Determination of bedrock depth in Universitas Indonesia using the seismic refraction method

N Herlambang and A Riyanto
Geoscience Study Program, Faculty of Mathematics and Natural Sciences (FMIPA), Universitas Indonesia, Depok, 16424, Indonesia

Corresponding author’s email: agus.riyanto@sci.ui.ac.id

Abstract. The seismic refraction method is used to determine the exact bedrock depth for placing a foundation pole. The study was conducted in Universitas Indonesia precisely at the Fasilkom Universitas Indonesia complex. The seismic survey configuration consists of 24 geophone channels with a length of 67.5 m, geophone intervals of 2.5 m, and near offset of 10 m. The wave source was generated using a hammer, and the distance between blows was 5 m. The secondary data used was geological data from SPT (Soil Penetration Test) borehole as a reference for comparison of seismic survey results. Seismic refraction data was processed using traditional techniques, namely the Hagedoorn’s Plus-Minus Method and tomographic inversion using Rayfract software. The correlation between the results of the process with the geological data from SPT drill point shows good results. However, the Plus-Minus Hagedorn method results are only able to show one refractor because of the data limitation, in contrast to the inversion method, which was able to show more than one refractor. There are two main refractors at a depth of 6 meters and 12 meters, and the adequate depth obtained only reaches 15 m. The maximum speed obtained is also around 900 m/s. It can be concluded up to a depth of 15 meters, and there is no recommended rock layer for placement of deep foundations for high rise buildings. A seismic survey with a longer seismic line is needed to get an underground picture exceeding 15 meters.

Keywords: Seismic refraction, geotechnics, bedrock

1. Introduction

The construction of a multi-story building requires a strong and solid foundation so that the building is made safe and can withstand. Analysis of geophysical investigations can reveal how the physical properties of the Earth’s interior vary vertically and laterally [1]. Traditional geotechnical investigations use trenching and boreholes at sparse data point intervals to obtain subsurface information. Therefore, the results obtained may be less representative, inefficient, and expensive.

Refraction seismology is a powerful and relatively cheap method for finding the depths to approximately horizontal seismic interfaces on all scales from site investigations to continental studies [2]. Conventional delay time or generalized reciprocal method refraction analyses make simplifying assumptions about the velocity structure that conflict with frequently observed near-surface attributes, such as heterogeneity, lateral discontinuities, and gradients [3]. Refraction tomography is not subject to these constraints and is therefore able to resolve velocity gradients and lateral velocity changes and can...
be applied in geological conditions where conventional refraction techniques fail, such as areas of compaction, karst, and fault zones [4].

The land near Fasilkom UI was planned as the location for a new multi-story building. There is already an SPT well conducted and analyzed by the Civil Engineering Laboratory of the Muhammadiyah University Jakarta, which provides geological data as a reference point for this research’s seismic refraction method.

With the data obtained from the seismic refraction method, 2 data processing was carried out, namely the conventional and refraction tomography methods. The results will then be compared with data from SPT well near the research location. So besides being able to see the differences that result from the two different methods, it will also be able to estimate the proper installation depth of the pole foundation and suitable equipment for excavation in the construction area. Thus, development planning will be more accurate and efficient.

2. Methodology

The data used in this study are seismic refraction data as the primary data and geological data analyzed from SPT borehole as secondary data. The authors’ team conducted the seismic refraction survey. The geological data from the SPT borehole at the Universitas Indonesia was completed and analyzed by the Civil Engineering Laboratory of the Muhammadiyah University Jakarta in 2017.

The seismic survey was conducted in line, and data stacking was carried out three times for each shot point to minimize noise with the schematic in figure 1.

The parameter used were:
- Near offset = 10 m
- Geophone interval = 2.5 m
- Far offset = 67.5 m
- Shot Point Interval = 5 m
- Data stacking = 3 shot/shotpoint

In the data processing stage used Rayfract Software, the processing is divided into two, namely data processing using the Plus-Minus method and the second using seismic tomography. In addition, several different parameters are used to see these parameters’ effect on the resulting model. The results will later be compared with the original rock layer obtained from secondary data from the SPT well.

