Hydrogeological and hydrochemical condition in planned tunnel B route of the Yogyakarta-Bawen toll road

Nur Itsnaini¹,²*, Doni Prakasa Eka Putra³, and I Gde Budi Indrawan³

¹Graduate Student in Underground Geological Structure, Department of Geological Engineering, Gadjah Mada University, 55281 Yogyakarta, Indonesia
²PT Hutama Karya (Persero), 13340 Jakarta, Indonesia
³Department of Geological Engineering, Gadjah Mada University, 55281 Yogyakarta, Indonesia

Abstract. The Yogyakarta-Bawen toll road tunnel, located in Magelang Regency, Central Java Province, is a national strategic project that connects Central Java and the Special Region of Yogyakarta. It has geology resulting from volcanic processes, resulting in rocks with moderate aquifer properties and low to moderate permeability. The study covers 24 observation points, with 11 locations sampling groundwater for chemical analysis. The analysis results of hydrochemical facies are Na-K-HCO₃. Water table depth varies from 623 m to 704 m above sea level, with the water table along the tunnel route at depths of 13-40 m above mean sea level, generally above the tunnel's elevation. The groundwater flow pattern tends to move from southeast to northwest, perpendicular to the tunnel's direction. Groundwater quality testing indicates that water in the research area falls under the category of fresh groundwater, based on electrical conductivity and total dissolved solids values. The overall acidity level is generally acidic, except at specific points. In general, the interaction of groundwater with concrete results in weak erosion. It can be concluded that the groundwater at the research location is shallow, situated above the planned tunnel elevation, exhibits hydrochemical facies variations, and has the potential to weakly erode concrete.

1 Introduction

The development of infrastructure such as highways or expressways plays a crucial role in the progress and advancement of a region. Besides enhancing accessibility and connectivity, toll road infrastructure also can shorten travel time [1]. In this context, a noteworthy infrastructure project is the Yogyakarta-Bawen toll road. This toll road holds significance as a national strategic project as it will connect the Central Java Province and the Special Region of Yogyakarta, spanning a total length of 76.3 km. Within the project structure, section 5, which connects Temanggung to Ambarawa, will pass through twin tunnels located in the Kragan Hamlet, Losari Village, Magelang Regency [2].

* Corresponding author: nuritsnaini@mail.ugm.ac.id

© The Authors, published by EDP Sciences. This is an open access article distributed under the terms of the Creative Commons Attribution License 4.0 (https://creativecommons.org/licenses/by/4.0/).
However, in every infrastructure development, negative impacts on the environment that are hard to avoid often emerge. Insufficient planning is frequently the trigger for these negative consequences [3], including aspects of water resource management [4]. Water resources are natural assets that are limited in terms of time and location [5]. Geoenvironmental impacts arise due to excessive exploitation of groundwater and the increasing human activities [6]. For example, Wahyu et al. [7] reported a decline in groundwater levels and seawater intrusion towards land due to the excessive withdrawal of groundwater for airport construction. Adelide et al. [8] reported the risk of acid mine drainage contamination in rivers and production wells arising from mining activities.

The importance of understanding the impacts of infrastructure development encompasses potential water supply shortages, declining water quality, and even the risk of water infrastructure failures [6]. Therefore, an in-depth knowledge of the geological conditions beneath the surface becomes a key element in identifying the types of materials that serve as mediums for groundwater movement. Additionally, rock weathering is a natural geogenic source that imparts dissolved substances to groundwater [9]. Another crucial aspect involves investigating the chemical content of groundwater within that environment. According to [10], water undergoes a series of complex interactions in the hydrological cycle. From interactions with gases and particles in the atmosphere to its descent onto land or into the oceans, water continues to engage with various materials. These interactions significantly contribute to the chemical composition of water.

Recognizing the significance of hydrogeological and hydrochemical issues in the context of infrastructure development, especially tunnels on the Yogyakarta-Bawen toll road, further research is warranted. Presently, no specific studies have investigated the hydrogeological and hydrochemical conditions in that region. Therefore, the primary objective of this research is to investigate and characterize the hydrogeological and hydrochemical conditions in the study area, as well as to identify the potential chemical aggressiveness of groundwater for tunnel construction. It is expected that the findings from this research will provide valuable information for stakeholders, helping to mitigate the potential damages resulting from chemical contamination impacts and thus ensuring the long-term sustainability of project operations.

