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On the development in digital engineering-seismic studies in Finland

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ABSTRACT

Shallow refraction and reflection seismic soundings were carried out in Finland using the newest portable digital seismographs. These improve the field investigation methods and introduce digital data processing techniques. New mechanical wave sources were developed to allow the conventional refraction soundings to be carried out in urban and industrial areas. The Finnish crystalline bedrock is covered by thin post-glacial overburden. With the present recording technology the bedrock refractions from the shots of a buffalo gun were recorded from shallow depths down to 15 - 20 meters. In the digital refraction records, reflected waves are also visible from depths of a few meters to the first hundred meters. In a combined interpretation of these sounding modes, the number of seismic layers in the soil sequence can be estimated from reflectors to avoid the well-known misinterpretations due to blind zones in the refraction survey.

Digital recording was also introduced into a slim acoustic logging system. This makes it possible to record whole waveforms to analyze the travel times and amplitudes of body and surface waves along 56 mm diameter boreholes. The acoustic logging is very sensitive to microcracking along the hole, requiring inversion techniques to calculate the velocities and attenuation factors in the formation. The velocity and attenuation of the body waves is connected to mechanical weakness in the bedrock using the calculated log of Young’s modulus. Furthermore, attenuation of the Stoneley-type surface waves can separate the water-bearing open fractures from the closed ones.

Subhorizontal fracture zones in the bedrock were mapped by high frequency soundings carried out on bedrock outcrops. The sonic logs at the same sites showed that the required thickness of these reflective horizons has to be a few meters. Unfortunately, most of the fractures intersected by boreholes are thinner than 1 m at the intersections making them difficult targets. The logs also indicate that the seismic velocity does not increase constantly with depth. There is a sharp increase in the velocity within the very topmost bedrock.

Dynamic rock mechanical elastic constants were calculated from borehole logs and from corresponding laboratory measurements of body wave velocities and density. The static uniaxial rock mechanical tests classify the samples presenting the intact bedrock in the same order as the dynamic analyses, but there are some differences due to different frequencies, stress levels and displacements in the test procedures. Moreover, the borehole logs give estimates of the deformation properties also in the unsampled fractured sections along boreholes.

PREFACE

The wide application area of the engineering-seismic methods covers several geological problems including landslide and erosion studies, stratigraphical investigations, estimations of soil masses or volumes, water prospecting in overburden and in the bedrock, mechanical analyses of soil or rock masses for foundation engineering, etc. In these environmental and engineering investigations, reasonable sub-soil information is typically required at minimum cost, in contrast to the oil and gas exploration practice from which the seismic methods originate. In Finland, mainly the refraction mode is applied to estimating the depth of bedrock surface and to locating fractured zones at the bedrock surface. The reflection mode, which can be used in areas where the geological stratigraphy, the built environment or the seasonal frost prevents or limits the refraction methods, is hardly used due its relatively high cost. However, the very site-specific borehole seismic methods have been used to some extent in the characterization of rock masses.

In this work, I have applied the digital recording and processing techniques which have become available also to shallow investigations in accordance with the development in digital computer technology. The case histories show the developments in seismic refraction and reflection sounding and in borehole logging when whole digital waveforms have been analyzed. The technological development has also improved the efficiency of the simple refraction mode; thus, the additional information is available only for some extra cost. Therefore, the few site-specific applications are to awake multi-disciplinary discussion including also authorities, contractors, project managers and other end-users of engineering-geophysical investigation results. For the future, I expect that the advanced digital seismic methods will reach wide applicability in environmental and engineering geophysics. In addition, several challenging aspects for future research and development related to the Finnish circumstances have already been pointed out in this work.

Espoo, March 1998

Olli Okko

LIST OF PUBLICATIONS

Paper I

Okko, Olli. Matalaseismiset menetelmät rakennusgeofysiikassa. (Shallow high-resolution seismic methods in engineering geophysics.) Espoo: 1989. Technical Research Centre of Finland, VTT Tutkimuksia - Forsknings-rapporter - Research Reports 655. 120 p.

Paper II

Okko, Olli & Hassinen, Pertti. Akustinen luotaus kallion rakennetutki-muksissa. (Acoustic logging for structural and hydrogeological bedrock investigations.) Espoo: 1992. Technical Research Centre of Finland, VTT Julkaisuja - Publikationer 762. 69 p.

Paper III

Okko, Olli T. Geophysical investigations in municipal engineering - the enlargement of the landfill area in Hanko City, southern Finland. Symposium on the Application of Geophysics to Engineering and Environ-mental Problems, SAGEEP'93. San Diego, California, 18 - 22.4.1993. Englewood, Colorado, USA: EEGS, Environmental and Engineering Geo-physical Society, 1993. Pp. 669 - 676.

Paper IV

Okko, Olli, Pitkänen, Petteri, Vaittinen, Tiina, Front, Kai, Hassinen, Pertti & Korkealaakso, Juhani. Interpretation methodology of borehole measure-ments for hydrogeological bedrock studies. Hydrogeology of Hard Rocks, XXIV IAH Congress. Ås (Oslo), 18.6. - 2.7.1993. Trondheim, Norway: Geological Survey of Norway and International Association of Hydro-geologists, 1993. Pp. 724 - 736.

Paper V

Okko, Olli, Hassinen, Pertti & Korkealaakso, Juhani. Location of leakage paths below earth dams by geophysical techniques. 13th International Conference on Soil Mechanics and Foundation Engineering, XIII ICSMFE, New Delhi, India, 5 - 10 Jan. 1994. New Delhi: Oxford & IBH Publishing Co. PVT. Ltd, 1994. Pp. 1349 - 1352.

Paper VI

Okko, Olli. Vertical increase in seismic velocity with depth in shallow crys-talline bedrock. Journal of Applied Geophysics, 32(1994), pp. 335 - 345.

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1 INTRODUCTION

Seismic sounding methods were invented after World War I. In war operations, seismic signals caused by artillery shots had been recorded, and consequently, the location of the enemy's guns was traced by analysis of seismic wave paths through the earth. It was noted that the velocity of the signals depends on the local geology. Soon afterwards, the first exploratory refraction surveys were carried out to locate geological formations with high seismic velocities because they were assumed to be gas- or oil-bearing salt domes. Later on, the surface seismic method using reflected seismic waves was developed to map out the lithological stratigraphy of sediments. At present, the reflection seismic method is applied in worldwide use by the oil and gas exploration industry.

One of the main problems in the interpretation of a processed reflection seismic survey is the correlation between the recorded travel time and the real depth of the reflective horizon. Velocity surveys were started in order to solve this problem. Since the 1920's the arrival times of the seismic waves from shots at the surface have been recorded at known depths in wells or boreholes. This VSP-technique became more common after World War II (Jolly 1953, Riggs 1955, Levin & Lynn 1958) and so did the acoustic logging made feasible by new borehole instruments developed to measure seismic velocities in situ (Summers & Broding 1952, Vogel 1952). It was also recognised that the porosity of the sediments can be calculated from the acoustic logs (Wyllie et al. 1956, and 1958). Although reflections can be recorded by borehole geophones (Hardage 1985), most of the VSP-surveys are carried out to measure the in-situ velocities.

Finland is located on the Precambrian crystalline Baltic Shield overlain by a thin cover of young glacial and post-glacial sediments. Because of the lack of hydrocarbons in these either old and hard rocks or young and soft soils, the reflection method has not been used in geological mapping of the subsurface in Finland. In contrast, the refraction seismic method has been adopted for engineering geological investigations. From the refraction seismic point of view, these formations are rather favorable targets: the layer thickness and velocities in the unsaturated and saturated overburden above the crystalline bedrock having high seismic velocities can often be measured easily. However, seasonal frost, aquifers of perched water or a thick layer of unsaturated sediments above the groundwater table or thin post-glacial sequences may introduce “blind zones” which are not observed as first arrivals in the travel time data.

The first engineering seismographs were imported to Finland in the early 1950's. The purpose of the first refraction soundings was to locate sites for hydropower plants on the Kemijoki and Oulujoki rivers on intact bedrock (Kalla 1954). Since then, engineering seismology has been used mainly in the detection of low-velocity zones in bedrock valleys. Often these zones indicate altered or weathered bedrock (Niini 1968). The fracture content of the bedrock and the depth to bedrock has been derived from measured travel times (Taanila 1963).

In refraction surveys, only the travel time of the P-wave from the wave source, usually dynamite explosives, to the geophones has been measured. Therefore, the old analog seismographs are still extensively used. The main interpretation techniques were also developed in the 1950's (Thornburgh 1930, Gardner 1939, Hales 1958, Hagedoorn 1959). The accuracy of the interpretation may be as good as +/- 10 per cent of the interpreted depth as given by Hasselström (1951). Although the instruments have been improved, this rule of thumb still remains (e.g. Sjögren 1984, Okko 1987b), mainly because of the sparse geophone spacing used in commissioned field surveys, which are typical in the cost-driven engineering geophysical site investigations and because of errors in velocity measurements. Often the limited amount data collected during the survey leaves much freedom for the person carrying out the interpretation as demonstrated by Ackermann et al. (1986).

The generalized reciprocal method, suggested by Palmer (1980), can reveal the existence of a rather thick hidden or blind soil layer which is not distinguished from the refracted waves. Also, the accurate location of a lateral change in the seismic velocity or in the topography of the bedrock can be found out by this method (Palmer 1987a). However, Dobecki and Romig (1985) remind us of the obligatory need for boreholes for the quality control of refraction seismic interpretations. Furthermore, Sjögren (1984) pointed out that the bottom of a narrow and deep bedrock valley or the deep edges of sharp faults are never reached by the fastest P-wave. Thus, the fracture content of such valleys cannot be derived from the refracted P-wave travel time data. In order to improve the depth information in deep bedrock valleys, one of the main targets of this study was to find out the possibilities of combining the reflections and refractions recorded by digital seismographs.

Portable digital engineering seismographs were developed in the 1980's in accordance with the progress in microprocessors and small-size computers. The new digital engineering seismographs can also be used to record the wave forms from weak non-explosive wave sources. The first reports on the detection of shallow near-surface reflectors including the bedrock surface by means of the reflection method were published already in the 1950's (Pakiser & Mabey 1954, Pakiser & Warrick 1956). Later on, Hunter and Hobson (1977) concentrated on the analysis of bedrock reflections in refraction records. Furthermore, Hunter et al. (1984) developed simple reflection seismic methods using the buffalo gun for the mapping of bedrock topography. In addition, different types of wave sources have been developed for shallow investigations (e.g. Miller et al. 1986). In the 50th anniversary volume of Geophysics, Dobecki and Romig (1985) predicted that within five years shallow reflection surveys would replace refraction surveys as the most common seismic tool for engineering and groundwater studies. In order to begin development work of the engineering-seismic reflection methods in Finland, the common Finnish practice to carry out and interpret seismic field studies was reviewed in the literature and interview study by Okko (1987b). In the present development work, the possibilities to use non-explosive wave sources, portable digital seismographs, and some new interpretation techniques in very shallow soundings in the Finnish geological environment are presented. Digital refraction and reflection data have been collected at various sites in Finland since 1987. The most up-to-date 12-bit OyO Mc-SEIS 1600 and Scintrex S-2 Echo seismographs were hired for the first tests in 1987 and 1988. Since then, the field surveys have been carried out with the ES-2401 seismograph, which involves the 16-bit floating point recording technique. The scientific purpose focuses on the improvement of the reliability of refraction seismic interpretations in difficult terrain in which blind zones may occur. This is done by analyzing the whole recorded wave forms, especially reflections in the digital refraction records obtained in several contracted surveys.

The engineering and environmental investigations often have to be carried out in urban or industrial environments at exactly defined locations, in contrast to the remote areas for which the geophysical methods were originally designed. The urban situations in which these methods are applied are often challenging due to such factors as large amount of background noise due to power lines, cables, traffic etc., confined space to work in and shallow targets, often in highly disturbed ground. Special approaches and innovative methods of interpreting the data are therefore sometimes required (e.g. Henderson 1992). In order to apply geophysical methods for underground construction projects, Julkunen (1987) evaluated the performance of several geophysical techniques within the city limits of Helsinki. During the field tests of this study, the performance of the digital equipment was analyzed when carrying out surveys in urban and industrial areas with high levels of background noise.

Seismic reflections from the crustal discontinuities have also been distinguished from deep seismic refractions surveys (e.g. Dohr 1972, Shive et al. 1975, Luosto 1987). The shallowest targets in reflection surveys carried out to map the inner structure of crystalline bedrock have been lithological contacts at depths of a few kilometers (e.g. Hobson & McAulay 1969, Killeen & Hunter 1971, Dahle et al. 1985). Green and Mair (1983) used seismic high resolution techniques in the detection of shallow subhorizontal fracture zones at depths of 200 - 400 m at the Underground Research Laboratory of Atomic Energy Canada Ltd. The Finnish nuclear power companies have also developed geophysical investigation methods in order to characterize crystalline bedrock to a depth of 1 km at sites selected for detailed investigations. The present study presents the interpretation methodology for systematic borehole logging and a case history with seismic reflections from fractures located shallower than 200 m in crystalline bedrock at the Loviisa nuclear power plant site. The vertical seismic velocities recorded in surface, surface-to-borehole, and borehole-to-borehole soundings indicated an increase in velocity with depth within the shallow bedrock. Therefore, the shallow fracturing and velocity with depth relation are discussed in this study.

