A Simulation Approach for Evaluating Asphalt Pavement Layer Thickness Using Ground Penetrating Radar

IAPA Scholarship Report

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Disclaimer

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Introduction

Ground penetrating radar (GPR) is a non-destructive test (NDT) method which can acquire underground images by electromagnetic (EM) radiation reflection. A typical GPR system usually includes five main components: a control unit, transmitter antenna, receiver antenna, distance measuring instrument (DMI) and global navigation satellite system (GNSS) receiver. During a GPR survey, the control unit sends signals to the transmitter antenna, then the transmitter emits electromagnetic radiation into the ground. After the radiation is reflected or scattered back by a target or a boundary between layers with different dielectric constants, the receiver antenna records the reflected radiation (*1*). At the same time, the DMI and GNSS receiver integrate the distance and location information with the GPR signal. The GPR signal is a two-dimensional function with time as x-axial and amplitude as y-axial, which is also called the signal in time domain. After the signal processing analysis, researchers can measure the pavement layer thickness, predict the mechanical properties, such as the density and stiffness modulus of pavement, evaluate the damage underneath the surface, and detect the subsurface targets, such as dowel and tie bars, pipes and unknown projects based on the signals (*2*).

Two typical types of GPR system are applied in pavement engineering, which are air-coupled and ground-coupled systems. In the air-coupled system, the antennas are launched about 150-500 mm above the ground, while in the ground-coupled system, the system's antennas contact fully with the ground. The advantage of the air-coupled GPR system is it provides a clean radar signal and allows for a high survey speed. However, part of the electromagnetic radiation sent by the transmitter is reflected by the pavement surface, thus the radiation energy decreases, and the penetration depth decreases. For the ground-coupled GPR system, the energy can be fully emitted into the ground, thus the penetration depth is further, but the survey's speed is limited. For flexible pavement, the air-coupled system is more common because it enables a high-speed survey, which does not need lane closure. Also, the signal acquired from the air-coupled system allows estimating the dielectric constants of pavement layers, which is a fundamental element in GPR signal analysis (*3*).

GPR was first adopted in geo-science after the mid-1950s. In 1986, the federal highway administration (FHWA) developed one of the first vehicle-mounted GPR for road inspection (*4*) Later then, GPR has been widely adopted thanks to the improvement of digital signal processing technology and computational power. A high demand for time-efficient and NDT method for pavement inspection also has promoted the development of GPR. Two reasons may explain the popularity of GPR. First, an understanding of underground structure or material properties can be acquired from GPR signals quickly or even on-site. The resolution of signals is on the scale of centimeter, which matches the requirement for pavement assessment (*5*). Second, traditionally pavement assessment extracts pavement cores from original pavement to evaluate pavement structure or properties, which is destructive, time consuming, and require traffic control. This traditional method is also less informative because cores are extracted every 300 m. In comparison, GPR enables engineers to assess pavement layer thickness, material properties on time and non-destructively.

The purpose of this paper is to present a simulation approach for evaluating asphalt pavement layer thickness using GPR. First, the physical and mathematical theory of GRP is reviewed. Then, a numerical method is presented to simulate the thickness measurement. Finally, a discussion is provided on the thickness measurement of thin overlay problem.

Theory review

Physical principles of GPR

The foundation of the GPR survey is the EM theory. In EM theory, Maxwell's equations describe the physical properties of EM fields, and constitutive equations are used to describe a material's response to EM fields. This theory supports the work of GPR (*6*).

$$\nabla \times E = -\frac{\partial B}{\partial t} \tag{1.1}$$

$$\nabla \times H = J + \frac{\partial D}{\partial t} \tag{1.2}$$

$$\nabla \cdot D = q \tag{1.3}$$

$$\nabla \cdot B = 0 \tag{1.4}$$

The Maxwell equations (1.1-1.4) were developed by James Clerk Maxwell based on the experimental discoveries of Andre-Marie Ampere, Michael Faraday, and Carl Frierich Gauss. The equations establish the relationship among the electric field strength E, magnetic field density H, magnetic flux density B, electric current density J, electric charge density q, and electric displacement vector D. t is the time. From the Maxwell equations, an electric field can be generated from a changing magnetic flux; a magnetic field can be produced from an electric current or a changing electric field; the electric field lines originate from positive charges and terminate at negative charges; and the magnetic flux lines form a circle in the field without origins (*7*).

