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A Comparative Study of Ground-Based and Drone-Based GPR: Opportunities, Challenges, and Applications in Bromo, Indonesia

Afni Nur Jannah[1], *Eksi Galih Kenya* Paramita[1], *Syabibah Zakiyya* Zukhrufah[1], *Juan Pandu Gya Nur* Rochman[1*], *and Firmansyah Maulana* Azhali[2]

[1]Geophysical Engineering Department, Institut Teknologi Sepuluh Nopember, Indonesia
[2]PT Terra Drone, Indonesia

Abstract. A drone-based GPR offers improved mobility and accessibility for subsurface exploration while delivering high-resolution detection of objects and soil layers, particularly in challenging areas. This study compares the performance and limitations of ground-based and drone-based GPR by analyzing their responses to surface condition using GPR radargrams. Data were collected from the Bromo-Tengger Caldera, East Java, Indonesia, using a 150 MHz antenna for drone-based GPR and a 500 MHz antenna for ground-based GPR. Data processing included filters like static correction, bandpass, gain, background removal, FK-filter, and time-to-depth conversion, with additional steps like time cut and trace editing for drone-based GPR. The results of ground-based GPR data appeared more random, with less distinct reflectors due to surface conditions like vegetation and rough terrain, despite noise filtering. Drone-based GPR faced challenges such as greater static correction due to higher altitude, and deviations from planned paths caused by GPS errors. The study concludes that both methods have unique strengths and weaknesses, and the choice between them should be based on the survey area's conditions and project goals.

1 Introduction

Ground Penetrating Radar (GPR) is a geophysical method designed to identify subsurface structures using electromagnetic pulses in the frequency range of 10 MHz to 3 GHz. The system operates with a transmitter that emits electromagnetic waves into the ground and a receiver that records the signals reflected from subsurface layers [1]. These reflections occur at boundaries where there are differences in the dielectric properties of the materials, such as between different soil layers or geological features [2]. The strength and timing of the reflected signals provide valuable information about the depth and composition of the subsurface. For example, materials with significant differences in their dielectric constants produce stronger reflections, which allows for clearer imaging of subsurface features. This makes GPR particularly effective in detecting buried objects, stratigraphic layers, or cavities. The effectiveness of GPR depends on factors such as the frequency of the

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[*] Corresponding author: djuan.rochman@gmail.com

electromagnetic waves, the material properties of the subsurface, and the contrast in dielectric constants. Lower frequencies enable deeper penetration but at the cost of resolution, while higher frequencies offer better resolution but are limited in depth [3].

The advancement of geophysical tools has extended beyond ground-based technologies like GPR to include aerial innovations, such as drone-mounted airborne magnetic systems. These developments significantly enhance data acquisition capabilities, enabling more efficient and precise subsurface investigations over larger areas [4]. Recent advancements in GPR technology have enabled the development of drone-based GPR systems. These systems offer significant advantages in terms of mobility and accessibility, especially in difficult-to-reach terrain where traditional land-based GPR systems are less effective [5]. The application of drone-based GPR is increasingly attractive due to its potential to map subsurface features in areas that are difficult to access. Studies have demonstrated the feasibility of deploying GPR on drones to detect geological features, such as subsurface layers and cavities, with minimal physical disturbance to the surface [6]. Despite these advantages, drone-based GPR systems also present challenges. These include positional accuracy, managing the antenna's distance from the surface (air gap), noise reduction generated by UAV platforms, ensuring accurate tracking during data acquisition, and signal attenuation at higher altitudes [7]. Furthermore, the frequency and design of the antennas significantly influence penetration depth and data quality, requiring careful consideration for specific applications.

