# APPENDIX D

# ASSESSMENT OF THE PHASE 1 FIELD TRIAL RESULTS

CONTENTS

## D.1 HIGH RESOLUTION SEISMIC REFLECTION

### D.1.1 Operation Procedure

The method was practised by three of the six contractors (see Appendix C). The equipment and set up used in the field by the three companies were very similar. A 2-6 kg sledge hammer was used as the power source (Plate D1). At Sites A, B and C spike geophones were inserted into pre-drilled holes (Plate D2). Along the vertical slope and wall traverses, geophones with flat surfaces were used by GSC to allow attachment using rapid hardening glue (Plate D3). This appeared to work reasonably well unless the surface was rough as in the case of the shotcrete along TA01 or some of the masonry blocks. In such cases a smooth area was prepared first. IGGE used plaster of paris to couple the geophones to hard surface cover (Plate D4). The geophone spacing used was 1m by GA, 0.5m to 1m by GSC and 0.25m to 0.7m by IGGE. Typically hammer blows were repeated 3-6 times at the source for stacking of seismic traces to enhance signals. The source location was moved along the traverse lines at predetermined intervals and the seismic data were recorded in separate data files. Notch and corner filters were sometimes applied during the field collection of data. Filters were normally applied in the data analysis.

A number of operations were carried out to process the field data. It appears that all of the three companies have canned software programs to process the data, but only GSC and GA detailed the data processing operations and the sequence of the data processing in their reports. Certain pre-processing operations were done as standard procedures. The data were first combined into a single file and converted into common depth point format. Subsequent data analyses differed between the companies but normally involved the following operations: adjustments and equalising of gains of seismic traces, filtering of noise, velocity analysis, dynamic correction, applying f-k domain filters, and stacking. The processing software used by IGGE was not standard and therefore the reliability of the results are difficult to assess.

### D.1.2 Summary of Results

(a) IGGE presented seismic sections of all traverses with reflectors marked on the sections. Interpretative cross sections are given along with the seismic cross sections. They claimed to have reliably determined the geometry of the retaining walls and identified subsurface strata at every site. They also claimed to have detected accurately the locations of anomalous structures.

(b) GSC presented seismic results of all traverses except TC03 and TD04. Interpreted cross sections are presented. This report suggests that the method did not determine the thickness and geometry of retaining walls but was able to identify voids, bedrock interfaces, and structural fractures.

(c) GA claimed that the method failed to identify unambiguous reflectors from any of the traverses, perhaps with the exception of TB04. Generally, no coherent reflectors were convincingly mapped.

D.1.3 Assessment of the Method

An experienced team can finish the fieldwork of shooting a traverse in 3-4 hours. Normally at least two persons are needed to conduct the survey. The layout of the seismic spread requires substantially more time than the data collection, especially if the geophones need to be glued onto the surface. Seismic methods are sensitive to environmental noise, especially vibrations caused by traffic and machinery operating nearby.

The seismic reflection surveys conducted by the three companies did not produce consistent and reliable results. The cross sections produced, even for the same traverse, differ substantially. The final section produced depends greatly on the parameters used in the data processing. A high level of subjectivity appears to have been involved in the selection of these parameters.

The claim made by IGGE in its draft interim report that the method produced accurate determination of the wall thickness and subsurface stratigraphy has not been repeated by other contractors. The reflectors in IGGE's report are ambiguous and unconvincing. The interpretation and placement of layer interfaces and subsurface anomalies were considered arbitrary and not well justified. Both IGGE and GSC made some speculative correlation's between the borehole information and the seismic results. Without any borehole information, it is considered that many features and interfaces would not have been identified on the seismic sections alone. GA's assessment of the method in that it failed to image major interfaces between different materials is considered to be a realistic evaluation.

The efficiency of the method also depends on the condition of the structure being surveyed. Air space present beneath the surface coverings can greatly affect the coupling of the geophones to the material beneath. Such problems may be remedied by burying the geophones deeper into the underlying material, but the process would then be invasive in nature.

Engineering and man-made structures, such as storm water drains and concrete tie beams, appear to have acted as wave guides along which seismic energy is diverted and channelled, resulting in strong attenuation of seismic energy with depth. The mortared joints between masonry blocks in a retaining wall greatly attenuated the wave velocity.

Since the surveyed structures are all relatively shallow, ground roll was a major problem because of the short separation between the arrival of the direct wave and the reflected wave.

Sucessful use of the method depends on a strong contrast in acoustic impedance between the target and the surrounding geology. The longitudinal compression wave velocity of the material itself is an undetermined factor that could affect the interpretation. In the contracted surveys, the velocity was generally estimated using either seismic refraction or from multiple reflectors. No consistent velocities were given. The depth profiles were normally constructed based on a single constant velocity which is an invalid assumption. Theoretically, the method has unlimited penetration dictated by the power source. Voids are difficult to locate and identify with the method, since it produces a negative acoustic impedance at the material-void interface.

## D.2 SPECTRAL ANALYSIS OF SURFACE WAVES

### D.2.1 Operation Procedure

SASW was carried out by five of the six contractors, each using different equipment (see Appendix A). Piezoelectric accelerometers coupled to hard surface protection using plaster of paris and spiked magnetic pads were used by BS and MW (Plates D5 and D6). Both IGGE and GSC used geophones coupled by inserting the spiked end into pre-drilled holes or with plaster of paris (Plates D7 and D8). GA used low-frequency geophones and seismic accelerometers (Plate D9). They coupled the geophones and accelerometers to the surface by various methods depending on site conditions. Hammers of various sizes were used as the power source. Small light hammers were used to generate high frequency waves and heavier sledge hammers were used to generate lower frequency waves (Plates D10 & D11). Typically the hammer blow was repeated 4 to 5 times at the source for stacking to enhance the signals. The site procedures were fairly consistent apart from GSC who used a multiple geophone array to collect the field data (Plate D12). The other contractors used either two or four geophones in a common receiver mid-point array (Plate D13). In this array the geophones spacing is doubled after each test about a common mid-point. Hammer blows were made at either end of the geophone spread.

All the contractors except MW used a spectral analyser on site to allow real time spectral calculations so that the quality of the data collected could be monitored and field adjustments made (Plate D14). MW recorded acceleration time histories on a laptop computer on site, with signal analysis carried out later using MATLAB software. Typically after signal analysis, dispersion curves (velocity versus wavelength) are constructed. From the dispersion curves, shear wave velocity depth profiles can be constructed by inversion or forward modelling techniques. Only GA, IGGE and MW have presented details of the full analysis procedure and produced depth versus shear wave velocity profiles.

### D.2.2 Summary of Results

(a) BS did not carry out the full SASW analysis, only presenting the characteristic Rayleigh wave velocity and frequency for surface materials.

(b) IGGE present interpretation of the SASW data for all traverses in the form of contoured shear wave velocity versus depth sections. They claim to have measured the thickness of retaining walls and have characterised the geology at each of the sites.

(c) GSC present pseudo-dispersion curves and interpreted geological models for all the traverses. The interpretation is based on the pseudo-dispersion curves as no inversion or forward modelling has been made. They claim to have successfully measured the thickness of the retaining structures and located voids below the shotcrete surface protection along TA02 and behind the masonry wall along TB03.

(d) MW present contoured shear wave velocity versus depth sections for the longer traverses. They were not able to measure the thickness of the retaining walls but were able to determine shear wave velocity depth information for fill and natural materials.

(e) GA present selected dispersion curves and shear wave depth profiles for all of the sites. They were unable to measure the retaining wall thickness but obtained consistent data for most of the horizontal traverses at the top of walls or at the slope sites.

D.2.3 Assessment of the Method

An experienced team of one geophysicist and a labourer can complete the field work of shooting one traverse in 1 to 2 hours. None of the contractors reported problems with vibration noise at any of the sites. The depth of penetration of the method is dependent on geophone spacing and is therefore constrained by site conditions. Where voids exist below a rigid surface cover, such as a concrete slab, de-coupling of the geophone from the soil below is reported by most of the contractors.

Depth of penetration and resolution is dependent on the wave length of the Rayleigh wave produced and detected. As noted above, the physical limitation of space on site will also affect the maximum penetration depth. MW and GA achieved resolution of between 0.1m to 0.2m while GSC and IGGE achieved resolution to between 0.5m and 1.0m. At sites with limited space, penetration depths of 3m to 4m were generally achieved. At Site D, the maximum depth of penetration was 12m. Depths to discrete objects were not reported by any of the contractors.

Both MW and GA were not able to interpret the SASW data obtained from the masonry walls at Sites B and C. They both report that reproducible dispersion curves could not be obtained for shallow depths into the walls. They suggest that this is probably due to the wall facing being made up of discrete blocks separated by cement mortar and therefore not being a continuum and producing very complex wave propagation patterns which cannot be interpreted with existing algorithms. The horizontal tie beams also cause similar effects, as demonstrated in the GA report (Golder Associates, 1996a).

The technique has the ability to produce high resolution cross sections to depths of 12m to 15m (see Meinhardt Works, 1996, Site D) if soundings are made at close spacing.

