K. K. K. SINGH
R. K. S. CHAUHAN
and
B. B. DHAR

Geophysical well-logging techniques for environmental problems – a review

Men's desires for prosperity and better quality of life prelude to more and more domestic and industrial wastes. There is serious waste disposal problems in developed countries. India started experiencing these problems since the onset of first Five Year Plan. One of the important constraints of waste disposal is to decide the dumping site which must not be detrimental to the environment.

The pith of the above discussion is that if the dumping site underlays with fractured and permeable sediments or rocks, migration of the wastes will contaminate surface and groundwater. In view of serious water pollution in industrial area and also contaminated groundwater due to leaching from the wastes, the selection of appropriate dumping site is an important aspect. Here, geophysical well logging techniques can play an important role. This review paper covers the principles and applications of different well logging techniques for determining porosity, permeability, density and temperature of the underground environment.

Introduction

The disposal of hazardous material from urban waste in garbage dumps, milling wastes in tailing ponds and industrial wastes in injection wells poses a considerably serious threat to the environment. If the geological and hydrogeological conditions at the disposal sites are favourable for the migration of these wastes, potential sources of surface and groundwater may be contaminated. Because the migration of contaminants is mainly by seepage through surface, therefore, selection of a proper site for disposal is essential.

In selecting a hazardous waste disposal site, one of the requirements is that the wastes be confined within the site of deposition and not migrate to contaminate any nearby surface or groundwater supply. Therefore site evaluation involves identifying unfractured rocks and impermeable sediments. Within a sedimentary environment, waste should be confined by formation of extremely low permeability. The permeabilities of most igneous and metamorphic rocks are very low, but most of these rocks are also highly altered or fractured. Fractured rocks are more porous and permeable, and may therefore provide paths for the transport of harmful subsurface contaminants.

Mr. K.K.K. Singh, Scientist, Central Mining Research Institute, Dhanbad, Prof. R.K.S Chauhan, Professor & Head, Deptt. of Applied Geophysics,Indian School of Mines, Dhanbad and Dr. B.B. Dhar, Director, Central Mining Research Institute, Dhanbad.

To check contamination of surface and subsurface water, the disposal site should have following characteristics:

(i) It should have no fracture zones.

(ii) It should have confining lithology that is impermeable to the migration of fluids.

(iii) It is not productive both geologically and biologically.

(iv) It does not contribute much to the catchment.

Geophysical well-logging techniques can play an important role in the selection and assessment of such a disposal site. Generally, physical characteristics of the rocks lying at different depths in borehole can be determined by this technique.

In this paper, the principles and applications of different methods are discussed in brief.

Geophysical well-logging methods

Most of the well-logging techniques that have been developed for hydrogeological investigation (Keys and MacCary,1971), mineral (Glenn and Nelson 1979; Hearst and Nelson,1985), Petroleum (Serra,1984,1986) geotechnical (Reeves,1989) applications can be used for investigating hazardous waste sites (Daniels and Keys, 1990; Howard,1990). Conventional borehole logging techniques which can be used at such sites are the followings :

- Natural gamma ray log
- Gamma gamma-ray log (Density log)
- Neutron neutron log
- Acoustic log
- Temperature log
- Caliper or section gage log
- Self-potential log

Not all of the techniques mentioned above may be successfully applied at any given site. The choice of techniques is dependent on the geological environment and the borehole logging environment (e.g. sedimentary igneous or metamorphic environments). The borehole logging environment creates one of the major constraints on which measurements can be made. Boreholes may be air or fluid filled, or they may be cased with either plastic or steel. Table 1 lists the methods that are best suited to the different borehole environments.

TABLE I: LOGGING PARAMETER IN DIFFERENT BOREHOLE ENVIRONMENTS:

	Uncased		Cased	
	Air-filled	Fluid-filled	Plastic	Steel
Gamma-ray	x	x	x	x
Gamma-gamma-ray	x	x	x	x
Neutron-neutron	x	x	x	x
Selfpotential(SP)		x		
Acaustic (Sonic vebcity)		x		
Temperature		x	x	x
Caliper	x	x		

Natural gamma ray log

It measures natural radioactivity of rocks occurring along the borehole wall. Practically all types of rocks possess radioactivity properties due to the admixture of radioactive elements which occur in scattered state in the crust. The main radioactive elements presenting the earth's crust are the isotopes of uranium (Ur) and thorium (Th) along with their decayed products K40 and partially Rb87. In general the content of radioactive minerals in rock are extremely small (varies from 10^{-11} to 10^{-12} gram equivalent of radium per gram of rock).

