Preliminary Study of Lab-Scale Railway Ballast Monitoring Using Ground Penetration Radar (GPR)

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Abstract. Railway ballast is generally composed of uniformly graded aggregate. It plays an important role in load stress distribution to subgrade as well as free-drainage system. Periodical ballast assessment using GPR is a relatively new method, yet has been actively adopted by several countries due to its ability to assess early-stage ballast deterioration. Thus, this method has become a paramount of importance to minimize the cost of maintenance and risk of accidents. Compared to the current assessment method, Indonesia still uses passing-tonnage method that may overlook premature damage of ballast. This research is a preliminary study that tries to provide visual imagery from GPR response of railway ballast in a lab-scale model using 1GHz Ground Penetration Radar. Testing chamber was manufactured and customized to facilitate GPR run in a lab-scale experiment. Ballast material was obtained from Tarahan quarry with specific gravity of 2.65. Sieve analysis was also conducted in accordance with ASTM E11 to meet the technical specification determined by Indonesia Ministerial Regulation No. 60 (2012). Ballast with the depth of 30 cm was laid out into testing chamber in two different methods; non-layering and layering; then scanned with GPR with trace length of 1.35 m. Result shows that non-layering method ballast composition exhibits bigger voids indicated by prevalent amplitude drop along the trace. Meanwhile, layering method exhibits better ballast structural composition with less voids being shown.

Keywords: Railway ballast, non-destructive, monitoring, GPR

INTRODUCTION

Conventional track system or ballasted track is the most widely used type of track for railways[1]. Ballast structure is a uniformly graded granular material which plays an important role in transmitting train load into base layer as well as a free-drainage system[2,3]. Ballast assessment is often conducted visually and by opening trenches at certain locations resulting in limited information[4]. In Indonesia, ballast condition is often measured by both visual survey and passing-tonnage calculation which indicates that periodical ballast assessment may be absent unless the passing-tonnage has been exceeded. This may result in an overlooked condition of ballast due to the dismissal of early-stage ballast deterioration and restricted information regarding ballast condition.

Nondestructive Testing (NDT) methods for ballast assessment has gained popularity at least in the last two decades for its capability to overcome the expressed restrictions in conventional assessment method. Ground Penetration Radar (GPR) is a nondestructive testing method that utilizes electromagnetic (EM) pulses to detect electrical properties of subsurface[5]. GPR transmits EM energy into the objected medium and of the emitted energy is then reflected back. GPR has a central frequency range from 10 MHz to 2.5 GHz that indicates its penetration ability. Several studies on ballast assessment have been conducted using GPR with different central frequency. GPR of frequency 450 MHz and 900 MHz were used to assess ballast and subgrade layer respectively[6]. GPR with central frequency of 400 MHz displayed better railway sub-structure layers in comparison with 100 MHz of frequency. However, GPR of 100 MHz frequency was able to penetrate deeper that it could locate existing water pocket[7]. As for ballast assessment nowadays, GPR of 2 GHz of frequency are commonly used[8,9] for deeper penetration range coupled with 400 MHz for a higher resolution of ballast structure[10]. This research tries to provide visual imagery condition of lab-scale ballast setting and its GPR response using 1GHz antenna, as GPR with this frequency has not yet been well explored for the purpose of ballast assessment. To this day, GPR has attracted both researchers and practitioners across the world in underlining ballast issue before it becomes too late to get fixed.

This paper tries to provide visual imagery condition of lab-scale ballast setting and its GPR response using 1GHz with specific local materials to replicate track field condition. This paper also tries to elaborate the advancement in railway track assessment as well as exploring the potentiality of 1 GHz GPR to be used for ballast survey in Indonesian railway track. Furthermore, this study aims to become the pioneer in introducing non-destructive ballast assessment method in Indonesia.

METHODOLOGY

GPR equipment

This lab-scale study used an antenna owned by the Department of Geophysics Engineering, University of Lampung; Geoscannners Akula 9000 C (ground-coupled antenna GCB 1000) with central frequency 1GHz including its body frame as shown in **Fig. 1**.

