Integrity inspection of main access tunnel using ground penetrating radar

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Abstract. This paper discusses the Ground Penetrating Radar (GPR) survey performed to determine the integrity of wall of tunnel at a hydroelectric power generation facility. GPR utilises electromagnetic waves that are transmitted into the medium of survey. Any reflectors in the medium will reflect the transmitted waves and picked up by the GPR antenna. The survey was done using MALA GeoScience RAMAC CUII with 250MHz antenna. Survey was done on the left, the crown and the right walls of the underground tunnels. Distance was measured using wheel encoders. The results of the survey is discussed in this paper.

1. Introduction

Ground Penetrating Radar (GPR) is becoming a common non-destructive method in detection of pipes and utilities, tank and drum location, concrete and rebar inspection, sinkholes, geology and geologic hazards, landfill and burial trenches, cemetery and grave sites and archaeological studies. It produces a continuous cross-sectional profile of different subsurface features. In civil engineering, parameters such as thickness of asphalt layer, bar location and void detection are made possible. On the other hand, the essential information in geotechnical studies such as the depth to bedrock, different soil layers and subsurface voids can be obtained from GPR survey.

The GPR technique is similar in principle to sonar methods. The radar transmitter produces a short pulse of high frequency (25 - 1000 MHz) electromagnetic energy, which is transmitted into the ground through an antenna. Variations in the electrical impedance within the ground generate reflections that are detected at the ground surface by the same or another antenna attached to a receiver unit. Variations in electrical impedance are largely due to variations in the relative permittivity or dielectric constant of the ground. The greater the difference of dielectric constants at an interface between two materials, the greater the amount of electromagnetic energy reflected at the interface. Consider the behavior of an incident beam of electromagnetic wave (EM) energy as it strikes an interface, or boundary, between two materials of different dielectric constants (Figure 1). A portion of the energy is
reflected, and the remainder penetrates through the interface into the second material. The reflection coefficient at the interface, $R$, is given by Equation (1),

$$R = \frac{\sqrt{K_1} - \sqrt{K_2}}{\sqrt{K_1} + \sqrt{K_2}}$$

where $K_1$ and $K_2$ are the dielectric constant of materials 1 and 2, respectively.

Equation 1 indicates that when a beam of microwave energy strikes the interface between two materials, the amount of reflection, $R$, is dictated by the values of the relative dielectric permittivity of the two materials. If material 2 has a larger relative dielectric permittivity than material 1, then $R$ would have a negative value; i.e., with the absolute value indicating the relative strength of the reflected energy and the negative sign indicating that the polarity of the reflected energy is the opposite of that arbitrarily set for the incident energy. Water has a dielectric constant of 80 (compared, for example, to 5 for dry soil and 8 for rock) and hence there are high reflection coefficients between dry and wet materials. In addition, the water table is a strong reflector.

After penetrating the interface and entering into material 2, the wave propagates through material 2 with a speed, $V_2$, given by

$$V_2 = \frac{C}{\sqrt{\varepsilon_2}}$$

Where $C$ is the propagation speed of EM waves through air, which is equivalent to the speed of light, or 0.3 m/ns).

As the wave propagates through material 2, its energy is attenuated as follows:

$$\alpha = 12.863 \times 10^{-8} f \sqrt{\varepsilon_2} \left(\sqrt{1 + \tan^2\delta} - 1\right)^{1/2}$$

Where $\alpha$ = attenuation, in decibel/meter, $f$ = wave frequency, in Hz, and $\delta$ = the loss tangent (or dissipation factor) is related to $\sigma$, the electrical conductivity (in mho/meter) of the material by:

$$\tan\delta = 1.80 \times 10^{10} \frac{\sigma}{f\varepsilon_2}$$

![Figure 1. Propagation of radar energy through dielectric boundaries.](image-url)
When the remaining microwave energy reaches another interface, a portion will be reflected back through material 2 as given by Equation 1. The resulting two-way transit time ($t_2$) of the microwave energy through material 2 can be expressed as

$$t_2 = \frac{2D_2}{V_2} = \frac{2D_2\sqrt{\varepsilon_2}}{C}$$  \hspace{1cm} (5)

where $D_2$ is the thickness of material 2.

2. GPR survey methodology

The survey was performed on an underground tunnel of a hydroelectric power generation plant. The tunnel functions as a Main Access Tunnel (MAT) which stretches at 1km long. Both of the tunnels lead to a cavern which houses the turbines and control room. The tunnels were constructed in the mid 1990's. This survey is intended to determine the integrity of the tunnels.

