1-Dimensional analysis of land subsidence in Semarang city due to anthropogenic forces

D. Sarah¹, E. Soebowo¹, N. A. Satrio¹, A. J. Syahbana¹, T. Wirabuana², Wahyudin¹

¹Research Center for Geotechnology, Indonesian Institute of Sciences (LIPI), Bandung, Indonesia
²Center for Groundwater and Environmental Geology, Indonesian Geological Agency, Ministry of Energy and Mineral Resources

*Corresponding author: dwi.sarah@lipi.go.id

Abstract. Anthropogenic factors play an important role in land subsidence. The northern part of Semarang City has long suffered from land subsidence since the 1980s. This paper aims to analyze the land subsidence process in the northern part of the Semarang city due to anthropogenic factors of groundwater exploitation and building loads. The analysis was carried out by using 1-dimensional numerical and analytical models. Results of modeling were subsequently compared to results from stable benchmark monitoring data in Madukoro and Kaligawe. Modeling results show that the contribution of groundwater level decrease accounts for 74-82% of the total subsidence, while the remaining 18-26% is attributed to the building load. The rate and magnitude of subsidence are higher at the northeastern part (Kaligawe) due to a thicker aquitard and more rapid groundwater level drop. Comparison of modeling and monitoring results signifies that the land subsidence in the northwestern part (Madukoro) approximately follows the model scenarios of groundwater level drawdown and surface loading; meanwhile the land subsidence rate in Kaligawe exceeds modeling results, most possibly due to the large discrepancy between the current conditions to modeling scenarios, presumably faster groundwater drawdown.

Keywords: Semarang city, land subsidence, modeling, anthropogenic factors, groundwater level, surface loads

1. Introduction

Land subsidence is a geological phenomenon where the ground surface moves vertically downwards due to the movement of the subsurface earth materials. The cause of land subsidence is often related to the overexploitation of groundwater. However, it can also result from natural factors such as tectonics, natural compaction of recent sediment, isostatic adjustments, peat oxidation [1,2], or the combination of all natural and anthropogenic factors. Land subsidence has affected many low-lying areas globally, making those areas vulnerable to increased coastal flooding, wetland loss, shoreline retreat, and loss of infrastructure [3]. The cities residing along the North Java coasts are inevitably prone to land subsidence [4], including Semarang City. Based on previous studies, it is understood that the land subsidence in Semarang city is mostly affected by anthropogenic factors of groundwater exploitation and building loads. Land subsidence problem is largely one-dimensional problem, where vertical deformation far exceeds the horizontal component, therefore one-dimensional analysis was chosen.

Semarang City has experienced increasing land subsidence for more than three decades. The impacts of land subsidence are widely visible in the forms of cracks and tilted buildings damaged...
houses and infrastructures, and regular coastal floods [5]. Previous studies on Semarang city land subsidence were mostly related to monitoring by geodetic methods such as GPS and interferometry using SAR imagery [6–9]. Geodetic studies are able to reveal the current rate of land subsidence at a large, spatial scale; however, the root cause and exact contribution of the factors causing subsidence cannot be clarified from geodetic method. This paper aims to analyze the land subsidence in the Semarang city due to anthropogenic causes of groundwater exploitation and building loads by 1-dimensional numerical and analytical models. Results of modeling are then compared to results from stable benchmark monitoring.

2. Study Location
This study area takes place in Semarang city that lies within coordinates of 110.4° to 110.50° E and -6.92° to -7.01° S. The geology of the study area comprises of Quaternary unconsolidated alluvial deposit of alternating clay, silt, and lenses of sand and gravels deposited on top of the Damar Formation of volcanic origin [10] (Figure 1). In this paper, particular locations analyzed are Madukoro (BM03) and Kaligawe (BM04) sites where stable benchmarks had been installed and anchored at the competent rocks of the Damar Formation. The stable benchmarks monitoring results would be used to verify the modeling results.

![Figure 1. Geological Map of Study Location [10]](image-url)

3. Methods
Numerical and analytical modeling of land subsidence was carried out to understand the contribution of anthropogenic forces of groundwater and building load to the land subsidence process and predict the future rate of subsidence based on model scenarios. Analytical and finite element analysis was employed using the 1-dimensional Terzaghi method, as elucidated in [11,12]. The subsurface model used in this model is shown in Figure 2, which comprises thick clay as aquitard at the upper part,
intercalated with lenses of Garang deltaic aquifer and sedimentary marine aquifer, and Damar Formation at the bottom part. It can be seen from Figure 2 that the clay layer becomes thicker to the east, indicating that the compressible layer prone to subside becomes more evident towards the east.

![Figure 2. West-East section of Semarang coastal plain from the correlation of boreholes (borehole data as obtained from Indonesian Geological Agency and LIPI)](image)

The parameters employed in the modeling resulted from laboratory measurements of undisturbed soil samples taken from BM03 (Madukoro) and BM04 (Kaligawe) boreholes, as presented in Table 1. The fluctuation of groundwater levels for the models were taken from observation wells that monitored the Damar Formation aquifer. The monitoring was carried out by the Geological Agency from the year 1980 to 2010 (Figure 3). The additional load was imposed based on the existing land use (i.e., residential and office buildings). Loads of buildings were calculated based on SKBI 1.3.53.1987 (Indonesian Ministry of Public Works Guidelines for Housing and Buildings Loads) consisting of static and live loads. Loads were imposed as distributed loads for simple residential housing (15 kN/m²) and four-story office building (85 kN/m²).