One of the applications of seismic investigations in civil-engineering is the derivation of elastic properties from P- and S-wave velocity and density measurements (e.g. Telford et al. 1976, Särkkä & Johansson 1982). In spite of this, the quantitative geomechanical applications are not well defined because there are significant differences between moduli calculated from seismic data, moduli measured in the laboratory, and the performance of foundation material in response to high-level, long-term loads (Dobecki & Romig 1985). In a seismic velocity measurement, the S-wave can be recorded only after the arrival of the fastest P-wave, which makes the accurate timing of the S-wave difficult. However, the S-wave velocities are of particular interest because they are related to the shear modulus without an influence of the water content of the foundation material. Besides, by introducing digital analysis to the velocity measurement, the attenuation properties of the media can be quantified. Therefore, digital three-component recording and careful processing assist in the evaluation especially of S-wave arrivals (Okko 1987a). In addition, according to the examples of Stephen et al. (1985) and Hardin et al. (1987), water filled fractures can be located from full waveform acoustic logs, and furthermore, the permeability of single fractures can be derived. During this study, a slim acoustic probe was modified to record digitally waveforms including P-, S-wave and tube waves in 56 mm diameter boreholes. Furthermore, the rock mechanical parameters derived from the acoustic and density logs are compared to field observations and field measurements on core sample as well as to laboratory investigations to analyze the acoustic and mechanical properties of the crystalline bedrock.

2 METHODS AND RESULTS

The present thesis is based on the following publications, which will be referred to in the text by Roman numbers I - VI.

The shallow seismic sounding techniques are described in Paper I. The methodology of acoustic logging techniques are described in Papers I and II. The author has been responsible for planning and performing the field surveys as well as for the design of the instrument development. Mr. Pertti Hassinen was involved mainly in assisting the software development and in the data recording system described in Paper II. Papers III and V present field cases in which the new seismic sources and site-specific geophysical survey methods were applied to environmental problems. The author was responsible for these investigations, while Mr. Hassinen assisted in the field surveys, and Mr. Korkealaakso carried out the resistivity imaging, inversion and interpretation. Paper IV is a joint paper presenting the interpretation methodology of borehole investigation adopted during the preliminary site investigation program for nuclear waste disposal in Finland during 1988 - 1992. The author was responsible for the preparation of the paper. Paper VI summarizes the author’s main observations on the seismic velocity gradient in the very shallow section of bedrock. The observations are based on the data presented in Papers I, II and IV.

Paper I

Paper I deals with the possibilities of digital seismographs in shallow soundings. This methodological paper presents a literature survey of the refraction and reflection sounding techniques and discusses the possibilities to introduce the shallow reflection techniques in Finland. In addition, Paper I describes the design of two new seismic wave sources, one based on an old Finnish rifle gun, the other built to explode blank 12 gauge cartridges in the soil like the buffalo gun. These new wave sources as well as the conventional wave sources, dynamite and shells are applied in the reflection and refraction surveys in the case histories of Papers I, III and V.

One of the advantages found in this report was the use of digital filters to reduce the background noise in urban areas. This makes the application of the weak seismic signal from engineering wave sources, especially from the buffalo gun, usable for application also in refraction surveys. With the present recording instruments, the bedrock should not be located deeper than 5 - 10 meters. The penetration range depends on the attenuation in the soil layer.

The bedrock reflections were observed and reported for the first time in Paper I. The seismographs of these first surveys had 12-bit fixed-gain A/D converters. Later on, the site at Harjavalta was revisited using the improved 16-bit floating point seismograph which recorded clear bedrock reflections, from which common-offset reflection profiles were easily processed (Okko et al. 1997).

A reflection seismic experiment using a sledge hammer as seismic wave source on the outcropped bedrock surface is also reported in Paper I. The observed reflections are related only with the aid of other borehole data to the horizontal fracturing reported from this site. Paper I presents estimates of the possibilities to obtain reflections from thin and dipping fracture zones. A recent more extensive literature survey on this subject (Front & Okko 1994) reviewed the more up-to-date recording and processing techniques and led to very similar conclusions.

Paper II

Paper II presents the applicability of the acoustic logging method in the slim holes in crystalline bedrock. The analog sonic logging system was purchased from ELGI, Hungary, because of the small diameter of the probe. In order to quantify the logging results, the system was digitized to record the full wave forms in which the P-, S- and tube waves are analyzed.

This digitized acoustic logging system is sensitive to all minor joints and cracks along the hole. These cause time shifts and damping in the first arriving P-wave signals as well as considerable time delays in the shear wave arrivals. Tomographic techniques, a simple back projection and the Algebraic Reconstruction Technique (ART) were used to convert the recorded travel times of the body waves (P- and S-waves) to the seismic velocities in the formation. The analyses show clearly that the ART method is viable in the analysis of the P-wave velocity when the ray coverage is at least 10-fold. The ART inversion of the amplitude does not converge, but the back projection describes smoothly the attenuation factor of the formation.

There are strong-amplitude tube waves visible in the full wave form records. Because of deviating holes and the lack of centralizing of the tool, the cylinder symmetry of the acoustic logging is violated and thus the numerical methods of calculating permeability are not appropriate. In spite of this limitation, the attenuation of the tube waves can be used to locate the water-bearing fractures as shown in the examples.

Paper III

Paper III presents a practical example of the application of combined refraction, reflection and resistivity surveys in a typical commissioned site evaluation project with an extremely small budget. Several geophysical techniques were used to correlate between the geotechnical weight sounding test to give confidence of the continuity of clayey soils, levels of ground-water and bedrock surface. According to the geophysical sounding data, the preliminary construction plans of the site were revised.

In this case study, the buffalo gun described in Paper I, was used to generate the seismic signals both for refraction and reflection analysis. The refraction mode was used to level the groundwater table and the reflection method was used to check that the bedrock ridges did not divide the groundwater surface into different aquifers. The continuity of the shallow clay layer was studied by the resistivity surveys. The cost efficiency in the field work was achieved by the simultaneous use of seismic cables for both seismic and resistivity surveys.

Paper IV

Paper IV presents the interpretation methodology of the borehole logging carried out in the preliminary Finnish site investigations for the disposal of spent nuclear fuel. This paper describes the borehole logging techniques applied to evaluate lithology, fracturing and natural water flow along a borehole. The typically different response of resistivity and acoustic logs in the shallow section of bedrock is clear (Figure 3 in Paper IV), The phenomenon is analyzed in the evaluation work of Paper VI.

Paper V

Paper V points out how the choice of the most viable geophysical surveying techniques depends on the local conditions at the site to be investigated. The leakage through fractures in bedrock was examined by different geophysical techniques at two technically relatively similarly built dams. The leakage paths were located at the Uljua reservoir dam mainly by ground penetrating radar surveys and resistivity profiling. At the Uusikaupunki dam the conductive leakage to brackish sea water was located only in the shallow section by resistivity surveys. The previous refraction seismic surveys carried out in the vicinity of the dam structures allowed the bedrock depression to be located owing to low seismic velocities. However, the non-homogeneous filling at the dam structures caused problems in the depth estimates and, therefore, the cross-hole surveys were carried out to establish the correct location of fractured bedrock.

The main achievement in the seismic surveying was the use of the rifle gun, described in Paper I, to produce vertically polarized P- and especially S-waves at the Uusikaupunki dam. Power lines above the dam prohibited the use of explosives in control wells drilled along the dam. Originally, the crosshole surveys were carried out to measure the P-wave velocity between two wells in which the borehole geophones were located. Since both P- and S-waves were visible in the three-component records, both P- and S-waves were processed and analyzed.

According to the case study at Uusikaupunki dam, a separation of 30 m between the source and receiver was required to give the P- and S- waves a large enough time difference during which the first arrival of the P-wave has time to pass the recording geophone before the S-wave arrival in crystalline rock. In formations in which the seismic velocity is not that high, a much narrower spacing can be allowed. Another example of crosshole surveys with a borehole separation of 5 m and a vertical drilling rod as the wave source has been recently presented by Okko (1995).

Paper VI

This paper summarizes the observations on different P-wave velocities on the bedrock surface and in the corresponding seismic soundings commonly reported, also commented on in Paper I and recognized in Paper IV. The full wave form analysis of Paper II is used to illustrate a significant increase in the seismic velocity with depth in the very near surface section.

This paper includes a presentation of the VTT test hole samples (Okko et al. 1994) tested for their deformation and strength properties. The purpose was to evaluate the applicability and reliability of the dynamic rock mechanical properties derived from the acoustic and density logs presented in Paper II. The borehole and laboratory seismic velocity tests, i.e., dynamic in-situ properties correlate well, but the uniaxial test results differ systematically. Probably this is not only due to the different loading rates, but also due to lack of confining pressure in the laboratory tests. However, all of these tests locate the weakest samples of the shallow granodiorite in the uppermost samples corresponding to the observation on the velocity gradient.

3 DISCUSSION

This thesis presents the development of shallow engineering seismic surveying techniques in Finland during 1986 - 1996. In the 1980'ies, the commercial technology in the seismic industry introduced new light-weight portable engineering seismographs with fixed 12-bit dynamic range and later with 16-bit floating point technology. Thus, this type of seismographs have been used in the field surveys discussed here. At present there are already 32-bit recording systems with a total weight less than 20 kg. These recording instruments fulfill the requirements considered necessary for shallow surveys in the late 1980's (Knapp & Steeples 1986) when the shallow reflection seismic method was developed. In addition, the development of the light-weight field instruments has reduced the need for man-power from 8 - 9 persons in early shallow reflection work (Pakiser et al. 1954) or 5 - 6 in refraction work (Kalla 1954) to only 2 - 3 persons in both modes in engineering applications (e.g. Paper I). Thus, the cost-efficiency in field work mainly depends on the shooting and recording rates (Doll 1994).

The development in computer technology allows large reflection seismic data sets to be processed on microcomputers at reasonable cost. Furthermore, the 3-D surveys that require a large number of receivers and shot points and are common in exploration seismics, are already available for high-resolution groundwater studies as well (Barnes & Mereu 1996). Similarly, the waveform analysis and tomographic inversion techniques developed by the exploration industry are available for engineering and environmental studies using the refraction method (e.g. Bruckl & Kohlbeck 1994, Boschetti et al. 1996, Orlowsky 1997). Palmer (1987b) already pointed out in 1987 the need for 3-D surveys also in refraction surveys owing to the unpredictable nature of geological formations, e.g., spatial variations at the bedrock surface and its weathering degree. However, most of the refraction surveys are carried out with 12 or 24-channel seismographs and very limited budgets in the common 2-D mode along single, sometimes closely spaced survey lines. Therefore, the emphasis in this work focuses on the innovative site-dependent and cost-effective applications of the shallow surveying technique in Finland.

Bedrock fractures can be characterized on different scales using seismic or acoustic methods. Large fracture sets may be located using seismic sounding techniques (Moon et al. 1993, Juhlin 1995, Cosma & Heikkinen 1996) while the effects of single fractures on wave propagation are studied using high-frequency acoustic techniques on laboratory scales (e.g. Pyrak-Nolte et al. 1987, Tanimoto & Kishida 1994, Watanabe & Sassa 1995). The systematic use of full waveform sonic logging in the Finnish deep boreholes produces detailed data on seismic velocity with depth that can be related to lithology and fracturing along the boreholes to an accuracy of a few centimeters. In the site investigations for nuclear waste disposal, the fractures are characterized by several means, which allows comparison between the different techniques and discussion on the contribution of the new acoustic data to fracture characterization and to rock mechanics.

3.1 TERMS OF ENGINEERING-SEISMIC INVESTIGATIONS

Although the modern engineering seismographs record both time and amplitude, in most of the commissioned field investigations often delivered after bidding, there are no economic possibilities for a critical analysis of all the data collected. Very often the amplitude information is neglected as can be recognized in Papers I, III and V. Furthermore, the amount of data collected, i.e., the geophone or line spacing, number of cross-lines etc. is often poor or at least questionable for a reasonable site characterization, but enough for the commissioner. This shows the main difference between exploration geophysics and engineering geophysics. Seismic exploration techniques are developed by the revenue-driven industry; whereas, engineering and environmental geophysics including shallow seismic investigations is often applied by companies or communities that have to satisfy regulatory requirements at minimum cost (e.g. Romig 1996).

Traditionally, exploration geophysicists are satisfied with a partial solution (describing e.g., the existence of an anomalous body, its location, type or shape, or further a semi-quantitative estimate of derived characteristic property) of anomalies, but in engineering applications exact digital values in location, geometry and engineering property (which often differs from the measured physical quantity) are typically required for further visualization and numerical analysis. Therefore, the accuracy of an engineering geophysical survey must reach a threshold level in reliability, before the survey is worth being carried out (Figure 1). Furthermore, in environmental and engineering surveys the interpretation may have to be renewed with sufficient data to be legally defensible even in court (Whiteley 1992). Implicitly, the necessary requirements for “good practice” have to be defined by authorized legislative organizations, and even standards for geophysical investigations should be developed.