$$J = \sigma E \tag{1.5}$$

$$D = \varepsilon E \tag{1.6}$$

$$B = \mu H \tag{1.7}$$

Furthermore, for the medium in the EM field, constitutive equations (1.5-1.7) are used to describe the electrical and magnetic properties of the medium. In these equations, electrical conductivity, dielectric permittivity, and magnetic permeability are three major material properties. Electrical conductivity σ builds the relationship between the electric current density vector J and electric field strength vector E; dielectric permittivity ε characterizes the electric displacement D to the electric field strength; and magnetic permeability μ depicts the relationship between the magnetic flux density B and the magnetic field intensity H. In general, the electrical conductivity of asphalt is 0, which means it is non-conductive; the magnetic permeability is 1, which means the asphalt material is non-magnetic. Hence, the most important electric and magnetic property in pavement engineering is dielectric permittivity (*8*). Another important property is the ratio between the dielectric permittivity of the material and the permittivity of space, which is called relative permittivity ε_r, also known as dielectric constant. The dielectric constant of the material, which also affect the frequency and the amplitude of the signal, decides the velocity of electromagnetic wave in the material.

Based on the Maxwell equations and the constitutive equations, GPR signals can be fully described, and further processed to characterize pavement properties.

The measurement of layer thickness

The measurement of pavement layer thickness is the most common application of GPR in pavement engineering. The purpose of measuring thickness can be (a) quality assurance of newly constructed asphalt pavement and pavement overlaying construction; (b) support of other test methods which use layer thickness as input; and (c) prediction of pavement service life (Z Leng, 2011).

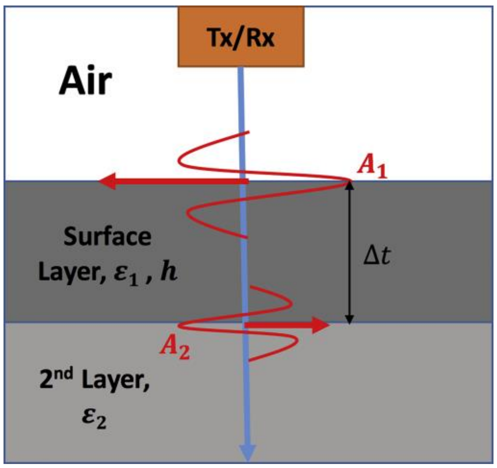


Figure 1 GPR signal reflected from a two-layered AC pavement

Figure 1 shows a typical GPR signal reflected from a two-layered AC pavement. In Figure 1, "Tx/Rx" represents a monostatic air-coupled antenna. The surface AC layer has a dielectric constant of ε_1 and thickness of h; the second layer (leveling binder or the old pavement) has a dielectric constant value of ε_2. A_1 and A_2 are the amplitudes of the reflection from the surface and the bottom of the surface layer, respectively. The two arrows represent the impulse response of the pavement system. It should be noted that the second reflection has a different sign in Figure 1, assuming $\varepsilon_2 < \varepsilon_1$.

In the scenario shown in Figure 1, the surface layer thickness can be determined by:

$$\mathrm{h} = \frac{v\Delta t}{2} \tag{1.8}$$

where Δt is the two-way travel time (TWTT) between the reflection from the surface and the reflection from the bottom of the surface, and

$$v = \frac{c}{\sqrt{\varepsilon_1}} \tag{1.9}$$

is the speed of the EM wave in the surface layer, and c = 3 × 10^8 m/s is the speed of light in free space. According to Snell's law of reflection, the dielectric constant of the surface layer can be determined using the following equation:

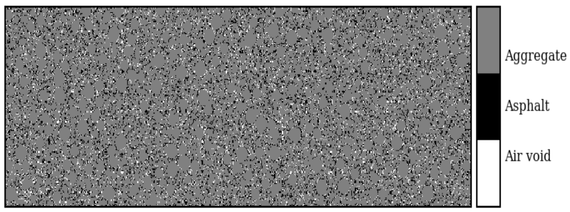
$$\varepsilon_1 = \left(\frac{1 + A_1/A_p}{1 - A_1/A_p}\right)^2 \tag{1.10}$$

where A_p is the amplitude of the reflection from a copper plate.

Numerical simulation of the thickness measurement

Numerical model development

The finite-difference time-domain (FDTD) simulation in this study was performed using an open-source GPR simulation program known as GprMax (*9*). It has been successfully applied to simulate GPR wave propagation in various materials. The FDTD method, also known as Yee's algorithm, is a differential equation-based solver that provides numerical solutions for Maxwell's equations in complex geometries (*10*). The FDTD method uses the second order accurate derivatives in space and time. It utilizes a mesh built from rectangular, or Yee cells, in which field values are updated time-step by time-step as EM waves propagate through a structure. In this paper, 2D FDTD simulations were performed considering the computational intensity of 3D simulations. Two-dimensional FDTD simulation has been proven to have similar results to 3D simulations in the case of AC pavement (*10*).



