Inverse distance weighting interpolated soil properties and their related landslide occurrences

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Abstract. The causes of landslides can be categorized into three factors: climate, topographic, and soil properties. In many cases, thematic maps of landslide hazards do not involve slope stability analyses to predict the region of potential landslide risks. Slope stability calculation is required to determine the safety factor of a slope. The calculation of slope stability requires the soil properties, such as soil cohesion, the internal friction angle and the depth of hard-rock. The soil properties obtained from the field and laboratory investigation from the western part of Central Java were interpolated using Inverse Distance Weighting (IDW) to estimate the unknown soil properties in the gridded area. In this research, the IDW optimum parameter was determined by validation toward the percent bias. It was found that the IDW interpolation using higher weighting factor corresponds with a higher percent bias in case of the depth of hard-rock and soil cohesion, while the opposite was found for the internal friction angle. Validation to landslide incidents in western parts of Central Java shows that the majority of landslide incidents occur at depths of hard rock of 6 m-8 m, at soil cohesions of 0.0 kg/cm²–0.2 kg/cm², and at internal friction angles of 30⁰-40⁰.

1 Introduction

Approximate regions of potential landslide risks in Indonesia have been identified based on their historical occurrences, from which it is analysed so that each regency has 1 landslide vulnerability index [1]. Land use and climate change have made many more areas vulnerable to landslides, because landslide occurrence is mostly related to an area’s topographic and hydrologic conditions. Therefore, data on topographic and hydrologic conditions are necessary to provide accurate information on the location of landslide vulnerable areas.

Identifying approximate regions of potential landslide risk based on their topographic and hydrologic conditions at some areas have been done by several researchers [2, 3]. The method used was by overlaying parameters of topography, geology, land use, and climate in which each parameter was scored to represent its effect on landslides [2, 3]. For instance,

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steep terrain was scored higher than mild terrain. The total score of all parameters was then used to determine the level of potential landslide risk at the area of interest [3].

Although it was based on topographic and hydrologic data, the aforementioned method did not take into account the slope stability factor by which the occurrence of landslides is mechanically decided [4]. Determination of the slope stability requires calculations of the driving forces (gravitational forces due to weight of soil and water, and other overburdening loads) and the resistive forces (soil shear strength). The soil unit weight has low spatial variability and can be measured directly from the laboratory test. On the other hand, the soil shear strength has a high spatial variability and instead of measuring it directly, it should be calculated based on the soil properties. Moreover, the soil shear strength has a positive correlation with the soil bearing capacity, which can be obtained from conducting a soil penetration test (SPT) or cone penetration test (CPT).

Data of the soil properties and CPT are required for designing a ground structure of a building so that it is readily available at some institutions that provide testing services. The soil mechanics laboratory of the Jenderal Soedirman University has recorded data of more than 200 sites of soil properties tests and CPTs around the western part of Central Java, which include the regencies of Kebumen, Wonosobo, Banjaranegara, Purbalingga, Banyumas, and Cilacap. A previous study presents a correlation analysis of CPT data and soil classification in Western Central Java [5]. As a preliminary step to obtain landslide vulnerability indexes based on the slope stability factor, this paper continues the previous study and describes the spatial distribution of the soil properties obtained from undisturbed soil samples and CPT data and their related landslide occurrences in the western part of Central Java.

2 Method

Soil properties data were obtained from 10 years of soil investigation carried out by the laboratory of soil mechanics of the Jenderal Soedirman University. The observations were conducted in the western part of Central Java, which consists of 11 regencies of Tegal, Brebes, Pemalang, Pekalongan, Batang, Cilacap, Banyumas, Purbalingga, Banjaranegara, Wonosobo, and Kebumen (Figure 1).

Fig. 1. Study location (http://psda.jatengprov.go.id).
Data were collected from 336 sites over the years of 2005, 2006, 2007, 2010, 2011, 2012, 2013, 2014, 2015 and 2016. The data include site coordinates, the depths of hard rock, cohesions, and internal friction angles. The depths of hard rock were determined by the criteria according to [6] as shown in Table 1. Soil cohesion and internal friction angles were determined from the direct shear test. The soil properties data were mapped by using a free and open source GIS software, Q-GIS 2.01, in the UTM projection. All regencies’ areas were combined to form one area allowing an interpolation method to calculate interpolation values using known values from sampling points outside of their regency boundaries. A gridding process was carried out to interpolate data from an arbitrary 2D sampling pattern to a uniform grid.

**Table 1.** Criteria to determine the depth of hard rock according to the relative density of fine sand, the SPT, the static cone resistance and the angle of internal fraction [6].

