http://journal.uir.ac.id/index.php/JGEET

E-ISSN : 2541-5794
P-ISSN : 2503-216X

Journal of Geoscience,
Engineering, Environment, and Technology
Vol 10 No 3 2025

RESEARCH ARTICLE

Investigation of Aquifer Model to Potential of Ground Movement at Brau Village, Kota Wisata Batu, Jawa Timur, indonesia

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Received: Apr 15, 2024; Accepted: Aug 13, 2025.
DOI: 10.25299/jgeet.2025.10.3.16836

Abstract

Soft soils at Brau Village area, Kota Wisata Batu (KWB) usually form in alluvial highlands due to weathering of sedimentary rocks. An upper and lower aquifer of sandy layer exist between soft soil. Groundwater pools into aquifer layers and infiltration from surface water into the soft soil layers (clayey and/ or silty) generated a ground movement potential. Study will elaborate the behavior of layers of clayey and/ or silty separated by 2 (two) aquifer layers in detail causing some damages to infrastructure. Wall and/ or floor cracks at school buildings and collapse and/ or differential settlement in road pavement are a failure of soil layers due to high pore water pressure coming from direction of aquifer zone especially during rainy season. Pore water pressures were determined by rate of settlement prediction from consolidation laboratory analyzed by Ying et al (2015) and actual measurement using electromagnetic data. Research results found that gradually increment of pore water pressure would exceed a total stress in reducing an effective stress drastically and created a location of initial ground movement at the toe of slope around infrastructure area. High pore water pressure due to the increment of water volume at aquifer layer can push down soil layers with safety factor (SF) < 1.0. At the same time, ground movement would generate cracks > 10 cm width at wall and floor of school building structure; and collapse or differential settlement occurred in road construction > 18 cm depth due to bonding agent separated between soil particles.

Keywords: Sedimentary Rock, Clayey-Silty Layer, Aquifer Layer, Pore Water Pressure, Ground Movement.

1. Introduction

Ground movement can refer to the shifting, settling, or displacement of the Earth's surface. It can happen naturally or as a result of human activity. Ground movement varies in type, speed, and cause. At the study area, there are some assumptions used in this research including: downhill movement of soil, rocks, or debris due to gravity; removal of underground materials (e.g., groundwater extraction), or natural processes like the soil settlement of soil; triggered by rain, earthquakes or volcanic activity, human excavation, etc.; land use change caused by infrastructure construction can lead to ground movement (Boone, 1996; Zheng et al., 2023).

Ground movement can lead to some damages to the infrastructure objects (school building and road construction areas), such as lifting and/or differential settlement of foundations, cracks in building walls, and bumpy road surfaces (Boone, 1996; Zheng et al., 2023). Both of these research results only assessed the damages of upper structure factors relating with the nature of the ground movement, settlement profile, and degree of slip between the foundation and ground. The results did not look further into the characteristics of soil conditions, so this assessment is only based on observation results in the field.

From some observations at the field, these problems are not only limited to settlement as well as the initial assumptions, but also include swelling-shrinkage potential relating to the physical properties of expansive soil. Some cracks at the ground surface are more caused by phenomena of swelling-shrinkage according to the variation of precipitation duration (Agung et al., 2024). This paper has modelled the expansive soil at the Cibitung area using Plaxis-2D and evaluated the factor of safety (FS). The research confirmed the importance of considering expansive soil characteristics to maintain soil water content stability.

In Kota Wisata Batu (KWB) area, East Java, the phenomenon of ground movement is found at Brau Village. The location exists at the bottom of the valley surrounded by low hill areas. This zone is not only a fertile area, but also has a large potential water supply resource coming from the biggest aquifer layer to be utilized by the surrounding community and as an area for cattle farming and as one of the largest milk-producing areas in KWB. In the past condition, the stability of soil structure in a balanced condition was maintained by some vegetation in a small pine forest and there was no ground movement. But now, after being converted into agricultural and activity infrastructure areas (school building, etc.), these land use changes result in a potential for ground movement, especially during the rainy season every year (Putra & Cupasindy, 2023).

