Report to

Forman Chung & Sykes Consultants Ltd

on the

UltraGPR Void Detection Survey

Florence Hall Development
Trelawny Parish
Jamaica

Date: **December 1, 2008**

Project: **08-024**
Date: December 18, 2008

Attention: **Lise Walter**

Dear Lise;

International Groundradar Consulting Inc. is pleased to present the following report entitled:

UltraGPR Void Detection Survey
Florence Hall Development
Trelawny Parish

We would like to extend our appreciation for the opportunity to work with Foreman Chung & Sykes on this project, and look forward to a continued long-term relationship.

Respectfully submitted

Jan C. Francké, M.Sc., P.Geoph.

TABLE OF CONTENTS

EXECUTIVE SUMMARY **1**

1. BACKGROUND AND SITE DESCRIPTION **2**

2. METHODOLOGY **3**

2.1 PREAMBLE 3
2.2 GPR SIGNAL PROPAGATION THEORY 3
2.3 INSTRUMENTATION 4
2.4 GPR SIGNAL SAMPLING THEORY 5
2.5 INTERLEAVED TIME SAMPLING 6
2.6 REAL-TIME SAMPLING 6
2.7 ULTRAGPR 6
2.8 ULTRAGPR LIMITATIONS 9
2.9 GENERAL DATA PROCESSING METHODOLOGY 11

3. DISCUSSION OF RESULTS **12**

3.1 SURVEY COVERAGE 12
3.2 DATA PROCESSING 15
3.3 RAW DATA 15
3.4 INITIAL SIGNAL PROCESSING AND GAINING 16
3.5 INTERPRETED VOIDS AND FRACTURED LIMESTONE 18
3.6 CONSIDERATIONS 18

4. CONCLUSIONS **20**

5. APPENDIX I **21**

EXECUTIVE SUMMARY

A comprehensive geophysical survey employing a recently-developed advanced form of ground penetrating radar (GPR) known as UltraGPR has been conducted on behalf of Foreman Chung & Sykes Ltd at Gore Development's Florence Hall Development in Trelawny Parish, Jamaica.

The survey covered over 58 hectares of the footprint of the future development. The geophysical surveys required approximately two weeks to complete and consisted of over 67 km of survey distance.

Although the prescribed survey coverage stipulated a uni-directional radar profile every 10 m, in practice some variations were required by the difficulty of presented by dense vegetation and topography. Prior to arrival at site, indications were that the project was "walkable". It was immediately determined that of the required 65 km of survey distance, only approximately 24 km would be walkable on old and overgrown survey lines. The remaining 40 km of survey lines would have to be cut either by hand or bulldozer. Initial attempts were made by three labourers to clear survey profiles by hand, resulting in a progress rate of only 100 m per hour. At such a rate, the project for line clearing alone would have required over two months. Gore Developments subsequently provided a bulldozer to clear lines for the geophysical survey.

Although ideal for the application over the majority of the project site, the bulldozer was not able to clear lines in the challenging northwest portion of the site. As such, sparse geophysical data were recorded in this portion of the project site, and care should be exercised when considering the long term geotechnical stability of this region.

Throughout the surveyed area, over 100 individual voids were detected by UltraGPR, varying in size from less than a metre wide to over 10 m wide in a few cases. The vast majority of voids appear to exist between 2 m and 6 m in depth, with nearly no voids detected within the shallowest 2 m. However, it should be noted that the UltraGPR system employed is generally unable to detect voids within the first 0.8 m, unless they are more than 1 m thick.

Depth slices have been provided in this report as plan maps as well as AutoCAD files, all in the JAD2001 co-ordinate system. The depth slices are taken in 1 m intervals from 0 to 10 m depth. In addition, regions which exhibit broken or fractured limestone, but not necessarily voids, are shown at depths of 1.5 m, 3 m, and 5 m.

Groundradar provides the data contained herein with no stated or implied guarantees that all voids at the Florence Hall Development have been imaged or mapped by UltraGPR. Groundradar has used best practice methods to acquire remotely-sensed data measured entirely by electronic means to estimate the position and depth of certain voids on the survey site. Based on the number and density of the interpreted voids detected by geophysical means, it is highly likely that other voids exist.

1. BACKGROUND AND SITE DESCRIPTION

In late November, 2008, Ms Lise Walter of Foreman Chung & Sykes Consultants Ltd contacted International Groundradar Consulting Inc. (Groundradar) regarding the technical suitability of ground penetrating radar technology to detect karstic solution voids beneath the surface of a planned residential development which Foreman Chung & Sykes was providing engineering consulting services.

Foreman Chung & Sykes had commissioned a comprehensive geotechnical investigation of the site. Boreholes encountered a number of karstic voids within the region of interest, which ranges from surface to 10 m. Concern remained as to the likelihood of the existence other voids within the footprint of the development. The presence of karstic voids may present a significant influence on the long term stability of the infrastructure to be constructed at the Florence Hall Development.

Ground penetrating radar (GPR) has long been used in the karst-prone southern states of the USA for the detection of voids beneath roads and proposed developments. Historically, instrumentation has been somewhat unwieldy and prone to penetration limitation in inorganic clays such as those typically found in Jamaica.

Groundradar has worked with GPR technology in Jamaica for nearly a decade, and undertakes on-going large scale investigations of deep bauxite deposits throughout the island. Although surveys in the 1990’s relied on commercially-available GPR technology, Groundradar has recently developed a proprietary radar technology which is ideal for the detection of voids to depths of 80 m. A more recent version allows very high resolution imaging of small voids to 30 m.

Based on discussions with Ms. Walter, voids of greatest interest at the Florence Hall Development are on a scale greater than 5 m in diameter, and within 10 m of the surface. Groundradar was provided with pages from the commissioned geotechnical report which suggested that Groundradar’s proprietary UltraGPR technology would be ideal for this application.

The site is located adjacent to the North Coast Highway, across from the newly-constructed Greenfield Stadium. The site spanning some 65 hectares, consists of typical varied vegetation found elsewhere along the coastal strip on the north coast of Jamaica.

Figure 1.1 shows a 3D representation of the site topography based on a 2003 cadastral survey. The terrain ranges from sea level to 45 m, with a maximum slope of 38°. As evidenced on the topographic data, as well as on the AutoCAD files provided by Foreman Chung and Sykes, a region of exposed karsts exists in the centre of the survey region.