2 Materials and methods

2.1 Location and general description

The Yogyakarta-Bawen toll road tunnel is located at an inlet position with coordinates 110°19'55" E longitude and 7°20'0" S latitude, while the outlet is situated at coordinates 110°20'2" E longitude and 7°19'45" S latitude [2]. This research was conducted in the area encompassing the tunnel, covering an area of 4 km², and situated in Losari Village, Grabag District, Magelang Regency, Central Java Province, Indonesia (Fig. 1). The climate characteristics of this region are tropical with two seasons, namely the rainy season and the dry season, and an air temperature range between 20°C and 27°C [11].

Generally, Magelang Regency features a highland morphology that forms a basin, surrounded by several mountains such as Mount Merbabu, Mount Merapi, Mount Sumbing, Mount Andong, and Mount Telomoyo. According to information from [12], land use in the research area is dominated by plantations and settlements. This situation impacts much of Magelang Regency, which serves as a rainwater catchment area, thus being rich in groundwater reserves that eventually emerge as springs [11].
2.2 Geological and hydrogeological setting

The geological setting of the research area lies within the Gilipetung Volcanic Rock unit (Qg). This unit consists of hollow, gray, solid to fine-grained lava flows with small mafic phenocrysts and is estimated to be from the Pleistocene era [13]. Visible geological structures exhibit linear trends with a dominant north-south orientation; however, no such structures were found passing through the toll road tunnel. Regional geology was utilized to aid in the geological data analysis derived from mapping in the research area.

Magelang Regency is situated within two watershed areas, namely the Progo watershed area spanning approximately 933 km² and the Bogowonto watershed area covering around 142 km² [11]. The Magelang-Temanggung Groundwater Basin indicates that the research area falls within the zone of moderately productive aquifers with widespread distribution and low to moderate permeability. The constituent rock comprises old volcanic deposits composed of andesitic to basal lava flows and breccias. Additional information reports that the groundwater quality in the research area has an Electrical Conductivity (EC) value of <300 µS/cm and the groundwater geochemical type consists of alkali-bicarbonate and magnesium-bicarbonate [14].

2.3 Research approach

2.3.1 Geomorphological and geological

Observations Geomorphological observations were conducted based on three primary criteria: morphography aspects encompassing the depiction of forms, morphometry involving quantitative assessments of landforms, and morphogenetic focusing on the processes shaping the Earth's surface. Quantitative assessment of landforms involved slope analysis and elevation differences, classified according to van Zuidam [15].
Meanwhile, geological mapping was carried out by observing rock conditions macroscopically at outcrops in the field and through subsurface observations based on core evaluation obtained from geotechnical drilling conducted by consulting firms. Data from these observations provided information about lithology, geological structures, and the presence of groundwater. The division of rock units was based on similarities in physical characteristics and the composition of rock materials. Geomorphological and geological maps for this study were created at a scale of 1:10,000 and used contour data as the base map.

Geomorphological and geological observations were undertaken with the aim of understanding the characteristics and interactions between land surface forms, geological formations, and groundwater systems in a specific area. Through this approach, a more comprehensive understanding of the hydrogeological conditions at the research location is expected to be attained.

2.3.2 Measurement of groundwater

Physicochemical Properties Water quality testing is used to determine whether the water's condition is within acceptable limits or exceeds the threshold levels for specific substances. Data collection was carried out through various observation points, including 21 dug well points, one geotechnical borehole point, one spring point, and one point of water intake from a river. It is worth noting that there is a presence of hot springs in the vicinity of the research location, with a surface temperature of around 35°C. These hot springs are situated approximately 51 km to the northwest of the research site. Parameters that exhibit rapid fluctuations, including pH value, temperature (°C), electrical conductivity (µS), and total dissolved solids (mg/L), were measured in situ using a handheld multi-parameter water quality measurement device.

3 Results and discussion

3.1 Geomorphological and geological map

The field observations revealed that the research area falls within the volcanic hill unit composed of fine to medium materials with an average elevation of approximately ±650 meters above sea level. The slope inclination varies and is classified into two classes: gentle to moderately sloping slopes with slopes ranging from 2% to 15%, and somewhat steep slopes with slopes ranging from 15% to 30%. Based on this, it can be concluded that the geomorphological unit consists of the high lava hills unit with gentle-moderate slopes and the high lava hills unit with moderately steep slopes (Fig. 2). The high lava hills unit with gentle-moderate slopes is depicted in yellow, while the high lava hills unit with moderately steep slopes is depicted in orange. The respective areas of these two units are 58% and 42%.
The results of surface geological mapping identify two rock units at the research site, namely andesitic breccia, and andesitic lava. The lithological contact boundary between the andesitic breccia and andesitic lava is gradational, indicating co-development during the Pleistocene period. Although faults or folds were not detected during field observations, some outcrops reveal the presence of bedding planes and extensional fractures. Macroscopic investigations provide an overview of the rock unit distribution at the research location, as illustrated in figure 3. In addition to surface rock observations, information on groundwater conditions, specifically water table depths, was also examined. Water table depths were obtained from the geotechnical investigation report conducted by a consultant. It was identified that the water table is situated at depths ranging from 13 to 40 meters below the surface.