As different rock types contain variable amounts of these radioactive minerals, therefore gamma ray logging has been used for the identification of rocks. The differences in radioactivity level between the limestones, dolomites, and sand stones are relatively insignificant when compared with the shales. The principal use of the Yray log is to distinguish between the shales and the nonshales.

Density log

The density log, or gamma-gamma log, was first introduced in 1954 to estimate the bulk density of formations in situ as an aid to gravity studies. The majority of applications are currently in formation (porosity) evaluation due to the correlation between density and porosity (Schlumberger, 1972; Telford et al., 1976; Doveton,1979; Roke, 1989). A radioactive source applied to the borehole wall in a shielded sidewall skid emits medium energy radiation into the formation. Shielding ensures that gamma rays reaching the detector are those that have travelled through the adjacent formation. Gamma radiation from the source interacts with the rock by compton scattering (loss of energy due to collision, continuation with diminished energy) and the detected gamma radiation intensity is proportional to average electron density of the formation, which can be converted to apparent bulk density. Maximum depth of investigation is approximately 15 cm.

It is most accurate for porosities greater than 8%. The density log response is highly variable and depends on the geological environment. In sedimentary environments, the density log is used to identify lithology or to determine porosity. In igneous and metamorphic rocks, however, density logs may be difficult to interpret because the density is altered by the presence of graphite, base metal sulphides, and oxides.

Neutron log

Neutron logs have been in use since 1941 and they record the response induced by bombardment of the formations of high energy neutrons (hydrogen nuclei). They respond primarily to hydrogen content and are particularly useful in delineating porous zones and determining the amount of liquid-filled porosity. Neutrons lose more energy per Collision relative to the mass of the nucleus with which it collides and the greatest energy loss occurs when a neutron strikes a nucleus of equal mass, i.e., a hydrogen nucleus. Ultimately, each neutron is reduced in energy to a thermal state at which point it is captured by a nucleus and captured gamma rays are emitted. Depending on the type of neutron logging tool, either the captured gamma rays or the neutrons themselves are counted by a detector in the tool (Schlumberger, 1972, Telford et al; 1976; Doveton, 1979). The reduction of the neutron flux is mainly a function equated with the pore fluid fraction. A high porosity results in a low count rate at the detector because most of the neutrons will be reduced to a thermal state and captured close to the source (or the reverse if the captured gamma rays are counted). A low porosity results in a high count rate, as a higher proportion of neutrons survive the distance to the vicinity of the detector.

In well consolidated sandstone and carbonate rock areas where the porosity is low, the neutron log finds an important place as a means of determining porosity. The neutron log has the advantage of a large sampling volume, a factor that can be of great importance when the porosity is very irregular. Corrections for the presence of shale are necessary. When the porosity is below 5% the neutron log becomes sensitive to lithologic changes.

Spontaneous polarization or self potential (SP)

The SP method involves the determination of natural potentials that arise from electrochemical differences in the subsurface.

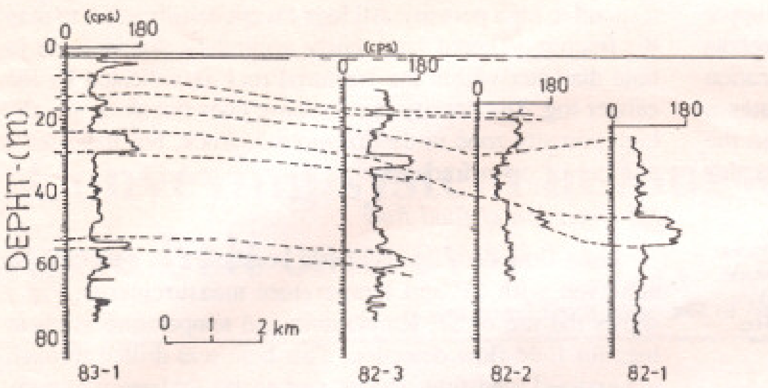

Fig.1 Stratigraphic correlation using natural gamma-ray logs. Numbers at the bottom (e.g. 83-1) are borehole numbers.