The dispersion curves obtained by each contractor were generally consistent in form. However, interpretation of the dispersion curves is inconsistent apart from at Site D. The inconsistency is likely to be due to the complex ground conditions, especially at the masonry wall sites. The consistency of the results obtained at Site D support this conclusion since the ground conditions are simple compared with the other three sites.

## D.3 RESISTIVITY IMAGING

### D.3.1 Operation Procedure

The method was practised by five of the contractors (see Appendix C). The dipole-dipole array configuration was used by most of the companies, except IGGE who used a tripolar configuration and GA, who employed dipole-dipole at one site and the Wenner configuration at others. Electrode spacing between 1m and 2m were generally used. BS drilled and inserted "Hilti" bolts into hard surface protection at calculated distances, which were used as electrodes (Plate D15). Most other contractors used steel pins inserted into pre-drilled holes through surface protection so that they could make direct contact with the soil beneath (Plate D16). Multi-conductor cables with takeouts for electrode connections which enabled current to be cycled to particular pairs of electrodes helped to minimise the time required for the electrode deployment (Plate D17).

In the tripolar or dipole-dipole configuration, the resistivity measured was plotted at the intersection of two lines extending at 45° from the centres of the current and potential electrode pairs. As the current and potential electrodes were moved, a pseudosection of resistivity readings of the subsurface is obtained. The depth depicted in the pseudosection does not represent true depth but is relative in nature. GA modelled the Wenner pseudosections using the programme RESIST to produce two-dimensional resistivity versus depth sections.

### D.3.2 Summary of Results

(a) BS conducted resistivity surveys at the relatively long profiles, including TA03, TA04, TB04, TB05, TC03, TD01, TD02. The depth of the section produced was generally about 5m. High resistivity areas were attributed to relatively unweathered rock where as low resistivity areas were attributed to high moisture zones.

(b) IGGE conducted resistivity surveys on all of the traverses. For the longer traverses (TA01, TA02, TB04, TB05, TB03, TD01, TD02) the depths of the pseudosections extended to about 8m. For the shorter sections, penetration depths are only about 2m. Their report contains cross sections showing interpretations of subsurface materials, and thickness of masonry walls.

(c) FGS conducted resistivity surveys on TA03, TA04, TB04, TB05, TC03, TD01, TD02. The report claimed to have successfully mapped out variations in resistivity values beneath slopes, which can be correlated to geological features.

(d) MW made resistivity surveys on all traverses and state that they have successfully obtained data of enhanced moisture zones and the geometry of structures.

(e) GA conducted the survey on the relative long sections, including TA03, TA04, TB04, TB05, TC03, TD01, TD02. Two dimensional cross-sections are produced from 1D models at point locations along each traverse.

D.3.3 Assessment of the Method

The method is efficient and quick in the field. The teams completed the measurement of a traverse in about 3-4 hours with a minimum of 1-2 persons to operate in the field. Good coupling between the electrodes and the ground is required. Short circuiting due to the presence of metallic objects in the ground severely affected the results at Site A, traverse TA04. Such problems can be partially overcome by using a conductive gel or cotton wool saturated with salt water around the electrodes (Plate 18). Resistivity surveying theory assumes point current source at a known position. However, by inserting the electrode into the slab only, this condition may not be satisfied, especially if a void exists between the slab and soil directly below the electrode position. This potential problem did not appear to affect the results obtained by BS. The method is not truly non-invasive, since it requires electrode insertion into pre-drilled holes, although no structural or irreparable damage occurred during the trials.

The usefulness of the method is limited by the extent of the traverse. On the relatively short traverses of about 6m to 10m, only a depth of approximately 2m is attained. For the longer traverses over 20m, a depth of 7m can normally be achieved. Resistivity sections at both end portions of the lines are normally not obtainable, because the resistivity value obtained is for the intersection point located along a line extending at 45° from the electrodes. Generally, the different resistivity sections obtained by different contractors and involving different methods are consistent. A comparison of the results on selected traverses is given below.

(i) TA03. A zone of low resistivity (less than 100Ωm), centred at traverse distance 28m, have been located by all of the contractors. This zone corresponds to the area affected by drainage water overflow (Figure 3).

(ii) TA04. All five profiles show a zone of low resistivity at traverse distance 0m to 14m and depth less than 2m. This is likely to be electrical noise from the electricity sub-station located at the beginning of this traverse (Figure 3).

(iii) TB04 and TB05. All of the reported resistivity sections show a value of about 250Ωm for the surface covering. Except for MW and IGGE's reports, the ranges of variations are quite similar, although individual reports may show different anomalies at various locations and depths.

(iv) TC03. All of the reported sections show a resistivity of over 800Ωm associated with the masonry wall and general decrease in resistivity with depth. Three to four isolated anomalies have been detected by some contractors but not all.

(v) TD01. A large zone of very high resistivity (greater than 1000Ωm) located at distance 40m to 60m and depth 0m to 6m has been located by all of the contractors. All of the cross sections show substantial variations in the resistivity values of the profile.

In general the results obtained by the different contractors, despite the different equipment, electrode configuration, and software used, are in good agreement with each other.

## D.4 SELF POTENTIAL

### D.4.1 Operation Procedure

The self potential method was tested by three of the contractors (see Appendix C). The equipment used is simple, consisting of two non-polarising electrodes and a resistivity meter (Plate D19). All three contractors used the fixed base electrode array in which one electrode remains stationary whilst the roving electrode is moved along the traverse, generally at 1m intervals. At Sites A, B and C, MW also used a gradient-type electrode array where the pair of electrodes are moved along the traverse at a fixed spacing of 1m. At vertical surfaces, MW and BS fixed a high porosity foam pad to the base of each electrode, saturated with either copper sulphate or conductive gel to lower the electrode-ground contact resistance and increase the excitation current (Plate D20). GA only carried out a survey at Site D as the field team stated that the measurements are only meaningful if direct contact with the soil can be made. This was not possible at the other three sites without excavating through hard surface protection. At Site D, GA excavated small holes for insertion of the non-polarising electrodes (Plate D21). During the survey the fixed base electrode was protected from the sun. The survey was repeated twice, once without soaking the soil at electrode locations and secondly after the electrode positions had been soaked with water overnight.

None of the contractors carried out any post-survey data processing and simply presented the data in the form of millivolt profiles along each of the traverses surveyed.

D.4.2 Summary of Results

(a) BS present profiles for all the traverses but no interpretations.

(b) MW present profiles and self potential vectors for traverses TA04, TB04, TB05, TC01, TC02, TC03, TD01 and TD02. Zones of higher moisture content at the base of the wall at Site C is inferred. Self potential lows along TD01 coincided with surface drain locations.

(c) GS present a profile for TD01 only. A self potential low coincided with a surface drain location.

D.4.3 Assessment of the Method

The self potential method was severely affected by surface or sub-surface metallic objects rendering it impossible to verify the interpretation of the survey results at Sites A, B and C. Only at Site D, which was relatively free from surface metal and had no hard surface cover which allowed positive contact of electrodes with the soil, could repeatable results be obtained by GA.

The results obtained by all three contractors for traverse TD01 are to a certain degree consistent. All show a slight general increase in self potential from north-west to south-east. Small negative anomalies were recorded at the location of surface water drains.

D.5 ELECTROMAGNETIC METHODS

D.5.1 Frequency-Domain Electromagnetics

D.5.1.1 Operation Procedures

Four of the contractors tested the frequency-domain electromagnetic method (see Appendix C). Each used equipment manufactured by Geonics, either the EM 31-D or the smaller EM38 (Plates D22 & D23). They both measure quadrature and in-phase components of the electromagnetic field produced by induced eddy currents. The sampling depth of the EM 31-D and the EM38 is about 5.5m and 1.5m respectively and is related to the induction coil spacing. In the field, readings were taken at 1m intervals along each traverse. At Site D, the survey made by GA was on a 1m grid over the platform area (Plate 24). Data loggers were used on site to collect the raw data.

Very little data processing is required and results are plotted as conductivity profiles along each traverse. GA did however produce contour plans of terrain conductivity for Sites C and D using the griding programme RANGRID and the contouring programme GEOSOFT™.

D.5.1.2 Assessment of the Method

Using either the EM31-D or the EM38, surveys are efficient and quick and can be carried out by a single geophysicist. Depth of penetration is limited by coil separation and the resistivity of the sub-surface soil and rock. The technique is best suited to producing conductivity contour maps of near surface-geology.

Anomalies due to surface or buried metallic objects are orders of magnitude greater than anomalies produced by geological or geotechnical features. All four contractors reported that near-surface metal or nearby machinery affected the results such that interpretation was impossible at Sites A and B. At Site C, generally consistent results were obtained by FGS, BS and GA. Along traverse TC01 and TC02, the measured conductivity increases towards the base of the wall. This may be due to an increase in wall thickness or an increase in moisture content in the lower part of the wall. At Site D consistent results were obtained by all contractors along TD01. Significant anomalies were measured at chainages 30m and 80m, attributed to a manhole cover and an electricity cable respectively. The background conductivity measured is low and constant along the traverse. No useful interpretation regarding the thickness or nature of the fill at this site could be made from the results.

