Experimental Detection and Characterization of Void using Time-Domain Reflection Wave

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Abstract. Recent technologies in engineering views have brought the significant improvement in terms of performance and precision. One of those improvements is in geophysics studies for underground detection. Reflection method has been demonstrated to able to detect and locate subsurface anomalies in previous studies, including voids. Conventional method merely involves field testing only for limited areas. This may lead to undiscovered of the void position. Problems arose when the voids were not recognised in early stage and thus, causing hazards, costs increment, and can lead to serious accidents and structural damages. Therefore, to achieve better certainty of the site investigation, a dynamic approach is needed to be implemented. To estimate and characterize the anomalies signal in a better way, an attempt has been made to model air-filled void as experimental testing at site. Robust detection and characterization of voids through inexpensive cost using reflection method are proposed to improve the detectability and characterization of the void. The result shows 2-Dimensional and 3-Dimensional analyses of void based on reflection data with P-waves velocity at 454.54 m/s.

1. Introduction

Underground void can delay construction operations and endanger civil structures foundations due to ground subsidence. The voids come in naturally formed of cavities and sinkholes in karstic limestone terrain, meanwhile man-made void due to the historical underground structures, abandoned wells, mine shafts, ground settlement, and underground scouring. Problems arose when the voids were not recognised in early stage and thus causing hazards and costs increment. The surface depression is an earlier stage of indicator of void underneath. Void beneath a road or underneath an existing property can lead to serious accidents and structural damages. The identification of hidden voids at the earliest possible stage is very important to avoid any casualties in engineering safety. Subsurface voids present a unique anomaly to be detected due to the stark difference in physical properties between the surrounding geologic medium and the void itself, especially when air-filled [1]. The contrasts in seismic velocity and density between void and medium interface are two important principles to be chosen as a suitable method for void detection.
Geotechnical site characterization techniques are used to identify underground features such as penetration testing and soil trenching [2]. These methods involve direct observation of underground materials. When drilling conducted over the void, the sudden drop of an auger and the loss of drilling fluid are expected. Therefore, the conventional methods are frequently failed to observe the void and misrepresent the subsurface geology. A rapid, inexpensive, and reliable void detection technique could have an enormous economic potential through improved performance in environmental and engineering applications. Of the range of in situ tests, penetration testing and geophysical testing are used for void detection. Cost and time constraint factors are the main reasons to explain the difficulty in investigating the subsurface using conventional methods [3]. Hence, conventional method only involves field testing only for limited areas. This may lead to undiscovered of the void position. Therefore, to achieve better certainty of the site investigation, a dynamic approach is needed to be implemented.

For the past few years, several studies have been undertaken to test the applicability of seismic methods for detecting subsurface voids based on P-wave reflection [4][5][6][7][8][9][10]. The seismic-reflection technique is convincing to detect the shallow and deep subsurface void. Moreover, this approach provides a cost effective way to assess site conditions while overcoming a key limitation of traditional investigative approaches [3]. This method can provide better traces resolution and thus, can define the geology of subsurface better with better thinner subsurface layers identification across a site [11]. The main advantages of these approaches are they are non-destructive, non-invasive, and require quick assessment. Such a method provides information with greater resolution in the lateral dimension and can therefore be used to obtain a qualitative assessment of the variability of geotechnical properties such as velocity and density [12].

The development of specialized seismic-reflection equipment to deploy the compressional waves into the ground using impact hammer is discussed in this study. It is worth noting compressional wave is a part of seismic wave, which is also called as P waves. Compressional waves are reflected when meet different densities of anomaly of soil layers or voids. In this paper, an experimental field study is performed to investigate the characteristic of reflected wave in the presence of a void in soil. An application based on air-filled void was constructed with objectives of detection and characterization. The round shape of air-filled void ball at size of 0.16 m was buried at 0.3 m depth. An implementation of new method to gather the reflection data was applied.

2. Methodology
This study is to counter-measure reflected data gathered from field experimental testing. Data were collected purposely for detection and characterization of void. In this study, a computer program for time-domain reflection analysis is used to generate time histories for each shot at different receiver. The next step is involving transformation of time histories into 2D and 3D stack overtone images. The final overtone images give a better analysis to characterize the presence of void.