Fig. 2. Geomorphological map of the research area.

Fig. 3. Geological map of the research area.
3.2 Groundwater flow

Direction The groundwater flow network constitutes a pattern of pathways through which groundwater flows within an area, with the flow direction depending on the contours of the water table. These flow lines have distinct characteristics: they flow perpendicular, at a 90-degree angle, to the groundwater contour lines, and they move from higher elevations to lower elevations. This study involved a comprehensive analysis of the groundwater table in the research area through observations at 22 location points, consisting of 21 dug wells and 1 borehole. The results of this analysis revealed that the groundwater table elevation in the research area varies, ranging from 624 m to 705 m above sea level. Overall, the groundwater movement pattern in this research area demonstrates a general tendency to flow from the southeast to the northwest, perpendicular to the planned tunnel alignment (Fig. 4).

3.3 Physical characteristics of groundwater

The analysis of major ion chemistry in groundwater samples is presented in Table 1. In-situ groundwater temperatures vary between 22.60°C and 27.30°C, with an average of 25.23°C. The pH distribution of the samples ranges from 5.18 to 8.67, with an average of 6.17 (figure 5a), indicating the slightly acidic to alkaline nature of the groundwater. The research area is predominantly characterized by acidic conditions, but at a few points, alkaline characteristics are observed with values above 7, namely in samples S1 (7.19), MA (7.90), and SG1 (8.67). Electrical conductivity (EC) ranges from 62 to 377 µS/cm, with an average of 175.29 µS/cm. Samples S7, S9, and S11 exhibit higher EC concentrations located in the southwestern part of the research area (figure 5b). Total Dissolved Solids (TDS) in groundwater samples range from 30 to 188 mg/L, with an average of 87.21 mg/L (figure 5c). Similar to the EC distribution, samples in the southwestern part of the research area show higher TDS values.
Table 1. Descriptive statistics for the concentration of chemical constituents in groundwater samples in the research area

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Unit</th>
<th>n (Sample number)</th>
<th>Min.</th>
<th>Max.</th>
<th>Mean</th>
<th>Std. Deviation</th>
</tr>
</thead>
<tbody>
<tr>
<td>T</td>
<td>°C</td>
<td>24</td>
<td>22.60</td>
<td>27.30</td>
<td>25.23</td>
<td>1.05</td>
</tr>
<tr>
<td>pH</td>
<td></td>
<td>24</td>
<td>5.18</td>
<td>8.67</td>
<td>6.17</td>
<td>0.831</td>
</tr>
<tr>
<td>EC</td>
<td>µs/cm</td>
<td>24</td>
<td>62.00</td>
<td>377.00</td>
<td>175.29</td>
<td>94.69</td>
</tr>
<tr>
<td>TDS</td>
<td>mg/L</td>
<td>24</td>
<td>30.00</td>
<td>188.00</td>
<td>87.21</td>
<td>47.09</td>
</tr>
<tr>
<td>Na</td>
<td>mg/L</td>
<td>11</td>
<td>2.71</td>
<td>8.04</td>
<td>5.66</td>
<td>2.153</td>
</tr>
<tr>
<td>K</td>
<td>mg/L</td>
<td>11</td>
<td>1.23</td>
<td>4.65</td>
<td>2.83</td>
<td>1.266</td>
</tr>
<tr>
<td>Ca</td>
<td>mg/L</td>
<td>11</td>
<td>6.06</td>
<td>84.20</td>
<td>24.10</td>
<td>23.031</td>
</tr>
<tr>
<td>Mg</td>
<td>mg/L</td>
<td>11</td>
<td>1.81</td>
<td>11.43</td>
<td>5.26</td>
<td>3.072</td>
</tr>
<tr>
<td>HCO₃</td>
<td>mg/L</td>
<td>11</td>
<td>24.40</td>
<td>305.00</td>
<td>87.54</td>
<td>83.243</td>
</tr>
<tr>
<td>Cl</td>
<td>mg/L</td>
<td>11</td>
<td>1.20</td>
<td>39.00</td>
<td>6.95</td>
<td>11.481</td>
</tr>
<tr>
<td>NO₃</td>
<td>mg/L</td>
<td>11</td>
<td>0.60</td>
<td>96.90</td>
<td>17.41</td>
<td>29.212</td>
</tr>
<tr>
<td>SO₄</td>
<td>mg/L</td>
<td>11</td>
<td>1.30</td>
<td>25.80</td>
<td>4.85</td>
<td>7.500</td>
</tr>
</tbody>
</table>