FIGURE 1. GPR body frame and 1GHz ground-coupled antenna

Testing Chamber

Railway ballast aggregates were investigated within a square-based 1cm-thick methacrylate chamber of 1.35 m and 1.16 m in length and width respectively. The testing chamber type or material, thickness, and size were determined in order to reduce edge effects which may cause noise disturbance to the EM signal as well as facilitating the load of ballast aggregates. The height of chamber is 0.5 m to facilitate 0.3 m ballast thickness as required by Indonesia Ministerial Regulation No. 60 (2012) or famously known as PM No. 60. Two detachable U-shaped steel bars were prepared to allow GPR run during experiment. L-shaped steel bars were embedded at each corner and the bottom part to increase chamber stiffness due to the load and angularity of ballast aggregates. Meanwhile, four wheels were added for mobility purpose. Measuring ruler were adhered on each side of testing chamber to assure ballast height conformity. Testing chamber design can be seen **in Fig. 2.**

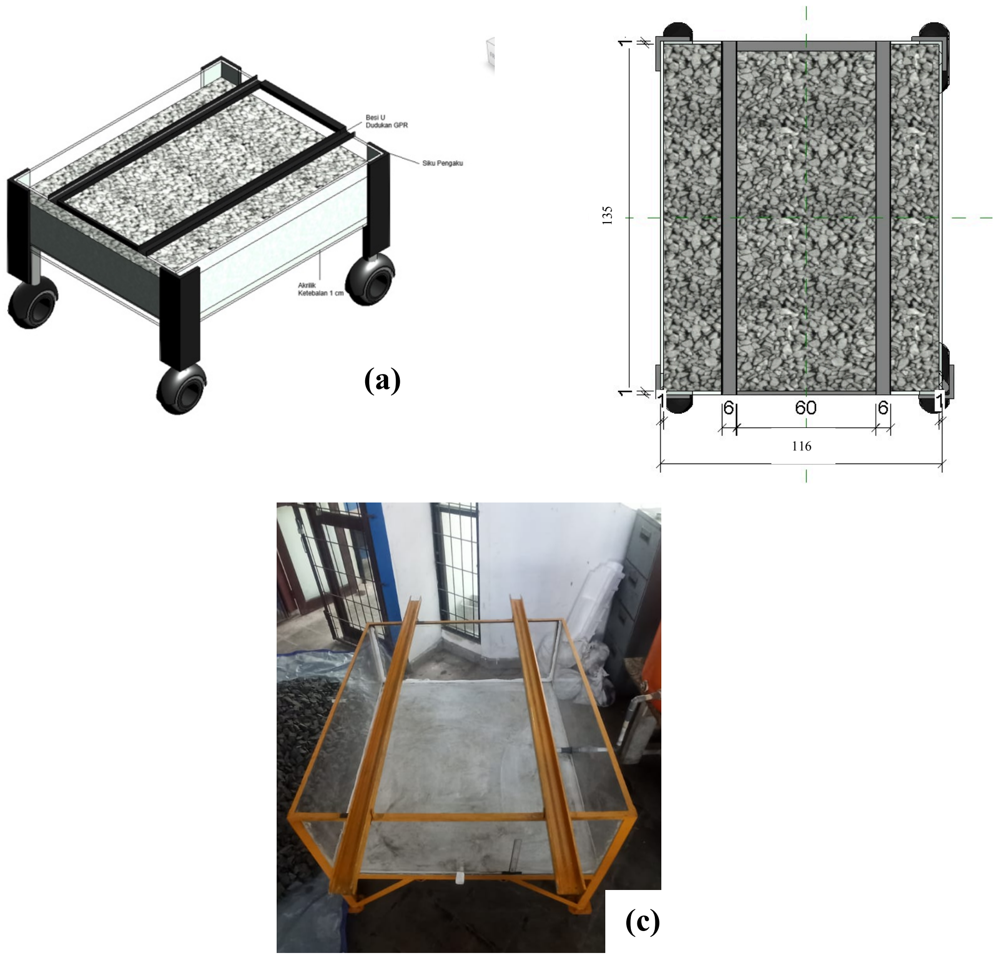

FIGURE 2. (a) 3D view of testing chamber design; (b) bird-eye view of testing chamber; (c) real testing chamber