2.1 Reflection Concept
Reflection signals were detected by the sensors that were place on the ground. The reflection coefficient is the amount of energy reflected at a boundary. The direction of signals propagation (e.g. reflection and refraction) affected by propagation medium such as in the air, soil, or rock [13]. Reflection method is much responsive to subtle changes and is capable of 2D or 3D imaging for finer details. However, data acquisition and processing are significantly more complex. Reflection coefficient is directly proportional to the difference in acoustic impedance [14] as in equation 2.1:

\[ Z = \rho \cdot V \]  \hspace{1cm} (2.1)

Where \( \rho \) is defined as the density and \( V \) is the P-velocity or the S-velocity.
The reflection coefficient of normal incidence, \( R \) is defined by the following equation from Dvorkin et al., [14]

\[
R = \frac{(Z_2 - Z_1)}{(Z_2 + Z_1)} = \frac{(\rho_2 V_2 - \rho_1 V_1)}{(\rho_2 V_2 + \rho_1 V_1)} \tag{2.2}
\]

Where \( Z_1 \) is the acoustic impedance in layer number 1, and \( Z_2 \) is the acoustic impedance in layer 2. The reflection coefficient can both be negative and positive. If the coefficient is positive, it is an indication of \( Z_1 < Z_2 \), and opposite, if \( Z_1 > Z_2 \) the coefficient would be negative. A positive coefficient means that most of the energies are reflected, and a negative coefficient implies that most of the energies are transmitted into layer 2. This equation can be applied both for the S-velocities and the P-velocities. The acoustic impedance is used to determine the amount of energy that is transmitted between the layers.

### 2.2 Equipment Setup

The equipment used in this study are piezoelectric as s trigger source and seismic receiver and hammer as a seismic source and data logger for data acquisition. Figure 1 illustrates a hammer with constant energy of 50 N force and located close to the trigger source sensor namely (R0). Receiver (R1) was placed on the surface of soil. The computer was connected to the Data Acquisition System (DAQ). Analogue-to-digital converter module sampled the reflected wave internally. Collected data were stored, and were processed after the completion of data collection. Receiver, R0 acted as a transmitted signal and R1 as a receiver signal similarly with the concept of ground penetrating radar (GPR). The time-domain reflection wave based on first arrival between the signals was evaluated from the output.

![Figure 1. Illustration of equipment setup.](image-url)
2.3 Testing Procedure

The ball at diameter of 0.16 m was buried at 0.3 m depth as shown in Figure 2. The centre of ball position was at R6. The spacing between R0 and R1 was 0.1 m. Each movement of source receiver (R0) was set at 0.1 m to control the constraint such as the upper limit of the bandwidth and also the useful distance between source and the receivers [15]. There were 10 shot points which gave 0.9 m length of testing spread line. The impact source was moved as shown in Figure 3 based on the sequence of data collection to detect the anomaly or void subsurface. Reflection data were processed using a scheme or sequence of data collection based on Figure 3. Like other reflection methods, such as GPR, it can read depth and area of void by just viewing GPR profile data but difficult to identify void size from the data [16]. Therefore, this paper has proposed straight-forward method based on sequence of data collection that can be generated by reflection method to simplify the problem of size estimation. Therefore, characterizing and detectability using 3D and 2D analysis will be discussed further in result and discussion.

![Figure 2. Void at real field condition.](image)

![Figure 3. Scheme of data collection.](image)
3. Result and Discussion

The reflection waves were extracted by using MATLAB and Origin Pro. Figure 4 shows the example of extracted reflections without void as a control while Figure 5 is with void. Signal amplification indicates that the time-domain reflection could detect the void along the subsurface. Therefore, this method has proven as the reflection signals affected by propagation medium through voids.

![Figure 4](image1.png) **Figure 4.** Reflection Time-domain data without void.

![Figure 5](image2.png) **Figure 5.** Reflection Time-domain data with void.

The figure shows the travel time of wave from source and reflection received by R1 to R10. For control test, the wave shows the amplitude without disturbance of wave propagation. Meanwhile for void, amplitude disturbance occurred at point R6 and R7 at 2.728 ms. It shows that the wave propagated through the void and the wave energy concentrated at the void and then, the wave reflected to the surface detected by the receiver at position R6 and R7. The analogy of wave reflection is shown at Figure 5.