2. METHODOLOGY

2.1 Preamble

The concept of applying radio waves to penetrate and map the subsurface is not new. Successful early work with GPR was the performed with standard military radar systems and radio echo sounders to map the thickness of ice sheets in the Arctic and Antarctic. Pioneering research was conducted by the Royal British Antarctic Survey in the 1960's. Work with GPR in non-polar environments began in the early 1970's, focusing on civil engineering applications. As the strengths and limitations of the technique became more apparent, the possible applications dramatically broadened.

The greatest historical inhibitor to the maturing of GPR as a recognised geophysical method was the inherent need for precise timing of sub-microsecond events. Computers that could capture and display such fleeting pulses of electromagnetic energy as radar reflections were extremely large and usually not portable. With the advent of the high-speed laptop computer in the early 1990's, the ability to capture, digitise, and store large volumes of radar data was realised. Although the technique has been successfully used for a myriad of applications around the world, it is still in its infancy. Today, typical commercial applications of GPR include engineering and environmental site evaluations, fracture mapping, stratigraphic mapping, void detection, forensic studies, glaciology and permafrost engineering, as well as archaeological studies. Modern GPR systems have fast data processors and data transfer circuitry, and are easily mounted within small boats, aboard sleds, or within backpacks.

2.2 GPR Signal Propagation Theory

Although the common perception of GPR as being a black box which scans the ground and produces “slices” of the subsurface is superficially correct, a cursory understanding of the interactions between electrical and magnetic fields and the electromagnetic properties of geological media can provide a greater appreciation of the richness of the data acquired, as well as the intrinsic limitations of the method.

The well-studied strong correlation between material characteristics of geological media and their inherent electromagnetic properties suggests that electrical geophysical methods are well suited for tasks involving imaging subsurface features. In general, geological materials such as limestone are considered to be semi-conductors, or dielectrics, and can be characterised by three electromagnetic properties: electrical conductivity, electrical permittivity, and magnetic permeability.

These properties are determined by the interaction of electrical fields and charged particles, particularly the electron. Electrical conductivity is the measure of a material's ability to transmit a DC current, which results in energy dissipation through the conversion of electrical energy to heat. Dielectric permittivity refers to the degree to which a geological medium resists the flow of electrical charge divided by the degree to which free spaces resists the same charge. The dielectric permittivity is thus defined as the ratio of the electric displacement to the electric field strength. Magnetic permeability is the result of electron spin and motion in atomic orbits, and also results in energy loss and storage.

Electrical and magnetic process are also coupled, with the corollary that accelerating electrons generate electromagnetic radiation, electrical currents generate magnetic fields, and time varying magnetic fields impart motion on electrical charges. The velocity of an electromagnetic wave propagating through a medium is the reciprocal of the square-root of the dielectric permittivity.

The propagation of these electromagnetic waves is governed by Maxwell's equations. The equations describe a coupled, three-dimensional polarised vector wave field. At the relatively high frequencies employed by GPR systems, the energy storage in dielectric and magnetic polarisation generates wave propagation. When these waves are propagated through geological media, they travel at velocities lower than the speed of light, and are scattered by variations in the electrical and magnetic properties of the subsurface. The magnitude of this scattering, either through reflection, refraction, or diffraction, is determined by a complex interaction of the Fresnel reflection coefficient, the angles of incidence determined by Snell's Law, and polarisation shifts governed by the Stokes-Mueller matrices. Further complicating the magnitude of scattering are factors such as the antenna radiation pattern, the distance from the antenna (geometric spreading losses and material property dissipation losses), and the spatial scale over which the change in electrical or magnetic properties occur, all of which are dependent on the wavelength of the imparted field. For geological applications of GPR, and in particular the detection of voids within limestone evaluations, these factors determine both the depth of penetration as well as the ability to discern a small void at significant depths within the limestone.

2.3 Instrumentation

Over the past 16 years, commercially-available GPR systems have been employed for void studies in limestone. However, these systems exhibit significant drawbacks due to technological and legislative limitations.

At present, there are four significant GPR system manufacturers worldwide. Approximately 95.3% of GPR system sales are dedicated to the lucrative civil infrastructure markets, such as utilities detection, rebar imaging in concrete, pavement studies, etc. The remaining systems are generally sold to research organizations for geotechnical applications and polar studies. The technology employed for these deeper-penetrating systems was developed in the late 1980's and has not been improved upon since.

The lack of development on deep GPR systems can be attributed to a number of factors. Firstly, there is a lack of a sufficient market to justify the significant research and development budget required for such system developments. Secondly, and perhaps as important, are the limitations imposed by legislation on ultra-wide band (UWB) radar technology in the United States and the European Union. UWB legislation protects certain bandwidths for use by mobile telephone companies for various existing and future mobile communication applications. Any long-range GPR system developed would be in breach of this legislation. Figure 2.1 illustrates the technological development of GPR systems over the past decades.

Finally, low frequency GPR systems which may be suitable for long range applications are designed for research use, and are extremely fragile. They rely on fibre optic cables to carry data between large control units mounted in wheelbarrows to large transmitters and receivers. Such systems are generally powered by vehicle batteries, which restrict their use to flat terrain.