GPR system is a real time technique making it a rapid and reliable method for tunnel wall integrity survey. The results are displayed on a radargram that represents the cross sectional view of the survey line. The x-axis is the distance travelled by the GPR antenna while the y-axis is the time of wave travel. Meanwhile, the colour scale represents the polarity of wave. The purpose of GPR survey is to map anomalies in the tunnel wall such as fracture lines, voids and determine water content relatively. Areas with relatively higher water content was identified. The tunnels experience areas of higher water content which can be seen visually with water dripping and seeping through the wall tunnel.

The GPR system used in this survey is MALA Geoscience RAMAC CUII. The antenna used is a shielded directional with 250MHz frequency. The choice of frequency is to ensure adequate penetration balanced to a reasonable resolution and sensitivity. Location was measured by a wheel encoder. The distance of survey was compared to the chainage labels of the tunnel and was found the variation was about 5%. This is due to the wheel experiencing bumps from the pavement which increases the distance and it accumulated over the total length of survey distance. The height of the crown of the tunnel was about 10 metres. Ideally the position of the antenna should be as close as possible to the wall surface. However, this is not possible since the use of a combustion engine is not allowed in the tunnels due to safety reasons. Therefore, the survey was done with the antenna placed on a battery operated carts with a antenna spacing of approximately one meter. It was found that the large gap did not produce any significant effects on the quality of results. Furthermore, the footprint of the wave is large, making the area of coverage larger. The gap was large enough for the crosstalk between the transmitter and receiver which appears as ringing to diminish and makes the reflection from the front surface of the tunnel wall 'clean'. Three surveys on the tunnel were done at the crown and two at angles on both sides of wall, respectively (Figure 2).

![Figure 2. Survey lines of GPR survey (view from the tunnel entrance).](image-url)
(a). The actual setup of the antenna for the left wall survey.

(b). The actual setup of the antenna for the crown wall survey.

(c). The actual setup of the antenna for the right wall survey.

**Figure 3.** GPR survey being done on three sides of the tunnel walls.

The radargrams were enhanced using post processing filters. A DC removal filter was added to normalize the voltage and remove effects of voltage drift due to electrical noise. Then a time corrected gain was applied which consist of a certain amount of linear and exponential amplitude time gain. The colour of radargram was selected to blue-white-red for easy viewing and interpretation. The
radargrams were interpreted with minimal filters and image post processing to ensure minimal loss of data.

3. GPR survey results
The survey results for the left, the crown and the right walls of the tunnel are displayed in figures 4, 5 and 6, respectively. The findings are categorized into two categories which are saturated fracture and unsaturated fracture. The areas with saturated fracture are areas with higher intensity of reflection which indicates that the area is wet and highly contaminated with fine clayey particles. Areas marked with unsaturated fracture contains less fractures and it is relatively much drier. It is recommended that areas marked with saturated fracture to be investigated thoroughly. Indications from MAT’s left wall shows several locations that are saturated fracture and much more significant. The indication is summarised in Table 1.

![Figure 4. Typical radargram for the left wall.](image)

![Figure 5. Typical radargram for the right wall.](image)
Figure 6. Typical radargram for the crown.

Table 1. Summary of GPR findings for MAT.

| Relative Degree of Fractures | Left Wall                | Crown                     | Right Wall               |
|-----------------------------|--------------------------|---------------------------|--------------------------|
| 20 – 289 m saturated        | 20 – 388 m saturated     | 20 to 280 m saturated     |
| 289 – 430 m unsaturated     | 388 – 430 m unsaturated  | 280 - 350 m unsaturated   |
| 430 – 566 m saturated       | 430 – 700 m saturated    | 350 - 388 m saturated     |
| 566 – 710 m moderate        | 700 – 1036 m unsaturated | 388 - 434 m unsaturated   |
| 710 – 780 m unsaturated     |                          | 434 - 530 m saturated     |
| 780 – 930 m saturated       |                          | 530 - 768 m unsaturated   |
| 930 – 1020 m unsaturated    |                          | 768 - 902 m saturated     |
| 1020 – 1046 m saturated     |                          | 902 - 1034 m unsaturated  |

4. Conclusions
This report highlights finding from GPR surveys conducted on the Main Access Tunnel of a hydroelectric power station. Areas of relatively saturated (wet) and unsaturated (dry) are identified. The wet areas are representing by fractures that is filled with water or clay particle, whereas the dry areas are representing by fractures that are dry and probably smaller in size. GPR 'sees' only fractures that is perpendicular to the radar beam as the reflected energy will be detected by the receiver. Reflected radar energy from fracture planes which are not perpendicular to the radar beam will be reflected towards the receiver.

5. Reference
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