Previous studies have demonstrated the complementary strengths and weaknesses of both ground-based and drone-based GPR technologies. In archaeological surveys, combining the two methods enhances the efficiency of subsurface mapping, particularly in challenging terrains such as clayey soils. While drone-based GPR provides better mobility and access to hard-to-reach areas, ground-based GPR offers more precise detection for deeper layers. This combination allows for comprehensive validation and data enhancement, overcoming the limitations inherent in each method [8]. Similarly, in detecting buried ice, drone-based GPR proved effective in complex and hazardous terrain where traditional methods would fail. However, despite its advantages in accessibility, the elevated antenna of drone-based systems can lead to signal degradation, making it challenging to measure the thickness of debris layers accurately [9].

Additionally, the use of GPR has proven valuable in analyzing the effects of traffic-induced soil compaction, as seen in studies of soil horizon delineation. GPR was effective in identifying compacted zones that may hinder plant root penetration and crop yields. These compacted layers, identified through changes in radargram amplitude, highlight variations in electromagnetic wave velocity caused by densification. However, the interpretation of radargrams can be complicated by material property variations and the potential for ringing effects, which may obscure the identification of compacted zones from other subsurface features [1]. Furthermore, combining GPR with geochronological techniques, such as optical dating, has significantly improved our understanding of dune migration. While drone-based GPR offers clearer imaging of dune movements, the resolution of shallow surface signals remains a challenge, requiring advanced data processing to improve reliability [10].

This study focuses on a comparative analysis between ground-based and drone-based GPR systems in the Bromo-Tengger Caldera Complex, East Java, Indonesia, an area characterized by diverse surface conditions that pose challenges for subsurface exploration. The comparison involves the analysis of radargrams before and after processing, an analysis based on processed data and field observations. Due to these aspects, this study aims to evaluate the performance and limitations of both methods in subsurface layer characterization. The study advances knowledge in optimizing GPR applications across various survey environments.

2 Material and Method

The study area is located at Sea Sand Caldera of Bromo Mountain, Probolinggo, East Java, Indonesia. The selection of the study area was carried out with consideration of the area which is quite challenging because most of the lithology is loose volcanic ash sand. The general flow of this study can be seen in Fig. 1. As shown in general flow processing chart, the data used in this study contains of drone-based and ground-based GPR data that will be compared to analyze each opportunity and challenges of both methods.

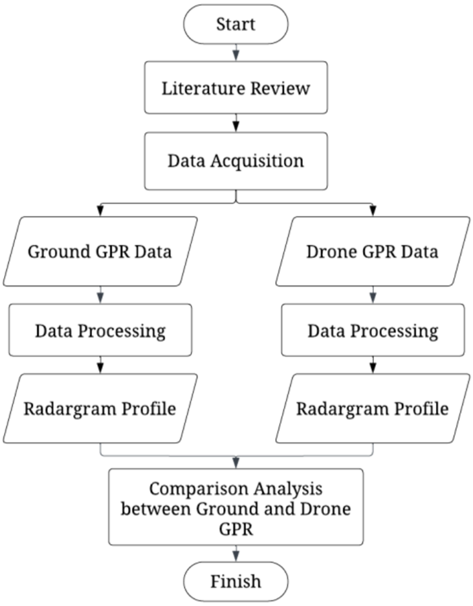


Fig. 1. Flowchart of the study

The data was taken using different equipment. The drone-based GPR data was taken using Radarteam Cobra Plug-In with antenna central frequency 150 MHz as a sensor with a DJI Matrice 600 as drone, while for the ground-based GPR data was taken using Oerad Scudo with central frequency 500 MHz. DJI Matrice is a series of DJI drone that are used for various applications, such as mapping and inspection. The drone-based equipment's flew around 2 meters above the surface during the data collection process. Though its different central frequency, the data still can be compared due to can still be compared because the similar