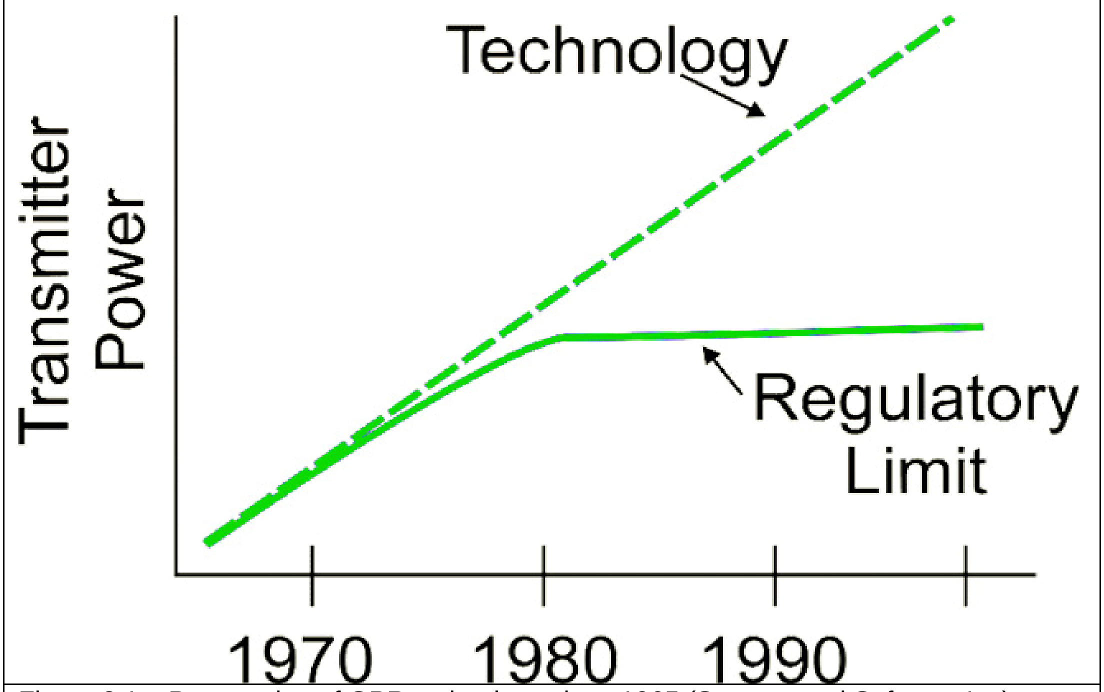

Figure 2.1 – Progression of GPR technology since 1965 (Sensors and Software Inc).

Nevertheless, a demonstrated niche market exists, primarily in the mineral resources industry, for long range GPR systems. Although such instrumentation would not be employable in the United States and the European Union, other countries do not impose such legislation on radio emissions.

As part of Mr. Francke's PhD research, a series of advanced long-range GPR systems have been designed and constructed. The instrumentation, known as UltraGPR, employs the absolute latest technology available to address to shortcomings of commercial GPR systems in mining applications.

2.4 GPR Signal Sampling Theory

The method by which GPR data are captured by the receiver is perhaps the most critical portion of a system's design. In the early 1990's, systems employed analogue recorders and electrostatic plotters to display the radar scans. By 1996, electronic circuitry was available which was sufficiently fast to permit real-time analogue to digital conversion of the recorded data.

GPR signal sampling is inherently challenging due to the need to sample returned signals which are travelling near the speed of light. For example, for a system with a centre frequency of 80 MHz, the effective bandwidth is 40 MHz to 120 MHz. Nyqvist's sampling theory stipulates that the returned signal must then be sampled at 3X the centre frequency, in this case at 240 MHz.

If $x(t)$ is a band-restricted signal with $X(jw) = 0$ for $|w| > w_{m,}$, then x(t) is specifically determined by its samples $x(nT), n=0, \pm 1, \pm 1, \ldots$, if $w_s > 2w_m$, where $w_s = 2\pi/T$, if T is the sampling period and w_s is the sampling frequency.

A periodic impulse can be thus created where every impulse corresponds to a successive sample value to reconstruct the signal x(t). To achieve the output signal that is precisely the same as x(t), the periodic impulse can be processed through a perfect low-pass filters with ain T and cut-off frequency w_x, whereby $w_M < w_x < w_s$-

w_M. Spatial aliasing occurs if these bounds are not achieved, resulting in a higher frequency content overwhelming the desired lower frequency.

2.5 Interleaved Time Sampling

Until as recently as October, 2007, the fast analogue to digital converters (ADC) needed for sampling GPR frequencies were either unreliable or excessively expensive. Due to this limitation, all commercially-available GPR systems are constructed using a sampling method to significantly reducing the sampling frequency required. The concept assumes that several scans taken within fractions of a second of each other would be similar provided that the antennas were not moved a significant distance.

Using interleaved time sampling, a single sample point is recorded with every scan. The first sample is recorded one the first scan at the top of the trace. The second sample is then offset by one sample, and so on. Thus, to complete a full scan of a typical 512 points, 512 individual pulses of the transmitter must be triggered and subsequently recorded 512 times.

2.6 Real-time sampling

Within the last year, the evolution of ADC converters has reached a level whereby entire radar traces may be digitized at once. However, these advances present additional issues, such as the bottlenecks caused by slower data buses, processors and memory devices.

The most technically feasible solution to these bottlenecks is to pre-process the recorded data by stacking, within the receiver. The most significant advantage of real-time sampling is the ability to stack individual radar traces extremely rapidly. Stacking is the averaging of several traces captures at nearly the same position. The premise is that each trace will consist of the same signal, except for the noise. By averaging these scans, the noise level will be drastically reduced, thereby improving the signal to noise ratio.

Although stacking is commonly performed with interleaved time sampling systems, the time required to stack even a few times is substantial. Most commercial systems (GSSI, Sensors and Software, Malå) operate at a pulse repetition frequency of 100 kHz. To stack a 512-point trace 64 times requires 0.3 seconds. Using real-time sampling, the same trace requires only 0.64 ms to capture. That is, in the time required for a commercial system to stack 64 times, a real-time sampling system may stack over 32000 times.

As the signal strength of a GPR system drops exponentially with depth, real-time sampling allows longer distances to be imaged for GPR. For example, by stacking 1000 traces improves a systems performance by 30 dB. A 30 dB gain may roughly double the penetration ability of a GPR system.

2.7 UltraGPR

The UltraGPR system employs the fastest ADC chips available to create a highly efficient and sensitive real-time sample GPR instrument for long-range imaging. In addition to advances in depth of penetration, the system has been designed by extreme ruggedness and portability in mind (Figure 2.2).

All wires and fibre optic links, a source of constant reliability issues on commercial systems, have been replaced by wireless Bluetooth® connections. The system has also been designed to conserve power for use in remote environments. The entire GPR system may be used continuously for nearly 70 hours before a recharging of the custom lithium polymer batteries is required.

Figure 2.2 – UltraGPR being used at the Florence Hall Development

Miniaturisation was also a foremost priority using the design phase of the instrumentation. The entire system (Figure 2.3) is housed within a 4 m long flexible snake with two shielded pods for the receiver and transmitter electronics. No backpack console unit is required as the data are fed directly into a Windows Mobile PocketPC or mobile phone. The system weighs less than 5 kgs and is easily transported in a small suitcase.

A NMEA-0183 compatible GPS device with OmniSTAR XP SBAS DGPS service is attached to the system to provide real-time *x,y,z* co-ordinates at 5 Hz. OmniSTAR XP services has a published accuracy of ± 0.15 m, although practical experience in Jamaica suggests that in reality, the accuracy is limited to ± 0.4 m in open terrain, and as much as ± 1 m under a tree canopy. It is believed that given the nature of the current project and the large area to be covered, such positioning accuracy is believed to be sufficient. In addition, the ability of UltraGPR to update the systems' position five times a second provides five times more data points than any other GPR system.