Fig. 5. Map of groundwater quality distribution (a) pH, (b) EC, (c) TDS, (d) Na.
Sampling at the hot spring location (CU) was conducted to analyze the physical and chemical properties of the groundwater present there. The results of the CU sample testing have been summarized and recorded in Table 2. Through this testing, information was obtained regarding the chemical composition of the groundwater as well as its physical characteristics, such as pH, ion concentrations, and other parameters listed in the table. The data from this testing play a crucial role in understanding the conditions and properties of the groundwater at the hot spring location.

Table 2. Descriptive statistics of physical and chemical properties in the CU samples

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Unit</th>
<th>Value</th>
<th>Parameter</th>
<th>Unit</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>T</td>
<td>°C</td>
<td>35.30</td>
<td>Ca</td>
<td>mg/L</td>
<td>88.66</td>
</tr>
<tr>
<td>pH</td>
<td></td>
<td>8.08</td>
<td>Mg</td>
<td>mg/L</td>
<td>19.84</td>
</tr>
<tr>
<td>EC</td>
<td>µs/cm</td>
<td>3244</td>
<td>HCO3</td>
<td>mg/L</td>
<td>549</td>
</tr>
<tr>
<td>TDS</td>
<td>mg/L</td>
<td>1623</td>
<td>Cl</td>
<td>mg/L</td>
<td>506</td>
</tr>
<tr>
<td>Na</td>
<td>mg/L</td>
<td>334.6</td>
<td>NO3</td>
<td>mg/L</td>
<td>6</td>
</tr>
<tr>
<td>K</td>
<td>mg/L</td>
<td>45.050</td>
<td>SO4</td>
<td>mg/L</td>
<td>5</td>
</tr>
</tbody>
</table>

3.4 Major ion chemistry in groundwater

When examining the spatial distribution of main ion concentrations in groundwater samples, it becomes apparent that there is variation in the sodium and potassium ion values within their designated concentration ranges. The findings of the study reveal that the concentrations of sodium ions vary between 2.71 and 8.04 mg/L, as depicted in figure 5d. Similarly, the concentrations of potassium ions range from 1.23 to 4.65 mg/L, as illustrated in figure 6a. The investigation of spatial distribution reveals that the regions in close proximity to the proposed tunnel exhibit the lowest levels of sodium concentration. Nevertheless, a notable disparity in potassium concentration is observed, with the BR1 sample, identified as a geotechnical borehole, displaying the highest recorded value for potassium concentration. This stands in contrast to other tunnel plan sites where minimal potassium concentration values are indeed present. The contents of calcium and magnesium range from 6.06 to 84.20 mg/L (figure 6b) and 1.81 to 11.43 mg/L (figure 6c), respectively, illustrating the variability of minerals in the water. The concentration of bicarbonate ions varies from 24.4 to 305 mg/L, with an average value of 87.54 mg/L (see Figure 6d). The results of spatial analysis indicate that the BR1 point exhibits the highest concentrations of calcium and bicarbonate, whilst the vicinity surrounding the tunnel design exhibits the lowest concentrations. In addition, the data presented in figure 6e indicates chloride values ranging from 1.2 to 39 mg/L, while figure 6f shows sulfate values ranging from 1.3 to 25.8 mg/L. These figures provide an insight into the concentrations of chloride and sulfate components present in the water. The western section of the study exhibits a greater concentration of chloride, whereas the northwestern part of the study has a larger level of sulfate.
Fig. 6. Map of groundwater quality distribution (a) K, (b) Ca, (c) Mg, (d) HCO3, (e) Cl and (f) SO4.

Based on the Piper diagram results, all groundwater samples collected fall into the main water type of Na-K-HCO3 according to the hydrochemical classification proposed by [16],
as observed in figure 7. All sampling points exhibit alkaline earth water characteristics, except for one sample (S6) which shows higher alkali properties compared to the others.