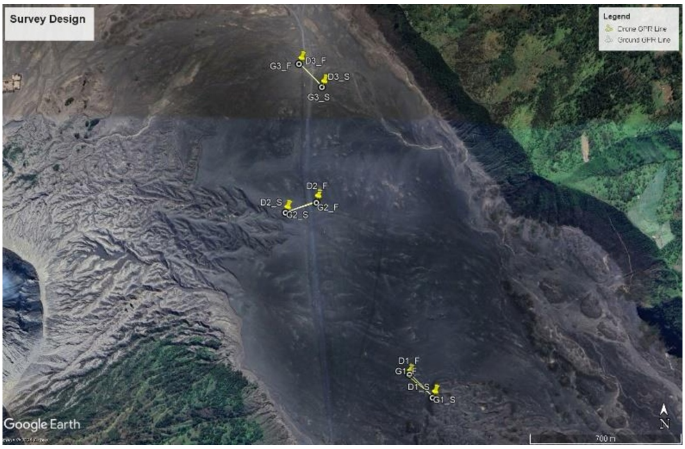
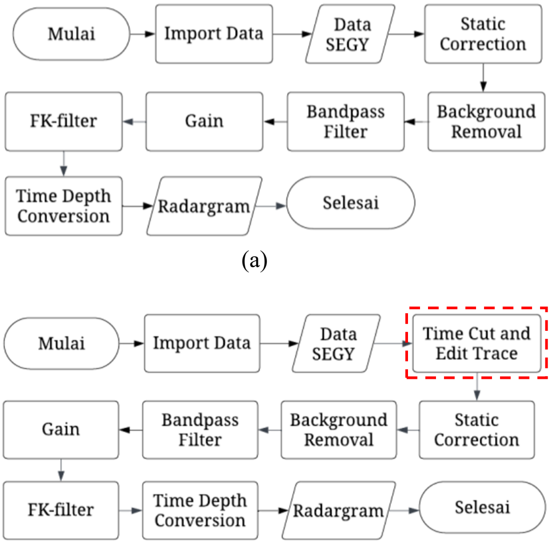


Fig. 2. GPR survey design

area of survey lines and almost overlaying. As shown in Fig. 2, there are three paths for each method with line G for ground-based GPR and line D for drone-based GPR. Line G1 and D1 located in the southernmost part of the area and are different from the others because they do not pass through the jeep road. Line G2 D2 and G3 D3 pass through the jeep road to be analyzed for estimating the depth of compact soil layer on jeep road at Sea Sand Caldera of Bromo Mountain.

The output of the data taken by drone-based and ground-based GPR equipment is in .sgy form that will be processed using geophysical software to get GPR radargram profile. The processing filters used for both methods are similar consisting of static correction, background removal, bandpass filter, gain, FK-filter, and time to depth conversion as shown in Fig. 3. However, there are two additional processes for the drone-based GPR data, namely time cut and edit trace. The time cut process is used for cut off the excessive radargrams based on time (y-axis), while the edit trace is used for traces recorded outside the survey design. The excessive traces outside the survey design resulted from the GPR tools that must go back to the drone pilot’s position or first survey point. It should be cut because it can bias the analysis and interpretation process.



(a)

(b)

Fig. 3. Processing flowchart (a) drone-based GPR (b) ground-based GPR

3 Result and Discussion

3.1 Opportunities

Collecting ground-based GPR data is relatively straightforward (Fig. 4b). Ground-based GPR is generally considered user-friendly and allowing individuals without specialized skills to collect data effectively. Many systems are designed with ease of use in mind, featuring automated data collection and user-friendly interfaces. This design enables professionals from diverse fields to operate the equipment effectively with minimal training. Basic tasks, such as concrete scanning, shallow subsurface mapping, or environmental surveys, typically require only introductory knowledge. However, interpreting more complex data, particularly for advanced geological applications, usually demands specialized skills. Meanwhile, on drone-based GPR, pilot doesn’t need to move as the drone-based GPR will move and measure remotely (Fig. 4a). Drone-based GPR systems are designed to operate autonomously, eliminating the need for the operator to move alongside the equipment. These systems allow the drone to conduct remote measurements and cover large areas efficiently. The pilot primarily controls the drone's flight path, while the GPR system gathers and processes data in real time. This approach not only enhances safety by keeping operators at a distance but also improves accessibility to areas that are challenging or hazardous for ground-based equipment.