| Stratification    | Unit weight (γ) (kN/m³) | Hydraulic conductivity (k)(m/s) | Coefficient of compression (c_v) (cm²/s) | Modulus of elasticity (E) (kPa) |
|-------------------|-------------------------|--------------------------------|----------------------------------------|------------------------------|
| Artificial fill   | 17.5-18.1               | 7.0x10⁻⁵                       | 0.24                                   | 1.8x10⁴                     |
| Aquitard          | 8.1-15.0                | 5.9x10⁻¹⁰                      | 0.34-0.43                             | 8.2x10⁻⁵ to 9.0x10⁻⁴       |
| Aquifer           | 13.0-18.3               | 3.0x10⁻⁵                       |                                        | 1.0x10⁴ to 1.5x10⁴        |
| Conglomerates     | 21.0-22.0               | 1.0x10⁻¹²                      |                                        | 2.0x10⁵                    |
4. Results and Discussions
Three scenarios of land subsidence models were considered: (1) consolidation due to lowering of piezometric levels from the year 1980 to 2010 (Figure 3), (2) consolidation due to combined loads of residential house and lowering of piezometric levels, and (3) consolidation settlement due to combined loads of four-story office building and lowering of piezometric levels. The results of the analysis are presented in Figures 4 and 5.

Figure 3. Piezometric levels in Madukoro and Kaligawe wells from 1980 - 2010

Figure 4. Results of Madukoro (BM03) subsidence analysis
Figure 5. Results of Kaligawe (BM04) subsidence analysis

Figures 4 and 5 show that land subsidence calculation using the analytical and finite element methods generally showed good agreement with a discrepancy of less than 10%. Figure 4 shows that the subsidence due to piezometric drop during 1980-2010 in Madukoro accounts for 74% of total subsidence and loads of buildings contributes 26%, and Figure 5 shows that in Kaligawe, the groundwater level drop accounts for 82% of total subsidence and loads of buildings contributes 18%. Both Figures 4 and 5 show that residential housing only adds 4-6% to the total subsidence caused by the lowering of groundwater level.

Figure 4 also shows that from the three scenarios considered, the rate of land subsidence in Madukoro until 90% of consolidation achieved is 0.67-0.89 cm/year. For the Kaligawe site, the land subsidence rate until reaching 90% consolidation is 0.31–0.37 cm/year (Figure 5). We can notice in Figure 5 that the fastest settlement occurs from the year 1980 to 2062, that is when 50% consolidation is achieved. The land subsidence rate taken at 50% consolidation is 0.73-0.89 cm/year, respectively.

A stable benchmark has been installed by the Indonesian Geological Agency in Madukoro (Figure 6a) and Kaligawe (Figure 6b) sites since 2012, the length of the metal rod sticking out from the ground shows the total subsidence that has taken place. Land subsidence monitoring results from stable benchmarks during 2012-2017 show that the subsidence rates are 0.81 cm/year in Madukoro (Figure 7a) and 3.53 cm/year in Kaligawe (Figure 7b).

Figure 6. The stable benchmark for land subsidence monitoring in (a) Madukoro and (b) Kaligawe sites
Comparing the 1-dimensional analysis results to benchmark monitoring for the Madukoro site (Figure 4 and Figure 7a) shows that the land subsidence rate derived from the modeling scenarios is close to the monitored subsidence rate. Thus, the recent groundwater level, and external loading condition are probably comparable to the modeling assumptions. For the Kaligawe site, the subsidence rate derived from 1-dimensional analysis results is much lower than the benchmark monitoring (Figure 5 and Figure 7b). Inferred subsidence rate during 2012 to 2017 from the consolidation modeling in Kaligawe results in a rate of 1.22 to 1.49 cm/year, much lower than the monitored rate of 3.53 cm/year. It indicates that the modeling scenarios of groundwater level and surface loading underestimate the present condition. The piezometric data utilized in this analysis is based on the monitoring data collected by the Indonesian Geological Agency until the year 2010, and after that, the groundwater level monitoring was handed over to the provincial government at lesser coverage. The present groundwater level in Kaligawe industrial site is probably much lower than the condition in 2010, resulting in a higher monitored subsidence rate. The total subsidence in the Kaligawe site (Figure 5) is expected to reach 1.40 to 1.45 m, which is higher than in the Madukoro site (Figure 4) of 1.03 to 1.30 m. The higher total subsidence in the Kaligawe site is attributable to the thicker compressible layer (aquitard) than in Madukoro (Figure 2). Figure 2 also suggests that the thickening clay layer to the east could generate higher total subsidence. The higher rate of land subsidence in Madukoro is related to the intercalations of the aquifer layer that provides faster drainage of aquitard (i.e., subsidence), while in Kaligawe, the aquitard layer is of substantial thickness that it takes more time to drain the excess pore pressures, in other words, longer period and a slower rate of land subsidence.

5. Conclusion
The intense impacts of land subsidence on the built and natural environment in Semarang city obligate further steps to be taken. Adaptation and mitigation measures to this silent disaster must begin from a thorough understanding of its mechanism. Land subsidence modeling carried out in this research showed that groundwater level exploitation accounts for 74-82%, and building load accounts for 18-26% of total land subsidence. The comparison of modeling results to stable benchmark monitoring shows a similar result in the Madukoro site for the period of 2012-2018, while for the Kaligawe site, the modeling result is less than the monitored rate. This discrepancy is most likely related to model scenarios that use the older groundwater level data (1980-2010); while there is a possibility that the groundwater level in the industrial estate of Kaligawe has decreased further after 2010. Thus, further study to model land subsidence rate in Semarang city shall utilize recent groundwater monitoring data.
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