<table>
<thead>
<tr>
<th>State of sand</th>
<th>D_r</th>
<th>N-SPT</th>
<th>q_c (MPa)</th>
<th>(\phi^o)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Very loose</td>
<td>&lt;0.2</td>
<td>&lt;4</td>
<td>&lt;2.0</td>
<td>&lt;30</td>
</tr>
<tr>
<td>Loose</td>
<td>0.2–0.4</td>
<td>4–10</td>
<td>2–4</td>
<td>30–35</td>
</tr>
<tr>
<td>Medium dense</td>
<td>0.4–0.6</td>
<td>10–30</td>
<td>4–12</td>
<td>35–40</td>
</tr>
<tr>
<td>Dense</td>
<td>0.6–0.8</td>
<td>30–50</td>
<td>12–20</td>
<td>40–45</td>
</tr>
<tr>
<td>Very dense</td>
<td>0.8–1.0</td>
<td>&gt;50</td>
<td>&gt;20</td>
<td>45</td>
</tr>
</tbody>
</table>

The interpolation method used was the Inverse Distance Weighting (IDW) method, of which its formulation was coded by R programming. IDW interpolation considers a number of known values at sampling sites to calculate unknown values at a gridded area. The known data were weighted according to their distance from the target point. The known data with closer distances to the target points have higher weighting factors than ones further away [7]. Mathematically, the IDW formulation is written as follows:

\[
\hat{q} = \frac{\sum_{i=1}^{n} \frac{1}{r_i} q_i}{\sum_{i=1}^{n} \frac{1}{r_i}}
\]

where:
- \(\hat{q}\) : interpolation target value
- \(q_i\) : known value at location \(i\)
- \(r_i\) : distance between the target and the known value at location \(i\)
- \(\alpha\) : weighting factor
- \(n\) : number of known data considered in the interpolation

The number of known data used for the interpolation are 336, 226, and 228 for the data of the depth of hard rock, soil cohesions, and internal friction angle, respectively. Furthermore, the distance between the target and the known value was calculated based on location coordinates. The weighting factors used in the interpolation were 1, 2, and 3.

A validation was made to evaluate the suitability of the interpolation method in estimating the soil properties at the interpolated points. For the purpose of validation, the data were divided into two groups: 15% for the target of validation, and 85% to be interpolated. The validation of the interpolation makes use of the percent bias. There were 10 interpolation trials per weighting factor, each of which were evaluated according to its percent bias. The percent bias was calculated as follows.

\[
\text{Percent Bias} = \frac{1}{n} \sum_{i=1}^{n} \left| \frac{\hat{q}_i - q_i}{q_i} \right| \times 100\%
\]
in which $q$ is soil properties, $u_{kur}$ and $inter$ are representing the measured and interpolated values respectively.

3 Results and discussion

3.1 Soil properties distribution

Spatial distribution of the depths of hard rock obtained from field investigation in the western part of Central Java is shown in Fig. 1. The data of the depths of hard rock were summarized to form grouped data with each class interval size being 5. The depths of hard rock falling within the class interval $0 \text{ m} – 5 \text{ m}$ mostly occurred in the regencies of Tegal, Banyumas, and Purbalingga. Class $5 \text{ m} – 10 \text{ m}$ occurs in all regencies. Class $10 \text{ m} – 15 \text{ m}$ mostly occurs in Brebes Regency. The last two class intervals, $15 \text{ m} – 20 \text{ m}$ and $20 \text{ m} – 25 \text{ m}$, were found in the regencies of Cilacap, Banyumas, and Banjarnegara.

Similarly, as with the data of the depths of hard rock, the data of soil cohesion were mapped and their spatial distribution are shown in Figure 3. It shows that the soil cohesion of $0 – 0.5 \text{ kg/cm}^2$ were found in all regencies. The regencies of Tegal, Purbalingga, and Kebumen were found to have a soil cohesion of $1 – 1.5 \text{ kg/cm}^2$. Furthermore, a soil cohesion of $1.5 – 2 \text{ kg/cm}^2$ was existent in regencies of Brebes, Cilacap, and Purbalingga.
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Fig. 2. Spatial distribution of depths of hard rock.

Similarly, as with the data of the depths of hard rock, the data of soil cohesion were mapped and their spatial distribution are shown in Figure 3. It shows that the soil cohesions of 0 – 0.5 kg/cm$^2$ were found in all regencies. The regencies of Tegal, Purbalingga, and Kebumen were found to have a soil cohesion of 1 – 1.5 kg/cm$^2$. Furthermore, a soil cohesion of 1.5 – 2 kg/cm$^2$ was existent in regencies of Brebes, Cilacap, and Purbalingga.

Fig. 3. Spatial distribution of soil cohesion.