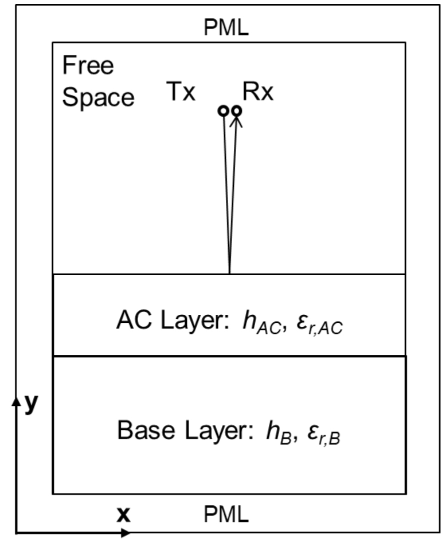


Figure 2 the three-phase asphalt mixture numerical model.

In this paper, AC mixture consists of asphalt binder, aggregate, and air voids. Coarse aggregates were generated as circles of different sizes. Considering the cubic meshes in the FDTD method, these circles were later approximated using unit squares of 0.001 × 0.001 m to acquire the required level of accuracy. The angularity of particles was not considered in this study because the angularity of aggregates mainly affects the mechanical properties of the material rather than its dielectric properties. The three-phase AC mixture generation algorithm is summarized as follows: (1) Choose a mean size between adjoining sieve sizes as aggregate size in each level. (2) Calculate the number of aggregates in each level from aggregate gradation data. (3) Randomly place the generated particles into a predefined sample with no aggregate overlapping. The generated circles in each level should not overlap with circles in other levels. (4) Approximate the generated circles using unit squares and check aggregate gradation. Complement fine aggregates using unit squares. (5) After all particles are completed, the region within the sample boundary, but not occupied by aggregate, is set as asphalt binder. Air voids are generated by deleting the asphalt binder elements randomly. It should be noted that the actual volume of aggregate is greater than the one used in the model because of the adsorbed portion of the asphalt binder by the aggregate.

The generated model in Figure 2 is used in GprMax simulation. The constructed numerical model of an AC mixture contains three phases: aggregate, asphalt binder, and air voids. Figure 3 shows simulated signal in GPR measurement.

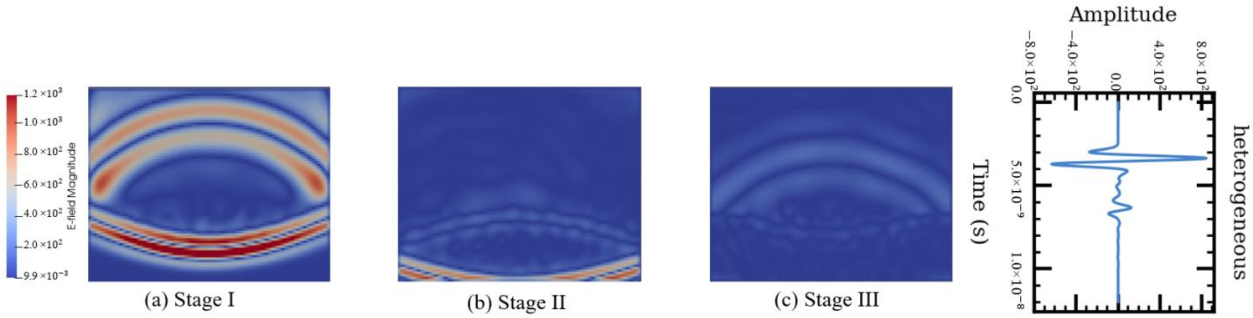


Figure 3 simulated signal in GPR measurement.

Calculated thickness in the numerical simulation

In this section, a number of numerical simulations were performed to show the accuracy of measuring asphalt pavement thickness using GPR. In the simulations, the asphalt concrete layer thickness was set between 100 mm to 250 mm to simulate thick AC pavements. GRP data was collected, and the AC layer thickness was calculated using the TWTT and surface reflection method shown in equation 1.8 to equation 1.10. The results are shown in Figure 4. The average estimation error is 0.79%.