According to the numerical modeling, the primary governing factors contributing to instability in topographical sections encompass slope gradient, rainfall, saturated soil permeability, porosity, pore water pressure etc., without considering the flow model through the aquifer layer. The highest pore water pressure was determined by topographical conditions only without the soil layers.

This research aims to study and investigate high pore water pressure from an aquifer zone; seepage and slope stability that frequently cause ground movement potentials in Brau Village, KWB. Seismic and/or volcanic effects are not considered further in this study; the ground shaking parameters (amax) are only input as the average vibration as a result of the earthquake in the south of Java Island (Spudich et al., 2019). Ground shaking caused by volcanic activity is very rare to give a large vibration parameter value (Moore et al., 1998).

2. Theoretical background

2.1 Ground movement

Ground movement is a broad term that refers to any displacement or deformation of the Earth's surface. It can occur naturally or be triggered by human activity (Paul et al., 2024). Ground movement can happen suddenly or gradually, and it often has significant implications for infrastructure, safety, and the environment (Petley, 2012). There are many types of ground movement from some references (Zhang et al., 2022; Li et al., 2022; Liverman et al., 2001), however, at the study case for Brau Village, KWB is only selected based on civil engineering and/or geotechnical engineering point of view, such as: land subsidence as the gradual sinking or downward settling of the ground due to extraction of groundwater, natural compaction of soil, or decay of organic material; landslides phenomena as the rapid movement of debris or soft soil layers down a slope caused by heavy rainfall and slope instability due to human activity (Mufundirwa et al., 2010); ground heave as the upward movement of the ground, typically due to the expansion of clayey soils when they absorb water (Collins, 2008); creep phenomena as the very slow, gradual downhill movement of soft soil layers, often unnoticed but can damage foundations and roads over time; human activities like construction and excavation (Pei et al., 2018). Excavation-induced ground movements would only occur during the construction phase, but primary consolidation settlement could commence in the construction phase and continue into the operational phase for a number of years. Ground movement impacts have been assessed against evaluation criteria established for buildings, infrastructure and utilities. These criteria are preliminary only and further discussion would be required to determine appropriate acceptability criteria for various buildings like the school building at the Brau ground movement area (Dahal & Hasegawa, 2008; Gao, 2014).

Some references have developed the implementation of a ground movement for the construction performed by the observation at the field, such as: identification of ground movement existing for buildings pavement; measurement of some cracks at the building or other infrastructure like the paving block at parking area or pavement access road; and detection of the settlement occurred on buildings where consolidation settlement may occur in softer soils due to groundwater drawdown. Drawdown describes the lowering of the water table that may occur due to pore-water change and/or groundwater extraction process (Suwa et al., 2010).

2.2 Pore-water pressure

In a stable condition, water in voids of an element of saturated soil has a pressure according to the physical location of the soil element or as an impact from some external forces. One of pressures is the existing pore water pressure. Generally, pore water pressure is measured by a relative atmospheric pressure. The pore water pressure is zero (equal to atmospheric pressure) when there is no flow. This condition can be assigned as the water table or phreatic line surface, or can be stated as a hydrostatic pressure condition. However, in fine-grained soils can generate a capillary water pressure exceeding the water table level. It can be assumed as positive pore pressure which varies linearly with depth, while negative pore pressure exists above the water table. Saturation process may not work to soil layers if the location of water table is very deep and there is no capillary effect because of evaporation process at the ground surface. The rise of negative pore water pressure can stabilize the soil layers in saturated condition. Distribution of pore water pressure may not be exclusively linear where during consolidation process at the ground containing layers of permeable soil (e.g., sands) interspersed with layers of much lower permeability (e.g., clays and/or silty soils) because there is a possibility of some change of water table level. Field investigation of alteration of water table is important to be implemented. Some errors can occur during estimation of in-situ pore pressure distributions. A local infiltration or seepage process from ground surface flow during rainy season can influence the hydrostatic pressure equilibrium and generate the pore water pressure. Groundwater flow which initially steady state can change into unsteady-state extending to the full thickness of a confined aquifer with the deeper elevation. Furthermore, alteration of pore water pressure according to the specific location or depth can be predicted by one-dimensional consolidation analysis (Lee et al., 1992; Yuan-qiang et al., 2001; Kim & Mission, 2011).