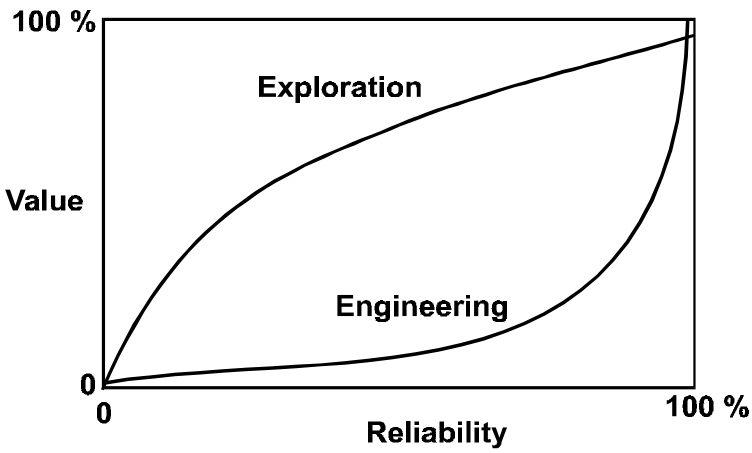

Figure 1. Value of geophysical information to end user as function of level of reliability (modified according to Doll 1994).

Often the professional and educational background of a civil engineer and an engineering geophysicist differ to such an extent that the site-specific problem may be understood in different ways. Therefore, it is suggested that a multidisciplinary team should coordinate the site investigations, because the expectations of a geophysicist, a geologist and a civil engineer may be different for the given seismic survey as demonstrated in several Engineering Geophysics Workshops. The geophysical interpretations are typically compared against penetration testing, drilling or soil sampling results, which may represent soils which are not encountered by the geophysical methods. In contrast, a seismic processing result or especially refraction seismic interpretation based on marginal data may contain questionable assumptions or unjustified interpretation methods even in textbooks (Palmer 1980, discussed by Whiteley 1990 and replied by Palmer 1990). In order to produce adequate documents for further use, reporting standards are needed (Whiteley and Frankcombe 1990).

Investigation results which are related to construction contracts, environmental or economical disagreements are often checked later (Palmer 1991, discussed by Whiteley 1992). Therefore, the original field data should be printed and even stored in the appendices of the field reports delivered to the commissioner. In the final reports greater attention must be given to the accuracy of interpretation and reporting of geophysical information in engineering terms. It is suggested (Fell 1990) that geophysicists should be trained for the engineering applications, and vice versa by Steeples (in Doll 1994). In order to improve the understanding between rock mechanical engineers, geotechnical engineers and geophysicists, a few symposia have been arranged in Finland also. The textbook of Triumf (1992) on the application of engineering-geophysical investigation methods to civil engineering in areas with Scandinavian geology has already been translated into Finnish by the Finnish Geotechnical Society (SGY 1993). However, the status of these booklets is unclear; these text books as well as the “Geophysical characterization of sites” edited by Woods (1994) differ from the handbook approach which is typical of engineering using strictly-defined manuals and standards for soil testing (e.g. SFS 1996, CEN 1996) and rock characterization (ISRM, edited by Brown 1981) .

In this thesis, the subjective practice in engineering seismic investigation using the most up-to-date equipment is demonstrated, but guidelines for design and reporting of site-dependent field surveys are not given. The geoscientific community, together with the other disciplines involved and covering the environmental offices, construction designers, insurance officers etc. has to define what is “good practice”, i.e., which standards and qualifications have to be required during the planning and execution of field work, data processing, interpretation and reporting, and finally, how much of the interpretations can be relied on only the individual judgment, typically of the cheapest bidder.

3.2 NEW WAVE SOURCES

New types of wave sources were constructed to generate seismic waves in order to avoid the use of explosives, which may be harmful to the environment and need special permission by the local police for purchase, transport, storage and explosion. Based on the field comparisons reported by Miller et al. (1986), simple guns were designed to suit the Finnish legislation and local cartridge types.

The buffalo gun (Figure 2) was designed to blow out a 12 caliber black powder cartridge which is used to start sailing competitions. These cartridges can be bought at special shops. The prototype used in the field surveys can be re-loaded manually at time increments of less than 2 minutes. In the field comparisons described in Paper I, the seismic wave energy of a buffalo gun shot is similar to the energy of a single detonator cap used to trigger dynamite. Therefore, the buffalo gun can be applied only in very shallow refraction surveys (e.g. Paper III) when the deepest refracting horizon is located at a depth of less than 10 m. On the other hand, the buffalo gun gives reasonable vertical energy for shallow reflection surveys. The deepest reflections are recorded at two-way travel time of 200 ms corresponding to very deep bedrock in Finland (Paper I). Thus, the buffalo gun is recommended for surveys when sedimentary horizons, or in particular the bedrock topography is to be mapped using the reflection seismic method in Finland.

The rifle gun (Figure 3) was designed and constructed according to the figures in Miller et al. (1986), but using a traditional 7.62 caliber Finnish military rifle. The rifle is considered as a shot gun by the Finnish authorities, thus when purchasing bullets, the license to carry the gun must be shown. Furthermore, the license always requires the permission of the local police before shooting in municipalities or urban areas as when using any other weapon. According to present experience, the gun gives powerful seismic energy when shooting into water-filled boreholes, as demonstrated in a few innovative surveys at sites with existing boreholes, e.g. in Paper V. The gun is not yet applied in reflection surveys, mainly owing to the dry top layers typical of the Finnish soil sequences. When shooting into dry soils, the noise level is rather high and the seismic energy is attenuated.

As the main purpose of a seismic source is to emit wave energy into the ground, the source has to be suitable for the local conditions with respect to the targets of the survey. Therefore, the same wave sources can be considered in a different preference order at different sites as admitted by Miller et al. (1992 and 1994) after the discussion on the first paper (Miller et al. 1986) and after new field comparisons of the same sources at several sites in the United States and recently in Europe by Karastathis et al. (1995) and Fruhwirth & Schmöller (1996).

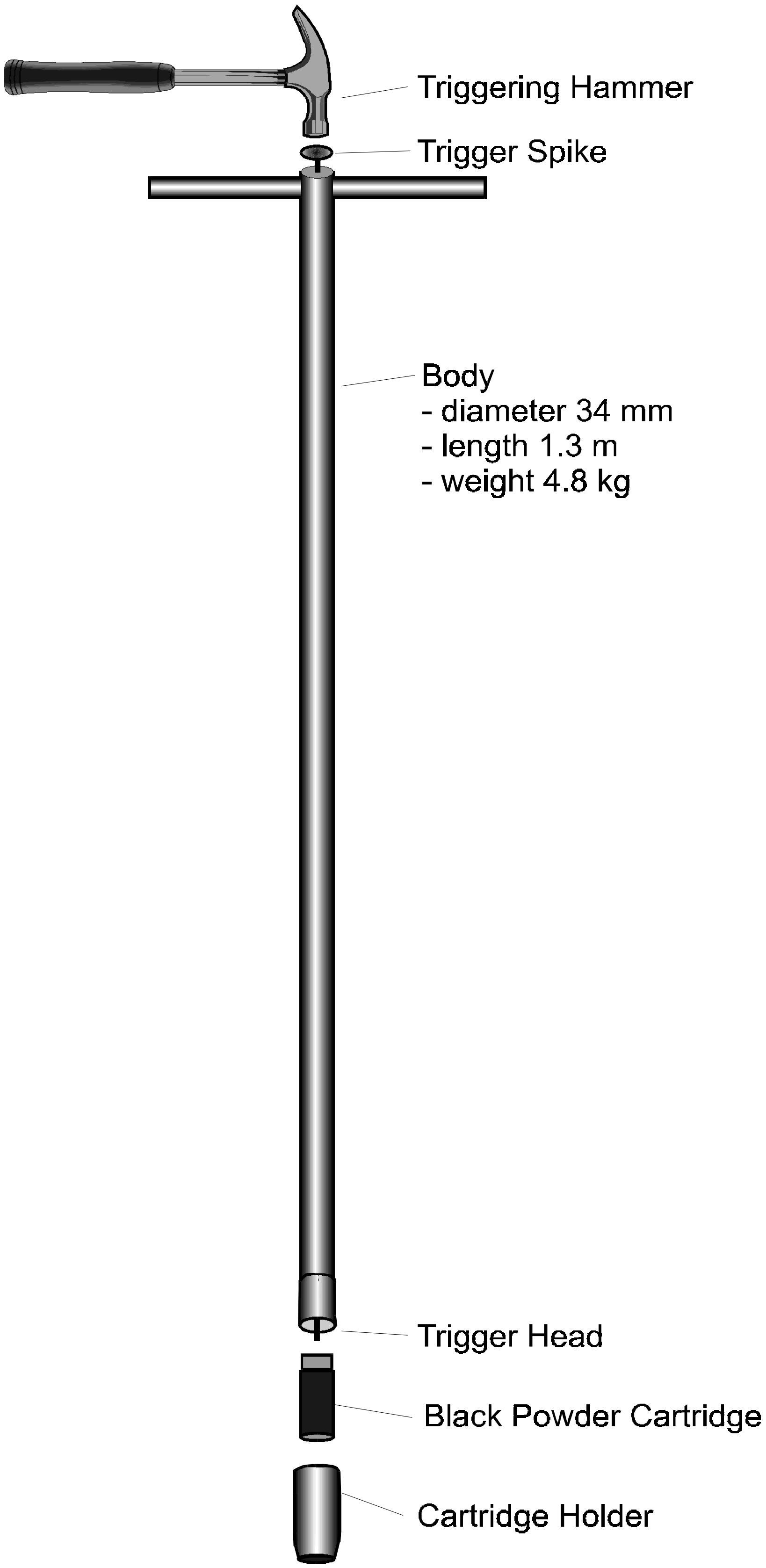

Figure 2. Buffalo gun (from Paper I).

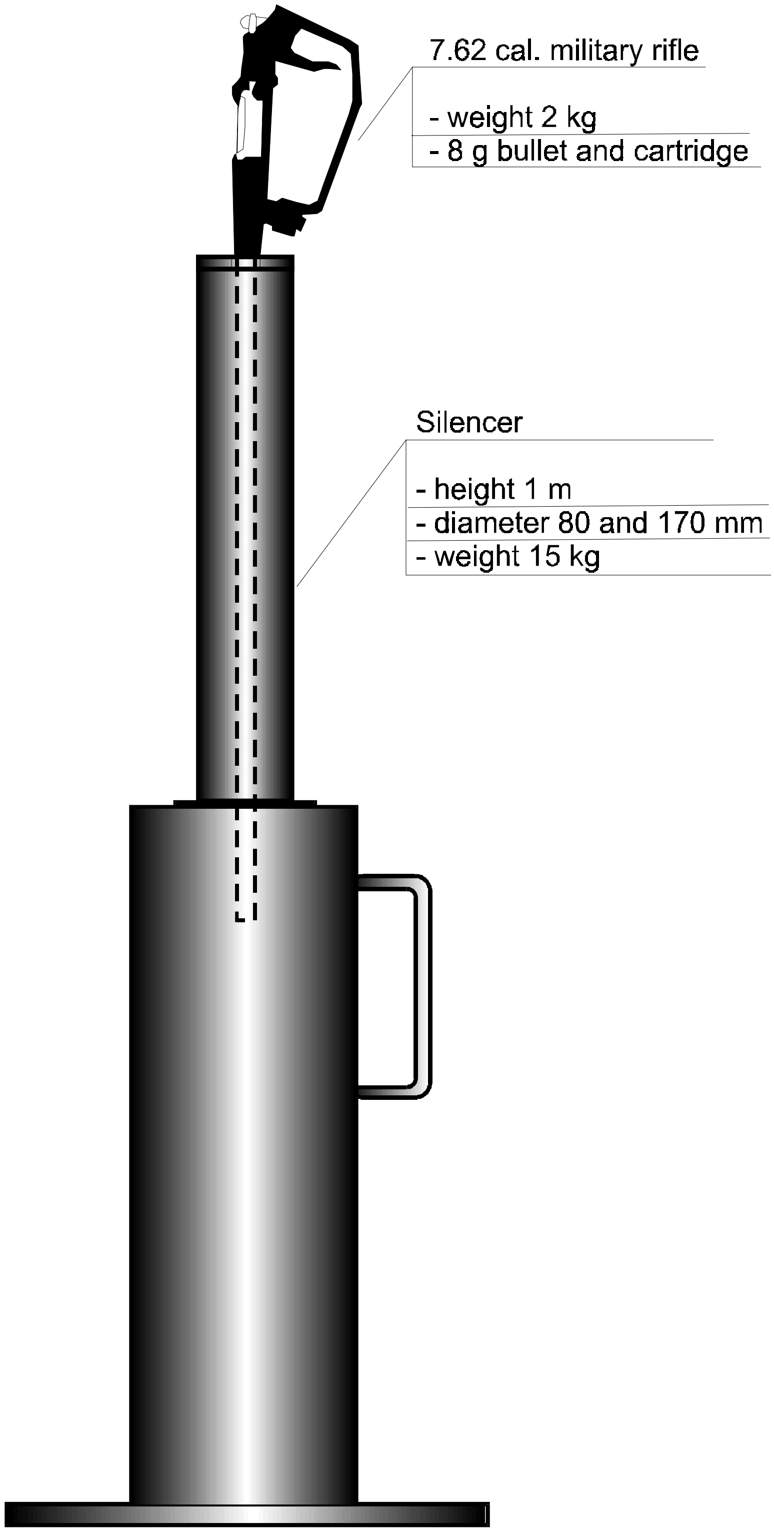

Figure 3. Rifle gun and silencer (from Paper I).

Sometimes, the waves sources must be modified at the site as described by Okko (1995) when using drilling rods to produce vertically polarized S-waves in a Swedish harbor area. At the time of that urgent survey, February 1994, the export and import of weapons and scientific instruments in

Scandinavian countries required special customs declarations, forcing the decision to use some innovative arrangements at the construction site instead of the rifle gun. Among other investigations, this case demonstrates the importance of finding a good mechanical coupling between the wave source and the local soil. The new wave sources have their advantages in repeatable shots, but some disadvantages: mainly the amount of energy for refraction surveys when compared to traditional explosives. However, it is clearly shown that the wave source for every site investigation has to be selected according to the local conditions, often after preliminary field testing. Even the daily moisture content in shallow soils can affect the selection of the most suitable wave source at the site (Baker et al. 1997).