D.5.2 Time-Domain Electromagnetics

D.5.2.1 Operation Procedure

The TDEM method was used by two out of the six contractors (see Appendix C). Both used similar equipment consisting of coincident loop transmitter and receiver coils. IGGE used a square (2m by 2m) transmitter coil with a horizontal circular 500mm diameter receiver located at the centre of the transmitter coil (Plate D25). GSC used a rectangular (2m by 1m) transmitter coil with a vertical rectangular (1m by 0.5m) receiver coil which was manufactured in-house (Plate D26). Receiver coil orientation determines which component of magnetic flux is being measured. A horizontal coil measures the vertical magnetic flux component while a vertical coil measures the horizontal magnetic flux component. Soundings were made by both contractors at 1m intervals along each traverse.

A number of operations were carried out to process the data. Initially voltage versus time sections are produced from the raw data after initial filtering. Apparent resistivity pseudosections are then constructed from the voltage versus time sections. The pseudosections can then be inverted into resistivity versus depth sections. GSC present both voltage versus time sections and apparent resistivity pseudosections. IGGE present inverted data in the form of resistivity versus depth profiles. The inversion process was carried out using an in house inversion software package TEMPRO.

### D.5.2.2 Assessment of the Method

The method is quick to use. A single traverse can be carried out by one to two persons in about one hour using the small coincident loop configuration equipment. It has distinct advantages over the more conventional resistivity traverses since installation of electrodes is not required and information is gathered to the full depth of investigation along the complete traverse with the small transmitter coils adopted. Depth of penetration is determined by the transmitter coil size and both contractors report investigation up to 20m deep with the coils used in the trials, however this depth will be significantly reduced if high-conductivity materials are encountered. Resolution is dependent on how quickly the transmitter current can be turned off and the receiver gates opened and shut. GSC used current turn-off time of 8μs and a first receiver gate cycle time of 20μs. IGGE used current turn-off time of 11.25μs and the first receiver gate cycle time of 15.75μs. Sampling times at short time intervals are required to investigate shallow surface materials with any accuracy. Both contractors report that high levels of noise was experienced at Sites A, B and C due to near-surface metallic objects which made the results difficult to interpret.

The results presented by each contractor are not directly comparable since different magnetic flux components have been measured and the results are presented in slightly different forms. However, there does not appear to be any consistency in the results. The claims made by both contractors that they are able to determine wall thickness and stratigraphy by this method are not substantiated by the GI results. The interpretation and placement of structural and stratigraphic boundaries appear arbitrary and poorly justified.

The apparent resistivity pseduosections produced by GSC and to some extent the resistivity depth sections produced by IGGE should be directly comparable to the apparent resistivity pseudosections obtained using the resistivity imaging method. However, there does not appear to be any consistency in the results between these two methods.

## D.6 GROUND PENETRATING RADAR

### D.6.1 Operation Procedure

Ground penetrating radar was tested by all six contractors (see Appendix C). Each used radar equipment manufactured by Geophysical Survey Systems Inc. (GSSI), either the SIR 2 or SIR 10 systems antennas ranging from high-frequency 900MHz and 1GHz (Plate D27) to low-frequency 100MHz (Plate D28) and 200MHz (Plate D29). GA also used a SIR 8 system with a thermal printer for initial surveys. FGS also used equipment manufactured by Sensors and Software Inc. (SSI) (Plate D30) and a 35MHz antenna manufactured by Radarteam (Plate D31). All the equipment used provide real time radargram sections.

The antennas were pulled along horizontal surfaces and either lowered or pulled up the sub-vertical and vertical structures using ropes attached to the antennas (Plate D32). MW and IGGE both used survey wheels which provide encoded distance information automatically on the radargram (Plate D33). The other contractors recorded manually electronic fiducial distance markers onto the radargram, generally at 1m intervals. It was noted that the teams from BS, MW and GA repeated traverses more than once, making adjustments to the gain levels, ranges, sampling interval and filter settings. FGS, MW and BS carried out common depth point surveys (Plate D34) and GA used known depths to reflectors such as utilities to try to measure radar wave velocity at each of the sites.

Sophisticated data processing techniques borrowed from seismic reflection data processing can be applied to ground penetrating radar data. All the contractors used the GSSI Radan 3 software which is an advanced signal processing package designed to process SIR systems data. The processing package includes high and low pass filters, gain control and colour tables, together with more sophisticated processing techniques such as migration, deconvolution and spatial filtering. General processing made by all the contractors consisted of applying low or high cut filters to remove noise, gain adjustments and colour enhancement. More complex Kirchhoff migration processing was made by GA.

### D.6.2 Assessment of the Method

An experienced team consisting of one geophysicist and one technician can complete a single traverse in one to two hours. The equipment is robust and relatively light and can easily be moved by one person, especially the SIR 2 and pulseEKKO 1000 systems. The larger low - frequency antennas are not as easy to manoeuvre and require two to three persons for the vertical traverses (Plate D35).

The method is not affected by vibration noise, however reinforcement in concrete slabs greatly reduces penetration depth as the radar waves are attenuated dramatically. Some penetration can be obtained by using high-frequency antennas such as 900MHz or 1GHz which effectively see between the reinforcing bars if the bar spacing is not too small. This was done at Site A along TA01 and TA04 by several of the contractors. Other metallic objects such as manhole covers, steel gratings and metal pipes cause localised high amplitude reverberations on the radargram which can obscure other information. This phenomenon was evident at most of the sites surveyed. All radar antennas used in the trails were shielded from extraneous radar waves, however, GA report that air wave interference with the 100MHz antenna was recorded at Site C.

The depth of penetration of radar waves are dependent on frequency and the dielectric constant of the ground. The high-frequency antennas achieve high resolution but poor penetration depths. At the trials the 900MHz and 1GHz antenna generally achieved penetration depths between 0.25m and 0.75m with resolution of 50mm at some sites. The 500MHz and 400MHz antennas generally achieved penetration depths of between 1m and 4m with a resolution of 100mm. The low-frequency antennas such as the 200MHz and 100MHz achieved penetration depths of up to 8m to 10m but resolution was relatively poor at about 1m.

The determination of depth is dependent on the electromagnetic wave velocity used in the analysis. Most of the contractors used values from published data or used a bulk velocity calculated from depth to known reflectors or from common depth point surveys made on site. The wave velocity used by each contractor varied by as much as 50% for the same site and traverse. In general, velocities ranged between 0.12m/ns to 0.08m/ns but values as low as 0.05m/ns were used by some of the contractors. It should also be noted that a single velocity was generally used by all contractors to calculate depths. This assumption is incorrect since each material through which the radar wave penetrates has a different velocity. The depths of penetration reported are therefore not accurate. For accurate determination of depth to reflectors the dielectric constant of each material in the section should be measured.

Maintaining antenna contact onto the vertical walls was problematic especially for the larger, low-frequency antennas (Plate D36). Antenna contact was also a problem along the lower section of the fill slope traverse TD02 due to the surface being composed of angular cobbles and boulders of rock fill (Figure 11). This was not a problem for FGS who used a non-contact 35MHz antenna (Plate D37).

Due to the complex data processing, a high level of expertise is required in both data collection, manipulation and interpretation. It is evident from the results contained in the contractors' reports that certain contractors were able to capture clearer radar images than others using the same equipment. It is considered that the best results were obtained by GA, MW and BS who all used the SIR 2 system with a wide range of antennas. It is noticeable that these three contractors repeated traverses more than once, making adjustments to the gain levels, ranges, sampling interval and filter settings at the data acquisition stage. Contractors who used the SIR 10 system did not produce as good as results as those using the SIR 2. It is not clear, however if this is contractor- or equipment-dependent. Results obtained using the pulseEKKO 1000 were not useable at any of the sites except for traverse TC03.

Consistent results were obtained by the different contractors along many of the traverses and are summarised in Table D1. An interesting point to note is the interpretation made by MW along traverses TB04 and TB05. Parabolic anomalies with long diffraction tails have been interpreted as thin vertical structures running perpendicular to the traverse line. Other contractors also recorded parabolic and other anomalies at the same locations but interpreted them as either utilities or surface artefacts such as manhole covers. This demonstrates the potential problems with differing interpretations of similar anomalies.

## D.7 THERMAL IMAGING

### D.7.1 Operation Procedure

Only BS and GA tested this method (see Appendix C). BS employed a thermal probe (Plate D38)which has a resolution of about $0.01^{m}$C and measures air and surface temperatures which are recorded on a data logger. GA used a Thermovision scanner (Plate D39) accurate to $0.05^{m}$C and recorded the infrared image on video. BS carried out the surveys between 24:00hrs and 02:00hrs and reported that 50 readings could be obtained in 30 minutes. Readings were made at 1m intervals along each traverse. GA carried out the survey during daylight after the surveyed object had been exposed to direct sunlight. Because of the low solar angle and the proximity of adjacent structures, direct sunlight only lasted for a few hours at each site. GA did not carry out any thermography at Site D.

BS did not carry out any post-survey processing and simply presented profiles comprising the air temperature, ground temperature and temperature difference along each traverse. GA analysed the data using the AGEMA C.A.T.S. image enhancing software which can present the data in either a grey scale or a colour enhanced image.