In study area, there are 2 (two) aquifer layer types, at the upper and at the lower. Generally, the soft soils (clayey and/or silt) exist between these aquifer types. One of layer models using first aquifer type is a fully saturated soil layer with a thickness of H which is loaded by the upper structure from (school building and road areas) with a limit of 2 (two) aquifer layers. The other type using second aquifer type is a fully saturated soil layer with a thickness of H which is loaded by the upper structure from (school building and road areas) with the upper boundary of the aquifer layer and the lower boundary of the impermeable layer. Existing conditions at the field with both previous top and bottom boundary conditions are shown in Fig. 1.

Fig. 1 shows both aquifer layer types where they were selected into consideration in this research. Pore water pressure variation at boundary conditions were described by a general time-dependent function according to groundwater table variation. An analytical solution to the equation governing the generation and propagation of excess pore water pressures in clayey soil layers can be applied to both layer models in Fig. 1 using Terzaghi's one-dimensional consolidation theory from Terzaghi (1943) for single system of soft soil (where number of layer i = 1) (dos Santos et al., 2023).

Final form of general equation can be written as:

$$c_v \frac{\partial^2 u_i}{\partial z^2} = \frac{\partial_u}{\partial t} \qquad (1)$$

(z) is the space or depth variable in the soil element. Partials differentials must be used because pore water pressure *(u)* is a function of both the position *(z)* and time *(t)*. And, the cofficient of c_v contains the material properties governing the consolidation process, furthermore, c_v is mentioned as the coeficient of consolidation, where:

$$\boldsymbol{c_v} = \frac{\boldsymbol{k}}{\boldsymbol{\gamma_w}}\ \frac{\boldsymbol{1+e_0}}{\boldsymbol{a_v}} \tag{2}$$

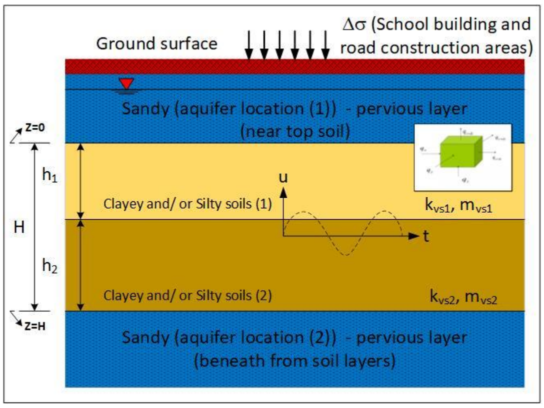
(a_v) is a a constant over the increment of applied stress; and (e_0) is initial void ratio of soil element.

There is no analytical solutions in previous research (Schiffman & Stein, 1970; Conte & Troncone, 2006; Ho et al., 2014; Huang et al., 2021). A complex upper boundary model in Fig. 1 involves the layered characteristic into account. However, with analogy by using Terzaghi's equation, except for pore water pressure at the upper boundary, the general equation governing and propagation of pore water pressure in existing soil layers (clayey and/or silty soils) can be expressed (Ying et al., 2015).:

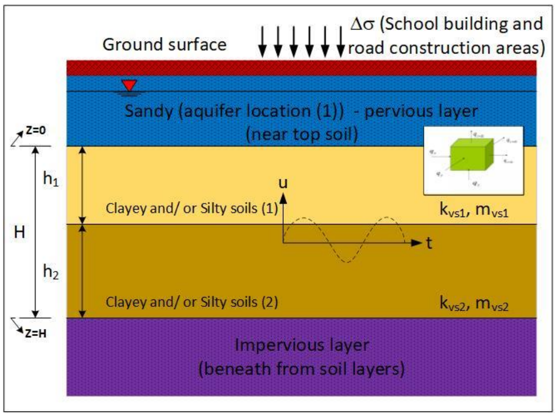
$$c_{vsi}\frac{\partial^2 u_i}{\partial z^2} = \frac{\partial_{ui}}{\partial t} \quad (i = 1, 2) \tag{3}$$

$$c_{vsi} = \frac{k_{vsi}}{\left(\gamma_{w}\, m_{vsi}\right)} \quad (i = 1, 2) \tag{4}$$

k_{vsi} and m_{vsi} are the coefficient of permeability in the vertical direction and the coefficient of volume change of the soil, respectively. It can be assumed that k_{vsi} and m_{vsi} are constants during analytical solution process and easily solvable (Leroueil, 2001).



A fully saturated soil layer with a thickness of H which is loaded by the upper structure from (school building and road areas) with a limit of 2 (two) aquifer layers



A fully saturated soil layer with a thickness of H which is loaded by the upper structure from (school building and road areas) with the upper boundary of the aquifer layer and the lower boundary of the impermeable layer

Fig. 1. One-dimensional consolidation model of two clayey soil layers due to groundwater in both previous top and bottom boundary conditions

Furthermore, detail for mathematical model resolve the general equation (2) with using analytical solution of harmonic groundwater fluctuations and an resolving of analytical solution of general groundwater fluctuations. All these solutions in generating pore water pressure of double-layered system are obviously more complicated than a single layer system. In this paper, calculation of pore water pressure of Fig. 1 uses one of numerical methods (EMACS-programming software). Prediction of excess pore water pressure at any time and depth was formulated by using a principle of superimposing all components of determined u_i *(z,t)*. Pore water pressure (u_i) could be resolved by analytical solution for u_i *(z,t)* which was developed to $\bar{u}_i\,(z, t)$ formed. Pore water pressure could be determined in dimensionless parameter.

Initial of pore water pressures increment is represented as a volume change of water at the aquifer zone according to duration of precipitation. Magnitude of pore water pressure during consolidation process can be determined by a model of soft soil double layers with both pervious at top and bottom or pervious at top and impervious at bottom. Axial and lateral displacement due to the actual ground movement is shown in Fig. 3. Ground movement expected by the change of magnitude of pore water pressure is depended on the location of the aquifer zone (Agraine et al., 2020). Pore water pressure from a hydrostatic pressure exceeding a total stress can decrease an effective stress (Di Francesco, 2013; Ndiaye et al., 2014). Effective stress plays a basic role in the ground movement potential.