(a)

(b)

Fig. 4. GPR acquisition process (a) drone-based (b) ground-based

In this study, background removal is applied to both types of GPR data. Background removal is used to remove or minimize signals from the surrounding environment that do not represent the subsurface features to analyze [11]. We can simplify that background removal is necessary to improve the quality of data interpretation by filtering out irrelevant or noise signals. The application results on both types of GPR show different results, related to the characteristics of the data. Background removal on the ground-based GPR data does not show significant changes, while the drone-based GPR data shows considerable changes (shown by the red box – Fig. 5 and 6). This suggests that drone-based GPR needs more extensive background removal compared to traditional ground-based GPR, primarily due to a combination of sensor dynamics, environmental factors, and data acquisition challenges specific to aerial platforms, that correlated to their noise data. Reasons that support this statement include:

- Drone-based GPR have significant variability in altitude and orientation during data collection. The distance between the radar and the ground or the subsurface target (air gap) can change frequently as the drone moves, affecting the strength and quality of the GPR signal. Meanwhile, ground-based GPR maintains a constant distance from the ground or the region being surveyed, so background signals tend to be more stable and predictable.
- Drone-based GPR systems are often used in open or large-area environments, where background noise from the atmosphere, moving objects, or reflective surfaces can be much more complex and dynamic compared to traditional ground-based setups. These external sources can interfere with the GPR signal, creating unwanted reflections and background noise. In contrast, ground-based GPR tends to focus on smaller, more controlled environments, where the radar waves interact mainly with the ground and subsurface features. This typically results in a cleaner signal with fewer non-ground reflections.
- Drone-based GPR systems often have smaller antennas, they may have lower signal strength and less directional focus, which can lead to more background noise, while ground-based GPR antennas are often larger, and their signals are usually stronger, so they can distinguish more clearly between background noise and relevant subsurface reflections. This is related to the results after background removal on the drone-based GPR radargram which is clearly visible or can be interpreted only in the depth range of 0-15 meters (Fig. 5).