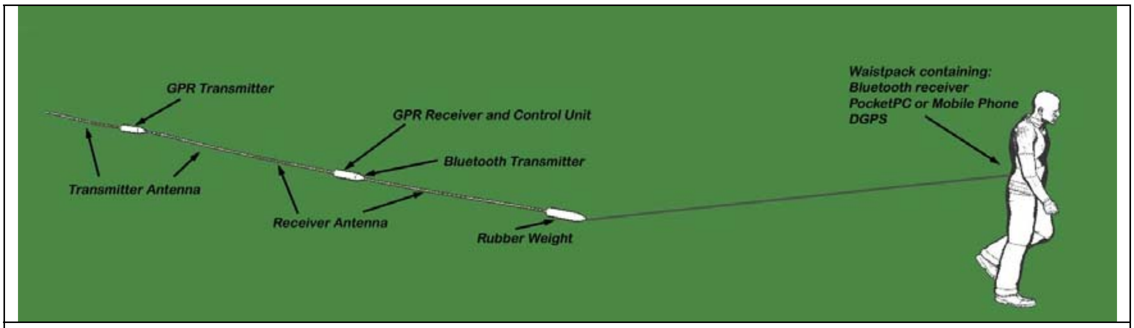

Figure 2.3 – UltraGPR components

For surveys over large areal regions such as Florence Hall, Groundradar has developed a live GPS tracking technology originally designed for the tracking of hunting dogs. The technology allows Groundradar's GPR Specialist to monitor the position, direction of travel and coverage of the labourer pulling the UltraGPR system, from up to 2 km away (Figure 2.4). By freeing the surveyor from the tasks of continuously monitoring the puller, the trajectories for subsequent profiles may be scouted and any bush clearing ordered. The lay-out of the backpack worn by the UltraGPR puller is showing in Figure 2.5.

Figure 2.4 – Remote tracking system adapted for UltraGPR showing the live positions of the UltraGPR system and the GPR Specialist.

Figure 2.5 – View of UltraGPR backpack with remote tracking system

2.8 UltraGPR Limitations

Although at the leading-edge of technology, a number of drawbacks exist for antennas in this configuration, as compared to conventional GPR systems (Figure 2.5).

Figure 2.5 – Common GPR systems used for void detection in limestone (GSSI at left and Sensors and Software at right).

The most important consideration in deep exploration surveys is a “blind zone” cased by the separation of antennas (Figure 2.6). Similar to the inability of human eyes to focus on objects placed near the bridge of the nose, the 3 m separation between the transmitting and receiving antennas effectively mask the shallowest 0.80 m of subsurface information.

Another important factor in instrumentation design is the concept of GPR “illumination zones” or footprints. The radiation pattern of a dipole antenna situated in a homogeneous non-dielectric medium (air) is symmetrical and aligned perpendicular to the dipole orientations. However, when the antenna is placed at the boundary between two half spaces such as air and ground, a significant change occurs in the radiation pattern due to ground coupling. Ground coupling is the ability of an electromagnetic field to be transformed from transmission in the air to transmission through the ground. Due to ground coupling, refraction, which occurs as the radar energy passes into the ground, causes a change in the shape of the radar beam, with most of the energy focussed into the ground in an elliptical cone whose apex is at the centre of the transmitting antenna (Figure 2.7). The angle of this cone is proportional to the dielectric permittivity of the ground. High dielectric permittivities produce lower radar wave velocities with a more focussed conical transmission illumination zone. Thus, the region of the sub-surface that is being imaged by the radar system is a weighted average of a footprint that extends not only directly beneath the antennas, but also in front, behind and to the sides.

This is of consideration when examining the correlation of the radar data to borehole information. The boreholes are essentially point samples along a complex geological profile, whereas the radar interpretations are smoothed generalisations. Most limestones exhibit a dielectric permittivity on the order of 9. Using the equation

$$v = \frac{c}{\sqrt{K}}$$

where *c* is the velocity of light in free space and *K* is the dielectric coefficient, and *v* is the radar wave velocity in the subsurface medium, a value of .105 for the velocity can be calculated. Using an antenna frequency of 80 MHz, an illumination zone of approximately 1.7 m X 0.9 m at 10 m depth can be calculated. It is however noted however, that the vast majority of energy relates to the central portion of the illumination zone, similar to the illumination zone of an incandescent flashlight against a wall. The concept of illumination zones is common to all GPR systems.