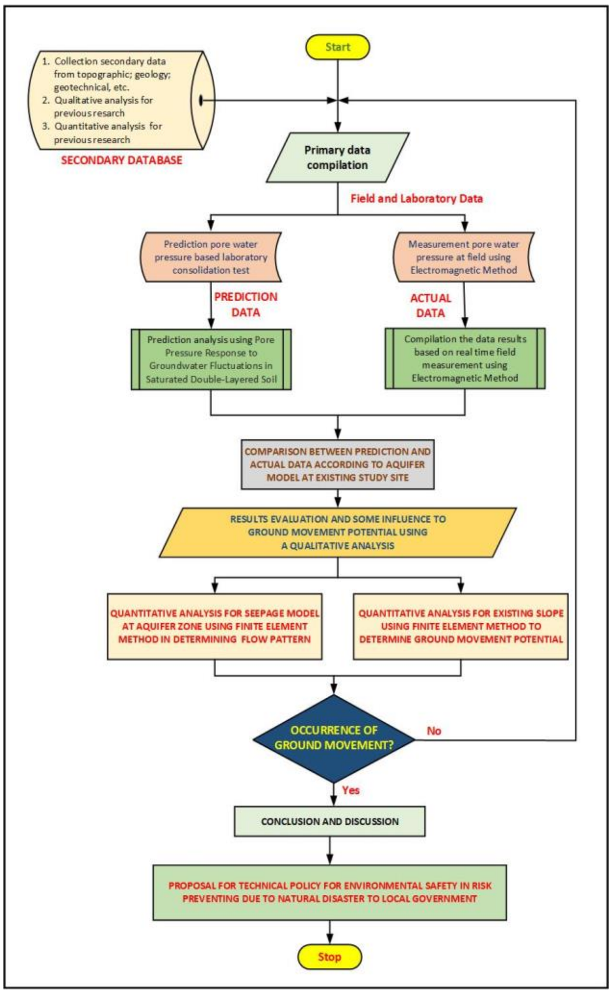


Fig. 2. Flowchart of research

3. Research method

3.1 Flowchart

In general, research implementation uses laboratory consolidation works for prediction of pore-water pressure and field survey for actual measurement of pore-water pressure using a geophysical method. A flowchart of research implementation is created in Fig. 2. Pore water pressure data can be predicted by a consolidation test results using an undisturbed sample, and then, these prediction results are compared with an actual measurement directly at the field.

3.2 Description of study site

Brau Village, Gunungsari, Batu, East Java is a village with an average elevation of around 1091 meters above mean sea level (MSL), topography consists of mountains, hills, and valleys. The location of the study site exists at -7^{o} 50’ 44,94” SL and 112^{o} 29’ 42,03 EL and is shown in Fig. 3. The local community reported that the potential for landslides in the Brau Village is very high. Most infrastructure was built without considering the existing groundwater level. Generally, soft soil layers constituted the general profile at the site and many water sources were found in this area through the aquifer layers consisting the sandy soil.

One of the disasters caused by the ground movement was Brau Elementary School, all parts of the building structure including the shallow foundation, wall, and floor systems were damaged by several cracks, heaving, etc. after the heavy rainfall hit the existing area during March, 2024. Some damages were also on the country road construction, such as differential settlement, heaving, etc., and very difficult to pass and serve each vehicle. From some observation data collected at the field, that the ground movement increases during the rainy season, likewise, there has been an increase in the width of cracks.

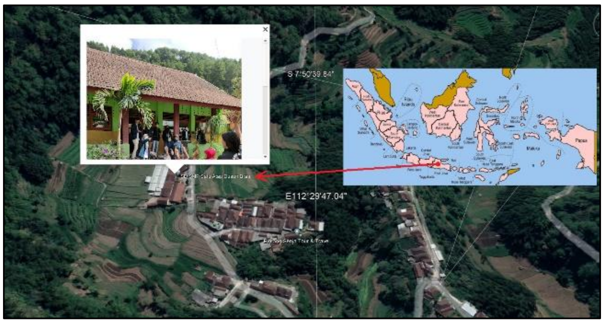


Fig. 3. Study site at Brau Village, KWB

Some damages of wall and floor of school building structures and collapse and/ or differential settlement of road construction due to a ground movement are easy to understand. Fig. 4 and 5 shows the scheme of alteration soil foundation behavior at the existing infrastructure areas. Based on the field observation, some damages of these infrastructure areas were expected by the ground movement (building school and road). Axial and lateral ground movements can be generated by a concentration of vertical and lateral stresses working at the axis and the edges of the infrastructure where high pore water pressure occurred. A large changes can be observed in the plastic points of soil foundation at the existing area. Shallow foundation system were embedded very close to the aquifer layer. Change of pore-water pressure gradually can be suspected to be the main problems faced in the field and cause the ground movements towards the lower elevation.