In sedimentary environments, SP anomalies may be generated by fluid flow (electro filtration), temperature changes (thermoelectric), changes in the chemical composition and concentration of electrolyte of the formation fluids, and shaliness of a porous formation. These measurements have, therefore, been used primarily for geological correlation, estimating groundwater quality (Radhakrishna and Gangadhara Rao 1990), detecting porous and permeable zone in a formation (Keys and MacCary (1971) and for investigating fluid flow (Corwin,1990). SP method is the primary method for distinguisting between shales and permeable non-shales. With fresh muds in low and medium resistivity formations the SP provides an excellent method of locating porous and permeable beds. In high resistivity formations it is still useful, but the bed boundaries cannot be picked with accuracy with salt muds the SP usually has very little definition and can best be described as having a wandering appearance. It does not work at all in holes drilled with oil-base muds.

Sonic or acoustic velocity log

This method was first developed in 1952 by Summer, Vogel and Broding. Acoustic log consists in recording the time necessary for an acoustic or sound wave to travel a definite distance through the rock formation. This timing is recorded continuously as a function of the well depth.The time is inversely proportional to the velocity of sound propagation within the medium surrounding the device. The speed of sound in the subsurface formation depends upon the elastic properties of rock matrix, the porosity of the formation and the fluid contained and their pressure. In hard formation the sonic log reflects the amount of fluid in the formation and hence, it correlates well with their porosity. In the unconsolidated formations which are usually of fairly high porosities the sonic log gives an approach to porosity determination when the readings are corrected for lack of compaction, shales and contained fluid.

Thus we see that in well consolidated formations containing little or no shaly material, the acoustic velocity log is probably the best wireline tool for porosity determination.

Temperature logging

The temperatures in the drill hole of a rotary drilled well are not in equilibrium with the temperatures of the surrounding rocks because of the circulation of the drilling mud. In fact, the temperatures measured on the ordinary logging surveys may be as much as 50° different from the rock temperatures.

The most prominent temperature anomalies are those caused by groundwater flow. Water has a heat capacity 3 to 5 times that of the rock. Fractured or shear zones that provide groundwater pathways can be located easily if hydrological gradients exist within the rock mass or if logging is done immediately after drilling (Drury and Jessop,1982).

Caliper logging

The hole diameter is measured by a caliper. Caliper measurements are primarily used for correcting log responses that are sensitive to hole size. Because hole is commonly enlarged within fractured zones, the caliper log is sometimes used in fracture detection.

Applications

The following are examples of how some of the geophysical logging techniques may be used in investigating waste-disposal sites.

(1) Lithology and stratigraphic mapping

Natural gamma ray logs are widely used to identify lithology and to map straitigraphy. Stratigraphic correlation permits lateral extrapolation of hydrogeological data. This is done by matching log character and amplitude between holes. The log-based interpretations are often confirmed with lithologic data where such data are available. Fig. 1 shows a crosssection of gamma-ray logs from four wells drilled for hydrogeological investigations. The sand and gravel layer between 30 m and 50 m is a potential aquifer, and the

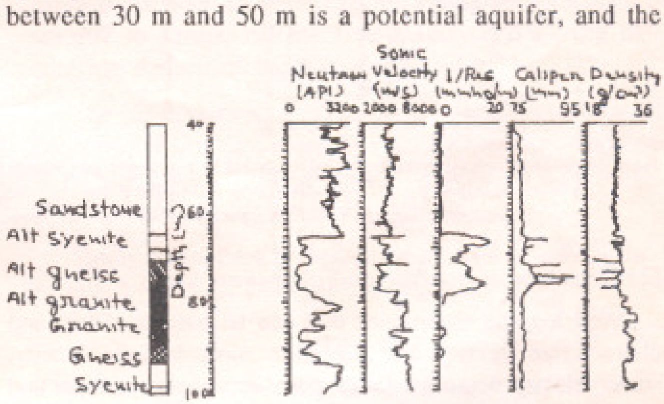

Fig.2 Neutron, sonic velocity, reciprocal of resistivity, caliper and density logs recorded in the Bells Corners hole BC-81-1. The wide fractured/ altered zone between 64 m and 78 m is clearly delineated by all logs except the density logs which indicates only narrow open fractures within this wide zone.

massive clay layer between 25 m and 30 m is a good upper confining bed. As this clay layer is not intersected in borehole 82-2, this location has an open groundwater communication system with the surface recharge area. This indicates a potential danger for groundwater contamination from the surface or near surface waters. Disposal of waste near this site should be avoided.