3.3 DIGITAL FILTERING OF URBAN NOISE

The digital filtering techniques of modern instruments make it possible to filter the urban noise and thus apply the developed engineering seismic sources in towns and cities. Typically urban noise has a dominant low-frequency component below 20 Hz. Therefore, a high-pass filter of 25 - 50 Hz allows the low energy sources to be used even in shallow refraction surveys. In the worst cases, this background noise reaches frequencies of the order of 70 - 75 Hz, which is still lower than the dominant frequencies of 100 - 150 Hz recorded from the different shots as demonstrated in Paper I. In order to maintain very exact timing of the first signal, the arrivals of refracted waves should be recorded with minimum filtering. Therefore, shooting in particular for a refraction record should be avoided when there is traffic nearby, e.g., vehicles passing, airplanes taking off, etc. In general, low frequency urban noise can be filtered from the time sections, even when working between railway tracks (Okko et al. 1995); even so, surveys carried out on artificially made soils are never recommended.

In urban and industrial areas there are often buried cables, pipelines, and other man-made objects in the shallow subsurface. These may limit the area of geophysical and geotechnical investigations and introduce distortion and 50 Hz noise in the seismic records. Therefore, the shot point locations have to be examined before the installation of any subsurface cartridges in urban areas. Similarly, the geophone locations should be selected in such a manner that the subsurface obstacles scattering the seismic signal are avoided. Although the 50 Hz filters may improve the data quality of the seismic records, often the nearest geophone is affected by nearby power lines or other electric cables. In addition, the grounding systems in urban areas may introduce currents in the subsurface which may cause triggering problems. These time shifts can be observed on the field records, and if necessary, the unstable shot may be re-shoot or the correct delay time must be adjusted for each shot in the beginning of the data processing. However, most of the urban noise can be reduced from the seismic records to a permissible level, but it can be expected that working in urban areas requires additional carefulness both in the field work and data processing.

3.4 RECENT ADVANCES IN DIGITAL REFRACTION SEISMIC SURVEYING

3.4.1 Development in refraction seismic surveys

The digital recording in the refraction seismic surveys gives the possibility to analyze and process the full wave form including the characterization of the first arrival and the later events. According to the interviews by Okko (1987b), the accurate timing of the first arrival was considered the most important factor affecting the accuracy of the interpretations in Finland. The old analog records give time breaks which are readable with an accuracy of 0.5 ms when the explosive charge is large enough. In typical shallow investigations in Finland the sampling interval can be 0.1 ms or even less according to the capabilities of modern seismographs. Therefore, the timing of the first arrival can be improved if the first arrival has a clear peak or break. However, on the digital traces the attenuation of the first arrival can be observed and measured. Due to attenuation the shape of the recorded first arrival varies with the distance from the shot point making the accurate timing more difficult on the digital records than on the paper printouts of the simple analog seismographs, although several automatic or semi-automatic picking routines for the digitally recorded first arrival have been developed (e.g., Peraldi & Clement 1972, Telford et al. 1976, Hatherly 1980 etc.). During the comparison of records made from the same shots by analog ABEM trio and digital ECHO S-2 (see Paper I, figures 18 and 19), the first arrivals were clear on both records, but there were obvious time differences of the order 0 - 3 ms owing to the different instruments. Therefore, the improvement in timing due to digital seismographs should be validated by more careful cross-checking and calibration of the recording systems. In any case, the picking routines operating on high-gained traces are to be considered more accurate than the manual picking on conventional records (Hatherly 1980, Sjögren 1984).

The spacing of geophones affects more the accuracy of the final interpretation than the accurate timing of the first arrival (e.g. Landa et al. 1995). Therefore, the geophone and shot point spacing should be defined in such a manner that there are continuously refracted waves observed from each of the refracting surfaces. According to Bower (1989) in the United States only 3 - 5 shots are used per geophone spread which is often not enough to cover all refracting horizons. The Finnish practice contains typically 5 - 7 shots per one 12-channel geophone spread with geophone spacing of 5 meters (Okko 1987b, see also Paper I). In order to improve the reliability of the survey method, Bower has proposed a new standard which requires more field data to be collected. Bower (1989) considers that the additional field work does not raise the total costs because of the increased power in computing the final cross-sections. In a similar way, Lankston (1990) suggests that the critical amount of data needed in order to judge the necessary interpretation procedure and its data requirements should be defined during the field survey, not beforehand. In complex geology, the

GRM method should be applied, and according to Palmer (1981) at least 3 geophones should be located within the XY-distance. Therefore, in order to locate the bedrock surface at a depth of 10 m a geophone spacing of 3 m should be applied (Palmer 1987a).

The blind zone is never observed in the first arrival data and the seismic velocity in an undetected soil layer remains unsolved. Typically, the thickness of an undetected layer has still been calculated only when there is borehole data available to control the soil sequence (e.g. Dobecki & Romig 1985, Kuma & Suorineni 1996). However, the blind zone can be detected when comparing the critical distances, the anomalous offset (Merrick & Greenhalgh 1990) or the XY-distance (Palmer 1980) on the traveltime curves. Furthermore, the bedrock topography below the blind zone can be mapped and the depth to bedrock surface can calculated with an accuracy of 5 % using the GRM-method if an adequate amount of first arrival data is collected (Lankston 1990). In a survey to map groundwater table at a depth of 6 - 7 meters in a shallow sequence with probable shallow perched water introducing the velocity inversion, a geophone spacing of 0.91 m (3 ft) should be applied (Lankston 1990) in order to obtain the correct XY-distance. However, the economic possibilities often preclude this theoretical requirement; besides that, Karastathis & Papamarinopoulus (1997) used the geophone spacing of 1 m in both reflection and refraction surveys to locate shallow archaeological refractors within the uppermost 15 m.

Refraction surveys have been carried out in Australia to locate the depth of the weathered zone at the bedrock surface as a common practice (e.g. Whiteley 1990). The good quality field data set collected by Dentith et al. (1992) to determine the structure and base of the weathered layer overlaying a basement granite and greenstones in an Archaean terrain of Western Australia was re-processed (Boschetti et al. 1996) using a genetic algorithm. During the field survey, shot holes for 7.5 kg charges were spaced at 25 m intervals and drilled to depths of between 10 and 20 m. Receivers were spaced at 25 m intervals and consisted of two strings of six 14 Hz geophones planted in bunches. The signal-to-noise ratio recorded on the 96-channel Sercel instrument was clearly excellent. Along the profile, the main interface is located at depths between 10 and 90 m with the plus-minus method of Hagedoorn (1959). The inversion of Boschetti et al. (1996) was carried out on a 3750 m long and 160 m deep domain, with a resolution of 75 m in the horizontal and 40 m in the vertical directions resulting in a 51 x 5 nodes grid which was divided into small overlapping subdomains. Owing to the low ray density in the subdomains and below the main refractor, the final solution gave only reasonably good reconstruction of the contact between the granitoids and greenstones and of the average refraction position.

The waveform analysis techniques and processing, originally designed for reflection seismics, can be applied to digital refraction data as well. Orlowsky (1997) describes the shallow underground using the spectral information (amplitude, frequency, phase characteristics) of the wave train following the first break. He uses Common Mid Point data in the roll-along mode typical of reflection seismics. For economic reasons, the CMPrefraction data is collected with sparse shot point intervals. In order to avoid the time consuming and sometimes inaccurate picking of first arrivals, Landa et al. (1995) use a coherency technique based on maximum semblance to build the velocity-depth model. Bruckl & Kohlbeck (1994) use the COS (Common Offset Stack) and N/R (stack of the refracted wavefields travelling in the Normal/Reversed direction) stacking and tau-p migration for the refracted waveforms. Both stacks are calculated separately for each layer. The COS-stack has proven to be an efficient tool for the verification of the interpretational model. In addition, vertical gradients within a layer can be evaluated and hidden layers may be detected. By using migration, the XY-distance of GRM-method can be evaluated and structures which would be hidden in a pure traveltime evaluation can be solved.

Refraction statics are used in reflection surveys in order to find out velocity variation in the near surface, which is neglected and often muted in the reflection data, because the ground roll and air waves contaminate the shallow part of the reflection records. The recently developed tomographic methods in reflection prospecting may have applications in refraction analysis as well (e.g. White 1989). However, the number of geophones or geophone string and shot points per geophone spread in a reflection survey is much higher than in a refraction survey. Thus, the shallow soil section is covered by multifold near surface refractions. In contrast, the channel spacing is of the order of a whole geophone spread of a refraction survey for environmental or engineering purposes. For example, Docherty (1992) located lateral changes in P-wave velocity between channels placed 100 m apart from each other. Borovikov et al. (1994) applied a tomographic algorithm with curved ray paths to map the limestone topography at 30 - 90 m below the surface with a sparse shot point interval. Belfer and Landa (1996) used 5 m geophone spacing and 10 m shot interval in the field study, from which the near surface 2D-velocity distribution with main refractors to a depth of 100 m was deduced using tomographic inversion. Hayashi and Saito (1996) aim at an automatic refraction tomogram or cross-section after the first arrivals are picked from shots at each geophone location.

In Finland the cost estimates are typically required in terms of costs per interpreted line kilometer, often even without a site visit; however, it is already suggested in Paper I that the costs should be calculated per geophone spread. Therefore, the field studies included in this thesis contain relatively large geophone spacing and some innovative simple ways to draw further conclusions on the attenuation of the body waves or on the reflections observed from a few additional shots.

3.4.2 Reflections in refraction records

In Paper I there are several weak indications (Figures 27 - 30) on reflections from bedrock surface. These observations encouraged us to make a rough interpretation based on the reflections observed during a refraction survey. An engineering case history using this approach is presented in Paper III.

The same esker formation in Hanko was re-visited in 1996 owing to another leakage located at an industrial plant 5 km north-east of the landfill site dealt with in Paper III. This time the northern groundwater pumping station was threatened by contaminated groundwater. Although a relatively large drilling and water sampling follow-up study was carried out, seismic field studies were commissioned for level groundwater table and to map bedrock topography. In the refraction records, the bedrock could be observed to divide the groundwater into several aquifers. In addition, there were indications of high velocities above 1000 m/s interpreted as located much higher than the observed groundwater table in the observation wells, indicating a sequence similar to the indication of perched water in Paper III. Thus, during the last field day of the new survey, a walkaway reflection test was carried out along the last line using the geophone spacing of 5 m applied in the last refraction survey (Okko et al. 1997). On the high-frequency records with shot increments of 5 m, there are clearly two shallow reflection-like events, which may be related to the two known water tables close to the pumping station, and to a deeper bedrock reflection. Thus, the further reflection seismic investigations can be based on these observations.

Similarly, the Harjavalta site was re-visited in 1989 in order to enlarge knowledge about the subsurface conditions in the exceptionally thick esker formation. The seismic stratigraphy in Harjavalta consists of unconsolidated sands and silts with a groundwater table at a depth of 18 - 20 m. The refracted velocities are 400 - 450 m/s above the groundwater table and 1700 - 1900 m/s below the groundwater table (Figure 30 in Paper I, and Figure 4). At the skirts of the main ridge there are impermeable silts with perched water within the depth interval of 5 - 10 m. These areas were avoided in the seismic investigations which were focused on mapping the bedrock topography.

In the 1988 survey, bedrock refractions appeared as first arrivals when the source offset was more than 375 m. However, the bedrock refractions could not be followed through the whole 24-channel geophone spread with 10 m geophone spacing; even so, in the refraction surveys, dynamite charges up to 0.5 kg - which was the maximum for environmental safety reasons without burying the charges by drilling - were used to generate seismic energy to be recorded with the S-2 Echo seismograph (Paper I).

The refraction survey in 1989 was carried out using the denser geophone spacing of 5 m and an increased number of shots per geophone spread. In addition to the typical refraction survey, a high frequency record was obtained using the 280 Hz high-pass filter of the advanced ES-2401 seismograph at each dynamite shot located at the end of the geophone spread. One of these records with two different displays is presented in Figure 4. On the left the refractions in a two-layer strata can be followed and the seismic velocities of 400 m/s and 1700 m/s can be fitted to the first arrivals whereas the application of the 80 ms long AGC window on the right reveals the bedrock reflection on the far channels. In both displays the triggering error of 15 ms and high peaks of industrial noise are evident.

However, both bedrock reflections and refractions could be related to the same depth estimate of 80 - 100 m below the surface. After the scheduled refraction survey, a common-offset profile was collected using the buffalo gun and a constant source-to-receiver offset of 85 m to map the bedrock topography at 130 - 160 ms two-way travel time. In the weak impulses from the buffalo gun the refracted waves were not detectable, but fortunately the same reflections as in the records from the dynamite explosions were visible also in the field records from the buffalo gun.

In the recent reflection survey, the CDP reflection sounding was carried out within the industrial area of Harjavalta. The single geophones were laid on as undisturbed and non-paved locations as possible. In order to increase coherency the geophone spacing was reduced to 3 m. The wave source, mainly the buffalo gun, was applied at 3 or 6 m increments in shallow holes. A sledge hammer was used on pavement and on very stiff ground. The 200 Hz high-pass filter of the ES-2401 seismograph was applied when recording the data (Figure 5).