Ballast Materials

Andesite ballast aggregates are typically employed for the construction of ballasted railroads in Lampung province. Ballast aggregates from Tarahan quarry, located in South Lampung region, were selected for testing purposes. Within PM No. 60, ballast aggregates need to meet several requirements needed such as specific gravity, particle size distribution, and resistance against abrasion

With regard to particle size distribution, PM No. 60 required ballast particle size to fall in between the lower and upper boundary. Sieve analysis was conducted in accordance with ASTM E11 to ensure materials fit the specification as the result can be seen in **Table 1**. Meanwhile, **Fig. 3** graphically shows that the obtained materials fulfill PM No. 60 specification with slight exceedance on sieve no 25.4.

Specific gravity is another important parameter required to be evaluated in accordance with ASTM C-127-68 to meet the technical specification of ballast. This test was conducted twice and an average specific gravity value of 2.65 was found, in line with the literature reference of andesite ballast aggregates[11].

TABLE 1. Particle size gradation of ballast aggregates

PM No. 60		Test Result
Sieve size (mm)	**Passing (%)**	**Passing (%)**
63.5	100	100
50.8	80-100	96.952
38.1	35-75	69.288
25.4	0-40	41.526
19.1	0-5	0

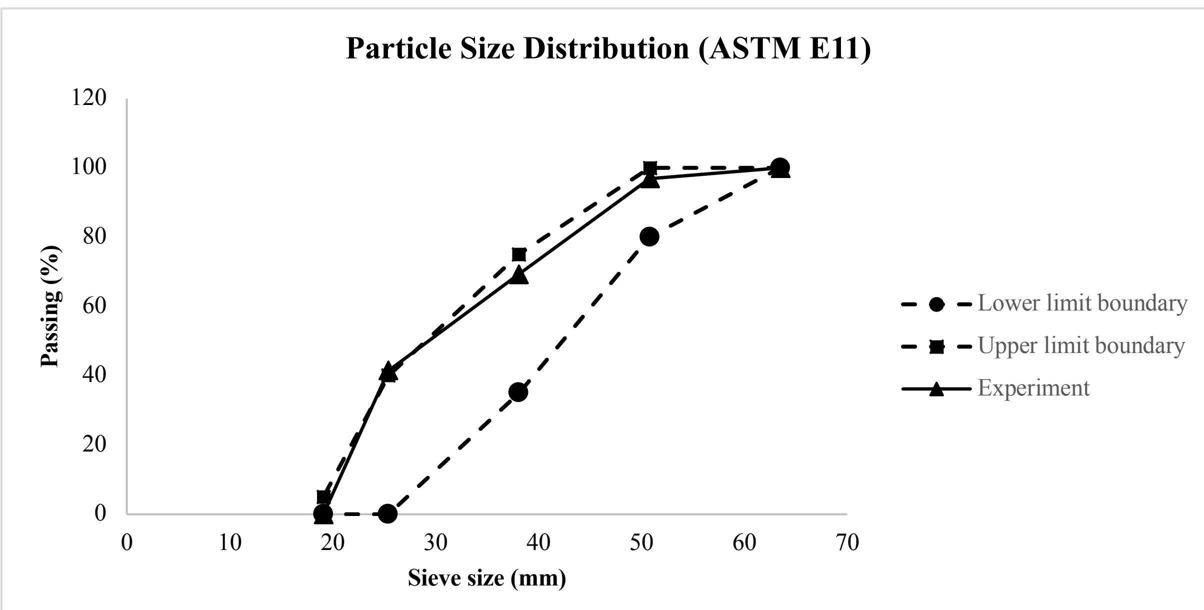

FIGURE 3. Ballast particle size distribution

The resistance of ballast against abrasion was assessed using Los Angeles testing method following ASTM C-535-03. The Los Angeles abrasion index was evaluated as follows:

$$LA_{RB} = \frac{m_1 - m_2}{m_1} \tag{1}$$

where m_1 is initial mass of sample (5 kg in weight and sieved) and m_2 is the mass of sample after Los Angeles test. Two samples were tested and an average abrasion index of 14.7% was found, fulfilling the upper limit boundary abrasion index of 25% as stated in PM No.60.