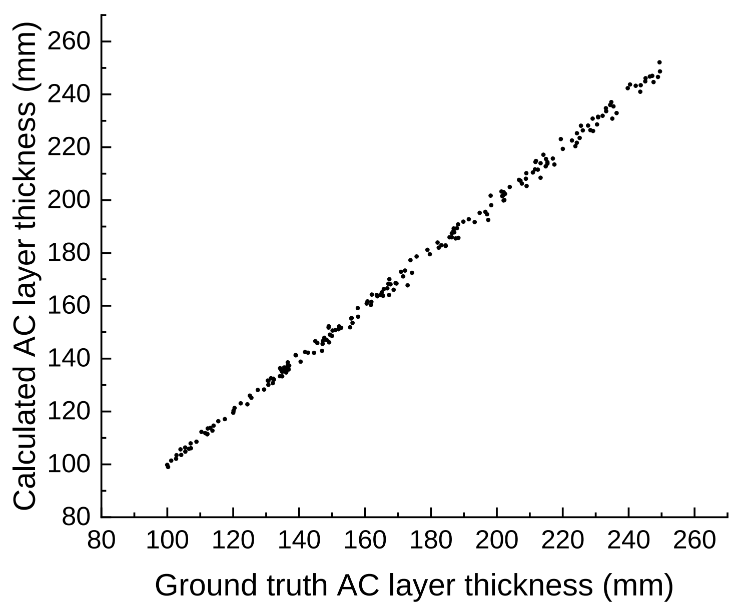


Figure 4 calculated thickness in the numerical simulation.

Thin overlay in the numerical simulation

The aforementioned methods for predicting AC layer thickness and density require an accurate determination of the TWTT and the surface reflection amplitude. This is not possible when the AC layer is thin compared to the EM wavelength. As a result, signal processing techniques need to be applied to solve the thin AC overlay challenge. In this paper, the nonlinear gradient descent algorithm proposes by Zhao et al. (*11*) is used to show the application of GPR in thin overlayer thickness measurement.

In the nonlinear gradient descent approach, a two-layered AC pavement can be represented as:

$$y(t) = x(t) * [R_1\delta(t) + R_2\delta(t - \Delta t)] = R_1x(t) + R_2x(t - \Delta t) \tag{1.11}$$

where $\delta(t)$ is the Dirac Delta function, and R_1 and R_2 are the EM reflection scale factors at the surface and bottom of the AC surface layer, respectively. Then, the problem becomes minimizing the residue cost:

$$z = argmin\{C(z)\} \tag{1.12}$$

This nonlinear can be solved using a gradient descent algorithm iteratively:

$$z^{n+1} = z^n - \gamma\nabla_z C(z) \tag{1.13}$$

where γ is the step size, and $\nabla_z C(z)$ is the Laplacian of $C(z)$ with respect of z.

Then, a number of numerical simulations were performed to show the accuracy of measuring asphalt pavement thickness in thin overlay problem using GPR. In the simulations, the asphalt concrete layer thickness was set between 10 mm to 40 mm to simulate thin AC pavements. GRP data was collected, and the AC layer thickness was calculated using gradient descent algorithm shown in equation 1.11 to equation 1.13. The results are shown in Figure 5. The average estimation error is 2.25%.

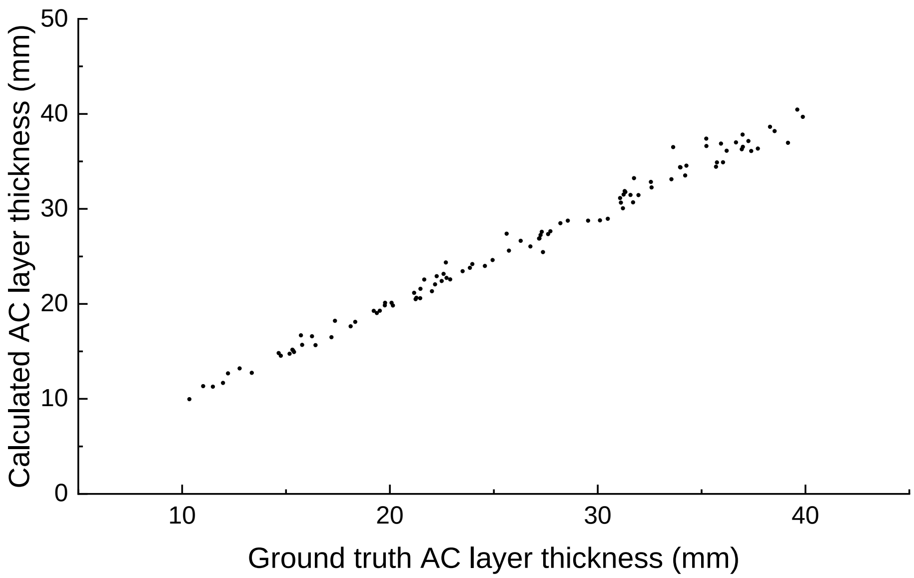


Figure 5 calculated thickness in the numerical simulation of thin overlay.

Conclusions

In this paper, a simulation approach is presented for evaluating asphalt pavement layer thickness using GPR. The thick asphalt pavement layer can be measured using the TWTT and surface reflection method. The numerical simulation shows that the average estimation error is 0.79%. For the thin asphalt overlay, the thickness can be measured using gradient descent algorithm. The numerical simulation shows that the average estimation error is 2.25%. The research in this paper demonstrates the application of GPR in pavement thickness measurement. In the future, field tests will be performed to validate the simulations in this paper.

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