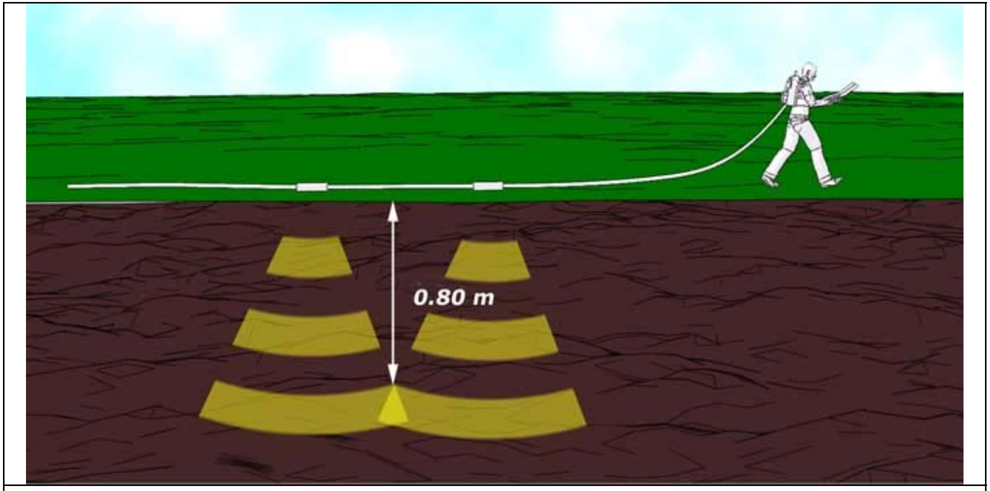

Figure 2.6 – Concept of a “blind-spot” beneath the UltraGPR antennas

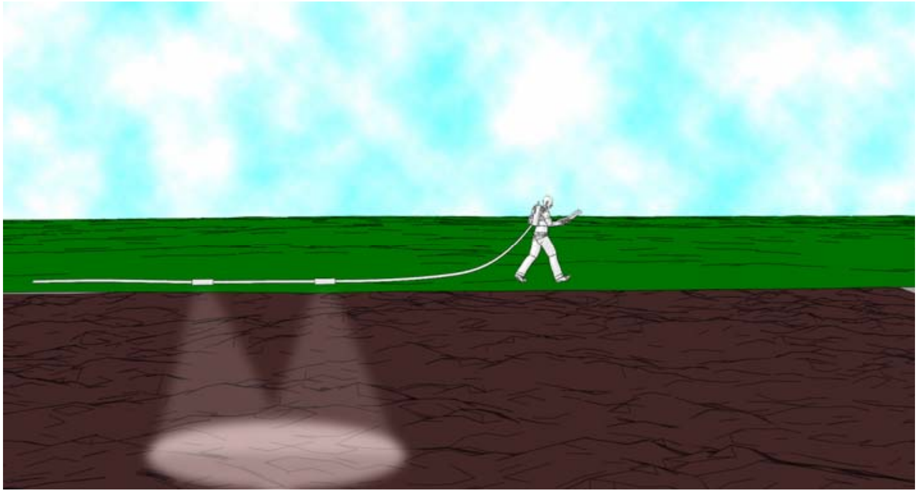

Figure 2.7 – Calculation of the illumination zone of a radar antenna.

2.9 General Data Processing Methodology

The most important and challenging phase of a successful GPR project is data processing and interpretation. GPR processing generally exploits many of the developments in seismic data analysis, which due to the importance of oil and gas exploration have evolved greatly over recent years.

The general processing for the GPR data acquired during the scoping survey is depicted in Figure 2.8. The stages of data processing can be generalised as GPS conversion, data editing, basic processing, and advanced processing. Each project, and indeed individual survey objectives within an individual project, requires specific processing steps. The steps employed for the UltraGPR data acquired the Florence Hall Development are described in Chapter 3.

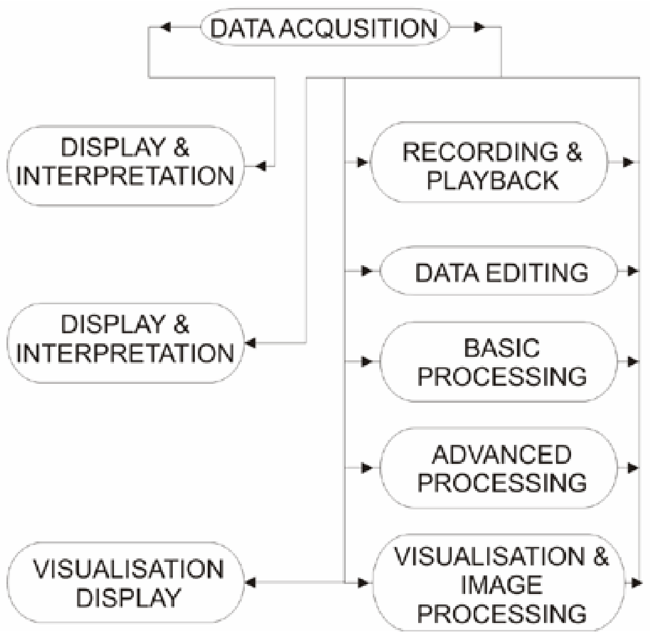

Figure 2.8 – Diagram of GPR processing flow.

3. DISCUSSION OF RESULTS

3.1 Survey Coverage

The UltraGPR survey conducted at the Florence Hall Development produced excellent quality radar profiles, from which numerous subsurface features were identified.

The survey entailed seven full days of surveying along with three partial days, spanning December 2 through December 15, 2008. In total, 69.5 km of survey data were acquired, of which 8.2 km spanned regions in duplicate and triplicate. 67 individual GPR profiles were acquired with an average length of 1.1 km.

Prior to mobilisation, it was indicated to Groundradar that the Florence Hall Development site was “walkable”, although initial photographs provided by Foreman Chung & Sykes indicated otherwise. Upon arrival at the site on December 2nd, it was immediately noted that the vast majority of the site consisted of impenetrable bush and undergrowth. Approximately 24 km of pre-existing lines existed, consisting of survey cutlines emplaced a number of years ago for a topographic survey (Figure 3.1), as well as a series of connecting trails and pre-existing foot paths. The survey cutlines were measured to be approximately 30 m apart, and did not extend across the survey region.

Figure 3.1 – Typical existing cutline showing degree of overgrown brush.

The contract stipulated that Groundradar would endeavour to achieve approximately 10 m spaced UltraGPR profiles where possible. As such, the existing cutlines were entirely insufficient for the present survey. The existing cutlines were easily surveyed within the initial three days of radar surveying.

Two options were available to ensure proper UltraGPR survey coverage. The first option involved assigning two or three labourers to the task of cutting new lines. However, as illustrated in Figure 3.2, the density of the undergrowth and bush at the Florence Hall Development was certainly not "walkable" by any means. Two surveys days were spent experimenting with the ability of three labourers to cut the additional 40 km of survey lines. On average, three labourers were able to clear a crude trail through this dense vegetation at a rate of 80 – 100 m per hour.

Figure 3.2 – Typical dense vegetation at the Florence Hall Development.

Considering the time frame for the present project, clearing the remaining 40 km of survey lines would have required an additional two and half months. Given this rate of process and the infeasibility of such delays, Groundradar requested that Foreman Chung & Sykes contact their client and the developer of the Florence Hall project, Gore Developments, to request the provision of a bulldozer to accelerate the line clearing task.

An initial wheeled bulldozer was provided on the 5th of December, but could only clear lines at a rate of 500 m per hour, which again was insufficient to maintain the survey schedule. Commencing December 6th, a tracked bulldozer was provided by Gore Developments to line clearing. With the exception of two days when the bulldozer experienced maintenance issues, all line clearing after December 6th was conducted using this bulldozer.

Although the use of a bulldozer allowed for the successful completion of the project at the required spacings on schedule, such an approach posed significant limitations and drawbacks to the execution of the UltraGPR project.

Groundradar's GPR Specialist was forced to divide his time between monitoring the UltraGPR system's progress and heading, scouting new locations for the subsequent profiles, as well as providing tracking information and guidance to the bulldozer operator.