Materials Layout

Ballast aggregates with the quantity of ~1500 kg was laid out in two different methods in order to check GPR response in different layout techniques; i) ballast aggregates were laid out in one layer reaching the thickness of 0.3 cm directly, ii) ballast aggregates were laid out in 3 layers starting from 0.1 m with 0.1 m of increment in each step, eventually reaching 0.3 m. Visualization of both layout techniques can be seen in **Fig 4.**

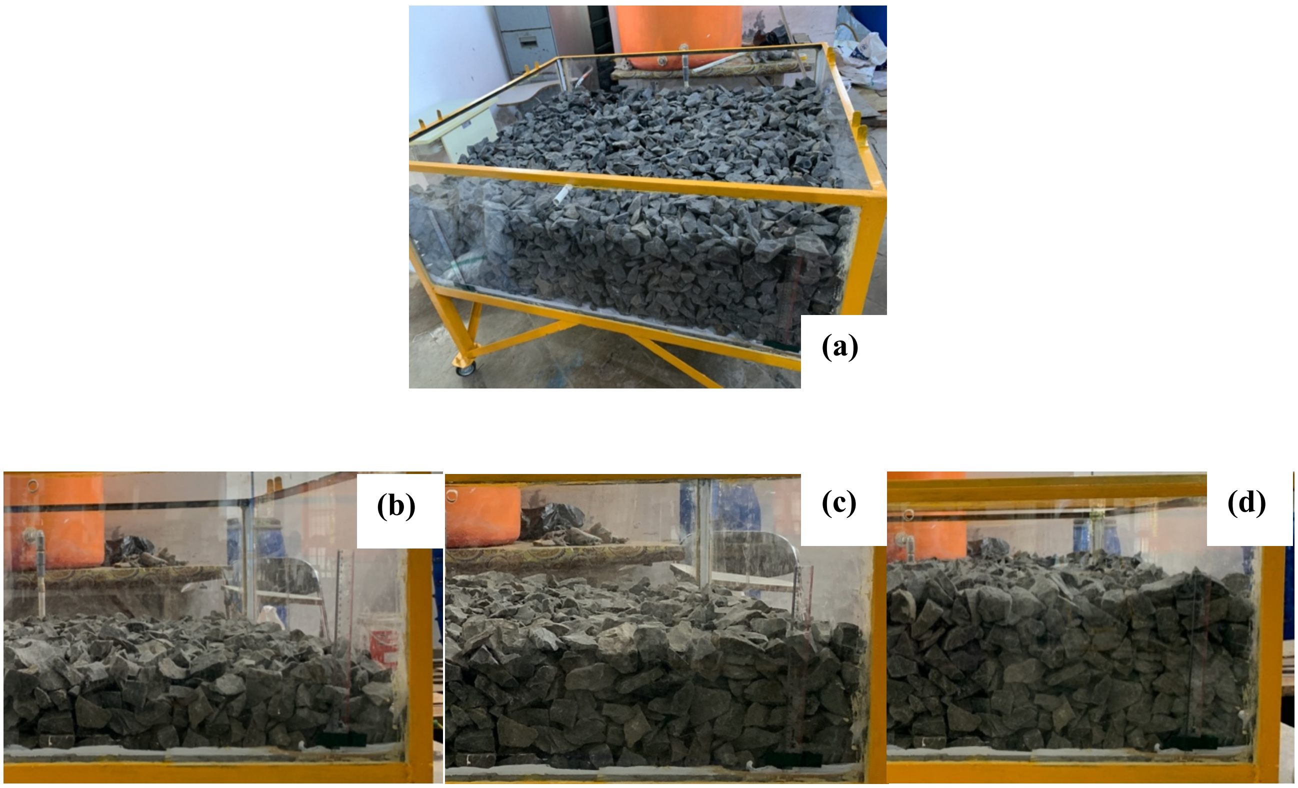

FIGURE 4. (a) non-layering laid out ballast; (b) 10 cm layering; (c) 20 cm layering; (d) 30 cm laid out ballast

Test Scenarios

Two configurations were manufactured in the laboratory environment; layering and non-layering configuration. In these two scenarios, the material investigated filled the chamber height of 0.3 m. GPR surveys were performed three times at each of the aforementioned configuration as seen in **Fig. 5,** in which generated three raw data sets for each configuration**.** Each survey with 1,35 m of trace length took 30 seconds to finish with average GPR running speed of 0.045 m/s. GPR running speed was attempted to be kept constant for the purpose of data consistency.