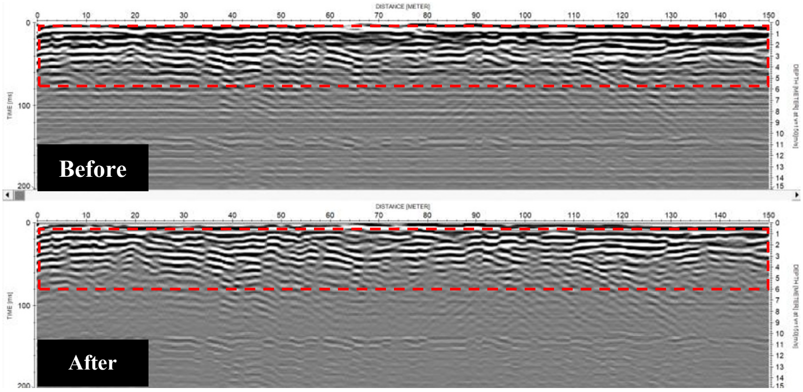


Fig. 5. Background removal process for D3 line drone-based GPR

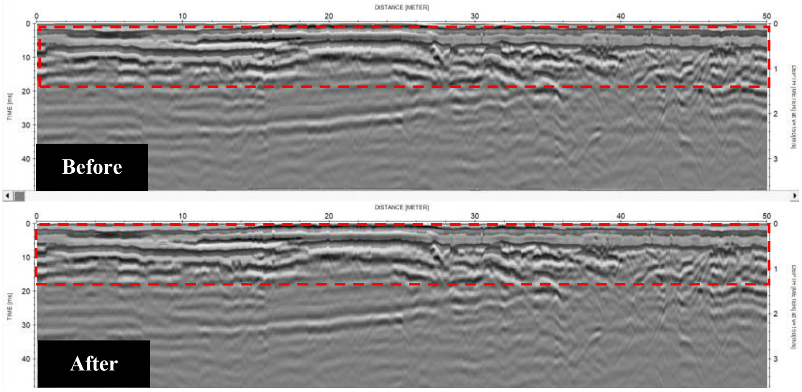


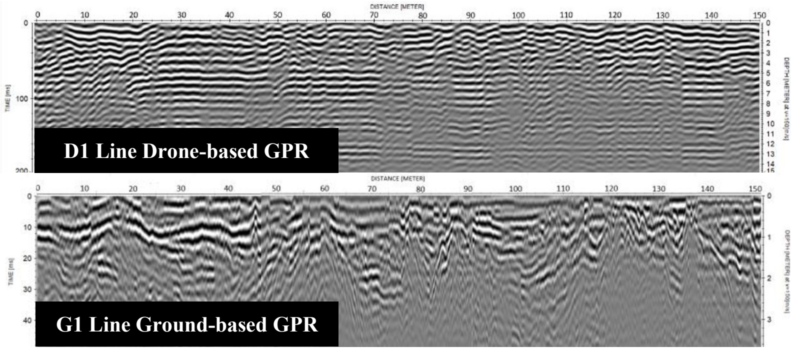
Fig. 6. Background removal process for D3 line ground-based GPR

The interpretation of GPR data is significantly influenced by topography, whether the survey is conducted with a drone-based GPR or a ground-based GPR. Line D3 and G3 show different radargram results (Fig. 6**).** Through the drone-based GPR radargram, the surface condition is not clearly depicted (looks linear laterally), while on the ground-based GPR the elevation changes (topography) are quite clear (shown by red colour box – Fig. 6**).** Other than topographic conditions associated with elevation changes, such as vegetation or rocks, the drone-based GPR showed minimum interference, but created gaps in the radargram, while on ground-based GPR, physical obstructions may cause signal interference (shown by the reflector pattern).

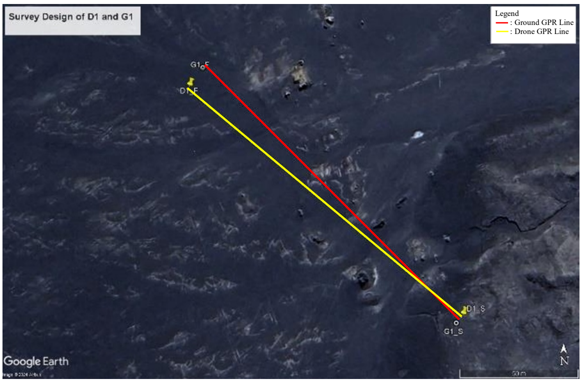
3.2 Challenges

Both drone-based and ground-based GPR data acquisition methods have their unique advantages and limitations. A common challenge in GPR data processing is static correction. Static correction aims to mitigate distortions in the data caused by variations in topography and the velocity of radar waves propagating through heterogeneous media. Drone-based and ground-based GPR data exhibit different characteristics, leading to varying challenges in the static correction process.

Fig. 7 presents the processing results for line D1 (drone-based) and G1 (ground-based), both are not directly aligned with jeep road. One of the most noticeable differences is the level of noise. Ground-based GPR data (G1) generally exhibit higher noise levels compared to drone-based data (D1). This can be attributed to various factors, such as the influence of vegetation, rocks, or metals in the survey area. High noise levels can obscure subsurface features of interest, such as compact soil layers.



(a)



(b)

Fig. 7. (a) Processing result for D1 and G1 line, (b) Survey design of D1 and G1 line

Fig. 8 and 9 present the processing results for G2 and D2 line after static correction. These figures show that after static correction, the data quality improves, with reduced noise and clearer reflectors. However, there are still differences in the level of detail of the reflectors between drone-based and ground-based data. Drone-based GPR data generally have higher resolution and can detect finer subsurface features compared to ground-based data. Fig. 8 shows the processing results after applying a static correction to ground-based GPR data. It can be observed that after correction, the noise in the data is significantly reduced, and reflectors become more distinct. However, some noise remains, indicating that the static correction process for ground-based GPR data is more complex compared to drone-based data.