Although the use of the bulldozer provided the only reasonable means to complete the geophysical survey within the prescribed timeframe, the use of such mechanised line clearing presents significant additional limitations. The turning radius of a large bulldozer is limited, rendering closely-spaced lines difficult to clear easily.

However, the most significant limitation of a bulldozer to clear survey lines is the inability of the machine to traverse steeply sloped ground or ground which has significant unevenness. Such ground was encountered through the northwest portion of the survey area. Although with significant delays, some lines were able to be pushed through in this region, it was calculated that to achieve optimal coverage in this difficult area, the bulldozer would have required an additional 1.5 weeks of work.

Based on the earlier experience of labourers being able to clear only 100 m in an hour, ideal coverage was deemed to be impossible in this region within the given time frame. A decision was made to re-assign the bulldozer to clearing the remaining areas of the survey area. This tasked alone required the full allotment of available survey days, proving that attempting further line clearing by either a bulldozer or labourers in the northwest region would have been unwise.

Figure 3.3 (not to scale) shows the location of the final UltraGPR profiles superimposed atop a plan showing the proposed plots of the Florence Hall Development. As evident on the map, few UltraGPR profiles were able to be surveyed in this northwest region.

To further illustrate the degree of coverage, a map showing the density of UltraGPR coverage is shown in Figure 3.4 (not to scale). Red regions indicate ideal or greater than ideal coverage, green regions indicate poor coverage, and white areas show no coverage.

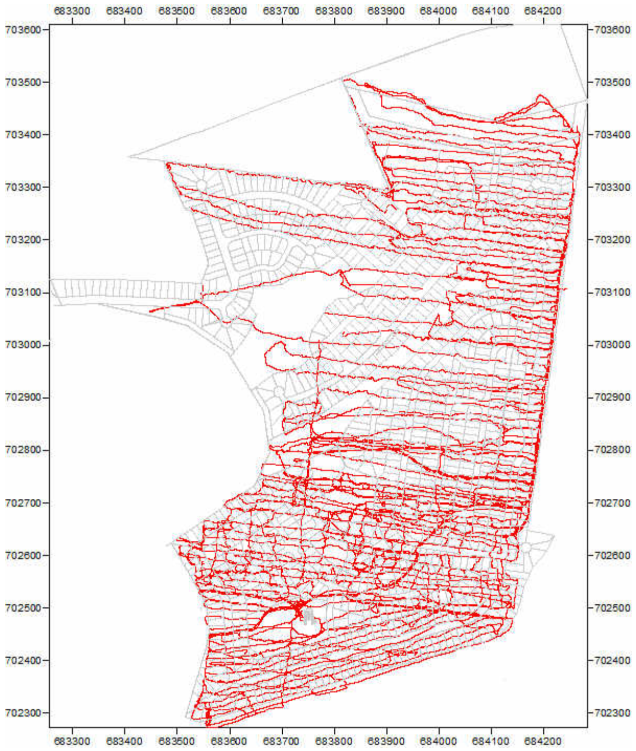

Figure 3.3 – Map (not to scale) showing location of UltraGPR survey lines at Florence Hall.

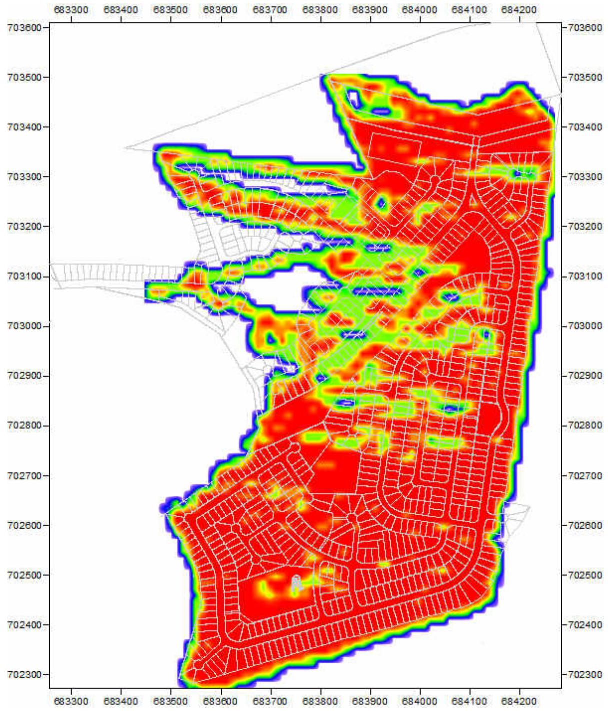

Figure 3.4 – Map (not to scale) showing UltraGPR data coverage density.

3.2 Data Processing

Based on experience gained on over 100 similar projects on six continents, Groundradar has developed a series of specialised processing routines to best enhance UltraGPR data acquired in these environments. Indeed, many of these routines are founded on concepts of digital image processing, rather than geophysical processing.

3.3 Raw Data

In the case of the present study, the UltraGPR raw data were acquired on a custom field computer mounted on the system's backpack.

Figure 3.5 shows a sample of raw data acquired at the Florence Hall Development.

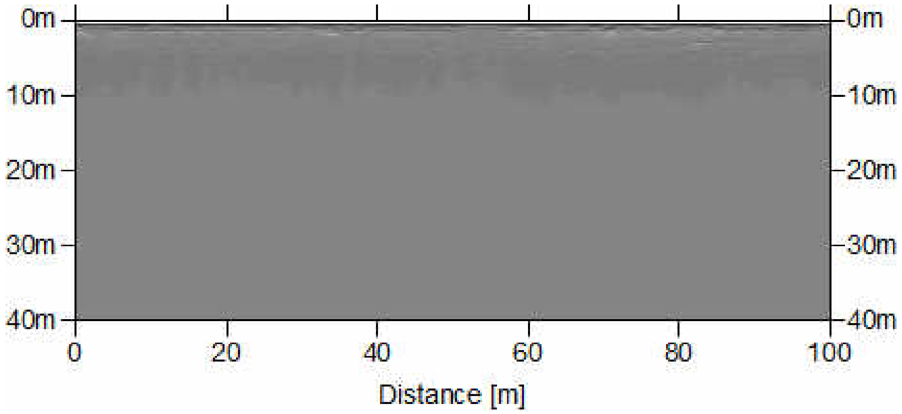

Figure 3.5 – Raw data.