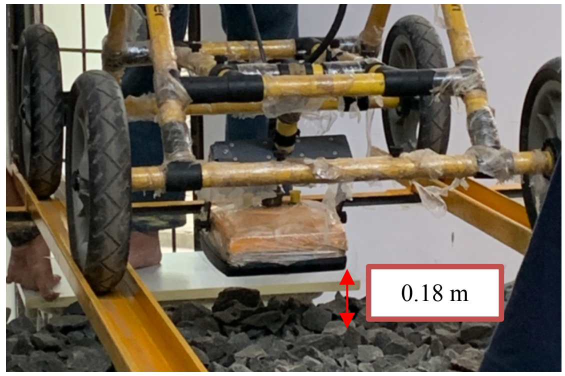

FIGURE 5. GPR survey performed on detachable railings

Data Processing

Performed GPR surveys resulting in raw data had to undergo several steps of data processing using REFLEXW software such as Static Correction, 1-D Dewow, Gain-AGC, 1-D Bandpass Frequency, 2-D Background Removal, 2-D Stack Trace, and FK-Filter.

Electromagnetic waves propagation in a medium follows Maxwell's equation. As ballast is generally considered non-magnetic, then the propagation waves can be described as follows[10].

$$\nabla E = -\mu \frac{\partial H}{\partial t} \tag{2}$$

$$\nabla H = \varepsilon \frac{\partial E}{\partial t} + \sigma E$$

where E is the electric field strength, H is the magnetic field strength, ε is dielectric constant, μ is the magnetic permeability, and σ is the electrical conductivity.

RESULTS AND DISCUSSION

Performed GPR survey results were imported to REFLEXW software to be analyzed. This analysis was conducted in order to portray and compare GPR response within clean ballast layer with two different layout technique in the form of radargram as shown in **Fig. 6.**

While ballast portrayal of both layout techniques does not give much distinct visual differences as can be seen in **Fig. 4**, radargram results prove otherwise. Radargram of non-layered ballast shown in **Fig. 6(a)** displays distinct prevalent amplitude drops along the trace length. While layered ballast shown **Fig. 6(b)** displays more of solid media with several fractions of amplitude drop. In case of ballast assessment, amplitude drop occurrences may indicate air voids from aggregates. This is due to aggregate size particles and angularity that are uniformly graded, leaving ballast layer with distinct voids in between particles. Layering technique also resulted in more compact ballast layer due to the given time for the aggregates to spread evenly, thus filling up larger voids in between particles. Filtered result for layered ballast is shown in **Fig. 7.**