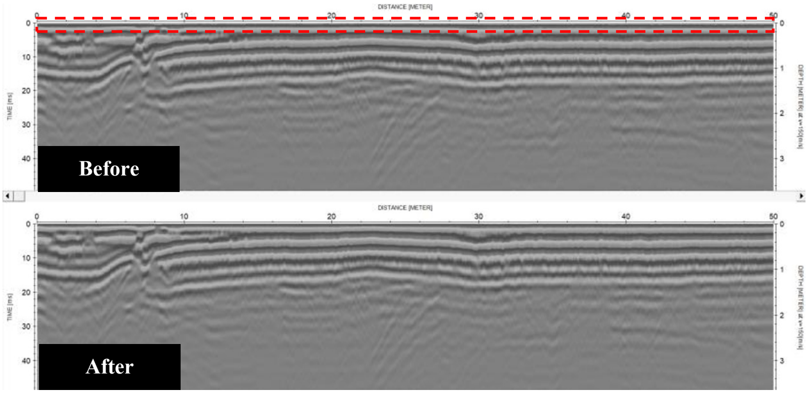


Fig. 8. G2 line ground-based GPR static correction processing

The depth of static correction is another challenge specific to drone-based GPR data. Since drones fly at higher altitudes, the topographic variations that need to be accounted for in static correction are also larger. Consequently, the depth of correction required for drone-based GPR data is generally greater than that for ground-based data. In conclusion, both drone-based and ground-based GPR data require static correction to produce accurate subsurface images. However, each data type presents unique challenges and characteristics in the static correction process. A thorough understanding of these characteristics and the selection of appropriate correction methods are crucial for obtaining reliable interpretations.

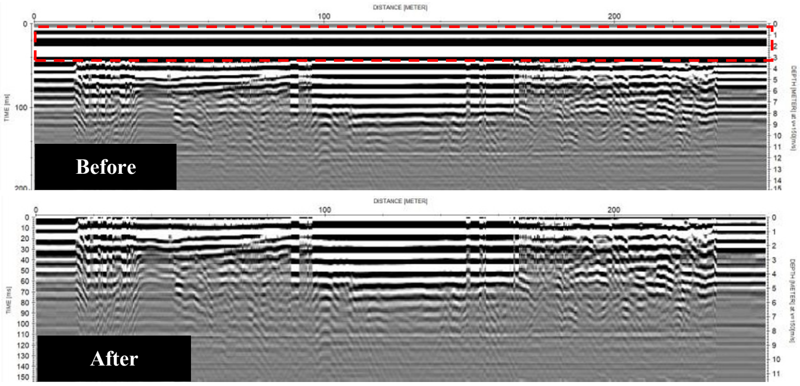
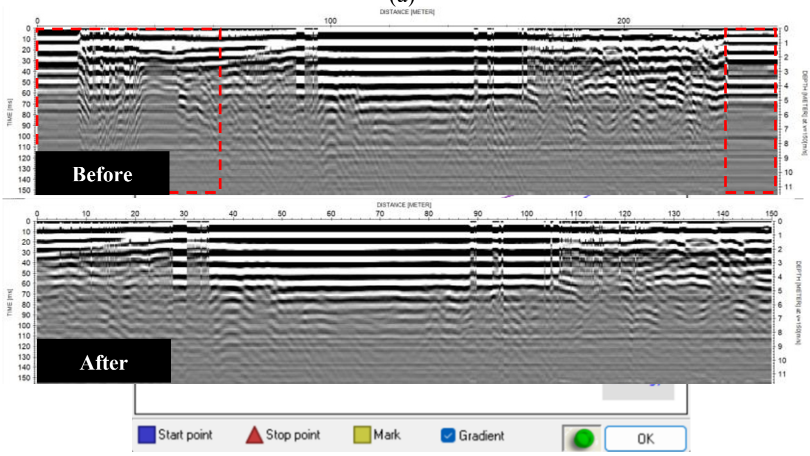


Fig. 9. D2 line drone-based GPR static correction processing

Another challenges we faced is drone-based GPR positioning, such as correlating drone-based GPR and ground-based GPR data, primarily lies in the differences of line length between the two. The difference in survey speed and flight path design means the drone may cover different lengths of terrain over the same period compared to the ground-based GPR [12]. As a result, data collected from each system may need to be resampled to match the line lengths or align the two datasets properly. In this study, we manually adjusted the line length of the GPR drone, considering the acquisition line plot, and then truncated the drone-based GPR line (remove traces processing) to match its line length with the ground GPR (Fig. 10).

