Determination of Weathered Layer Thickness Around the Landslide Zone using the Seismic Refraction Method

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Abstract. The thickness of the weathered layer in the landslide zone can be determined by the seismic refraction method. This study aims to determine the thickness of the weathered layer based on the primary wave velocity (P-wave or \( V_p \)). Data acquisition is taken around the landslide zone, namely above the landslide, parallel to the landslide, and perpendicular to the landslide. The data were collected using a digital seismograph 16S24. Furthermore, the data obtained in the field is processed to obtain a 2-D model. The results showed that the thickness of the weathered layer above the landslide was 2.15 m - 4.59 m with a \( V_p \) value equal to 185 m / s. For the thickness of the weathered layer parallel to landslides is 0.80 m - 4.11 m with a \( V_p \) value equal to 300 m / s and the thickness of the weathered layer perpendicular to landslides is 0.01 m - 2.35 m with a \( V_p \) value equal to 300 m / s. Meanwhile, the bedrock layer under the weathered layer has \( V_p \) of between 517 m / s to 1065 m / s in the form of sub-consolidated clay to very dense clay lithology.

Keywords: weathered layers, landslide, seismic refraction, and bedrock

1. Introduction

1.1 Background

A landslide potential zone is an area that is prone to landslides with terrain and geological conditions that are very sensitive to external disturbances, both due to natural factors and human activities as triggers of land movement, so the potential for landslides to occur. Landslides can occur when the driving force on the slope is greater than the restraining force. The restraining force is generally influenced by the strength of the rock or the density of the soil, while the driving force is influenced by the magnitude of the angle of the slope, water, load, and the density of the soil or rock [1]. Volcanic sedimentary rock and sedimentary rock of sand size and a mixture of gravel, sand and clay are generally less dense. These rocks will easily become ground when subjected to a weathering process, so they are prone to landslides on steep slopes [2]. Geological and hydrological conditions, topography, climate, and weather changes will also affect slope stability resulting in landslides [3]. According to Zhang et al. [4] and Nepop and Agatova [5],...
earthquakes and high rainfall are the main factors causing landslides. High rainfall in a place will affect
the rate of rock weathering, thereby increasing the potential for landslides.

To determine the landslide zone and its potential, it can be done by measuring the microtremor and slope data
[6], geoelectric methods of resistivity and seismic refraction [7,8], Multichannel Analysis of Surface Wave
(MASW) method [9], Horizontal to Vertical Spectral Ratio (HVSR) and Simple Additive Weighting (SAW)
methods [10] and others. This study aims to determine the thickness of the weathered layer around the landslide
zone in the area of Bengkulu - Kepahyang KM 50 main road. This area is an area prone to landslides because it is
close to the Sumatra fault in the Musi Segment which can cause ground vibrations during an earthquake [11,12].
This area also has high rainfall, 3000 - 3500 mm / year [13]. Rainfall more than 2500 mm / year will potentially
cause landslides [2].

1.2 Theory

In this study, the seismic refraction method approach was used with the time-term technique. The time-term
technique is a linear least-squares approach to determine the best arrangement of solutions per layer based on the
data. In the time-term technique, the time delay is calculated automatically through the least-squares linear
inversion technique [14]. The time-term technique only requires layer marking for every first break in the
traveltime data analysis. This method requires a minimum of two shot points that are put together in the traveltime
data analysis. The resulting inversion model is a simplification model of the subsurface layer. In the inversion
model, the refractor is drawn under the first geophone from the first shot point to the first geophone from the last
shot point which is a combination of the forward from the first shot point with the reverse from the last shot point.
For this reason, in order to obtain an image of the refractor just below the first geophone to the last geophone, the
positions of the first shot point and last shot point must be placed outside the geophone arrangement [15], so that
it can be modeled in 2-D.

A simple mathematical approach refers to Figure 1. "Slowness" $S$ is the opposite of velocity ($V$), namely [14],

$$S_1 = \frac{1}{V_1}.$$  \hspace{1cm} (1)

$$S_2 = \frac{1}{V_2}.$$ \hspace{1cm} (2)

From Snell's Law,

$$\sin (i_e) = \frac{S_2}{S_1}.$$ \hspace{1cm} (3)

![Figure 1. Wave propagation on the refractor parallel to the ground (modification from [14])](image)

The total travel time from source to receiver is,

$$t = 2S_1 \cos (i_e) z + xS_2,$$ \hspace{1cm} (4)

when defined,
\[ c = 2S_1 \cos(i_c), \]
then,
\[ t = 2cz + xS_2, \]
\( z \) and \( S_2 \) are unknown.