D.7.2 Assessment of the Method

The method is quick and easy to carry out by one person. The equipment is portable and robust. There are some conflicting views as to the optimum time to undertake the survey. BS recommended that surveys are best done at night to minimise background noise from artificial heat sources. GA suggest that surveys should be made in the early evening so that the feature has adsorbed as much direct radiation as possible. The method appears to be subject to constraints of time, weather and climatic conditions. The radiance from the surveyed surfaces was dependent on the orientation of the surface with respect to the sun, time and duration of exposure to solar heat, weather conditions at the time of the survey, and seasonal conditions such as the strength of the solar radiation and the attitude of the sun. GA recommend that surveys should be made during the summer months when solar radiation is at its highest. This would also be beneficial in that zones of high moisture content would be at a maximum during the wet season. The temperature of "hot" and "cold" spots relative to the surrounding material can reverse from day to night if the anomaly is produced by an air-filled void. During the day an air-filled void heats up quicker than its surroundings and therefore appears as a "hot" anomaly. During the night it cools down quicker than its surroundings and appears as a "cold" anomaly. Therefore it is important to carry out the survey when the anomaly is either "hot" or "cold" rather than during its transition phase.

Only traverses TA01, TA02 and TB04 have thermal results from both teams for comparison. There appears not to be any consistency between the results obtained. It also appears that the temperature anomalies identified by GA are related to surface reflectivity, organic growth and shadows, rather than to sub-surface features.

# LIST OF TABLES

# Table D1 - Summary of Results Obtained using Ground Penetrating Radar

| Traverse | FGS | BS | IGGE | GSC | MW | GA |
|---|---|---|---|---|---|---|
| TA01 | Shotcrete thickness not resolved. | Reinforced shotcrete 500mm thick. | Shotcrete 50mm thick. | Reinforced shotcrete 200mm - 290mm thick. | No radargram. | Reinforced shotcrete 50 - 100mm thick. |
| TA02 | Not consistent. | Parabolic anomaly at 10m from top of slope 1m deep. | Not consistent. | Not consistent. | No radargram. | Parabolic anomaly 10m from top of slope 1m deep. |
| TA03 | Not consistent. | Point anomaly at 27m. Voids below slab at 0m-14m, 26m and 38m-48m. Poor penetration with 500MHz antenna at 10m-12m and 28m-30m. | Point anomalies at 2m, 8m, 14m and 27m. | Voids below slab at 11m-13m and 27m-29m. Poor penetration with 500MHz antenna at 10m-12m and 28m-30m. | No radargram. | Point anomalies at 2m, 8m and 14m. Voids below slab at 0m-14m, 26m and 38m-48m. Poor penetration with 500MHz antenna at 10m-12m and 28m-30m. |
| TA04 | Not consistent. | Reinforced slab at 15m-34m. | Poor data. | Poor data | Reflector 3m deep. | Reinforced slab at 24m-34m. |
| TB01 | Poor data. | Concrete tie beams extend 2m-2.5m from face of wall. Bright reflectors directly behind facing. Vertical reflectors from body of wall. Wall 2m thick. | Poor data. | Poor data. | Section not made at TA01 but good wall resolution obtained from horizontal traverse perpendicular to wall. | Concrete tie beams extend 2m-2.5m from face of wall. Bright reflectors behind facing. Vertical reflectors from body of wall. Two wall models. |
| TB04 | Manhole cover at 7m. Parabolic anomaly at 18m. | Point anomaly at 10m. Joint in slab at 18m. | Poor data. | Poor data. | Four parabolic anomalies interpreted as vertical structures at 7m, 9m, 13.5m and 18m. | Manhole cover at 7m. Parabolic anomaly (utility) at 9m. Parabolic anomaly (utility) at 13.5m. Steel drain at 18m. |
| TB05 | Parabolic anomalies at 1.8m, 6m and 20m. Anomalous zone at 7m-10m. | Parabolic anomaly at 6m. Point anomaly at 20m. Zone of high permittivity contrast at 7m-10m. | Poor data. | Poor data. | Two parabolic anomalies interpreted as vertical structures at 1.8m and 6m. Parabolic anomaly (utility) at 20m. | Not radargram. |
| TC01 | Poor data. | Wall 0.9m at top, 1.5m at bottom. | Poor data. | Poor data. | Wall 1.3m at top, 1.6m at bottom. | Wall 1m at top, 1.5m at bottom. |
| TC02 | Poor data. | Wall 1.6m at top, 1,5m at bottom. | Poor data. | Poor data. | Wall 1.2m at top, 1.8m at bottom. | Wall 1.5m at top, 1.8m at bottom. |
| TC03 | Wall 1.5m thick. Poor reflection at 17m-31m. | Wall 1.3m thick. | Poor data. | Wall 1.75m-2m thick. | Wall 1.9m thick.<br>Poor reflection at 19m-31m. | No radargram. |
| TD01 | Internal structures in fill evident on radargram but not interpreted. Cavity at 45m. | Point anomaly at 3.5m and 32m. Fill not as thick at DH2 as log indicates. Poor penetration at 45m. | Poor data. | Internal structures in fill evident on radargram but not interpreted. Fill not as thick at DH2 as log indicates. | Internal structures in fill. | Internal structures in fill. Point anomalies at 3.5m-5m and 32m. Fill not as thick at DH2 as log indicates. |

# LIST OF PLATES

Plate D1 - 6 kg sledge hammer being used at Site A (TA04) as energy source for high resolution seismic reflection. Contractor Golder Associates. (EG96/28/21)


Plate D2 - Spiked geophone adjacent to pre-drilled hole prior to high resolution seismic reflection survey at Site A. Contractor Guandong South China EGTD Co. (EG96/07/20)

Plate D3 - 65Hz geophone being fixed to shotcrete slope surface during high resolution seismic reflection survey at Site A (TA01). Contractor Guandong South China EGTD Co. (EG96/08/23)

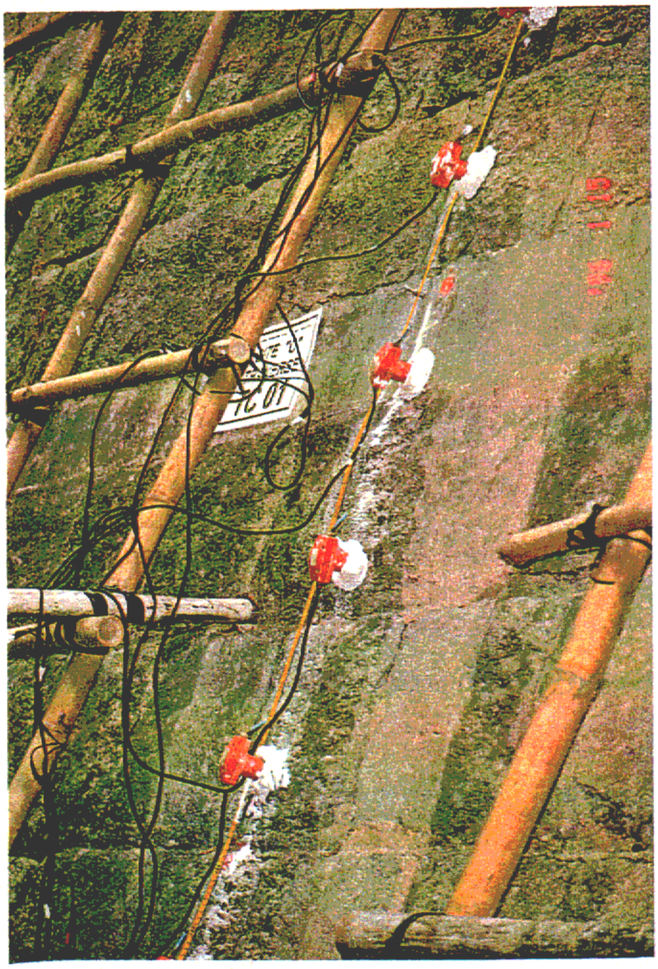

Plate D4 - Geophones attached to the masonry wall with plaster of Paris at Site C (TC01) during seismic reflection survey. Contractor Institute of Geophysical and Geochemical Exploration. (EG96/10/6)


Plate D5 - Metravib CSH05 Piezoelectric accelerometer attached to masonry wall with plaster of Paris at Site C (TC03) during SASW survey. Contractor Bachy Soletanche. (EG95/143/14)