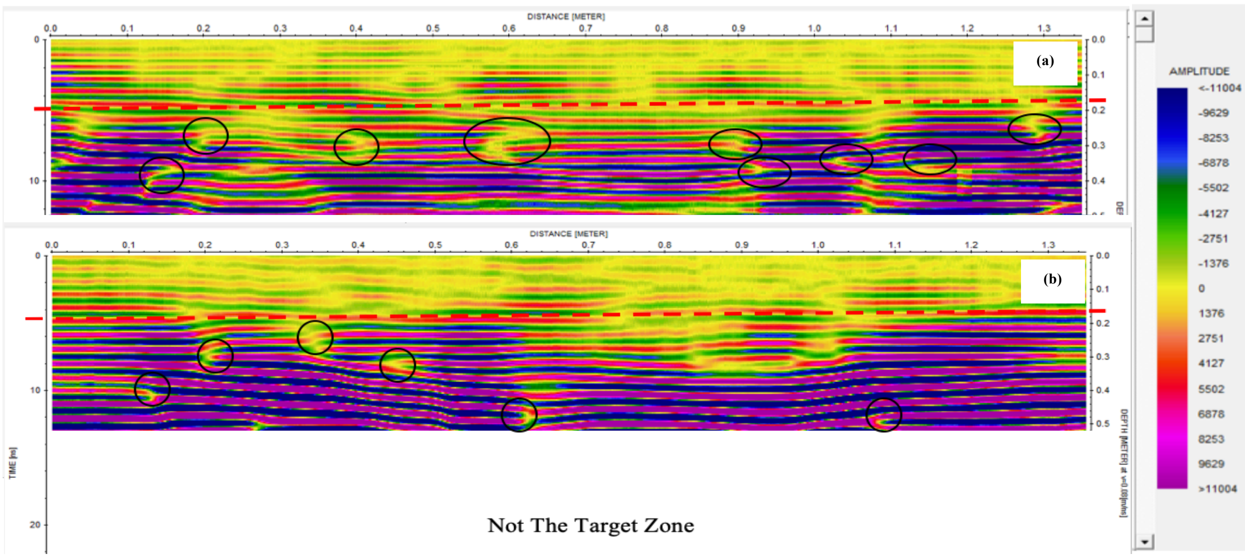

FIGURE 6. Radargram of (a) non-layered ballast; (b) layered ballast (a)