Last but not least, the data angles of internal friction were also mapped as seen in Figure 4. The internal friction angle of 0$^\circ$ – 20$^\circ$, typical values of organic to clay soil, and the commonly found internal friction angle of 20$^\circ$ – 40$^\circ$ were spatially well distributed in all regencies, except in the regencies of Batang, Wonosobo and Pekalongan. All regencies were found to have angles of internal friction of 40$^\circ$ – 60$^\circ$, while angles of 60$^\circ$ – 80$^\circ$ were mostly found in the regencies of Banyumas and Purbalingga.

Fig. 4. Spatial distribution of internal friction angle.

3.2 IDW parameter

The optimized parameter of IDW to produce realistic soil properties distribution is the distance weighting factor ($\alpha$). Ten trials were carried out to obtain the optimized weighting factor $\alpha$. Each trial makes use of randomly selected 85% data for the interpolation and 15% data for the validation. The average of ten percent bias was calculated. Three different distance weighting factors, i.e. $\alpha = 1$, 2, 3, were evaluated according to their percent bias. The effect of different values of distance weighting factors on the percent bias in mapping the depths of hard rock is shown in Figure 5.
The interpolations of the depths of hard rock data show that different weighting factors will result in different percent biases. The averages of ten trials were -103.12%, -135.31%, and -154.56% for $\alpha = 1$, 2, and 3 respectively. The interpolations show that higher weighting factors resulted in a higher percent bias. The mapping of IDW interpolated depths of hard rock data is shown in Figure 6, in which it shows that a higher weighting factor resulted in more unevenly distributed depths of hard rock.

![Map of interpolated depths of hard rock.](image)

**Fig. 5.** Weighting factor effect on percent bias resulted from depths of hard rock interpolation.

The effect of the different values of distance weighting factors on percent bias in mapping of soil cohesion is shown in Figure 7, which shows that a different weighting factor highly affects the percent bias. Quantitatively, the percent bias of ten averaged trials were -149.427%, -173.718%, and -180.672% for $\alpha = 1$, 2, and 3 respectively. The interpolations show that higher weighting factors resulted in a higher percent bias. The mapped IDW interpolated soil cohesion data is shown in Figure 8, in which it shows that a higher weighting factor resulted in more unevenly distributed soil cohesion.

![Map of interpolated soil cohesion.](image)

**Fig. 6.** Map of interpolated depths of hard rock.
Fig. 5. Weighting factor effect on percent bias resulted from depths of hard rock interpolation. The interpolations of the depths of hard rock data show that different weighting factors will result in different percent biases. The averages of ten trials were -103.12%, -135.31%, and -154.56% for $\alpha = 1, 2, \text{ and } 3$ respectively. The interpolations show that higher weighting factors resulted in a higher percent bias. The mapping of IDW interpolated depths of hard rock data is shown in Figure 6, in which it shows that a higher weighting factor resulted in more unevenly distributed depths of hard rock.

Fig. 6. Map of interpolated depths of hard rock.

The effect of the different values of distance weighting factors on percent bias in mapping of soil cohesion is shown in Figure 7, which shows that a different weighting factor highly affects the percent bias. Quantitatively, the percent bias of ten averaged trials were -149.42%, -173.72%, and -180.67% for $\alpha = 1, 2, \text{ and } 3$ respectively. The interpolations show that higher weighting factors resulted in a higher percent bias. The mapped IDW interpolated soil cohesion data is shown in Figure 8, in which it shows that a higher weighting factor resulted in more unevenly distributed soil cohesion.

The effects of weighting factors for interpolating the internal friction angles were also shown by their associated percent bias as can be seen in Figure 9. Similarly, as with the two previous interpolated soil properties, the interpolations of internal friction angle data show the effect of different weighting factors on the percent bias. However, the effect occurs adversely, i.e. higher weighting factors resulted in a lower percent bias. The percent bias of ten averaged trials were -34.844%, -32.556%, and -7.488% for $\alpha = 1, 2, \text{ and } 3$ respectively. Confirming the previous two results, the uniformity of the internal friction angle spatial distribution obtained from the IDW interpolation reduces, as a function of the weighting factor increase (Figure 10).
3.3 Validation on landslide occurrences

The National Board for Disaster Countermeasures, abbreviated BNPB, had recorded 64 landslide occurrences in the western part of Central Java in 2011-2015. Locations of such landslides, shown by dot symbols, have been plotted on top of the map produced from the IDW interpolated depths of hard rock (Figure 11). Furthermore, the number of landslide occurrences and their associated depths of hard rock are shown in Table 2. It shows that most landslides had occurred at locations with depths of hard rock of 6 m – 8 m.
Fig. 11. Landslide occurrence and interpolated depths of hard rock data.