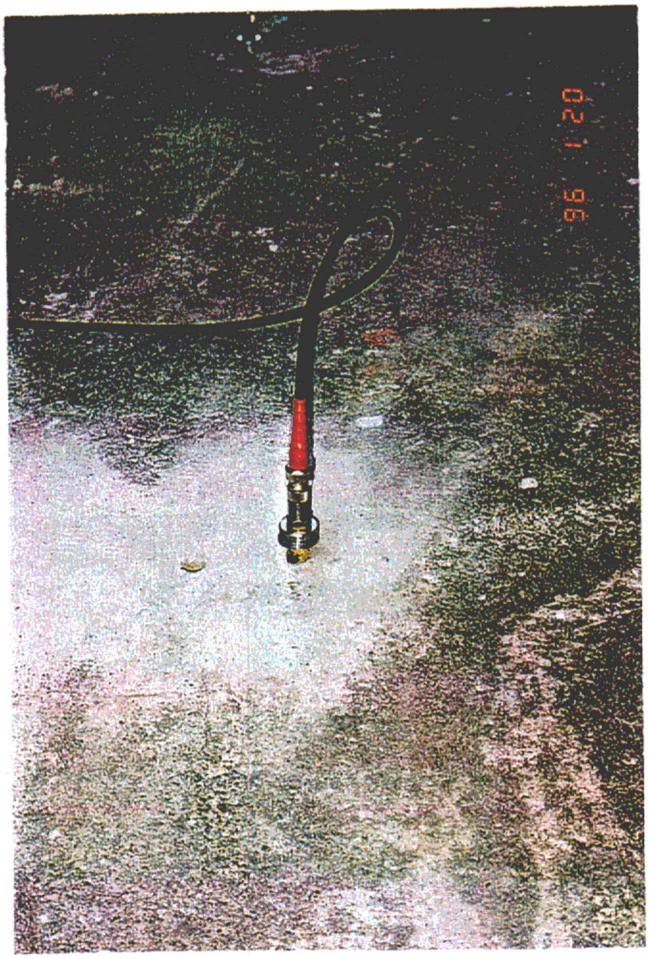

Plate D6 - Bruel & Kjaer piezoelectric transducer coupled to the concrete slab through a spiked magnetic mandrel during a SASW survey at Site A (TA04). Contractor Meinhardt Works. (EG96/33/13)

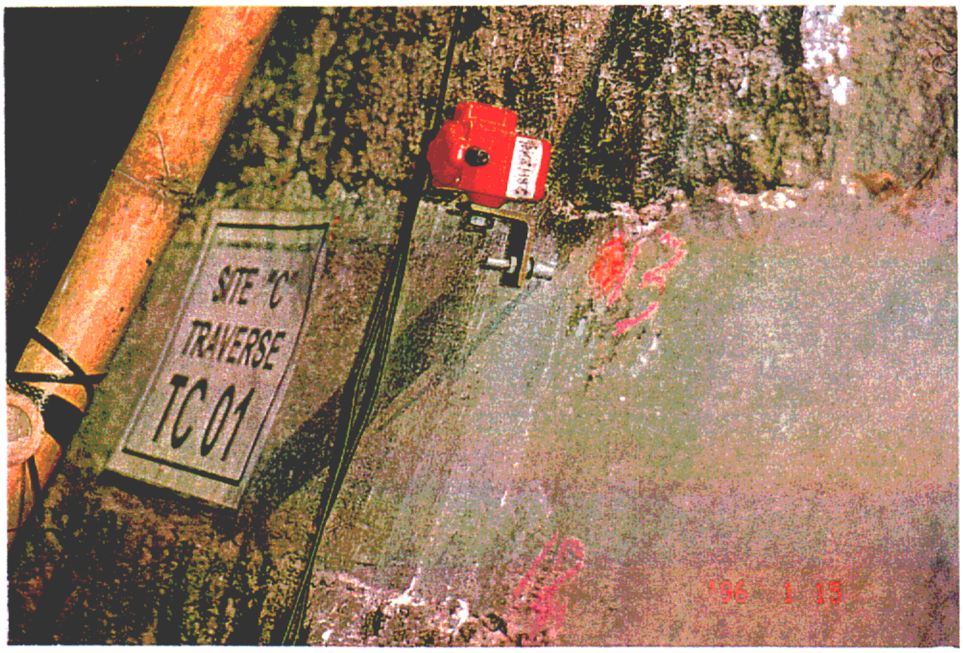


Plate D7 - SASW geophone inserted into pre-drilled hole along the masonry wall tie beam at Site C (TC01). Contractor Institute of Geophysical and Geochemical Exploration. (EG96/14/7)

Plate D8 - Plaster of Paris being used to fix 10Hz geophones to masonry wall at Site B (TB02) during SASW survey. Contractor Institute of Geophysical and Geochemical Exploration. (EG96/27/20)

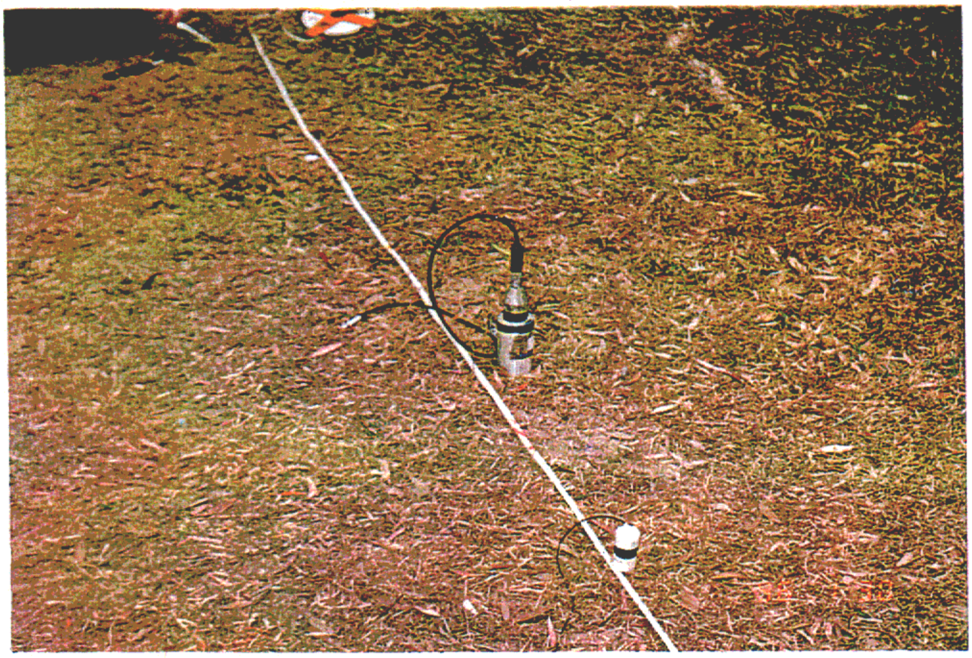

Plate D9 - Low frequency 1Hz geophone used to record long wavelength surface waves during SASW survey at Site D (TD01). Contractor Golder Associates. (EG96/45/6)

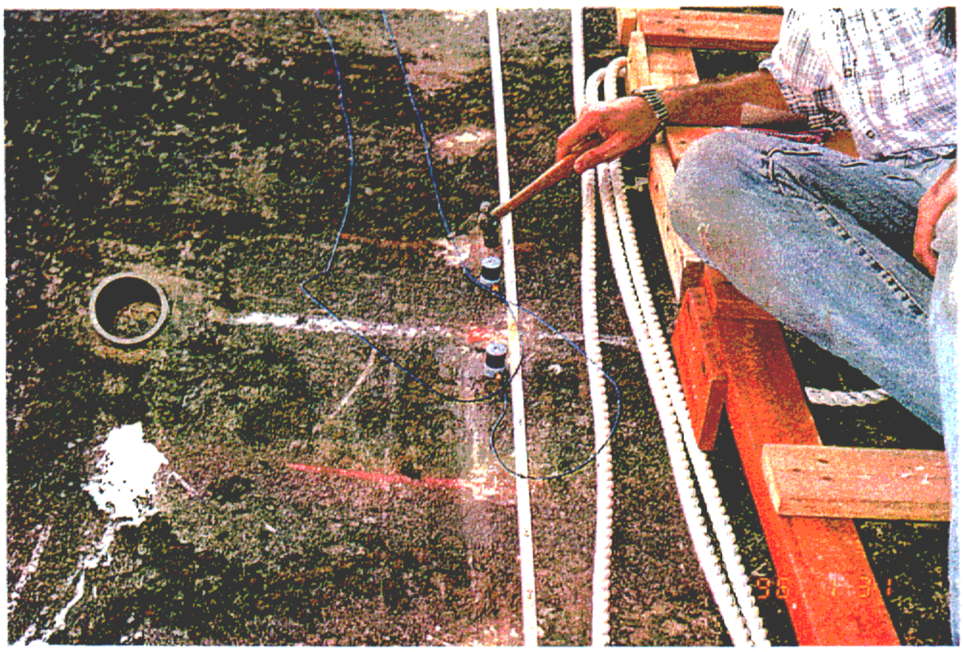

Plate D10 - 20 gram hammer being used at Site A (TA02) to produce high frequency surface waves for SASW survey. High frequency accelerometers being used as sensors. Contractor Golder Associates. (EG96/45/17)

Plate D11 - 6kg sledge hammer being used at Site D (TD01) to produce low frequency surface waves during SASW survey. Contractor Golder Associates. (EG96/45/9)

Plate D12 - SASW survey in progress with a multiple geophone array at Site B (TB04). Contractor Guandong South China EGTD Co. (EG96/23/22)

Plate D13 - Common mid-point receiver array being used for SASW survey at Site B (TB05). Sounding point is mid-way between the two geophones. Contractor Institute of Geophysical and Geochemical Exploration. (EG96/26/24)