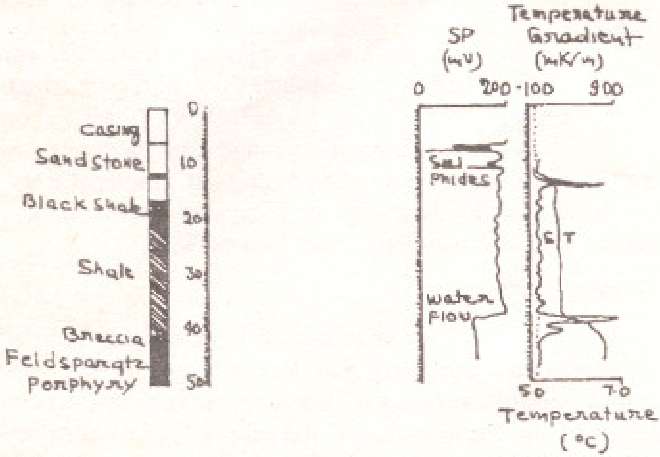

Fig.3 SP, temperature, temperature-gradient logs recorded in hole YA407 at the YAVA lead deposit, Nova Scotia. A temperature and SP anomaly caused by ground water flow is indicated at approximately 40 m.

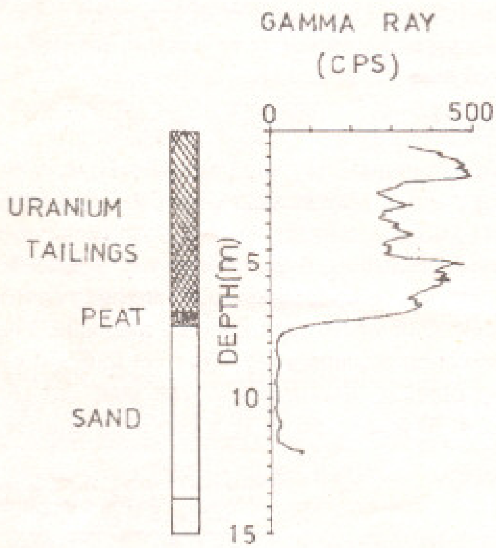

Fig.4 Total-count natural gamma-ray log recorded in a hole drilled through a uranium tailing pond. The radio-active wastes have not migrated far into the underlying sand aquifer.

(2) Detection of fracture and alteration zones

Well logging techniques that can be used to detect and characterize fracture and alteration zones include density, sonic velocity, neutron-neutron porosity, acoustic, caliper and temperature logs, Fig.2 shows some of these logs acquired through fractured and altered granite and gneiss. The neutron log is in API units, where low values correspond to high porosity; low values on the interval sonic-velocity log correspond to high porosity. All logs except density seem to map the fractured/altered zone fairly accurately. An increase in hole diameter within the fractured rock is indicated by the caliper log. The density log response does not show a wide, high porosity zone in the fractured bedrock, but indicates a number of open fractures.

(3) Detection of fluid flow

Fluid-flow detection within a borehole can generally be achieved with SP and temperature measurements. Fig.3 shows the use of SP, temperature and temperature gradient logs for fluid-flow detection. This hole was drilled through mineralized sandstone, shales, and quartz-feldspar porphyry. SP anomalies observed within the sandstone are due to the presence of lead mineralization. A major water producing zone at approximately 39 m is indicated by a significant change in the SP response, and the temperature and temperature gradient. This SP anomaly apparently is generated by fluid flow and a temperature change. Another zone of water flow occurs at approximately 14 m, within the sandstone.

(4) Monitoring contaminant migration from a uranium tailings pond

Fig.4 shows a gamma ray log through a plastic-cased hole in a uranium tailings pond. The uranium ore at this mine comes from a quartz-pebble conglomerate containing 5 to 15% pyrite. The tailings consist of a mixture of sand and siltsize particles in a porous, moderately permeable mass consisting of quartz, feldspar, and approximately 5 % pyrite. The tailings are deposited in a valley formerly occupied by a spruce log, which has formed into peat, underlain by a very permeable glaciofluvial sand and gravel aquifer. The gamma-ray log shows that the radioactive wastes from the tailings had not migrated through the peat layer into the aquifer.

Conclusions

Geophysical well-logging techniques can give valuable information necessary for the selection of suitable waste disposal sites. The choice of the techniques is dependent on the geological environment (sedimentary vs igneous/metamorphic) as well as on the borehole environment (air filled vs fluid-filled, cased vs uncased holes).

The physical property determinations from density, sonic and resistivity logs can be used in interpreting and modelling geophysical data, caliper and temperature logs may also be used in correcting other logs, such as, density log, so that accurate hydrogeological parameters are determined.

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