According to ISA (International Standard Atmosphere), the density of air at temperature 35 °C is 1.1455 kg/m3 while the velocity, V is 351.88 ms-1 as shown at Table 1. Meanwhile, soil density properties are determined using core cutter testing based on BS 1377-1990 in-situ density test. Therefore, the bulk density of the soil is 1780 kg/m3. Furthermore, soil velocity is determined using direct wave method which is the velocity, Vp 454.54 ms-1. Even though the result has been determined using various methods, it is clearly an advantage for this proposed method which is to verify the properties of air and soil.
Table 1. Properties of Air and Soil.

| Properties                  | Soil, $Z_1$ | Air, $Z_2$ |
|-----------------------------|-------------|------------|
| Density, $\rho$ (kg/m$^3$)  | 1780        | 1.1455     |
| Velocity, $V$ (m/s)         | 454.54      | 351.88     |
| Seismic Impedance, $Z$ (kg/s.m$^2$) | 809.08 x 10$^3$ | 403.07 |

Based on Table 1, $Z_1$ is the acoustic impedance in soil layer, and $Z_2$ is the acoustic impedance of void. The reflection coefficient, $R$ is negative, it is an indication of $Z_1>Z_2$. When the acoustic impedance of the first medium, $Z_1$ is greater than the second medium, $Z_2$, $R$ will be negative, and the reflection will return to the surface with its polarity reversed [17]. A negative reflectivity implies that most of the energies are reflected. Thus, in this study the negative reflectivity causes the seismic reflections whereas most of the energies are concentrated at void before reflected to the surface. On the other hand, P-wave energy is mainly concentrated and makes strong reflection or scattering energy when meeting the air-filled void because of the great difference in acoustic impedance and such energy will spread to the surface [18].

![Figure 6. Analogy of reflection wave.](image)

Computer analysis was performed to analyse the amplitude wave pattern change with distance. Figure 7 shows 2D contour of amplitude along the horizontal shot position, R1 till R10. In this study, reflection technique which has 10 steps of gathering shot was proposed. From the figure, yellow area indicates high amplitude of energy when the wave propagated and reflected to the surface. Meanwhile, the blue area indicates negative amplitude where the energy is concentrated in the void before reflected to the surface. The 2D contour of amplitude was aligned using first arrival as a reference. Thus, the voids length was directly determined by scheming the 2D contour of amplitude.
Figure 7. 2-Dimensional contour image.

From Figure 6, the diameter of the void shown is 0.16 m, which was successfully estimated as 0.13 m by using this 2-Dimensional contour of amplitude method. The void diameter has been accurately estimated. The error calculation is shown as below:

\[
\text{\% Error} = \frac{\text{Experimental} - \text{Actual}}{\text{Actual}} \times 100 = 18.75
\]

Figure 8 is an example of wave propagation in 3-Dimensional view from the experimental data. From 3-Dimensional of void reflection image as illustrated as Figure 8, positive amplitude, negative amplitude, and direct wave, are included respectively. As illustrated in Figure 5, the time arrival of reflection wave is at 2.727 ms. Meanwhile, the time arrival of direct wave is at 0.22 ms. In this case, direct wave acted as a reference point before meets reflection wave. Hence, using direct wave as a reference point shows significant value to construct the 3-Dimensional image of reflection wave for verification. As illustrated in Figure 8, the disturbance of high amplitude shows the propagation of wave was propagated through void and recorded by receiver R6 and R7. Low amplitude of signals indicated that there is no anomalies or disturbance occurred at the experimental area of measurement. Therefore, by plotting in 3-Dimensional as additional measurement, hence the concentrated and reflected energies at receiver R6 and R7 are verified.
Figure 8. 3-Dimensional image of void reflection.

4. Conclusion
In conclusion, the great difference between acoustic impedance and two media (soil and void) shows a great potential to characterize the size of void. A great deal between the acoustic impedance and the two media would affect the reflection coefficient, R and intuitively shows the energy of wave propagation is reflected before it reaches surface. 2-Dimensional contour plot of amplitude analysis is convincing to estimate void diameter. By plotting in 3-Dimensional as additional measurement, hence the concentrated and reflected energy at receiver R6 and R7 is verified. On the other hand, the energy pattern of wave propagation can be visibly seen via 3-Dimensional plot at receiver R6 and R7. The diameter of void shows the percentage of error is 18.75%. Therefore, the diameter of void can be estimated more accurately, by varying the size of void and depth using this approach for further research.

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