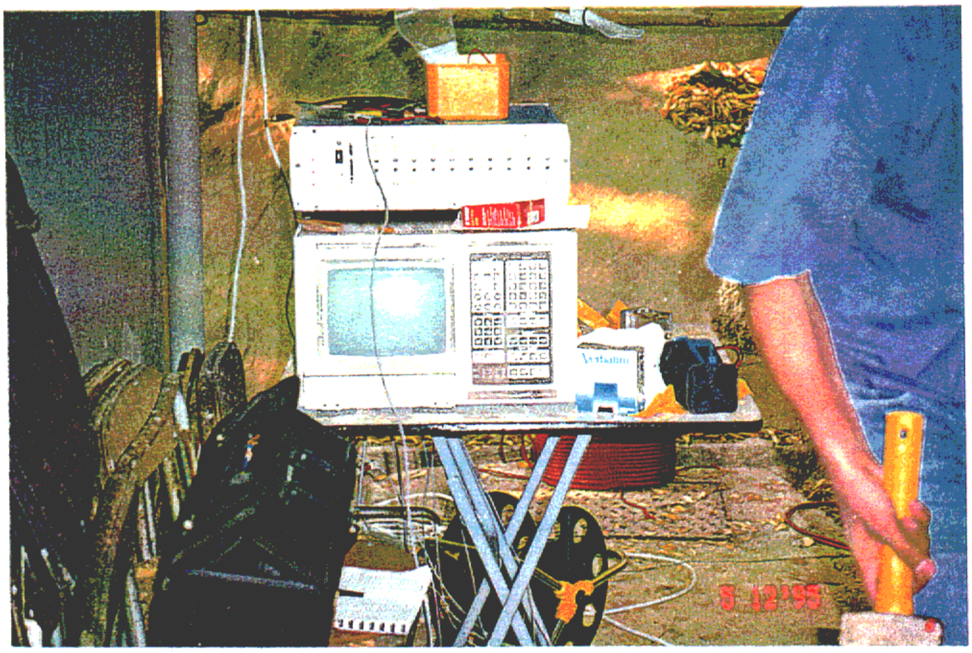

Plate D14 - Metravib RAIO seismograph and Scientific - Atlanta Spectral Dynamics SD380 Signal Analyser used for SASW survey. Contractor Bachy Soletanche. (EG95/144/13)

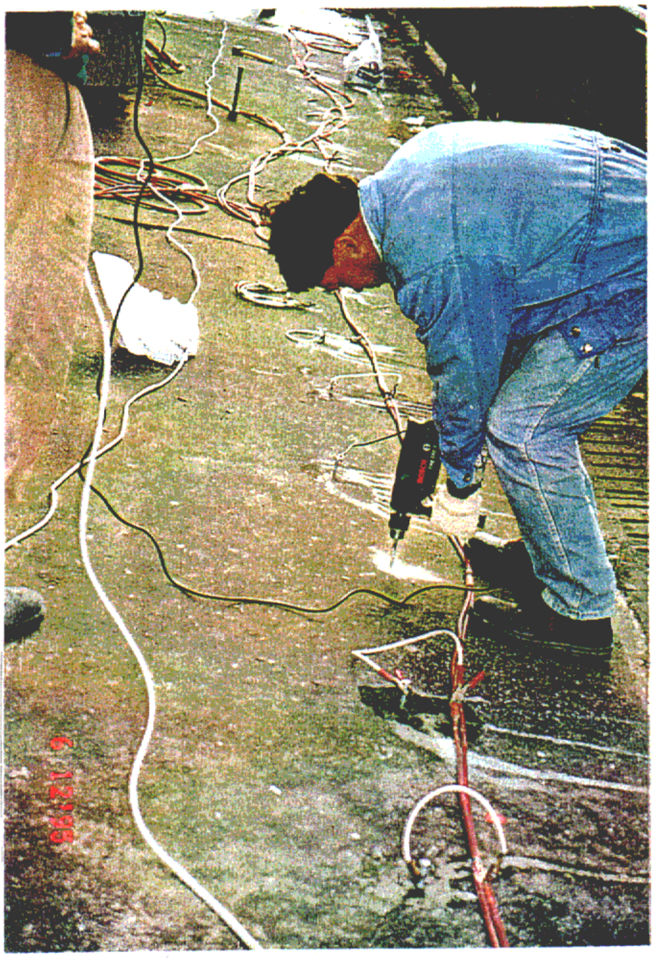

Plate D15 - Hilti-bolts being inserted into pre-drilled holes and used as electrodes at Site A (TA03) during resistivity imaging survey. Contractor Bachy Soletanche. (EG95/150/18)


Plate D16 - Steel pin electrodes inserted through concrete slab to ensure contact with soil beneath at Site A (TA03) during resistivity imaging survey. Contractor Fugro Geotechnical Services (HK) Ltd. (EG95/159/8A)

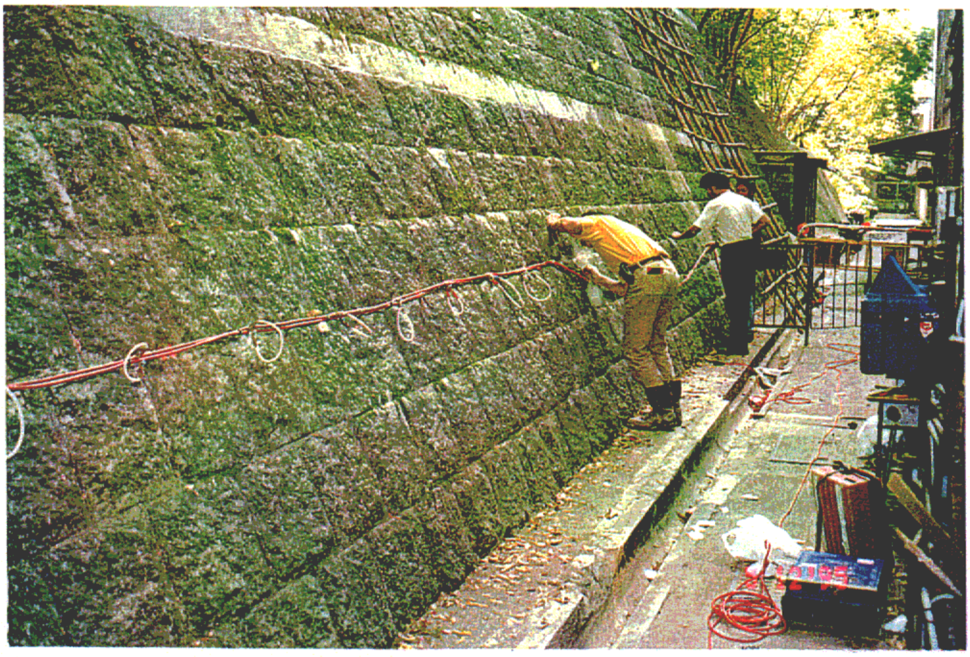

Plate D17 - Multi-takeout cable being attached to electrodes during resistivity imaging survey at Site C (TC03). This system allows each electrode to be identified so that surveys with different electrode spacing can be made automatically. Contractor Bachy Soletanche. (EG95/143/13)

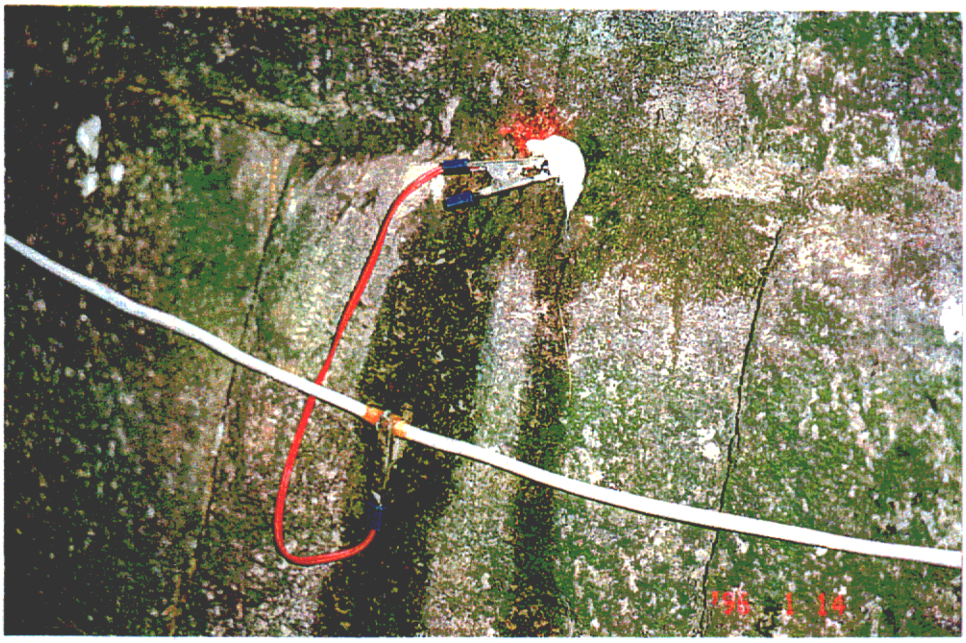

Plate D18 - Cotton wool soaked in salt water and wrapped around electrode inserted into wall to improve contact resistance at Site C (TC03) during resistivity survey. Contractor Institute of Geophysical and Geochemical Exploration. (EG96/09/5)

