but statistically significant correlation (0.39 ± 0.07) with the distribution of observed fractures in the drill cores.

(iii) Lam, C.P., and C. Wright, Seismic Wave Velocities in a Rock Body at Chalk River, Ontario, Part 1.

Using a mechanical hammer and a shear wave gun as sources, seismic wave velocities in the rock body at Chalk River were determined along three profiles (1, 3 and 2) radiating at azimuths of 33^o, 133^o and 331^o from a central borehole. The average P and S wave velocities were 6.56 ± 0.30, 6.09 ± 0.30 and 5.40 ± 0.30 km/s, and 4.09 ± 0.18, 4.15 ± 0.18 and 3.18 ± 0.18 km/s along profiles 1, 2 and 3 respectively; the error estimates are quasi-absolute values, the calculated standard errors for the P and S wave velocities being 0.09 and 0.05 km/s respectively. The P and S wave velocities for two profiles are significantly higher than those measured in the laboratory on samples from the borehole, suggesting a change in lithology below the profiles to the northeast and northwest of the borehole. The P velocity of 6.56 km/s to the northeast of the borehole, in particular, is attributed to propagation mainly through gabbro. The mechanical hammer provides a good and reasonably cheap source of P wave energy at distances up to at least one kilometre. The shear wave gun gave clear S wave arrivals only along profile 1, so that the absolute errors in S wave velocities along the other two profiles may have been underestimated; the gun functions well only if conditions below the source, which are difficult to specify precisely, are suitable, and it is very expensive to use.

(iv) Wright, C., M. Johnston and C.P. Lam, Seismic Wave Velocities in a Rock Body at Chalk River, Ontario, Part 2.

Two shallow reflection profiles, each about two kilometres long, and running from northwest to southeast (profile A) and from northeast to southwest (profile B) were recorded over the rock body at Chalk River. These data were interpreted as a series of overlapping reversed refraction profiles. Profile A corresponds to profiles 2 and 3 of the foregoing work of Lam and Wright. A smooth velocity-distance curve for profile A yielded velocities between 4.5 and 5.6 km/s for the uppermost regions of the rock body, with the velocities below 5.0 km/s confined to narrow regions at the ends. The velocities are significantly lower than those of profiles 2 and 3 of Lam and Wright, partly because the seismic waves interpreted by Lam and Wright had traversed the deeper and presumably less fractured and weathered regions of the rock body, and partly because of the presence of gabbro at depth below the northwest end of profile A. The velocities along profile B are more scattered than those of profile A, but clearly exceed 6.2 km/s over a distance of about 250 m at the northeast end; these high velocities are attributed to the presence of gabbro. Further south the velocities are close to 5.5 km/s. No clear correlation with the surface geology is evident from the velocities of either profile, although lower velocities appear to be correlated with lithological changes that may in turn be associated with extensive fracturing.

(v) Wright, C., The Search for Temporal Changes in Seismic Velocities at Chalk River, Ontario

Significant changes in P wave travel times of up to 0.8 ms over a distance range of 200 - 700 m have been detected within a period of twelve hours; they appear to be due to real seismic velocity changes, but could be due to small systematic variations in the wave form of the source. These time changes are not correlated with the computed variations of tidal strain along the lines of geophones, and also seem too large to be caused by the earth tides. The standard errors on the time differences between geophones are generally less than 0.1 ms, and for high quality data are as low as 0.03 ms.

3. Recommendations and Suggestions for Future Research

My recommendations and suggestions for future work can be divided into five distinct categories: (a) source properties, (b) in-situ velocity and attenuation measurements, (c) mathematical theories of cracked solids, (d) supportive laboratory studies, (e) methods of data interpretation.

(a) The weight drop device described in report (iii) has now been modified to function as a shear wave generator. This modified hammer is expected to provide P and S wave arrivals at distances up to at least 500 m. A trial experiment should be conducted in which the source is placed both on glacial overburden and on rock outcrops. Surface recording should include both vertical and transverse horizontal-component phones, whilst a three-component lock-in phone should be placed in a borehole within 500 m of the source. The testing of the shear wave source is envisaged as the initial phase of any future field program. If useful shear waves are not obtained from the modified hammer, other sources of shear wave energy should be tried.

(b) In report (i) an outline was given of recent theoretical work that has established quantitative relationships between seismic velocities, elastic wave attenuation, crack parameters, porosity, fluid content and inter-crack permeability. After the establishment of a useful source of shear waves, the second phase of a field program would therefore be an attempt to obtain attenuation measurements for both P and S waves in addition to the elastic wave velocities themselves; again, recording on the surface and in a borehole would be used.

(c) Further work on the development and applications of the mathemetical theories of the elastic properties of cracked solids is necessary in order to derive a model that approximates better both attenuation mechanisms and crack shapes, and also predicts accurately any observed frequency dependence of seismic velocities and attenuation.

(d) The use of crack theories in the interpretation of field data requires the existence of both P and S wave velocity measurements in the laboratory at pressures up to at least 2 kb, and the availability of modal and petrographic analyses of the cores. More extensive laboratory measurements of P and S velocities at potential disposal sites would also enable effective mineral velocities as a function of pressure to be estimated by regression analysis, thus providing an independent check on the accuracy of calculated intrinsic P velocities. Laboratory studies are therefore essential for the detailed interpretation of field data. Laboratory measurements of the attenuation of P and S waves in dry and saturated crystalline rocks should also be made in order to better understand possible attenuation mechanisms.

(e) It would be valuable to establish a set of reference effective mineral velocities as a function of pressure to be used for comparison with the measured rock or mineral velocities at a particular site; this would enable simple statistical methods to be used to determine whether or not the rocks of one locality were more cracked and altered than those of other localities. The reference mineral velocities could be determined by a multiple regression analysis on a large set of existing laboratory measurements of P and S wave velocities of rocks for which modal analyses of the samples are available; widely ranging compositions, several localities and different laboratories should be used. Provided that allowances can be made for systematic discrepancies between laboratories, site anomalies, defined as the mean difference between the measured velocities and those calculated from the modal analyses and the effective mineral velocities, could be calculated to express the average degree of fracture of each site.

4. Incomplete Studies

The P wave data from the hammer used to search for temporal variations in seismic velocities (report (v)) have now been supplemented by data from the shear wave gun. The errors in the new data are significantly larger, and the travel-time differences show no significant trends. Although the search for temporal changes in velocities that might be associated with the earth tides was therefore unsuccessful, there is still some useful information that can be extracted from the seismograms.

The large number of almost identical seismograms recorded during this experiment enables the errors in travel times and in relative amplitudes to be determined empirically; all this is valuable information for the planning of future experiments to measure accurately seismic velocities and attenuation. The surface waves generated by the shear wave gun might possibly be used to estimate the shear wave velocities in the rock body. Analysis of the surface waves has therefore been started. Finally, an interesting phenomenon remains only partially explained. For two shot locations, the first arrivals from the shear wave gun for both surface phones and the hydrophones in the borehole were at times intermediate between those of the P wave and those of the S wave. Some theoretical calculations on the nature of these first arrivals may help in explaining why the shear wave gun was not a reliable source of shear wave energy.