Seismic data processed using the Plus-Minus Method and produced 1D-Gradient Model is then inverted using WET (Wavepath Eikonal Traveltime). The parameters used are 20 iterations, 50Hz, and 13.0 % width. Then the inversion result is displayed in (.GRD) format. To produce this format, the Surfer V.17 software is used.

![Seismic survey line diagram.](image)

Figure 1. Seismic survey line diagram.
Seismic survey data is processed to get a 2D model containing the layer boundary's depth and velocity by following the process in figure 2. In making this 2D model, two methods are used, namely Plus-Minus and Tomogram Inversion. In the Plus-Minus method, five different models are made again and see which parameters best match the available geological information (table 1). The processed seismic data is then compared with the actual geological condition seen from the study area's regional geology. Then as a constraint, used SPT borehole data located near the seismic survey location. In the end, it will be seen how the relationship between the seismic model is made and the actual soil condition. This information will combine the parameters of rock type, layers velocity, layers boundary, and seismic refraction capability with different processing methods in interpreting the data obtained.

3. Results and discussion
The Plus-Minus method is carried out using a different overburden filter (OB) and base filter (BF) (table 1). When these parameters are changed, the horizontal and vertical structures will have different weights.

| Overburden Filter (OF) | Base Filter (BF) |
|-----------------------|-----------------|
| 2                     | 2               |
| 2                     | 10              |
| 5                     | 5               |
| 10                    | 2               |
| 10                    | 10              |

Figure 2. Seismic refraction processing flowchart.
The mean of all inversion results in an RMS error of 5.3%, with figure 4c having the smallest RMS error with 5.2%. The color difference shows a difference in velocity. The most notable difference between the five inversion results is the shape of each layer's boundaries. The inversion result produced three layers where the third layer appeared at a depth of more than 10 m. The similarity occurs in the shape of the layers and the velocity of Plus-Minus results in figure 3a and 3d which also occurs in the inversion results in figure 4a and figure 4d where there is a high velocity in the middle. Meanwhile, the inversion results in figure 4b and figure 4e do not have this feature—the inversion results in figure 4c show different results from the other inversions. The inversion results in figure 4c with an overburden filter of 5, and a base filter of 5 also have the smallest RMS error both from the plus-minus start model, which is 8.2%, and the inversion result 5.2%, shown in table 2. The maximum inversion depth is approximately 15 m.

In addition to using the start model from the Plus-Minus method for WET Tomography inversion, the 1D-Gradient start model is also used. The 1D-Gradient start model is the simplest method to work with.

In the initial model in figure 5a, the velocity increases with increasing depth. Speed starts from 161.09 m/s to 768.91 m/s. The depth reached in this initial model reaches a depth of 21 m. The RMS error obtained is 7.5% (5.59 ms), which is the initial model with the lowest RMS compared to the initial Plus-Minus model. Layer boundaries are also quite visible in this initial model, which consists of 3 layers.

It can be seen that the highest ray coverage is in the area of 20 m to 40 m horizontally and -5 m to -10 m vertically in figure 5b. Ray coverage at -20 m is 25 or only a quarter of the maximum value. However, the distribution is fairly even, and there are no blank spots because the distance between the shots is relatively close, and there are many.

The inversion result of the 1D-Gradient start model in figure 5c shows the same velocity range as the initial model; likewise, the layers have three layers. The maximum depth reached is 20.4 m. However, at a depth of 15 meters and below, only a few areas are visible, so it can be assumed that it is relatively inaccurate, which can be seen from the ray coverage shown in figure 5b. The first refractor is at a depth of 5.13 m to 7.54 m. The second refractor, which is the interface of layer two and layer 3, has a depth of 11.29–15.28 m. The first refractor's shape was relatively flat, with a maximum height difference range of only 2 m. There is a relatively concave drop in the second refractor center and at station no.23 in the first refractor. The velocity of each layer from the closest to the surface is 200 m/s to 350 m/s, 500 m/s to 650 m/s, and 750 m/s to 900 m/s.