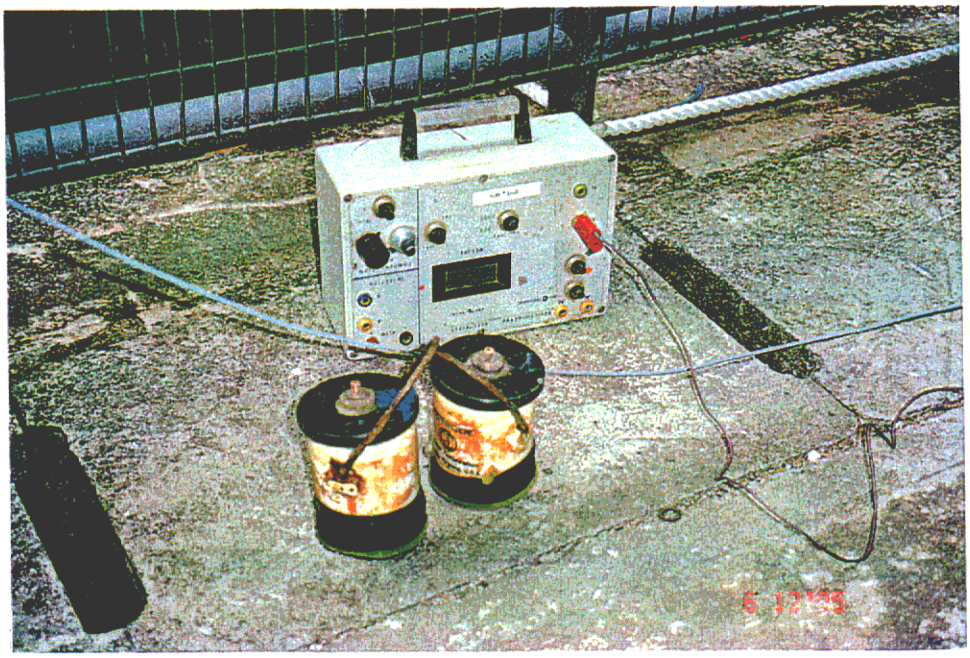

Plate D19 - Geotrode non-polarising copper sulphate electrodes with voltmeter for self potential survey at Site A. Contractor Bachy Soletanche. (EG95/148/3)

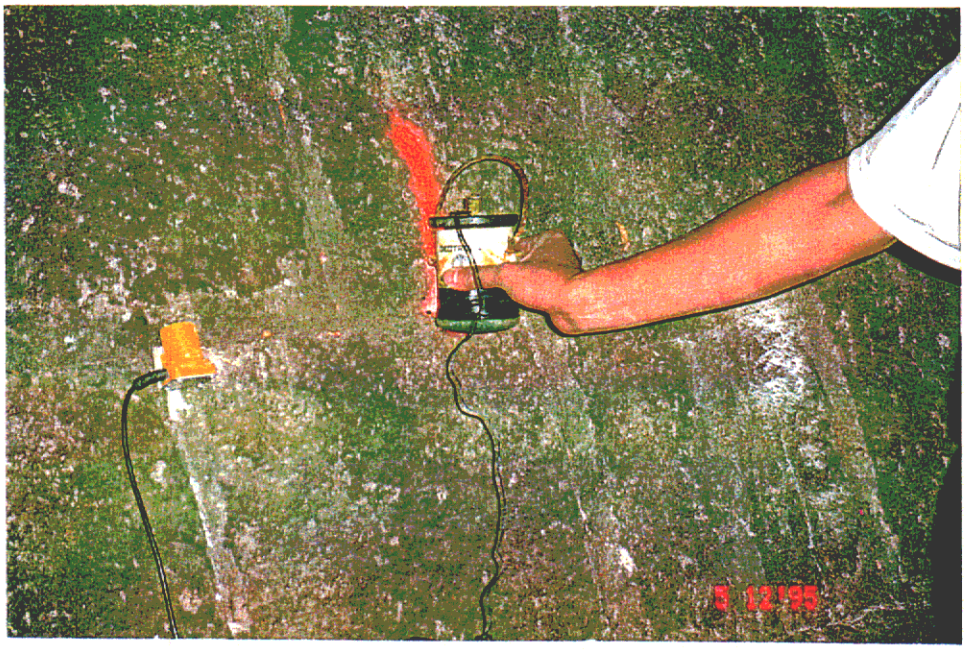

Plate D20 - Non-polarising copper sulphate electrode being held against the masonry wall at Site C (TCO3). Copper sulphate soaked sponge has been attached to base of electrode to ensure good electrode - wall contact. Contractor Bachy Soletanche. (EG95/144/1)


Plate D21 - Sting non-polarising copper sulphate electrode inserted into a shallow excavation at Site D (TD01) during self potential survey. Contractor Golder Associates. (EG96/41/4)

Plate D22 - Geonics EM31 conductivity meter being used at Site A (TA01). Two-man job to carry out the survey up the slope at the site. Contractor Fugro Geotechnical Services (HK) Ltd. (EG95/156/17)

Plate D23 - Geonics EM38 conductivity meter being used at Site D (TD01). Contractor Bachy Soletanche. (EG95/155/19)

Plate D24 - Geonics EM-31 being used for FDEM survey of fill slope platform at Site D. Red flags define the 1m grid used to carry out the survey. Contractor Golder Associates. (EG96/39/4)

Plate D25 - Crone Geophysics & Exploration Ltd. digital pulse TDEM system being lowered down fill slope at Site D (TD02). Contractor Institute of Geophysical and Geochemical Exploration. (EG96/17/21)

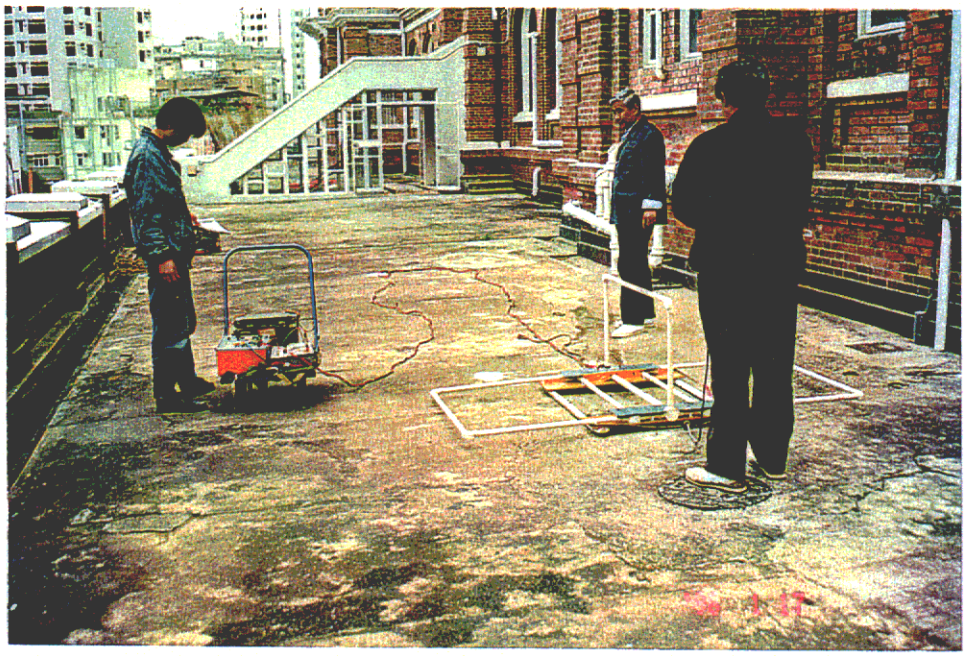

Plate D26 - Time Domain EM coils (1m by 2m), power pack and voltmeter at Site B (TB04). Contractor Guandong South China EGTD Co. (EG96/19/13)


Plate D27 - 1GHz GSSI antenna being used to penetrate mesh reinforced shotcrete at Site A (TA01) - Contractor Golder Associates. (EG96/28/9)

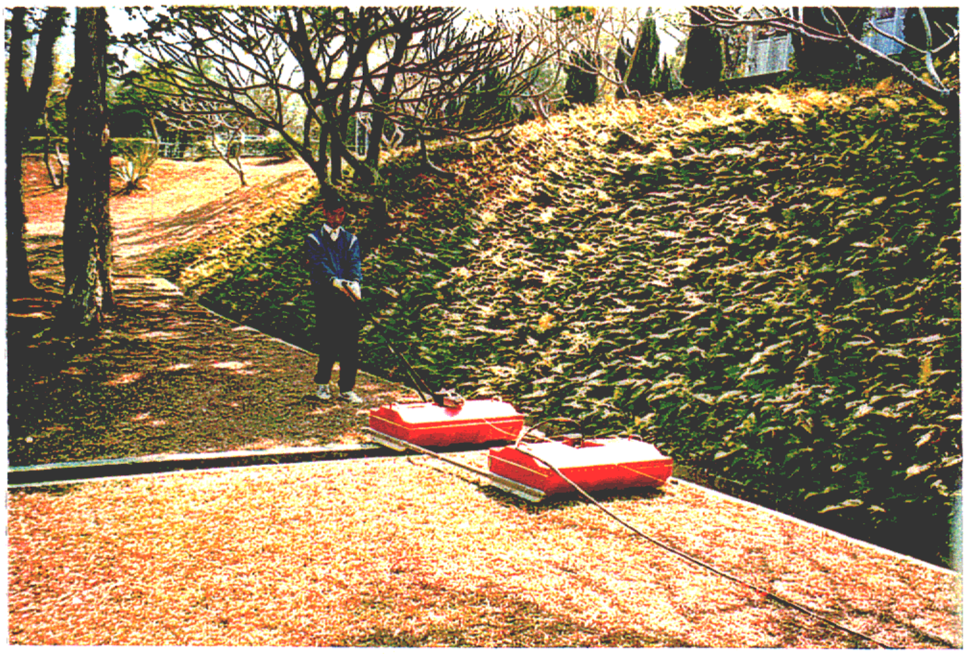

Plate D28 - GSSI 100MHz bistatic antenna being used in GPR survey at Site D (TD01). Contractor Guandong South China EGTD Co. (EG96/02/16)