Table 2. Number of landslide occurrence according to depths of hard rock (m).

<table>
<thead>
<tr>
<th>Weighting factor</th>
<th>2 – 4</th>
<th>4 – 6</th>
<th>6 – 8</th>
<th>8 – 10</th>
<th>10 – 12</th>
<th>12 – 14</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\alpha = 1$</td>
<td>-</td>
<td>1</td>
<td>52</td>
<td>10</td>
<td>1</td>
<td>-</td>
</tr>
<tr>
<td>$\alpha = 2$</td>
<td>1</td>
<td>12</td>
<td>29</td>
<td>18</td>
<td>2</td>
<td>2</td>
</tr>
<tr>
<td>$\alpha = 3$</td>
<td>8</td>
<td>12</td>
<td>21</td>
<td>15</td>
<td>1</td>
<td>7</td>
</tr>
</tbody>
</table>

Just like the depths of hard rock, the locations of landslide occurrences and their related interpolated soil cohesion have been plotted in a map to show their relationship (Figure 12). The number of landslide occurrences and their related soil cohesion is listed in Table 3. This shows that the weighting factors of $\alpha = 1$ and $\alpha = 2$ result in landslide occurrences at interpolated soil cohesions of 0.2 kg/cm² – 0.4 kg/cm². The weighting factor $\alpha = 3$ results in landslide occurrences at interpolated soil cohesions of 0.0 kg/cm² – 0.2 kg/cm². For soil cohesion values resulted from the IDW interpolations that are larger than 0.4 kg/cm², the customization of three weighting factors reduces the degree in landslide vulnerability.

Fig. 12. Landslide occurrence and interpolated soil cohesion data.

Table 3. Number of landslide occurrence according to soil cohesion (kg/cm²).

<table>
<thead>
<tr>
<th>Weighting factor</th>
<th>0.0 – 0.2</th>
<th>0.2 – 0.4</th>
<th>0.4 – 0.6</th>
<th>0.6 – 0.8</th>
<th>0.8 – 1</th>
<th>1 – 1.2</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\alpha = 1$</td>
<td>2</td>
<td>61</td>
<td>-</td>
<td>1</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>$\alpha = 2$</td>
<td>28</td>
<td>32</td>
<td>-</td>
<td>2</td>
<td>2</td>
<td>-</td>
</tr>
<tr>
<td>$\alpha = 3$</td>
<td>36</td>
<td>22</td>
<td>3</td>
<td>2</td>
<td>-</td>
<td>1</td>
</tr>
</tbody>
</table>

As with two previous soil properties, the interpolated internal friction angle was mapped along with the location of the landslide (Figure 13). Furthermore, Table 4 shows the number of landslide occurrences and their associated IDW interpolated internal friction angle. They show that, making use of all three weighting factors, IDW interpolated internal friction angles of 30° - 40° is the range where most landslides happen. Furthermore, it shows fewer landslide occurrences as the interpolated internal friction angle goes beyond 40°.
Fig. 13. Landslide occurrence and interpolated angle of friction data.

Table 4. Number of landslide occurrence according to internal friction angle (°).

<table>
<thead>
<tr>
<th>Weighting factor</th>
<th>10 – 20</th>
<th>20 – 30</th>
<th>30 – 40</th>
<th>40 – 50</th>
</tr>
</thead>
<tbody>
<tr>
<td>α = 1</td>
<td>-</td>
<td>29</td>
<td>35</td>
<td>-</td>
</tr>
<tr>
<td>α = 2</td>
<td>1</td>
<td>18</td>
<td>43</td>
<td>2</td>
</tr>
<tr>
<td>α = 3</td>
<td>1</td>
<td>16</td>
<td>37</td>
<td>10</td>
</tr>
</tbody>
</table>

4 Conclusion

The soil properties in the western part of Central Java obtained from field and laboratory investigation were spatially interpolated using the Inverse Distance Weighting (IDW) method and mapped to determine their spatial distribution. Depending on the nature of each soil property, the resulting spatial distributions varied according to the selection of the weighting factor. IDW interpolation using higher a weighting factor corresponds with a higher percent bias in case of depth of hard rock and soil cohesion, while the opposite was found in the case of the internal friction angle. However, it was unsatisfactory in terms of the percent bias. Nevertheless, the IDW interpolation results in some realistic conclusions according to the data of landslide locations. Validation to landslide incidents in the western part of Central Java shows that the majority of landslide incidents occur at depths of hard rock of 6 m - 8 m, at a soil cohesion of 0.0 kg/cm² – 0.2 kg/cm², and at an internal friction angle of 30° - 40°.

References