The assumptions used in Figure 1, the refractor is parallel to the ground. When extended to the general case on non-parallel curved surfaces, as shown in Figure 2, then the completion of more than two parameters namely \( z_1 \), \( z_2 \), and \( S_2 \). Based on Figure 2, then the total wave propagation time is,
\[ t = cz_1 + cz_2 + xS_2, \]
so it gets,
\[ t_j = \sum_{k=1}^{n} c_{jk}z_k + x_jS_2. \]

In the form of a matrix is as follows,
\[
\begin{bmatrix}
    c_{11} & c_{12} & c_{13} & \ldots & c_{1n} & x_1 \\
    c_{21} & c_{22} & c_{23} & \ldots & c_{2n} & x_2 \\
    c_{31} & c_{32} & c_{33} & \ldots & c_{3n} & x_3 \\
    \vdots & \vdots & \vdots & \ddots & \vdots & \vdots \\
    c_{m1} & c_{m2} & c_{m3} & \ldots & c_{mn} & x_m \\
\end{bmatrix}
\begin{bmatrix}
    z_1 \\
    z_2 \\
    z_3 \\
    \vdots \\
    z_n \\
\end{bmatrix}
= 
\begin{bmatrix}
    t_1 \\
    t_2 \\
    t_3 \\
    \vdots \\
    t_m \\
\end{bmatrix},
\]
where \( m \) is the number of propagation times and \( n \) is the number of receivers (depth to be calculated), so that the matrix solution for \( z_1, \ldots, z_n \), and \( S_2 \).

*Figure 2. Wave propagation on non-parallel curved surfaces (modification from [14])*

2. Method
Data were collected in the area around the landslide of Bengkulu - Kepahyang KM 50 main road, Bengkulu Province, Indonesia (Figure 3) with three survey lines. The first line is perpendicular to the landslide (N 30° E) who was above the landslide, the second and third lines are in the parallel (N 100° E) and perpendicular (N 30° E) on the landslide. Measurements in the field use a 24 geophone channel seismic refraction device mounted in a straight line on the ground (Figure 4). The distance between geophones and offsets is adjusted to local field.
conditions, the sampling rate is 125 μs and the recording time is 512 ms. Recording time is the length of time for recording surface waves generated by the source then recorded using a geophone and forwarded to a digital seismograph 16S24-P (s.n.: 121217044). The sampling rate is the recording loop of the total time. The distance between geophones on line 1 is 2 m with the offset distance is 6 m outside the stretch, the distance between geophones on line 2 is 1.5 m with the offset distance is 4.5 m outside the stretch, while the distance between geophones on line 3 is 1 m with an offset distance is 3 m outside the stretch (forward and reverse).

**Figure 3.** Study area around the landslide of Bengkulu-Kepahyang KM 50 main road, Bengkulu Province, Indonesia (modification from [16])

The output of the seismic refraction method is the value of the $P$-wave velocity ($V_p$, Profile) at each sediment layer along the measurement stretch. The recording result of this seismic refraction method is in the form of shotgather data which is then transferred for further processing. Data from this field does not contain field parameters, such as spacing between geophones, source offsets, path lengths, and others. For this reason, it is necessary to first define the geometry of the field.

The data obtained in the field are then processed by software SeisImager / 2-D ver. 3.3 which consists of the Pickwin and Plotrefa programs. This software is an inversion program package to determine the thickness of the weathered layer from the ground surface to a certain depth. The field data was then inputted into the Pickwin...
Program. The next step is to enter the shot gather data geometry parameters according to the conditions at the time of field data acquisition. Furthermore, picking first break shotgather data is determined for each shot, both forward and reverse, which are ready to be inverted. The shotgather data that has been picked is then carried out to determine the arrival layer and the layer/slope boundaries in the Plotrefa Program by first entering the elevation data. The next step is to do the inversion process. The inversion process is carried out automatically until a minimum error is obtained. The result of the inversion process is an initial $V_p$ velocity model. Furthermore, ray tracing is carried out until the observation vs theoretical results are obtained. After that, the final $V_p$ model can be obtained in the form of a 2-D model which is then ready to be analyzed [14]. The flow chart is briefly shown in Figure 5.

**Figure 5.** The study flowchart uses the seismic refraction method with the time-term technique (modification from [14])
3. Result and Discussion

To obtain very good data, field data validation was carried out by determining the boundaries of the first and second layers based on the smallest root mean square error (RMSE) which showed the suitability of the field data and the model created. This study was conducted on an oblique layer, so it is necessary to use an alternating method of forward shot and reverse shot. This method is used to determine the layer thickness with unknown interface conditions [18]. The following is a seismic cross section of the shotgather data of the seismic refraction method with the time term technique that has included the field geometry factors (forward shot and reverse shot) as shown in Figure 6.

**Figure 6.** Shotgather data and picking results for forward and reverse shot on lines 1 (a) and (b) with a distance between geophones of 2 m and an offset distance of 6 m, lines 2 (c) and (d) with a distance between geophones of 1.5 m and an offset distance of 4.5 m, and lines 3 (e) and (f) with a distance between geophones of 1 m and an offset distance of 3 m.

In each seismic cross section, both forward shot and reverse shot, the first break is then determined, in order to obtain the travel time curve of the distance function of each geophone as shown in Figure 7. Determination of the first layer and the second layer in the travel time curve of the distance function will determine the RMSE value.
The smallest RMSE value was chosen to produce a 2-D model of subsurface structure based on the $P$-wave velocity ($V_p$). Figure 7 is the result of data processing with the selected RMSE value. However, based on the results of this processing it is difficult to get a small error. This can be caused by various factors, one of which is noise, where the data collection is carried out near a highway, making it a bit difficult to get completely noise-free data. Another possibility is that only two shot points are taken, namely outside the geophone and the last one is a very steep topography. From the 2-D model of the subsurface structure based on $V_p$, it can also be seen that the thickness of the first layer, which is the weathered layer in each geophone, can be seen as shown in Figure 8, Figure 9, and Figure 10.