Plate D29 - GSSI 200MHz monostatic antenna being pulled along platform above the masonry wall at Site B (TB05) during GPR survey. Contractor Meinhardt Works. (EG96/12/8)

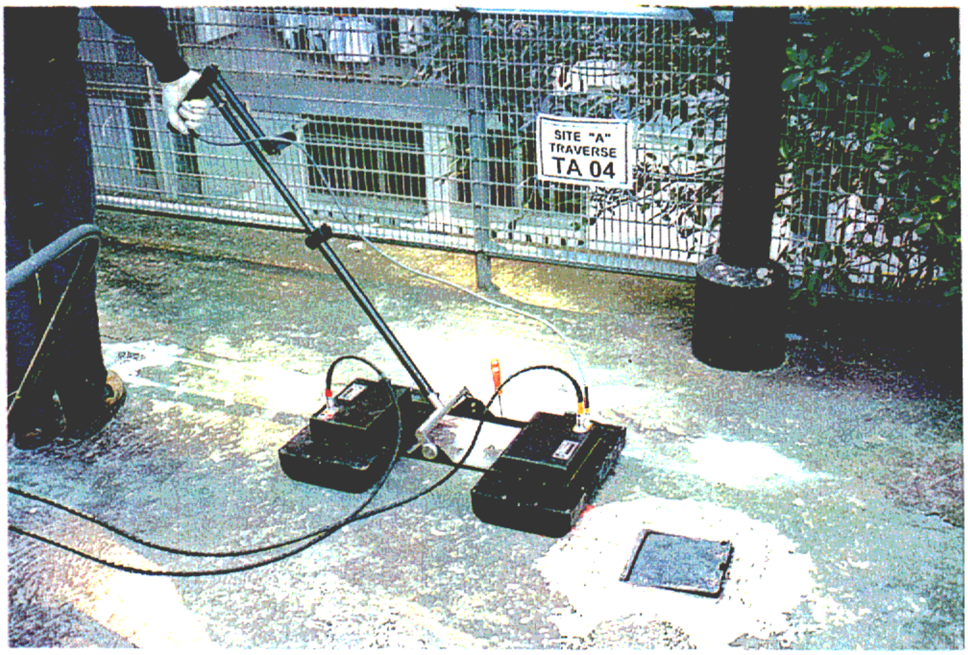


Plate D30 - Sensors & Software Inc. PulsEKKO 1000 bistatic 225MHz antenna being used during GPR survey at Site A (TA04). Contractor Fugro Geotechnical Services (HK) Ltd. (EG95/159/20A)

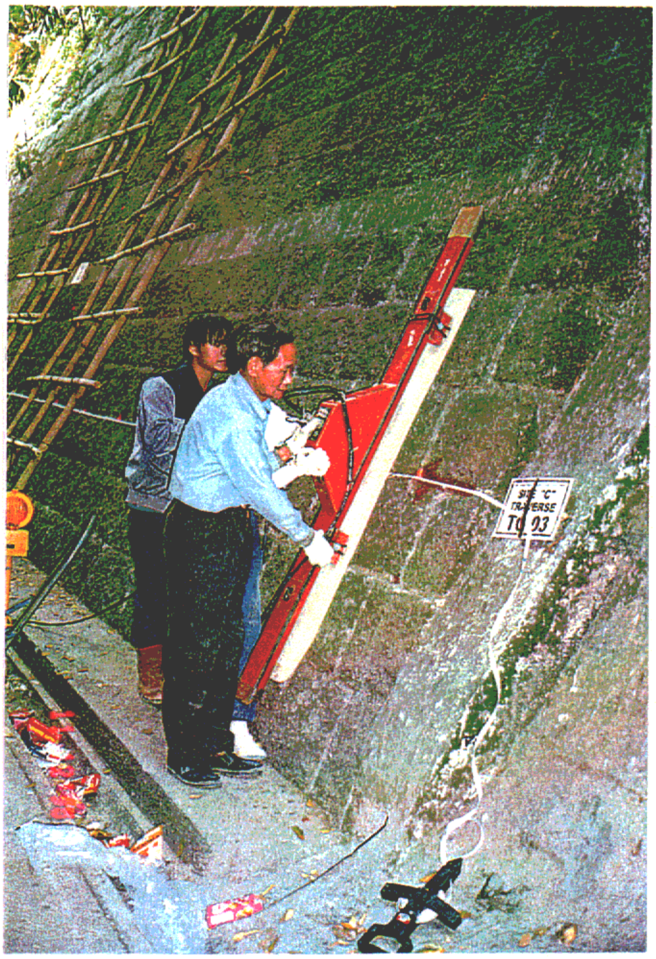

Plate D31 - Radarteam - Sweden A - Model subecho 40 - monostatic 35MHz non-contact antenna being used during GPR survey at Site C (TCO3). Contractor Fugro Geotechnical Services (HK) Ltd. (EG95/162/15A)

Plate D32 - GSSI 500MHz monostatic antenna being lowered down vertical masonry wall on a rope at Site B (TB02). Contractor Guandong South China EGTD Co. (EG96/20/24)

Plate D33 - GSSI 200MHz monostatic antenna being pulled up fill slope at Site D (TD02) during GPR survey. Note survey wheel attached which automatically encodes the radargram with a distance measurement. Contractor Meinhardt Works. (EG96/30/17)

Plate D34 - Sensors & Software Inc. PulsEKKO 1000 System 225MHz antenna's being used in a Common Depth Point (CDP) GPR survey for masonry wall velocity determination at Site C (TC03). Contractor Fugro Geotechnical Services (HK) Ltd. (EG95/165/20)

Plate D35 - GSSI 100MHz antenna being lowered down masonry wall at Site C (TC02). Note three men required to manhandle the large antenna to ensure proper contact with the wall. Contractor Institute of Geophysical and Geochemical Exploration. (EG96/11/8)


Plate D36 - SIR 2 System 500MHz monostatic antenna being held against masonry wall at Site B (TB01) during ground penetrating radar survey. Contractor Bachy Soletanche. (EG95/158/12)

Plate D37 - Radarteam - Sweden A - Model subecho 40 - monostatic 35MHz non-contact antenna being used during GPR survey at Site D (TD02). This non-contact antenna has obvious advantages over the contact type of antenna in rough ground conditions. Contractor Fugro Geotechnical Services (HK) Ltd. (EG95/172/18)

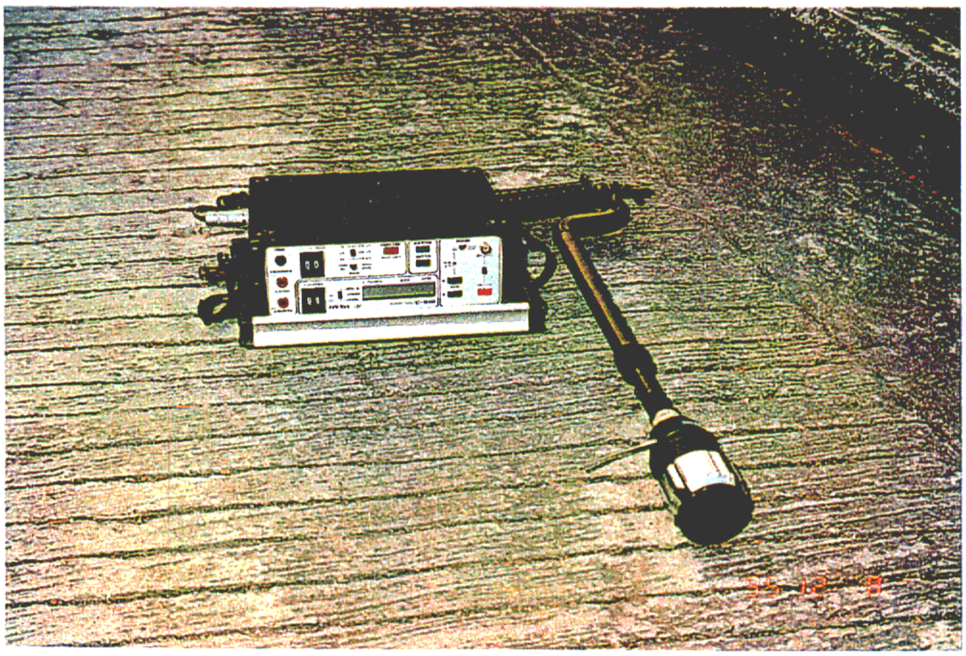

Plate D38 - AP PAAR IRS3 thermal imaging equipment. Contractor Bachy Soletanche. (EG95/154/19)