3.4 Initial Signal Processing and Gaining

Zero time correction – Time zero correction involves the compensation for jitter from trace to trace of the first arrival peak caused by small variations in antenna separation and surface ground conditions. This is accomplished by a cross power correlation in the frequency domain. Time zero is also assigned to the profiles to define the zero depth level.

Gaining – GPR signals are subject to an attenuation that increases exponentially with depth. The concept of attenuation describes the intrinsic losses that arise from a number of factures such as geometric effects of wave spreading and volume scattering. In order to compensate for these losses, a post-processed gain function is used. Although many gains are available in GPR processing, a simple energy decay compensation has been found to be most suitable for lateritic environments. Energy decay compensation extracts the energy decay curve from the trace and applies the inverse of the function to the data.

Dewowing – Depending on the proximity of the transmitter and receiver, as well as the electrical properties of the ground, the transmitted signal may induce a slowly decaying low-frequency “wow” on the trace, which is superimposed on the higher frequency reflections. The removal of this effect is accomplished by transforming the data from the time domain into the frequency domain using a fast Fourier transform (FFT). A cut frequency is then assigned to the point of inflection that defines the change from the spectral peak of the antenna centre frequency and the wow effect. The data are then high-pass filtered to remove the effects of the signal wow, which allows better resolution of geological features. Occasionally, a small portion of remnant wow is visible on standard radar amplitude plots as slight background colour shifts.

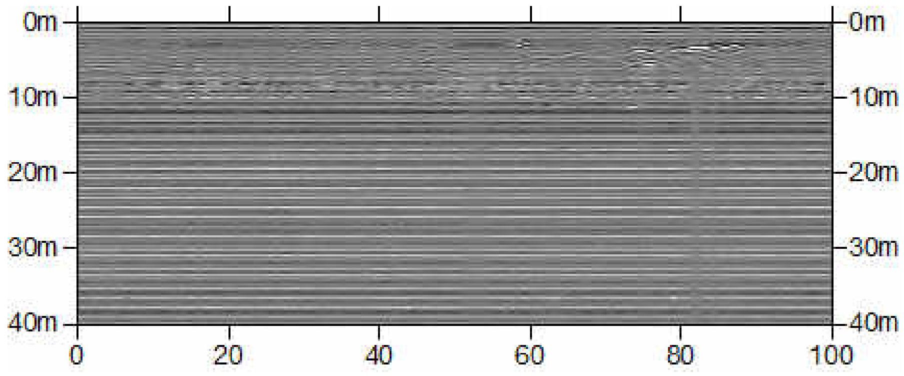

Figure 3.6 – Data after initial processing and gaining.

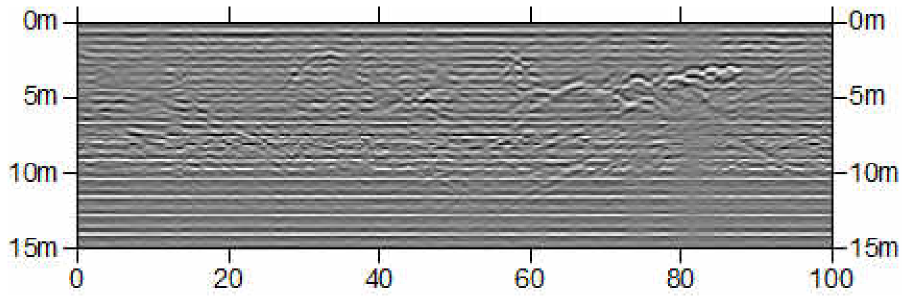

Figure 3.7 – Data after temporal re-sampling and time-cutting

Removal of Signal Ring-Down

Although UltraGPR represents the most advanced GPR system available for ultra-deep applications, the combination of the principal electronic components within the same circuit board produces an undesirable effect of a ringing effect exactly at 40 MHz. This issue is easily addressed using a FFT routine to remove a narrow band exactly at 40 MHz.

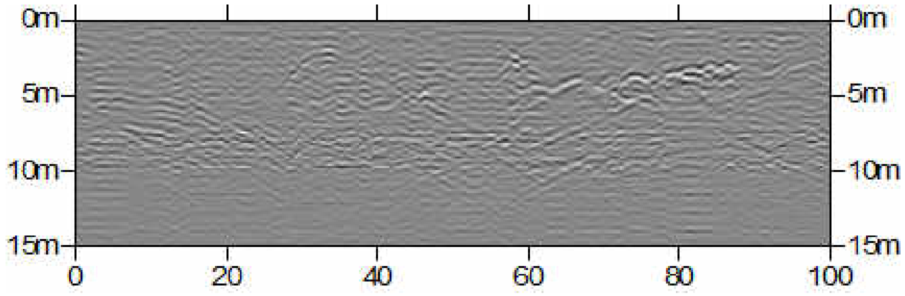

Figure 3.8 – Data after signal ring-down removal

Morphological Analysis and Interpretation

The richness of information contained with the processed UltraGPR can be overwhelmingly complex. Although traditionally a human interpreter would be tasked with determining the location of voids, modern semi-automated morphological analysis methods enable more consistent and precise interpretations to be made.

Any mathematical morphology process involves the input of an image to be processed, in this case the UltraGPR data profile, and a structuring element, or kernel. For each data point of the UltraGPR data, an absolute amplitude is taken to represent the height above a base plane, so that the GPR data represents a surface in three dimensional Euclidean space. In this context, the set of co-ordinates associated with this "image" surface is simple the set of three-dimensional Euclidean co-ordinates of all the data points within this surface, as well as all the points below the surface to the level of the base plane.

The structuring element is a set of point co-ordinates which differ from the input data co-ordinate set in that it is much smaller (in this case 4 x 4 pixels). The morphological operation works by translating the structuring element to various points in the input data, and examining the intersection between the translated kernel co-ordinates and the input image co-ordinates.

In the case of the data acquired at Florence Hall, the result is an image of the likely void targets in a GPR profile (Figure 3.9).

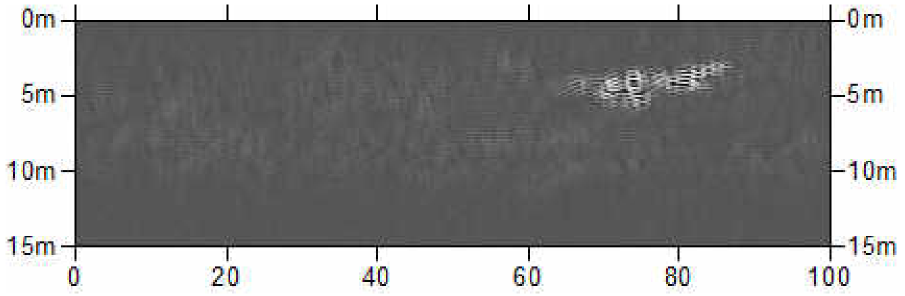

Figure 3.9 – Morphological analysis showing interpreted void target.