![Figure 7](image-url)  
**Figure 7.** Travel time vs distance curve with its RMSE on line 1, line 2, and line 3
On line 1 above perpendicular to the landslide (Figure 8), the velocity of the $P$-wave is obtained ($V_p$) in the first layer it is $185 \text{ m/s} \approx 200 \text{ m/s}$ and in the second layer it is $1065 \text{ m/s}$ with a thickness of the first layer between 2.15 m to 4.59 m or the average thickness is 3.42 m. The rock type in this weathered layer is thought to be unsaturated sand. According to Burger [19], $V_p$ in the range of values for unsaturated sand is between 200 - 1000 m/s, weathered layers are between 300 - 900 m/s, and clays are around 1100 - 2500 m/s. The rock underneath is bedrock with a $V_p$ in this layer of 1,065 m/s which is thought to be very dense clay lithology. According to Capizzi and Martorana [20], $V_p$ values above 1000 m/s are interpreted as very dense clays. The correlation between the values of $P$-wave velocity ($V_p$) and the thickness of the weathered layer at the perpendicular location above the landslide (line 1) obtained using the seismic refraction method with the time-term technique is shown in Table 1.

For line 2 which is parallel on the landslide (Figure 9), the velocity of the $P$-wave is obtained ($V_p$) in the first layer it is $300 \text{ m/s}$ and in the second layer is $946 \text{ m/s}$ with a thickness of the first layer between 0.80 m to 4.11 m, while for line 3 which is perpendicular on the landslide (Figure 10) obtained $P$-wave velocity ($V_p$) in the first layer is $300 \text{ m/s}$ and in the second layer is $517 \text{ m/s}$ with a thickness between 0.01 m to 2.35 m. For line 2, which is parallel to the landslide, it has a very steep slope angle of 43°. The slope height from the ground is about 26 m. The average thickness of the weathered layer on this line is 2.24 m. The $P$-wave velocity ($V_p$) in this weathered layer is $300 \text{ m/s}$ which is assumed to be unsaturated sand, while the bedrock layer underneath is a sub-consolidated clay lithology with $V_p$ is $946 \text{ m/s}$. According to Capizzi and Martorana [20], sub-consolidated clay rock types have a $V_p$ value range between 500 m/s - 1000 m/s. This layer between sand and clay is a slip plane which can weaken the cohesion of the rock and increase the driving force as well as reduce the restraining force when water enters the boundary of the slip or due to other factors such as earthquake vibrations.
Figure 9. 2-D raytracing model on line 2

Figure 10. 2-D raytracing model on line 3
Table 1. The correlation between the values of the $V_p$ and the thickness of the weathered layer at line 1

| Layer   | Thickness (m) | $V_p$ (m / s) | Explanation               |
|---------|---------------|---------------|---------------------------|
| First   | 2.15 – 4.59   | 185           | Weathered layer           |
| Second  |               | 1065          | Very dense clay (bedrock) |

On line 3, which is perpendicular on the landslide, average thickness of the weathered layer is 0.98 m. The $P$-wave velocity ($V_p$) at this line is 300 m / s which is assumed to be unsaturated sand. The bedrock underneath is a sub-consolidated clay lithology with a $V_p$ of 517 m / s. The correlation between the values of the $P$-wave velocity ($V_p$) and the thickness of the weathered layer at line 2 and line 3 is shown in Table 2 and Table 3.

Table 2. The correlation between the values of the $V_p$ and the thickness of the weathered layer at line 2

| Layer   | Thickness (m) | $V_p$ (m / s) | Explanation               |
|---------|---------------|---------------|---------------------------|
| First   | 0.80 – 4.11   | 300           | Weathered layer           |
| Second  |               | 946           | Sub-consolidated clay (bedrock) |

Table 3. The correlation between the values of $V_p$ and the thickness of the weathered layer at line 3

| Layer   | Thickness (m) | $V_p$ (m / s) | Explanation               |
|---------|---------------|---------------|---------------------------|
| First   | 0.01 – 2.35   | 300           | Weathered layer           |
| Second  |               | 517           | Sub-consolidated clay (bedrock) |

4. Conclusion
In general, the thickness of the weathered layer based on the value of seismic wave velocity ($P$-wave) is between 0.01 m - 4.59 m with $V_p$ between 185 m / s - 300 m / s, while the $V_p$ in the bedrock layer is between 517 m / s - 1065 m / s which is a lithology of sub-consolidated clay to very dense clay. In this study, the cause of noise can be caused by data collection on the side of the highway. To minimize noise, the data collection needs to be done during quiet times, for example at night. The magnitude of the error can be caused by the steep topography of the study area. To minimize this error, it is necessary to add shot points within the geophone stretch.

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