**Fig. 7.** Piper diagram of groundwater chemical content in research area.

The concentration of ions in groundwater is depicted in diagram form to aid in understanding the origin of groundwater, the geochemical processes affecting it, and the potential interactions with rocks and other materials beneath the ground surface. In this study, ion concentration analysis was conducted using a composition diagram by comparing Cl-ions with cations such as Na+, K+, Ca+, and Mg+ (Figure 8). Chloride ions are considered conservative ions due to their stable behavior and generally insignificant changes in the environment caused by hydrological and geochemical processes. Therefore, they can be regarded as a good indicator to evaluate hydrochemical changes within aquifers or groundwater.
Analysis based on Figure 8 reveals that the hot spring sample (CU) exhibits higher ion concentrations compared to the other samples. This suggests that all sampling points can be classified as shallow groundwater, while the hot spring sample (CU) falls under the category of deep groundwater influenced by geothermal processes. The higher ion concentrations in the hot spring sample may indicate more complex chemical reactions or interactions between groundwater and deeper rock formations. Consequently, the hot spring sample (CU) tends to have a chemical composition influenced by geothermal processes occurring at greater depths beneath the ground surface. Meanwhile, the other samples showing lower ion concentrations...
tend to reflect the characteristics of shallow groundwater with more limited interactions with deeper rock layers.

### 3.5 Chemical aggressiveness of groundwater towards concrete

Groundwater significantly influences the strength of concrete through chemical interactions with elements present within it. This impact is primarily manifested in the form of corrosion and a reduction in concrete compressive strength. Table 3 provides limit values for assessing the acidity level of water, which mainly comprises natural components according to DIN 4030 standards [17]. Previous groundwater analyses have revealed that relevant aggressiveness parameters, such as pH, magnesium, and sulfate, can be reflected in Table 1. Based on this data, it can be concluded that the groundwater aggressiveness in the research area falls within the category of low erosion.

**Table 3.** The value of the acidity level limit of water [17].

<table>
<thead>
<tr>
<th>Investigation</th>
<th>Chemical Aggressiveness</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Weak</td>
</tr>
<tr>
<td>pH Value</td>
<td>6.5 to 5.5</td>
</tr>
<tr>
<td>Magnesium (Mg²⁺) in mg/l</td>
<td>300 to 1,000</td>
</tr>
<tr>
<td>Sulfate (SO₄²⁻) in mg/l</td>
<td>200 to 600</td>
</tr>
</tbody>
</table>

### 4 Conclusion

The research area has geomorphological characteristics consisting of volcanic hills with gentle to steep slopes, as well as high hills with slopes. The rock formations in this area consist of andesite and breccia tuff. The existing geological structures include bedding planes and faults with extensional types. Groundwater in this area is located at depths ranging from 13 to 40 meters from the surface, with the water table predominantly above the planned tunnel elevation.

The hydrochemical characteristics of this area indicate that the direction of groundwater flow ranges from 624 meters to 705 meters from the surface level of the sea, flowing from southeast to northwest. Analysis of Electrical Conductivity (EC) and Total Dissolved Solids (TDS) values show that the groundwater type in this area falls within the category of fresh groundwater. Most of the groundwater pH is acidic (pH < 7), except at specific observation points such as S01 and MA, which have alkaline pH values (pH > 7). The chemical facies of groundwater are dominated by Na-K-HCO₃, and this groundwater type falls into the category of alkaline earth water with a predominance of bicarbonate ions. The chemical aggressiveness of groundwater in the research area falls into category of weak.

The authors like to extend their appreciation to PT Jasamarga Jogja Bawen for granting permission to carry out study on the Tunnel B Route of the Yogyakarta-Bawen Toll Road. The financial support for this research is provided by PT. Hutama Karya (Persero) under the super specialist program scheme, which is administered by the Ministry of Public Works and Housing in the year 2022.
References

1. Republik Indonesia 2005 Peraturan Pemerintah Republik Indonesia Nomor 15 Tahun 2005 Tentang Jalan Tol (Jakarta: Republik Indonesia) p 6
2. PT Cipta Strada, PT Planosip Nusantara Engineering, PT Cipta Sarana Marga and PT Wiratman Infrastructure 2022 Laporan Detailed Engineering Design Terowongan Yogyakarta-Bawen (Kota Yogyakarta: PT Jasamarga Jogia Bawen) p 4
10. Anonymous 2014 Gambaran Umum Kondisi Daerah (Magelang: Pemerintah Kabupaten Magelang) p 1
12. Thanden R E, Sumadirdja H, Richards P W, Sutisna K, and Amin TC 2006 Peta Geologi Regional Lembar Magelang dan Semarang, Jawa Skala 1:100.000 (Bandung: Pusat Survei Geologi) p 1