(a)



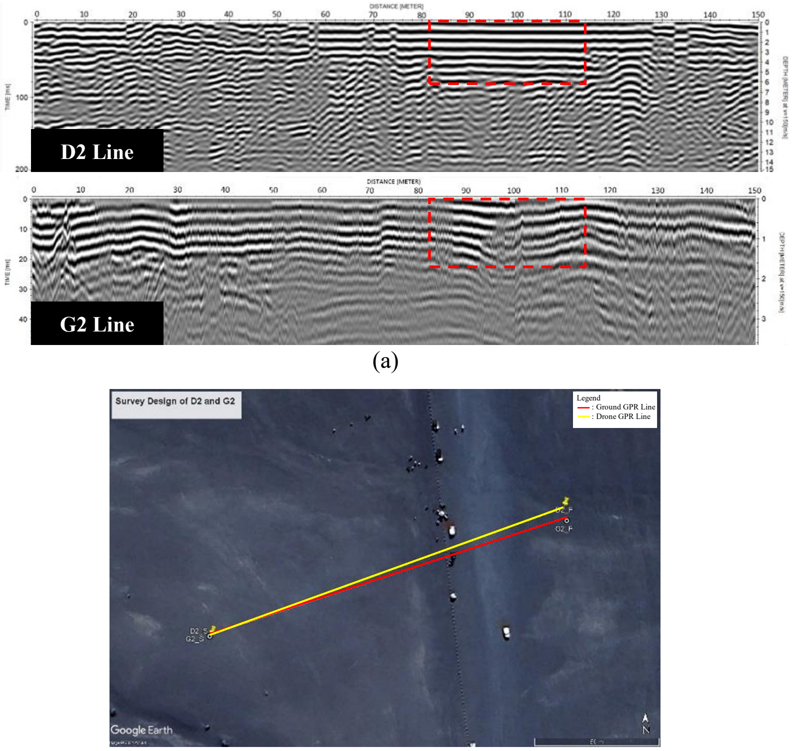
(b)

Fig. 10. (a) D2 line trace (b) D2 line droned-based GPR remove traces processing

3.3 Applications

In this study, the GPR was employed as the primary tool to estimate the depth of compact soil layers along the jeep road in Mount Bromo. The primary objective of this GPR application was to acquire accurate data regarding subsurface conditions, specifically concerning the presence of compact soil layers capable of supporting road construction. Strong reflectors indicate significant changes in the subsurface material, such as differences in soil type, water content, or the presence of buried objects. Based on the analysis and the field condition, the presence of strong reflectors on the radargram indicates the existence of compact soil layers. The validation of the Jeep Road position on the radargram further corroborates this. However, it is essential to note that not all strong reflectors necessarily correspond to compact soil layers. Other factors such as changes in soil type, water content, or the presence of subsurface objects can also cause the appearance of strong reflectors on the radargram.

Analysis of the GPR data revealed a significant difference in the estimated depths of compact soil layers obtained from drone-based GPR and ground-based GPR. Drone-based GPR could detect compact soil layers to approximately 5 meters, whereas ground-based GPR was limited to around 1 meter. This discrepancy is likely attributed to differences in antenna frequency, the distance between the antenna and the ground surface, and varying field conditions. To ensure more accurate and reliable results, field verification through direct observation and excavation is necessary. Fig. 11 and 12 present a comparison between drone-based GPR (D2 and D3 Line) and ground-based GPR (G2 and G3 Line) radargrams, compared with corresponding field conditions. The dashed red lines on the radargrams highlight areas of interest, particularly the presence of strong reflectors.