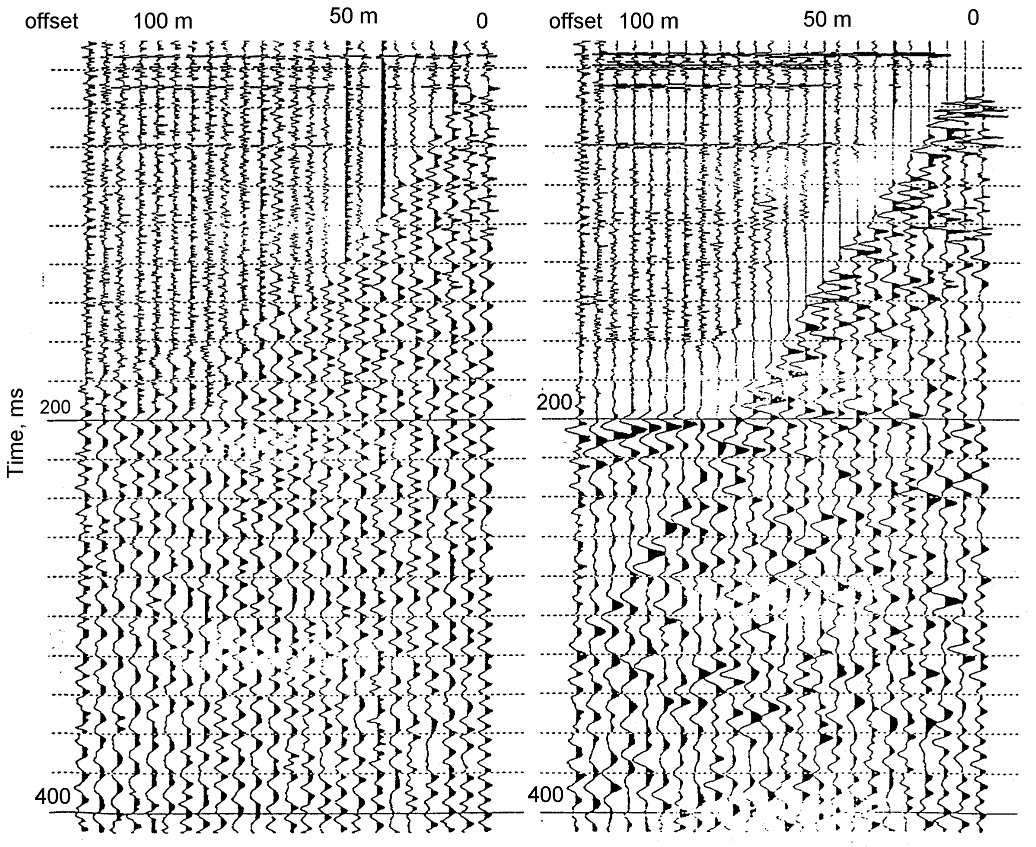

Figure 4. High-frequency seismic record from a dynamite source at Harjavalta recorded with 5 m channel spacing and displayed with two AGC windows: on the left the 6 ms window is short and the refracted arrivals are visible, on the right the window is 80 ms long and the bedrock reflection is clear on the far channels.

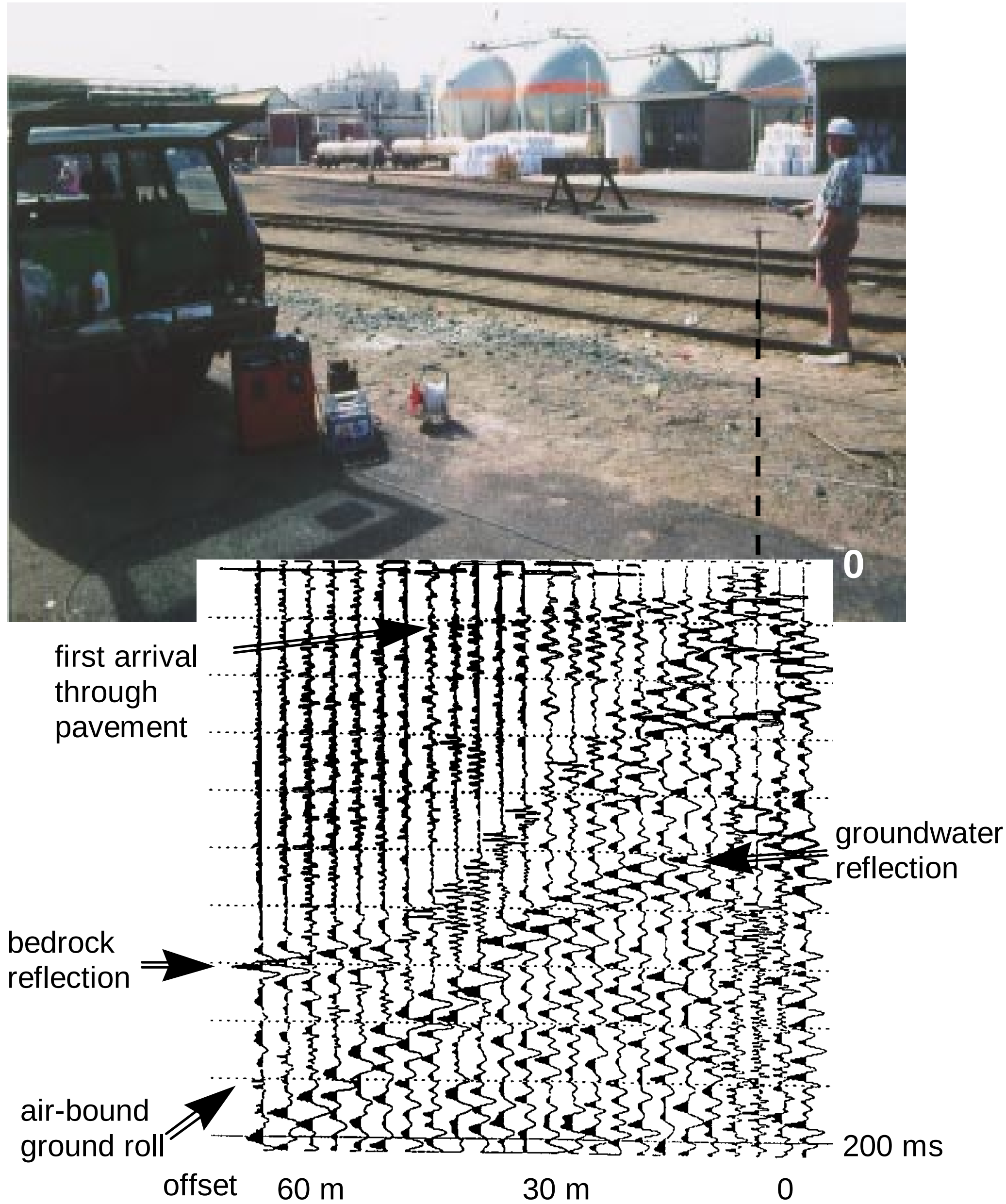

Figure 5. High-frequency seismic record with reflections from groundwater and bedrock in the industrial area at Harjavalta. In order to avoid additional noise due to poor seismic contact with the ground, the buffalo gun and the single geophones were located on as undisturbed ground as possible. The geophone spacing was squeezed to 3 m to improve coherency.

A high-frequency field record obtained using the buffalo gun on the unpaved ground within the industrial area is presented in Figure 5. In spite of having the survey line located on almost natural ground, the pavement-bound surface wave with a high velocity of the order of 3500 m/s occurs as the first arrival. However, the bedrock reflection at 130 - 140 ms can be recognized on the far channels and a clear groundwater reflection observed at the two-way travel time of 90 ms on channels close to the shot point in addition to the ground roll similar to the previous records. A careful inspection of the right record in Figure 4 can detect the same groundwater reflection already in the previous survey with the larger geophone spacing. This reflection, with the curvature corresponding to the velocity of 450 m/s at two-way travel time of 90 ms, is easily related to the groundwater table at 18 - 20 m. However, the survey focused only on mapping the bedrock topography by recording the reflections at large offsets. Consequently, the ground roll and the noise before the bedrock reflections were muted from the data sets to be processed.

The survey budget allowed the collection of a few CDP gathers along several short lines within 4 working days. On the field records the noise level and the bedrock reflections were controlled; and according to this, the survey plans were revised if the data quality was not satisfactory as was the case on two of the 6 originally planned profiles. During the data processing, the velocity analysis for the NMO correction was carried out separately for each of the records. The individual NMO velocities varied between 900 and 1300 m/s indicating more variations in the velocities than recognized in the previous refraction surveys. The triggering errors were corrected first manually on the raw data and before the stack using a coherency optimization for static corrections in 5 ms window. As the result of the reflection survey, 6 short individual profiles with a total length of 1 km were processed applying the 75 - 450 Hz band-pass filter and mainly 6-fold CDP stack to map relative variations in the depth of the bedrock surface. The most evident indications on bedrock depressions were visible as time delays on the field records, and one of these depressions is visualized in the stacked section in Figure 6. According to these results, drilling and sampling has been proposed to verify and characterize the bedrock depressions located along the profiles.

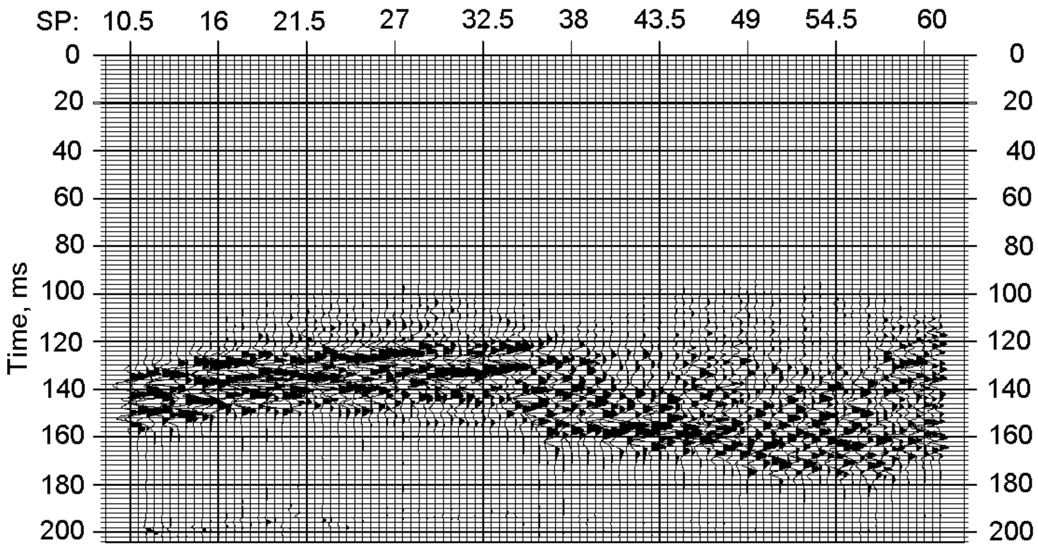

Figure 6. Processed reflection seismic 6-fold CDP stack focused on the visualization of the bedrock topography at 120 - 160 ms: the 55 m wide bedrock depression is located between CDP stations 39 and 57.

In groundwater related studies, the geophysical investigations and reports are often verified or controlled by other methods. In the interviews (Okko 1987b) it was already commonly observed that the bedrock surface is often located somewhat deeper by drilling than by refraction seismic surveying. More recently, Mäkelä (1994) presumes that thin layers which are typical in thick Finnish post-glacial esker formations are not detected by the refraction method. Thus, undetected layers remain in thick heterogeneous formations causing inexactness in the interpreted cross-sections. Seismic velocity or a probable velocity gradient with depth is not derived for these layers. The sedimentation history gives a reason to assume that there is anisotropy between the vertical and horizontal velocities. In general, the application of the refracted velocity in the reflection analysis has not yet given reasonable consistency when estimating the depth to a common surface. Probably this is due to anisotropy and heterogeneity of seismic velocities in soil layers as presumed also in the recent investigations in Harjavalta. Therefore, the reflection and refraction investigations should be planned and interpreted separately in order to solve the site-specific problems. In general, the large spatial separation of the shallow groundwater and deep bedrock reflections indicates that, the groundwater levels or the bedrock can be mapped using reflection analysis, but not necessary simultaneously from the same records.

As a result of the ability to record reflections below a high-velocity surface layer (Figure 5), it can be assumed that a careful comparison of the seismic layers interpreted from reflected waves in refraction surveys should reveal hidden or blind layers or velocity inversion, invisible in refraction surveys. Typically, the amount of data collected should be increased in both sounding modes; the ambiguities and personal judgment in refraction surveying should be reduced and a proper processing of shallow reflection data should be allowed. Furthermore, the recently demonstrated processing techniques can be applied to study the Finnish near surface soil conditions. The main advantage of reflections in digital refraction surveys this far is the possibility to observe the number of reflective horizons, especially when making high-frequency recording using the geophone spread defined for the refraction method. The observed reflection-like events can be used only as qualitative control during the interpretation of the refraction surveys if the amount of data collected is not sufficient for a proper velocity analysis and CDP processing.

3.4.3 Applicability of refracted amplitudes

In refraction surveys the economy requirement often allows only the analysis of the first arrivals. However, the examples re-analyzed by Palm (1981) show how the attenuation of amplitudes can be used to refine the interpretation of thick layers with almost similar velocities. In any case, most Finnish soils are too thin in layering to be even recognized from different velocities in refraction sounding with the geophone spacing used. Therefore, the refraction amplitudes are analyzed only when locating weathered bedrock surface, accordingly the analysis of Young and Hill

(1986) when locating the disturbed zones close to mine-pit excavations. Nevertheless, the case study of Roblee et al. (1989) showed that the seismic velocities are much more sensitive to induced fracturing than the corresponding amplitudes.