3.5 Interpreted Voids and Fractured Limestone

Plan maps provided in Appendix I as well as in AutoCAD format show the results of the UltraGPR interpretation across 1 m depth slices ranging from 0 m to 10 m.

As evidenced in these maps, the vast majority of voids detected by UltraGPR appear to exist within the zone of 2 – 6 m in depth. In addition, the voids appear generally to be small, with only a small portion over 7 m in size.

It is noted that due to the one-dimensionality of the UltraGPR survey, voids may appear to be artificially elongated in one direction (usually west to east). This is due to the absence of other UltraGPR profiles immediately to the north and south of each survey line. It is not believed that any void has been detected which spans two adjacent UltraGPR profiles 10 m apart. As such, care must be taken in appreciating that the void shapes displayed on the maps and AutoCAD files are only the portion of these voids imaged (crossed) by UltraGPR, and that each may extend many metres offline as well.

Although the maps suggest that the majority of voids exist to within the southern portions of the project site, the lack of voids in the north and northwest are likely more due to the sparsity of UltraGPR data in these regions than a lower likelihood of voids.

A series of apparently connected voids near 684000E, 702496N warrants further investigation. These voids were imaged on multiple UltraGPR profiles which passed over the same survey trail and appear to be relatively deep.

The general rule of thumb when assessing the ability of a radar system to image a void is that an individual target is likely to be detected when its size is least 10 – 15% of the target's depth. That is, a 20 cm thick void may be detected at 2 m, but not at 10 m. At 10 m, a void may need to be in the range of 1 m in thickness to be detected in limestone.

In addition to the maps showing the location of interpreted voids, depth slices have been provided in Appendix I which illustrate the degree of limestone fracturing imaged by UltraGPR. Although these maps are generally much less precise that those of the void locations, an examination of the distribution of fractured limestone may be of interest when considering preferential water migration pathways.

Of specific interest are the regions to the extreme north, bordering the marshland, as well as those in the southwest, which appear to show a lenticular body of fractured limestone. A final region of note on all three depth slices is a region of fractured limestone located near 684097E, 703307N.

3.6 Considerations

Due to the process of scattering of radar energy when an electromagnetic wavefront encounters a sharp change in dielectric permittivity (i.e. between limestone and air or water in a void), little radar energy penetrates into the void. As such, it is often difficult to discern the exact thickness or vertical size of a void. This limitation is common to both UltraGPR as well as commercially-available GPR systems.

As such, the most accurate information provided by the present survey is that of the top of each void. The thickness of each void has been attempted to be interpreted from the UltraGPR profiles and is shown on the various depth slice maps contained in Appendix I of this report. However, these depths slices and the thicknesses of each void should be accepted only a generalisations and not be considered as accurate as the information pertaining to the top of the void and the exact location of the void.

In addition, although adequate coverage was achieved over the vast majority of the prescribed project area, significant regions of sparse or missing data were necessitated due to the inaccessibility of those regions. As such, no UltraGPR information is available for these regions and no assumption should be made that there regions are free of voids. Indeed, even in regions where adequate UltraGPR coverage was achieved, it should be noted that there exists the possibility of large voids existing between the UltraGPR profiles which were not imaged. Although the illumination zone concept does allow for some lateral beam coverage, it should be considered that any GPR system is effectively a “knife-slice” through the ground, and targets even a few metres to the left or right of a survey line may not be imaged.

Based on these limitations, Groundradar provides the data contained herein with no stated or implied guarantees that all voids at the Florence Hall Development have been imaged or mapped by UltraGPR. Groundradar has used best practice methods to acquire remotely-sensed data measured entirely by electronic means to estimate the position and depth of certain voids on the survey site. Based on the number and density of the interpreted voids detected by geophysical means, it is highly likely that other voids exist.

4. CONCLUSIONS

A survey encompassing 58 hectares has been conducted on behalf of Foreman Chung & Sykes Consultants Ltd on Gore Development's Florence Hall Development in Trelawny Parish. The objective of the survey was to locate suspected karstic solution voids within the outcropping limestone.

The survey encompassed 8.5 days of field work, and required over 67 km of UltraGPR profiles. The prescribed line spacing was 10 m, although the difficultly of the terrain dictated that some regions were surveyed with a finer spacing than 10 m, whilst others, specifically in the northwest, were surveyed with much sparser spaced profiles, or were not able to be surveyed at all.

The geophysical survey employed a newly-developed ground penetrating radar technology, known as UltraGPR. This instrumentation, housed in a 5 m long snake and towed behind a surveyor, supersedes any commercial technology by offering significant improvements in depth of penetration and ruggedness. Rather than interleaved time sampling, used in all commercially-available GPR systems, UltraGPR employs a novel real-time sampling technology. In so doing, the effective stacking increases from a maximum of 32 times to over 32,000 times. This improvement alone over doubles the penetration of GPR in limestone, where the limit of penetration is the noise floor in the received signals. In so doing, a higher frequency bandwidth may be employed to achieve maximum penetration with hitherto impossible resolution capabilities.

UltraGPR also improves ruggedness by eliminating all wires by using Bluetooth® technology. The UltraGPR concept eliminates the need for laptop computers and employs a PocketPC or mobile telephone to store acquired data.

Groundradar provides the data contained herein with no stated or implied guarantees that all voids at the Florence Hall Development have been imaged or mapped by UltraGPR. Groundradar has used best practice methods to acquire remotely-sensed data measured entirely by electronic means to estimate the position and depth of certain voids on the survey site. Based on the number and density of the interpreted voids detected by geophysical means, it is highly likely that other voids exist. As such, it is strongly recommended that care be taken in selecting the footprint of individual structures and that geotechnical drilling be conducted to ensure that no voids exist in critical locations which may jeopardise the safety of the project or installations.

It is noted that Groundradar retains all data for a minimum period of seven years. These data are available for reprocessing or re-examination at no cost to the client, upon request during those seven years. As such, should an issue regarding voids occur during construction, the UltraGPR data in that region may be re-examined to determine if it was detected and what its spatial extent may be.