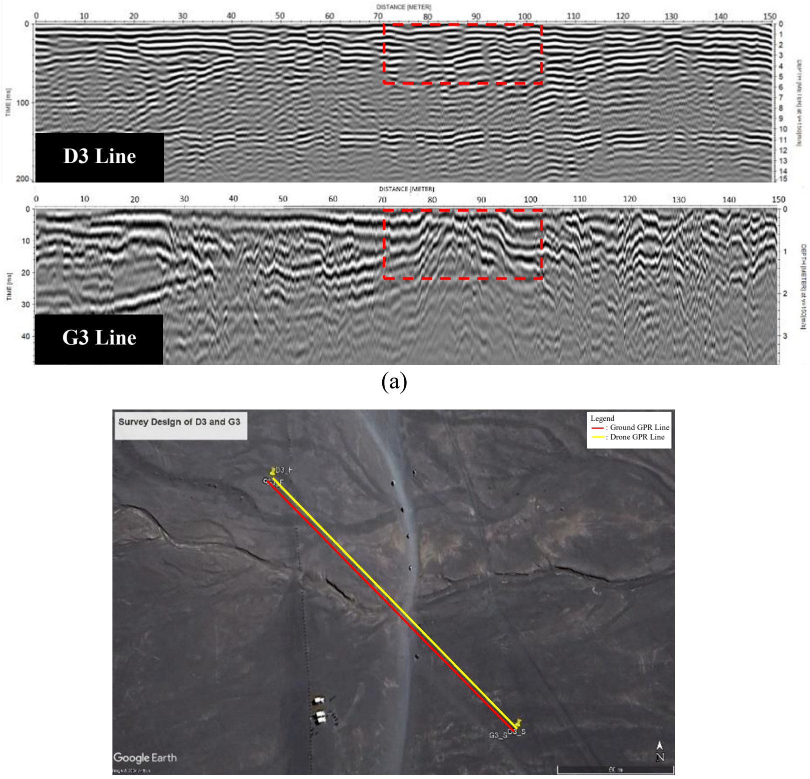


(a)

(b)

Fig. 11. (a) D2 and G2 line GPR radargram (b) Survey design of D2 and G2 line

The analysis of the radargrams reveals several key findings. Firstly, the strong reflectors observed in both Fig. 11 and 12 are directly aligned with the jeep road, indicating significant changes in the subsurface material at the road's location. Secondly, the areas surrounding the road show distinct reflector characteristics, suggesting substantial variations in the physical properties of the soil or material between the road and its surroundings. Regarding the causes of these strong reflectors, several factors are likely at play. Differences in the physical properties of the road material, compared to the surrounding soil can lead to strong reflections. Furthermore, variations in water content within the soil can affect the reflection strength, with drier materials generally producing stronger reflections.



(a)

(b)

Fig. 12. (a) D3 and G3 Line GPR radargram (b) Survey design of D3 and G3 line

Lastly, comparing the D2 - D3 Line and the G2 - G3 Line highlights potential differences in resolution and penetration depth. The D2 - D3 Line, likely a drone-based survey, appears to have a higher resolution, enabling the detection of finer details in the subsurface. Conversely, the G2 - G3 Line, potentially a ground-based survey, may have a deeper penetration depth but lower resolution.

4 Conclusion

The comparison between drone-based and ground-based GPR reveals distinct challenges, adjustments, and opportunities for each method. Drone-based GPR requires adjustments for positioning due to elevation changes, flight noise, and stability issues, but it performs well in rough terrain. On the other hand, ground-based GPR is easier to process but produces less distinct results because of surface conditions. In estimating the depth of compact soil layers along the jeep road in Mount Bromo, drone-based GPR offers higher resolution, capturing finer subsurface details, while ground-based GPR may achieve deeper penetration but with lower resolution. Both methods face challenges in this study area, such as interpreting deeper features in compacted soil, which reflects strongly at the surface and weakens subsurface signals.

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