The data used to compare the plus-minus method are the results with the overburden filter parameter of five and the base filter of five because the results of these parameters have the smallest RMS error. The interval between the sampling point in SPT well data is 2 meters so that the maximum resolution of the well data is only 2 meters. The layer interface itself is identified from the different types of rock in the sample. For example, if there are rock type differences between the sample at a depth of 6 m and a sample at a depth of 8 m, the layer interface may be between 6 m to 8 m.

| (OB, BF) | Plus-Minus’ layer 1 depth (m) | Plus-Minus’ layer 1 velocity (m/s) | Plus-Minus’ layer 2 velocity (m/s) | Plus-Minus’ RMS error (%) | Plus-Minus inversion RMS error (%) |
|---------|-------------------------------|-----------------------------------|-----------------------------------|--------------------------|----------------------------------|
| (2, 2)  | 5.51–6.45                     | 190.57–245.8                      | 387.8–727.32                     | 13.6                     | 5.3                              |
| (2, 10) | 5.69–5.96                     | 190.57–245.8                      | 588.91–607.57                    | 13.6                     | 5.3                              |
| (5, 5)  | 5.74–6.1                      | 190.66–241.53                    | 495.69–637.9                     | 8.2                      | 5.2                              |
| (10, 2) | 5.62–6.17                     | 191.21–232.21                    | 387.8–727.32                     | 9.4                      | 5.3                              |
| (10, 10)| 5.56–5.94                     | 191.21–232.21                    | 588.91–607.57                    | 12.6                     | 5.3                              |
Figure 3. Plus-Minus results (a) OF=2 BF=2, (b) OF=2 BF=10, (c) OF=5 BF=5, (d) OF=10 BF=2, and (e) OF=10 BF=10.

Figure 4. Plus-Minus inversions results (a) OF=2 BF=2, (b) OF=2 BF=10, (c) OF=5 BF=5, (d) OF=10 BF=2, and (e) OF=10 BF=10.
Figure 4 (continued). Plus-Minus inversions results (a) OF=2 BF=2, (b) OF=2 BF=10, (c) OF=5 BF=5, (d) OF=10 BF=2, and (e) OF=10 BF=10.

Figure 5. (a) Initial model, (b) coverage diagram and (c) inversion result of 1D-gradient method.
From figure 6 and table 3, it can be seen that there are differences that are more limiting in the respective process results compared to differences in the results of the layers itself. In the results of the Plus-Minus method, it can be seen that there is only one refractor, and the resulted layer is also relatively flat because inclination and declination are one of the weaknesses of this method. Although the depth can reach 20 m, the limitation of the number of layers makes the depth of the results obtained cannot guarantee the results’ accuracy.

In the plus-minus method’s inversion result, there are three layers, but it can only reach a depth of 15 m. Then, for the 1D-Gradient inversion, it also shows three types of layers and can reach a depth of 20 m. However, for a depth of more than 15 meters, the coverage obtained is relatively small, so the results cannot be justified. It can be concluded that the effectiveness of this study’s results only reaches a depth of 15 m.

The comparison between seismic refraction results with geological data from SPT well also yields quite good results based on the correlation of boundaries shown in table 3 and figure 7 despite the inability to determine the third refractor. The borehole data location is within a radius