The study of amplitudes of the refraction survey carried out in Kuhmo (Okko 1991b) reveals difficulties in the analysis of the attenuation and velocity of P-wave at a bedrock slope. In the field work, repeatable, controlled impulses from rifle gun shots into boreholes drilled into the bedrock were recorded as in a digital refraction survey, and a bedrock fault with a change in the thickness of soil cover was located owing to the low P-wave velocity and owing to the attenuation as pulse broadening and damping of amplitudes of the P-waves along the survey line (Figure 7a). Although equal shots were applied to several boreholes, e.g., SR2 and SR3 along the survey line, the joint effect of change in soil cover thickness and in rock quality could not be separated in the attenuation behavior. Thus, the weakness in rock quality was confirmed seismically only after the amplitude analysis from off-line shot (location in Figure 7b) made similarly to the hole SR1 drilled into the bedrock. This example of the careful processing of amplitudes shows how the information content of an unconventional survey can be improved significantly.

In the sonic logging, the wave path along the borehole wall is very similar to a small-scale refraction survey using controlled sources and receivers in well-defined conditions. Thus, the amplitudes can be analyzed carefully in the sonic logs, e.g., in Paper II. The individual measurement shows large scattering in the amplitude, probably due to small cracks or joints in the vicinity of either the transmitters or the receivers of the probe. If the successive individual travel times and amplitudes are logged with closer spacing than the source-receiver spacing of the tool, tomographic inversion techniques can be applied to present the acoustic properties, i.e., seismic velocities of P- and S-waves and attenuation of P-, S- and tube waves in the formation, and some further interpretations can be made.

The variations in lithology may be identified as minor changes in the velocity and attenuation logs of P- and S-waves. The S-wave is sensitive to the schistosity of rock types, which may cause notable attenuation in mica-bearing formations (Okko et al. 1996). However, in the logs most of the attenuation of the signals takes place at fractured sections along the borehole as the velocity decreases typically at the same intervals. The attenuation of tube waves is related only to water bearing fractures. In Figure 8 the borehole RO-KR2 in Kuhmo, is re-logged after grouting in the main fractured section between depth intervals 410 - 440 m where the coring and fracture counts are incomplete. The effect of grouts is minimal as seen in the resistivity logs. Although the sonic logging was carried out only after the grouting, it can be assumed that the attenuation in tube wave log only at interval 423 - 425 m corresponds to the poorly grouted section along the borehole. In the P-wave velocity and resistivity logs, the 4-fold character of the fracture section is rather similar.

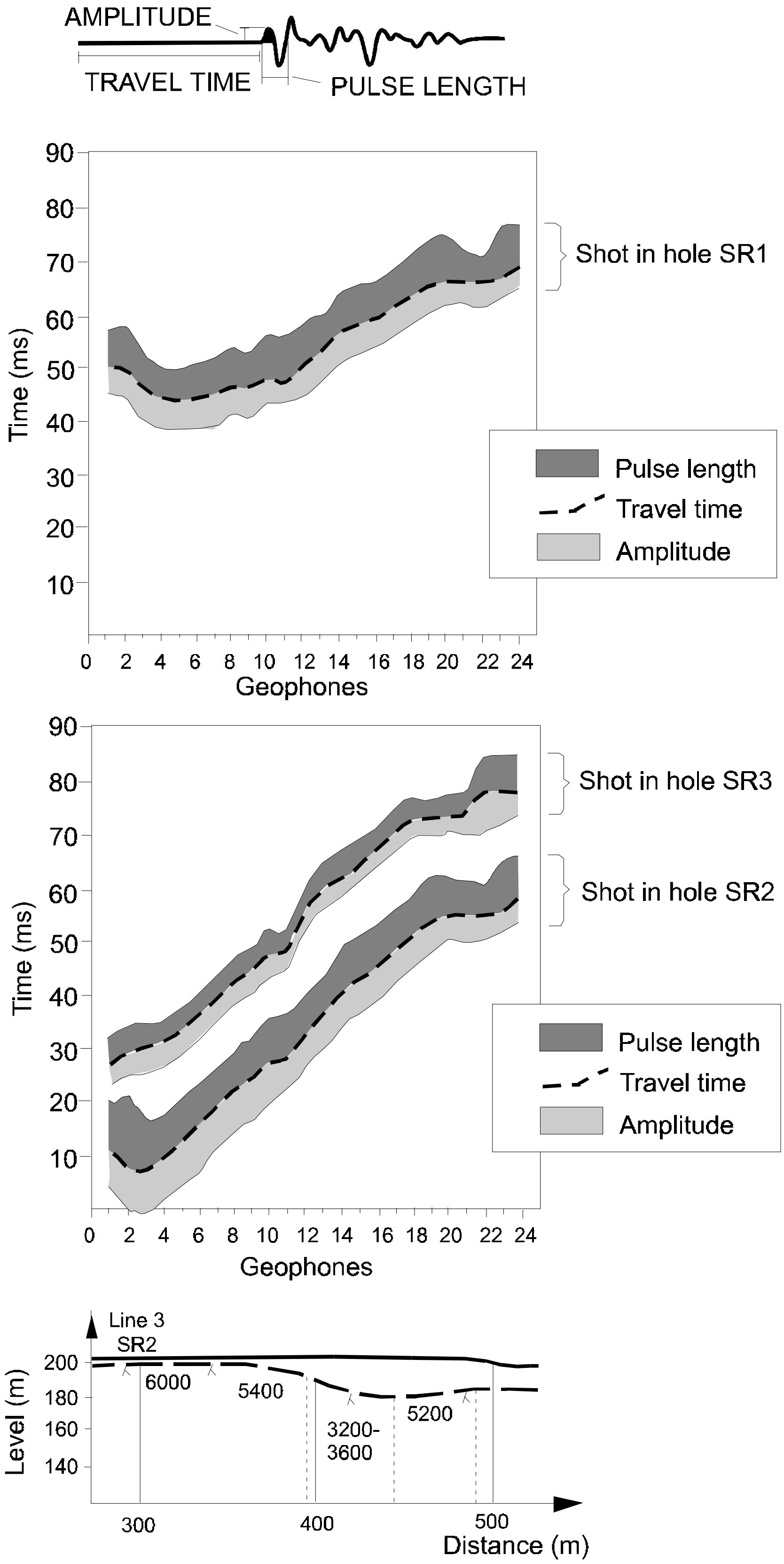

Figure 7a. Attenuation of amplitudes along the survey line from several rifle gun shots to water-filled boreholes in Kuhmo (based on Okko 1991b).

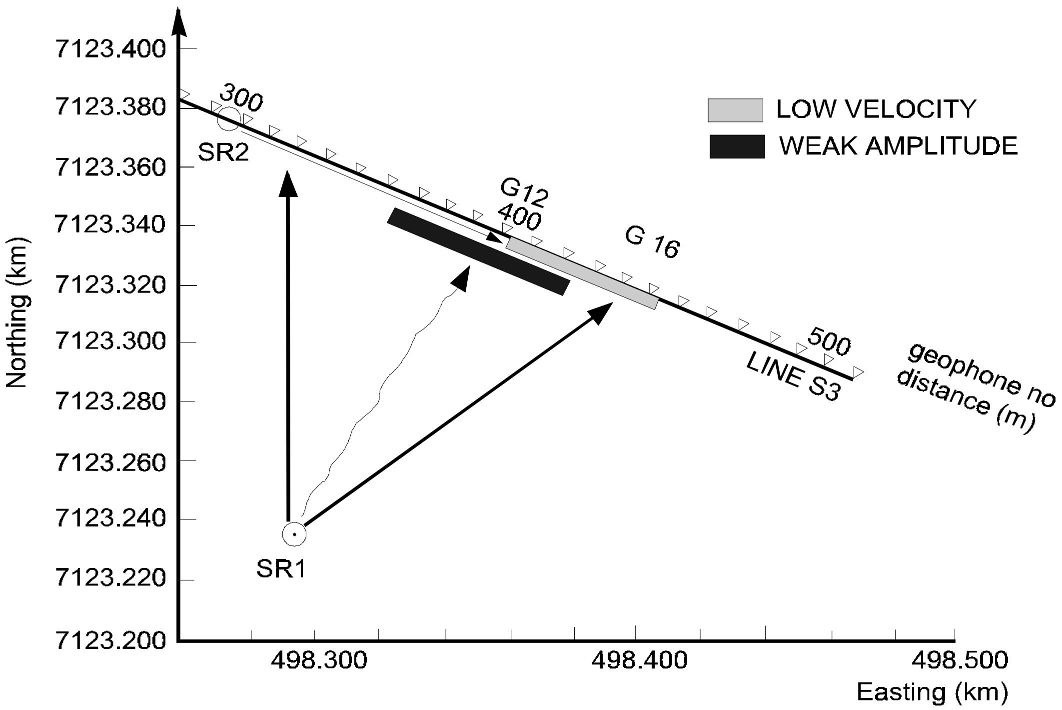

Figure 7b. The interpretation of the attenuation of amplitudes and decrease of seismic velocity from several rifle gun shots to water-filled boreholes in Kuhmo (Okko 1991b).

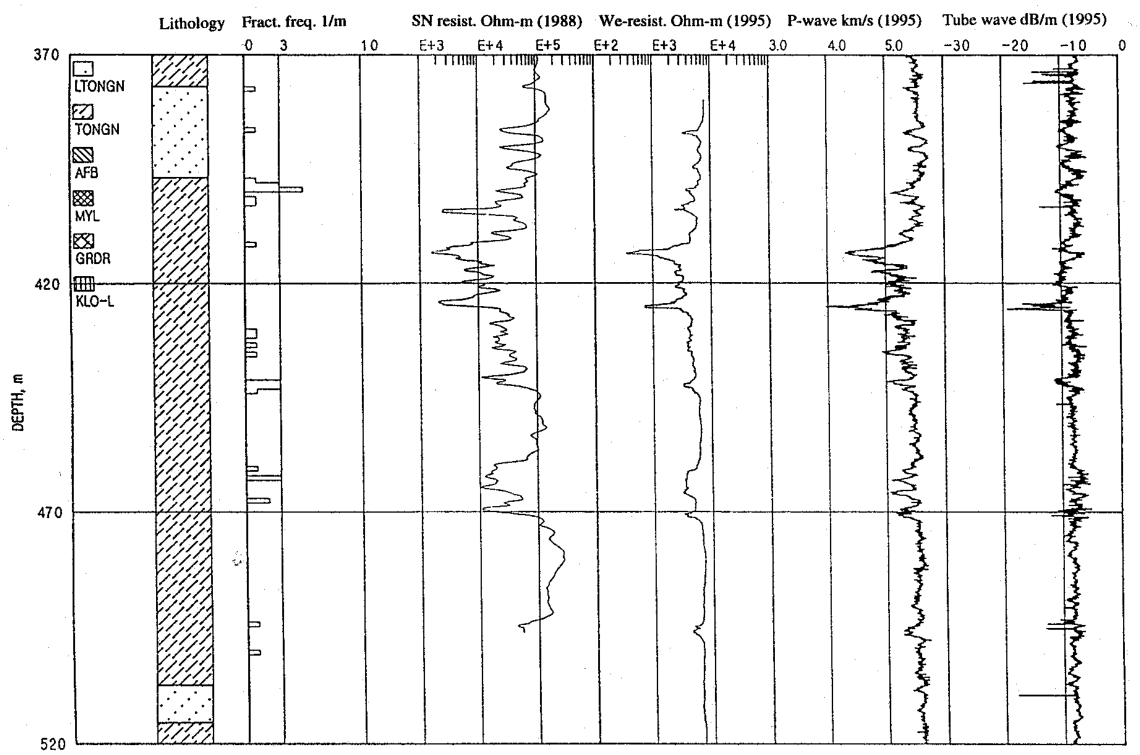

Figure 8. Geophysical logs in hole RO-KR2 Kuhmo before and after grouting of the major fracture zone at interval 410 - 430 m. The attenuation of tube waves reveals the unsuccessful grouting at 423 - 425 m (Okko 1996).

3.5 SEISMIC VELOCITY WITH DEPTH IN BEDROCK

Bedrock mass contains fractures and discontinuities on all length scales introducing time delays, attenuation and converted wave modes, when a seismic wave is propagating through the fractured rock mass. The lithological confining pressure is assumed to compress bedrock fractures with an increasing effect with depth. During the site investigation program carried out for nuclear waste disposal in Finland, open permeable fractures were found by resistivity and temperature logging and hydraulic tests within the uppermost 150 - 200 m of the cored bedrock mass (e.g. Paper IV). However, the seismic log is rather insensitive to this depth interval, as demonstrated in Paper VI. The main increase in seismic velocity takes place in the very shallow bedrock.

The annual temperature fluctuations in the Finnish bedrock are limited within the uppermost 15 - 25 m of bedrock. These annual temperature variations decay exponentially below the surface as calculated by Poikonen (1983) and observed by Kukkonen (1986). The recent field observations in the underground facilities (Ritola & Vuopio 1996) show that at these locations the annual temperature variation decay at the depth of 15 m. Similarly, the postulate of Paper VI relates the sharp increase in velocity with depth to the same depth interval of 15 - 20 m; although, in the engineering-geological studies to design rock caverns in the Porvoo area Johansson (1985) observed dense surface-bound fracturing within the depth of 5 - 20 m, but the arithmetic mean depth was only 8.3 m. In any case, it can assumed that the zone with annual variations in physical properties due to climatic variations in the open shallow fractures can be considered as a very shallow low-velocity zone in the Finnish bedrock.