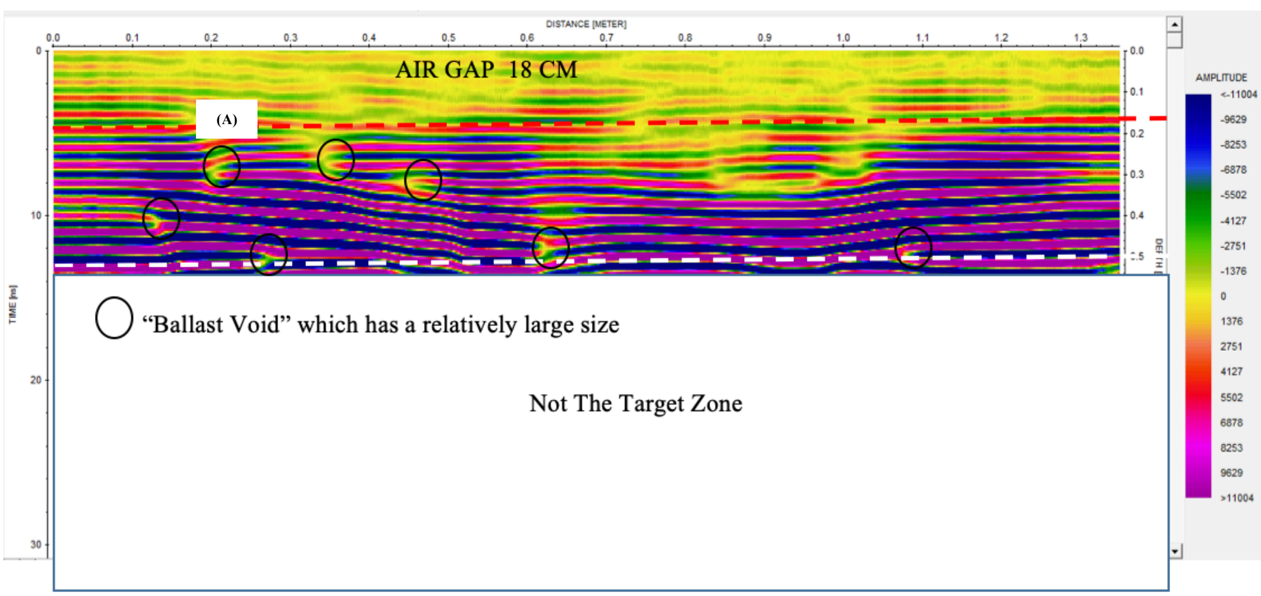

FIGURE 7. Filtered radargram of layered ballast

As the utilized 1 GHz GPR has the ability to penetrate until 2 m of depth, while GPR response to ballast layer is the only desirable result to obtain, filtering procedure should be performed. **Fig. 7** shows the result of filtered radargram of layered ballast. Air gap of 0.18 m is the measured distance of antenna to ballast surface. The occurrence of processing ballast effect is due to over filter during raw data processing, while point A to F indicate larger voids occurrences as the amplitude in those points suddenly drop to almost zero. **Fig. 8** shows the propagated wave of point A. *'Not The Target Zone'* is the zone where ballast layer is no longer existed, thus can be omit. Results indicate that 1 GHz GPR has the ability to pin-point relatively large size voids in between particles. Hypothetically, this method may be applicable during ballast construction process in real field track to ensure that ballast aggregates are laid out in proper manner. However, 1 GHz GPR may not be able to generate results for smaller size of voids. Thus, STFT (Short Time Fourier Transform) analysis is needed to be performed. In addition, due to its' 2 m penetration capability, depth correction should be performed during data processing.

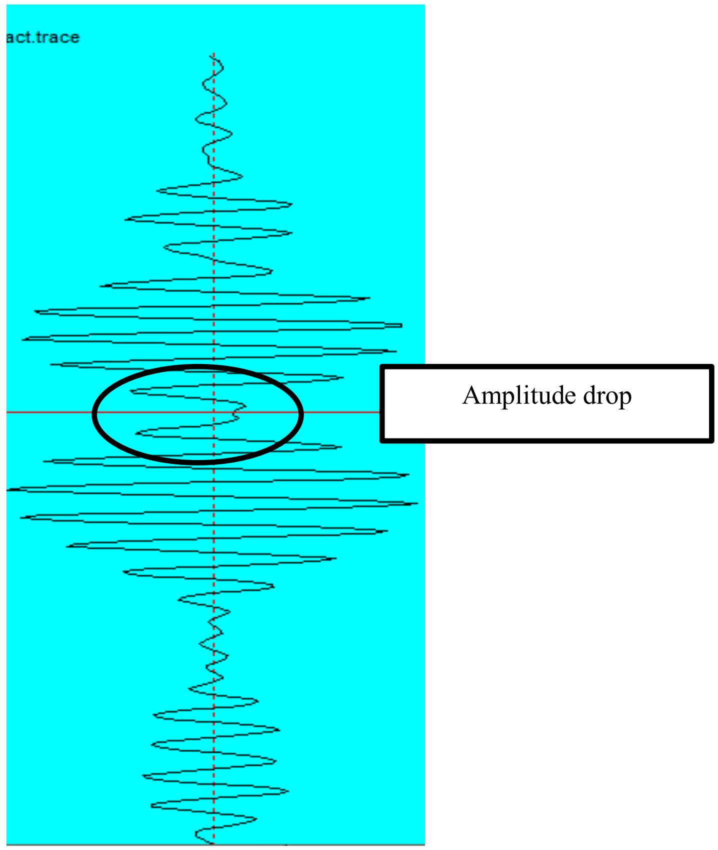

FIGURE 8. Propagated wave of point A

CONCLUSION AND FUTURE PERSPECTIVES

This research is a preliminary study that tries to provide visual imagery from GPR response of railway ballast in a lab-scale model using 1GHz GPR. GPR was applied to estimate ballast layer imagery condition such as depth as well as capturing anomalies that may occur within the layer. After performing this study, the following conclusions are drawn:

- Single use 1 GHz GPR is able to penetrate deeper under ballast layer. Thus, suitable for real track field survey (ballast, sub-ballast, and sub-grade). However, in order to get a higher resolution of the ballast layer itself, coupling 1 GHz GPR with a higher frequency GPR is desired.
- Layered ballast gives a more distinct GPR response of solid medium and anomalies caused by large voids.
- 1 GHz Ground Penetration Radar has a potential to be utilized as a newly proposed method of ballast assessment.
- Hypothetically, non-destructive testing method with GPR may also be applicable during ballast construction stage in real field track to ensure that ballast aggregates are laid out in proper manner.
- This study has not yet fully depicted the real ballast condition as applicated in the real track due to non-tampered layering process. Future consideration is expected.

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