![Figure 6. Comparison of data processing results (a) Plus-Minus (b) Plus-Minus inversion and (c) 1D-gradient model inversion.](image)

| Data type                        | First layer interface depth (m) | Second layer interface depth (m) | Third layer interface depth (m) |
|----------------------------------|---------------------------------|---------------------------------|---------------------------------|
| Geological data from SPT well    | 6–8                             | 10–12                           | 14–16                           |
| Plus-Minus method                | 5.74–6.1                        | NA                              | NA                              |
| Plus-Minus method inversion      | 5.43–6.42                       | 11.29–15.28                     | NA                              |
| 1D-gradient method inversion     | 5.13–7.54                       | 11.29–15.28                     | NA                              |
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of fewer than 10 m from the survey trajectory. However, it is not sure that the borehole point from the survey path is not known because the borehole coordinates are not available, and there is only information in the form of a map of the drilling point scheme. Besides, the accuracy of the well data is only 2 m. Then in figure 7 the boundaries of the possibility of the refractor are drawn, indicated by the green dotted line. The inverted background image is a 1D-Gradient inversion then overlaid with the Plus-Minus method's refractor boundary, which is shown with dotted black lines and the refractor from the Plus-Minus inversion with a red line shown in figure 7. The first refractor is located between the refractor boundary mentioned earlier, with most of it being in the upper limit. The three methods also produce similar shapes and positions of the refractor. For the second refractor, the plus-minus method cannot display. Several parts of the refractor resulting from the Plus-Minus inversion and 1D-Gradient inversion are between the refractor boundary in the borehole mentioned earlier. However, some parts fall outside this limit. Two things can cause this discrepancy. The first is the accuracy of the inversion results, which is no longer accurate with increasing depth due to reduced coverage. Then the second is the absolute position between the survey trajectory and the unknown drill data, so it is not known with certainty whether the position of the well is closer to the start of the path where the refractor fits the boundary of the borehole or is in the middle which then will not match the data boreholes. For the third refractor, there is no processing method that can be shown. This is probably due to the lack of coverage of the survey results.

Figure 7. Comparison of seismic refraction processing results with SPT well data.

Figure 8. The geological section derived from SPT well data with the method of (a) Plus-Minus, (b) Plus-Minus inversion, and (c) 1D-gradient inversion.
The three methods' results are almost the same in terms of velocity and depth of the layers, therefore the geological interpretation will be combined. The geological interpretation was made by correlating seismic refraction results based on layer boundaries and velocity with geological data analyzed by the Civil Engineering Laboratory of the Muhammadiyah University Jakarta from SPT well in the research area. In figure 8, two types of layers are produced, namely silty clay with soft to medium-firm hardness in the first layer with the velocity of 200 m/s to 350 m/s and the second layer of silty sand (silty, loose) with the velocity of 500 m/s to 650 m/s. Meanwhile, the inversion results resulted in a layer with a velocity of 750 m/s to 900 m/s, which is a silty clay with a medium hardness level. The N-SPT parameter that can be analyzed is the value that has a value of less than 8. A. A. Bery and R. Saad classify N-SPT correlations of less than 50 into Residual Soil with Vp between 400 m/s to 1000 m/s [5]. Also, for cohesive soil, N-Values less than ten were categorized as very soft - medium, while non-cohesive soils were categorized as very loose-loose.

Based on the seismic survey results, the maximum Vp speed does not reach 1000 m/s. In general, speed increases with increasing density [6]. Vp values below 1000 are included in the rippable category [7]. Besides, the SPT value shows a value of less than 10. So it can be concluded that up to approximately 15 meters, no bedrock is suitable to be used as a deep pole for foundation support because it requires a hard layer of soil and an SPT value of more than 50.

4. Conclusion
The resulting correlation between seismic refraction survey and geological data from SPT well to a depth of 15 m in the first layer being silty clay with a depth of 0–6 m having the velocity of 200–350 m/s, and the second layer was silty sand with the depth of 6–12 m has a velocity of 500–650 m/s. The third layer is a layer of silty clay with a depth of more than 12 m, having a velocity of 750–900 m/s. The results from the conventional method (Plus-Minus) produce better depth data when coupled with tomographic inversion. The correlation between borehole data and seismic surveys shows promising results. Despite the excellent correlation stated above, based on the research results, the maximum depth the seismic refraction line can achieve is only down to 15 m. So it can be concluded that up to approximately 15 meters, no layer of bedrock that can be used as a deep pole for foundation support because it requires a hard layer of soil and an SPT value of more than 50, therefore a longer seismic line is needed.

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