In surveys carried out on bedrock outcrops, a difference between the horizontal velocity of refracted waves and vertical velocity is often observed. This may be due to the anisotropy of seismic velocity in the bedrock. The analysis of the increase of seismic velocity with depth (Paper VI) is derived only from velocities measured in the vertical direction in reflection surveys and in down hole surveys, acoustic logging and laboratory measurements along the sample. During the excavation of the repository at the same Loviisa power plant site, acoustic emission studies were carried out (Saari 1996). The acoustic emissions were monitored using borehole accelerometers and surface geophones. For the calculation of the hypocenters a horizontal velocity of 5900 - 6000 m/s to the borehole accelerometers and a vertical velocity of 5400 - 5900 m/s to the surface geophones were used. The vertical velocities along the hole have been approximated to be of the order of 5800 m/s below the depth of 10 m and the horizontal velocity at surface of the order of 5100 m/s. Thus, the uppermost section reduces the average velocity from 5800 m/s to 5400 m/s. The comparisons between horizontal crosshole and vertical uphole velocities in the bedrock of Oswego sandstone by Glynn (1987) reveal similarly 10 - 15% lower velocities in the uphole direction. At the Loviisa site the temperature logs (Poikonen 1983) also show strong near surface anomalies to depths of 15 - 20 m. Thus, the seismic and thermal anomalies are related to the same shallow depth section.

The near surface section is often considered as a low-velocity layer. Most of the model studies are done in sedimentary environments, e.g. Sams (1994) found out that in the near surface with less lithospheric stress in a clastic clean sandstone, the acoustic waves are attenuated more than in deformable clays and shales due to the distribution of microcracks. These microcracks introduce dispersion between sonic and VSP based velocity measurements as well (Sams 1994). The shallow weathered section attenuated the vertical waves more than the horizontal waves in the combined VSP and crosshole tests of Chen et al. (1990). The near surface heterogeneities introduce local conversions and strong scattering, which often leads to an overall distortion in the multicomponent VSP surveys using shear waves (Zeng and MacBeth 1997). In the systematic multioffset VSP surveys carried out within the Finnish borehole investigation program for nuclear waste disposal, seismic anisotropy is this far reported only at one borehole (Heikkinen et al. 1995). Moreover, the near surface section in crystalline rock can be examined on the seismic (Vasco et al. 1996) or radar (Korkealaakso et al. 1993) crosshole tomograms at the Raymond test site. Although the ray coverage is poor in the near surface, both cross-sections indicate slight decays in the velocity or amplitude, which may occur due to microcracking in the surficial intact granitic bedrock.

The vertical increase in horizontal velocity in bedrock is very typical in refraction soundings as well. An increased seismic velocity in the upper bedrock is commonly observed below the same geophones when applying far offset shots. So, the Finnish organizations RIL (1976) and SGY (1987) have recommended that two seismic velocities should be interpreted for the bedrock: one for the weathered top layer and another for the intact deep bedrock. The comparisons between vertical seismic velocities measured in boreholes and horizontal velocities interpreted from refraction surveys confirm an increase in seismic velocity at a shallow depth. The increase in lateral seismic velocity with depth observed in refraction surveys takes place at depths less than 15 - 20 m. Thus, this type of engineering-seismic refraction method is limited to the very topmost bedrock.

Several mathematical velocity functions have been proposed to present the increase of seismic velocity with depth (e.g. Hagedoorn 1955, Greenhalgh and King 1980, Greenhalgh et al. 1980). This increase in velocity can be observed as non-linear travel time data of refracted P-waves or by anomalous velocities in the reflected waves. The present observations contain only the difference between the surface and the depths below 10 - 15 m. Thus, no well-defined velocity functions can be deduced to model this velocity step without additional data.

3.6 BEDROCK FRACTURES AS SEISMIC REFLECTORS

Fractures and fractured rock masses have been considered as thin low-velocity layers within intact high-velocity rock mass when planning and modeling seismic sounding techniques to map the fractures. Although the fractured sections in crystalline bedrock are relatively thin and often geometrically unpredictable, making their detection by seismic techniques difficult, several attempts to analyze these anomalous sections have been made, especially after the encouraging work of Green and Mair (1983). The possibilities to locate these features in bedrock are described in Paper I, and afterwards in Okko1991a, and recently reviewed by Front and Okko (1994). The shallow depth section 10 - 100 m especially is difficult to characterize by surface seismic sounding techniques. In the sounding geometry used at the Loviisa site (Paper I) the hammer-generated surface waves hide the two-way reflections from the shallow depth below 60 - 80 m. Similarly, the careful analysis of re-processed reflection data with larger geophone spacing by Moon et al. (1993) shows that this shallow section is a very problematic depth interval in seismic surveying. The shallow fracturing may be imaged by ground penetrating radar (e.g. Holloway 1992, Okko and Korkealaakso 1994, Stevens et al. 1995, Grasmueck 1996), which also involves a wave propagation method with a higher resolution than the seismic method, but limited penetration to a depth of 30 - 50 m in crystalline rocks. In contrast, the deepest seismic reflection recorded using the sledge hammer on bedrock originate from a fractured section at a depth of 460 m at Lavia (Okko 1988). Nevertheless, most of the shallow seismic investigations are carried out by using explosives in drilled holes.

The continuous character of a reflection in bedrock is not as obvious as in sedimentary basins because the width of a reflector consisting of a single fracture, several fractures or sets of fractures is often much less than the seismic wave length and resolution of the method. The thickness of a fractured section is typically less that 1 meter along the borehole intersection, although a fractured zone may consist of several closely spaced fractures or fractured sections instead of a stratigraphic interface in a sedimentary basin. These weathered shear zones in rock may be several meters or tens of meters long. In a fresh core sample and the corresponding borehole logs, the individual fractures can be classified and characterized according to several properties, e.g., filling and aperture. The coring in a densely fractured section may fail, but the borehole logs can be used to characterize the fracturing. In crushed and weathered clayey sections, the individual fractures cannot be identified within the rock mass by any means. Consequently, these different types of fractures affect the seismic wave propagation owing to their thickness and internal properties. Shoenberg (1980) showed that the reflection and transmission coefficients are frequency dependent. According to Pyrak-Nolte et al. (1987) the ratio between the stiffness of fracture and the seismic impedance of the rock affect the amplitudes, while low frequencies are mostly delayed at fractures. Moreover, the hydraulic properties in the fracture plane also affect the wave propagation (Pyrak-Nolte 1995). However, all these rock properties are involved in the seismic sounding, which typically implies seismic waves with a wavelength of 20 - 30 m. Furthermore, in the field cases the orientation and location of probably reflecting fractures in bedrock are difficult to locate, due to their unpredictable orientation and continuity. Therefore, the reported field cases so far demonstrate the applicability of the reflection seismic method in mapping hazardous bedrock sections in simple geological environments consisting of thick subhorizontal planar sets of fractures in crystalline rock.

3.7 CLASSIFICATION OF BEDROCK QUALITY ON THE BASIS OF SEISMIC VELOCITY

In Finland, the seismic velocity has traditionally been related to the amount of fracturing and to the rock quality by the simple experimental relationships of Sjögren et al. (1979); however, the seismic velocities are affected by the rock type, mineralogy, anisotropy, type of fracturing and weathering. The seismic displacement discontinuity theory used by Pyrak-Nolte et al. (1987) has been applied to several fractures by Pyrak-Nolte et al. (1990) and Myer et al. (1995). These studies relate the frequency of the seismic wave, the mechanical and hydrological (Pyrak-Nolte 1995) properties of fractures, the elastic properties of rock including anisotropy (Pyrak-Nolte et al. 1990 and Pyrak-Nolte 1997) to the wave propagation in fractured rock.

In the recent comparison by Pöllä (1996) at Finnish underground construction sites, the following correlation between rock quality and seismic velocity measured at the surface by the refraction method was found: the velocities in intact bedrock are 4800 - 5400 m/s, in sparsely fractured bedrock 4600 - 5000 m/s and in fractured rock 4300 - 4800 m/s. In the generalized statement a 50 % probability for the existence of a fractured section is estimated if the velocity is below 4600 m/s and a 95 % probability for velocities below 4300 m/s. Borehole measurements, without taking mineralogy or rock texture into consideration, are classified according to fracturing as follows: for 0 - 3 fractures/m measured velocities are 5560 - 5580 m/s, for 4 - 10 fractures/m 5510 - 5550 m/s and for more than 10 fractures/m 5430 - 5490 m/s. Therefore, considerable fracture zones may be located in bedrock in which the seismic velocity is above 5000 m/s. The difference in these values in seismic velocity at the surface and in boreholes clearly confirms that these measurement have to be analyzed separately, probably as a result of the sharp increase in seismic velocity in the very shallow bedrock. Besides, the seismic wave paths and frequencies are different in these surveys, which leads to the same conclusion.

During the evaluation of the conceptual bedrock model of the Olkiluoto Site (Front & Okko 1996), only 20 fractured sections along the 7 boreholes were considered to be included in the model, although in total over 50 fractured sections, most of them belonging to the densely fractured categories RiIII with fracture-structured rock and RiIV with crush-structured rock (Korho nen et al. 1974, Gardemeister et al. 1976) were reported in the latest phase of borehole studies (Okko et al. 1996). Typically, there are 10 - 15 classified fractured sections along each of the 500 m deep boreholes. The common feature of the section selected for the conceptual model was an acoustic anomaly at least 2 - 3 m wide with a seismic velocity below 5000 m/s. In addition, seismic reflections have been related to most of these borehole sections in the multi-offset VSP surveys carried out along the holes (e.g. Cosma et al. 1996).

In order to demonstrate the characterization of fracturing, processed borehole logs from the recent borehole no 11 at the Kivetty Site are presented in Figure 9 using the methods described in Paper IV (with examples from the same Kivetty Site) and Okko et al. 1994. The apparent porosity log derived from the P-wave velocity log has a character similar to the fracture frequency log; whereas, the Young's modulus log combines two acoustic velocities derived from the sonic log and the density log and demonstrates the mechanical properties of the formation with depth in similar manner as the velocity log. The RiIII-classification and the field laboratory tests for Young's modulus from the drilling report (Rautio 1996) are also shown in Figure 9. The field description on fracturing along the hole differs typically in some extent from the logging information. Thus, the following comments can be made owing to the acoustic logs in this particular borehole: firstly, the large number of cracks and pieces of rock in the obtained core sample at depth interval 552 - 554 m should not be considered as two sections of fractured rock but as damaged core owing to probable drilling difficulties in the deep rock; and secondly, the main fractured sections within the shallow weathered porphyritic granite (the uppermost PGR in the lithology column) should be located at different levels than reported in the drilling report. Moreover, the field laboratory tests at 30 m increments for rock mechanical parameters scatter remarkably compared to the continuos and overlapping borehole logs for the same parameter. The depth control along this core sample is relatively good, there is only 1.18 m core loss at 6 depth sections.

A seismic classification of fracturing with categories I - IV in a slightly different mode than in the Ri-classification is often attached to the reports of Finnish geophysical contracting companies owing to the companies' experience in refraction seismic interpretation. The seismic scale takes the width and velocity in the fractured section at the bedrock surface into account. In the intact bedrock, deeper than 15 - 20 m, the seismic anomalies in vertical borehole logs are due to individual fractured weakness zones. These are often are too thin to be characterized with the borehole geophone spacing of VSP or cross-hole seismic investigation. Typically in the borehole logs there are short fractured sections, which have an intersection length less than 1 m, Figures 8 and 9 or Figure 3 in Paper IV. These weakness zones introduce velocity anomalies to borehole logs with minimum velocities corresponding to realistic in-situ velocities.

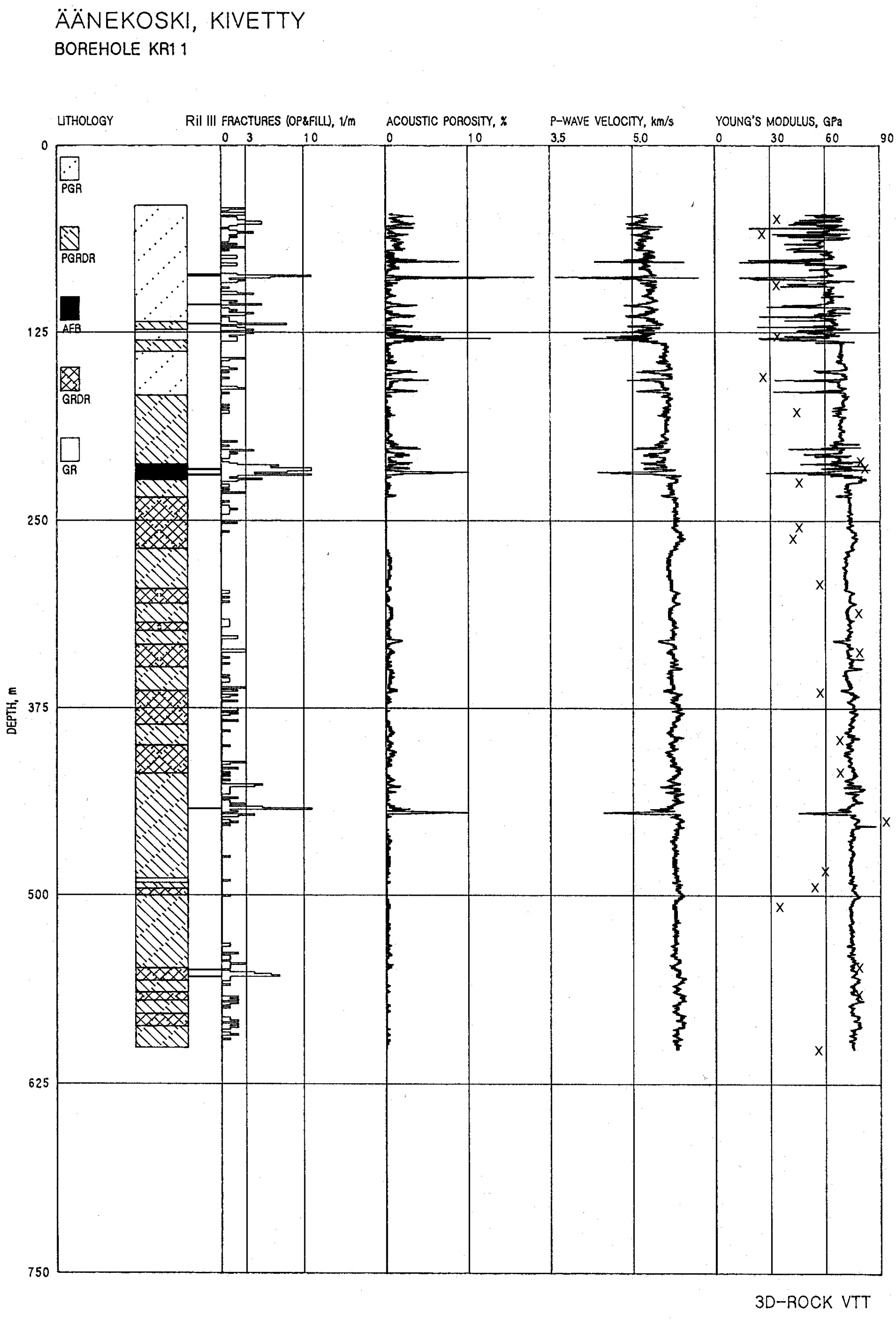

Figure 9. Acoustic logs transformed to present porosity and Young's modulus logs together with the lithology column, Ri-classification for fracturing and fracture frequency log, and field laboratory tests for Young's modulus marked in the corresponding log column along borehole KI-KR11 at Kivetty site (combined from Rautio 1996 and Front et al. 1997).

The P and S-wave amplitudes are delayed and strongly attenuated at minor cracks along the borehole; whereas the tube waves are attenuated only at permeable fractures. In contrast, all the short weakness zones reported by the geologists of the drilling crew as belonging to the RiIII category, are not visible in the acoustic velocity logs, as can be derived also from the comparisons of Pöllä (1996). When interpreting cross-hole seismic measurements, e.g. by tomographic inversion techniques, the limited width of the intersected zone in comparison to the geophone spacing may cause an overestimate in the seismic velocity and further in the rock quality, as demonstrated in Paper V. In addition, the laboratory experiments of Watanabe & Sassa (1995) in the scale of sonic logging show that the seismic velocity and attenuation depend on the number of low-velocity sections presenting fractures along the one-dimensional test specimen. In the experiments, the constant test length of 65 cm high-velocity material was divided into a constant length of low-velocity material, and the number of the low-velocity sections having the constant total length was varied when propagating high-frequency waves through the specimen. Due to dispersion, the velocity was reduced with the increased number of the low-velocity sections but the amplitude was attenuated mostly when there were 2 - 3 low-velocity sections present. According to this experiment, the seismic velocity cannot be related directly to the number of fractures per unit length. If the fractured low-velocity section consists only of a few individual fractures, the rock quality is overestimated. Therefore, the simple seismic classification of fracturing along a borehole should be based both on seismic velocity and intersection length similarly to the refraction survey practice. Furthermore, a log of Young's modulus gives an estimate of the mechanical fracture properties and thus the fractures should be characterized by the elastic modulus and the intersection length if these data exist, instead of using only the P-wave velocity.

3.8 ROCK MECHANICAL PARAMETERS ON THE BASIS OF ACOUSTIC LOGGING

Rock mechanical parameters have been derived systematically since 1993 from the P and S-wave velocity and density logs during the site investigation program for nuclear waste disposal in Finland. The first attempts to estimate rock mechanical profiles from geophysical logs were published in Paper VI using density and P-wave velocity logs and a constant velocity ratio to calculate the shear modulus. The velocity ratio was determined from the P- and S-waves, which were obvious on the full wave form displays, because the S-wave arrival was not visible enough to be followed accurately through the borehole section. Since then, the improved digital recording using the 12-bit A/D converter developed for the KAS-2-43-probe described in Paper II allows the S-wave velocity to be measured from the individual traces reliably, although the timing of the S-wave arrival is done semi-manually. Thus, the accuracy of the individual picks may be questioned, but the advantage in estimating rock mechanical properties from geophysical logs is mainly in the repeatability of the measurements along the continuous profile. Moreover, the scattering in the log-based values for deformation modulus is considerably less than in the geomechanical laboratory tests (Paper VI, see also Figure 9). The determination of the arrival time of the S-wave is also problematic in the laboratory. Thus, the anomalous values for Young's modulus and Poisson ratio in Paper VI are obviously due to this type of weak signal.

The strain level in acoustic tests is much lower than in static laboratory tests. Thus, the dynamic modulus values are assumed to be higher than the static values, as can be seen in Figure 9. Furthermore, the velocities measured from core samples in the laboratory were smaller than those of sonic logs, probably due to lack of in-situ stress and due to dry samples in the laboratory (Paper VI). Although the samples for laboratory tests were carefully selected in order to avoid any visible cracking in the samples, the dry storage and release of in-situ stress may have affected the laboratory tests. The acoustic velocities in sonic logs are 10 - 15 % higher than those in the laboratory and lead to the highest moduli values.

The behavior of microcracks along the test samples affects the strength and deformation in compressional test in the laboratory; whereas, in the sonic measurements, these mainly scatter the signal. Thus, Glynn (1987) used confining pressure during laboratory tests for modulus values using uniaxial and biaxial tests. Because cracks develop as a results of the unloading taking place during coring, the unconfined strength (UCS) values scatter more and are systematically lower than the standard UCS values and the realistic in-situ strength of rock mass. In order to have improved estimated of the UCS, Kenter et al. (1997) have introduced the CMS (Constant Mean Stress) test, in which the sample is first brought hydrostatically to a stress level close to half of the expected UCS value. After this, the sample is loaded axially and unloaded radially until the radial stress vanishes, and finally the sample is loaded in a purely uniaxial stress mode. The CMS measured strength values are systematically higher than the UCS loaded values; thus the UCS value from core measurement may be significantly underestimated.

Young's modulus and Poisson ratios have been derived from field rock tester and recently by biaxial field tests in the first large 76 mm diameter holes in addition to the uniaxial laboratory tests during the site investigation program for nuclear waste disposal in Finland. The reported values obtained with the field rock tester and with the UCS indicate large scatter even when making double tests at both ends of the same core sample. Probably this is due to cracks in the sample. Only in the biaxial test is a confining pressure focused on the sample, and probably therefore these results correspond best to the high values derived from the geophysical logs (Okko & Paulamäki 1996). Thus the compression test for mechanical parameters should be carried out in triaxial cells in which the hydrostatic stresses can be applied to the sample. The samples should also be tested in the horizontal direction in order to evaluate the anisotropy in the seismic velocity and in moduli, which can be expected due to the anisotropic stress field in Finnish bedrock (Ljunggren & Klasson 1996).

The coring of rock samples in fractured weakness zones is difficult or impossible, and thus the mechanical parameters in weakness zones have still to be estimated according to empirical relations based on the characterization of the core and the observed fracture frequency (Johansson & Pöllä 1996). Syrjänen (1997) proposed that the Young's modulus should be estimated using the Q (Barton et al. 1974) or RMR (Bieniawski 1978) rock quality classifications. However, these classifications require numerically determined parameters describing several fracture surface properties. The present estimate for Young’s modulus in typical zones of weakness in Finnish bedrock is 0 - 32 GPa; the strength values are obtained from literature (Johansson et al. 1996). In the geophysical logs transformed to present Young’s modulus, the elastic modulus in intact bedrock varies between 60 and 75 GPa according to rock type; and moreover, the modulus in the weakness zones can be quantified. The derived elastic modulus from acoustic logs is typically between 15 and 55 GPa in fractured rock, a threshold for a notable and often aerial fractured zone of weakness is 50 GPa (Figure 9). Based on this, the combination of acoustic and density logs can be used to quantify Young’s modulus in the weakness zones in bedrock. In order to apply the borehole logs in numerical rock mechanical modeling, a reduction chart (see Mohammad et al. 1997 for a comparison of the present practices) should be developed also for the borehole geophysical measurements in the Finnish circumstances.

4 SUMMARY

This long-term study presents the introduction of digital seismic sounding techniques in Finland during the years 1986 - 1996. The basic reports and the published conference papers present innovative cost-effective applications using both refraction and reflection soundings, borehole logs and their combinations in geotechnical and rock mechanical engineering.

Two engineering seismic wave sources, a buffalo gun and a rifle gun were constructed and introduced in Finland during the basic phase. The case histories present examples of how these instruments can be used in engineering surveys. The buffalo gun especially proved to be very useful in reflection surveys to a depth of at least 100 m when a sensitive digital seismograph was used as the recording unit. The reflections can be recorded also in areas with high-velocity near-surface, i.e., pavement and probably also frozen ground that are serious limitations in the traditional refraction survey. The rifle gun gives a reasonable signal when shots are done into water filled boreholes. There are records of refracted waves through a 20 m thick soil layer over a distance of 150 m from the rifle source. The digital recording techniques allow the processing and analysis of the whole waveform. The analysis of reflected waves in refraction data gives qualitative support to the analysis and interpretation of the refraction survey, indicating the minimum number of layers present.

The literature review on the interpretations methods and on the accuracy of the refraction method clearly indicates the requirements to increase the number of source locations and to reduce the geophone spacing in order to apply the generalized reciprocal method or semiautomatic tomographic processing techniques. The application of these techniques would reduce the personal influence on the interpreted cross-sections derived from marginal data that it still allowed as a common Finnish practice.

The high-resolution seismic experiments present the capabilities of the reflection seismic technique in the studies of shallow subhorizontal zones of mechanical weakness in crystalline bedrock. According to the field studies, the fractures or fractured sections have to be at least 5 m thick and located subhorizontally below a depth of 60 - 80 m in bedrock. However, most of the fractured sections studied in deep bedrock are observed only in intersections less than 1 m along the boreholes, although there are exceptions with thick weathered intersections. The fractured sections can be mapped from the surface only in the most favorable geological and geometrical conditions.

The development of the sonic logging technique focuses on the determination of the seismic P-wave velocity in the formation from surveys carried out in deviated slim 56 mm diameter boreholes. The acoustic velocities and the damping of amplitudes in a sonic log have to be determined by tomographic techniques. The field examples show that the amplitudes of refracted waves both in refraction survey and in sonic logging are related to the rock quality. The attenuation of tube waves in acoustic logs identifies the hydrologically important fractures.

The analysis of the vertical velocity in relation to depth shows the increase of velocity within the 15 - 20 shallowest meters of bedrock. This local information can most easily be obtained from the full waveform sonic logs, in which the weakening of rock causes time delays in the P-wave and especially in the tube waves. The same phenomenon is well known in refraction surveys in which the horizontal P-wave velocity is measured. Also, the annual temperature fluctuations are as well limited to the 15 m uppermost meters of bedrock. Therefore, this interval has to be considered as the thin low-velocity zone at the surface of the crystalline bedrock.

The seismic response of fractures in the surficial low-velocity zone and in the deep intact rock differ from each other. Therefore, a refraction seismic investigation and a borehole log must be interpreted separately. In the weathered zone, velocities below 4600 m/s over a distance of geophone spacing applied in the refraction surveys, often 5 m, can be considered to present a fractured zone; whereas, in the deep bedrock, seismic velocities below 5000 m/s over a very short distance refer to fractured zones. As the bedrock fractures and fractured sections along the boreholes are typically thin, less than 1 m in thickness, the velocity should be measured with sounding geometries including this spatial resolution of less than 1 m, in order not to overestimate the seismic velocity and the rock quality in the zones of mechanical weakness. Furthermore, it is suggested that fractures should be characterized by Young’s modulus and intersection length if full waveform data with P- and S-velocity logs and density logs exist, instead of using only the P-wave velocity.

The laboratory tests show the similarity in in-situ and laboratory measurements of seismic velocities in intact rock, although the in-situ values are higher due to the in-situ stress. In any case, there is much more scattering in the laboratory tests for seismic velocities and rock mechanical moduli than in in-situ measurements. In order to correlate the rock mechanical parameters obtained in laboratory with the in-situ studies, laboratory tests should be carried out in a triaxial cell, where a hydrostatic confining pressure can be applied to the samples. Furthermore, the fractured sections are difficult to core and almost impossible to test for their mechanical properties, but the acoustic in-situ measurement can be converted to logs of deformation modulus also over the fractured sections. Numerical values of the order of 15 - 50 GPa for Young’s modulus have been derived for each individual fractured section intersected by logged boreholes in bedrock.

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