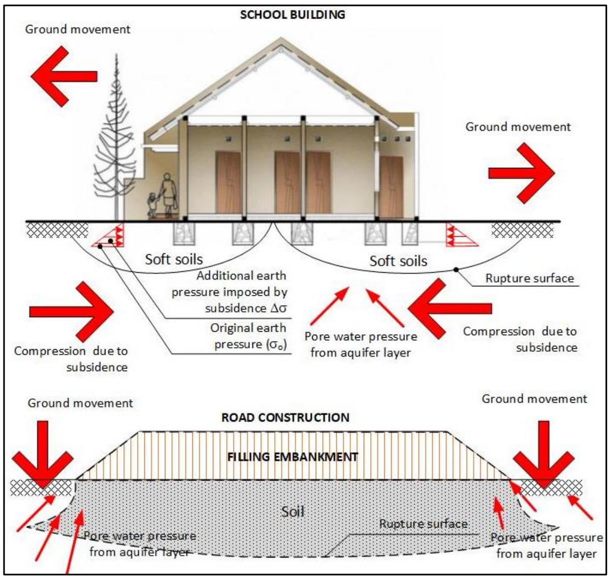


Fig. 4. Behavior of soil strain area below the structure

Fig. 5. Existing width of the cracks or fracture occurred

3.3 Geological and geotechnical point of view

Brau Village as a part of KWB consists of four formations, such as Arjuna Welirang $(Q_{vaw}\ \&\ Q_{v(p)})$, and then, Anjasmara Tua $(Q_{pat}\ \&\ Q_{p(kb)})$ for volcanic rock deposits. Rock formations are dominated by compacted igneous rocks, while surface layer is dominated by clayey and/ or silty layers from sedimentary rocks deposits (Fig. 6). Meanwhile, fine grain layers from sedimentary rocks fragments have properties which are easily separated, not compacted, and easily saturated by water, thus, these geological classification have a potential to move all layers of ground.

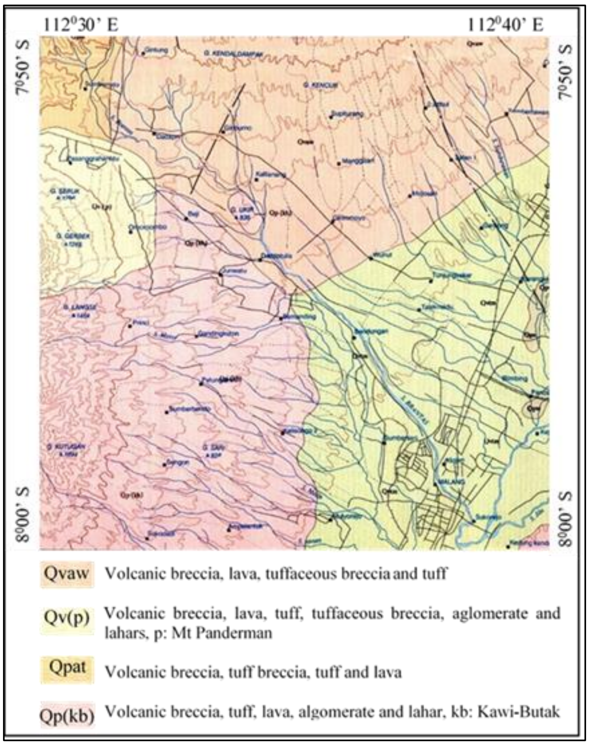


Fig. 6. Geological map of Brau Village as a part of KWB (Source: Peta Geologi Lembar Malang, 1992)

From a geology point of view, precipitation or surface water will infiltrate into the ground surface through various soil layers. There are 2 (two) types of rocks passed by the groundwater (Feng et al., 2021), such that: firstly, permeable layer that can be penetrated by groundwater. These layers consist of gravel, sand, pumice, and some cracks in rock coming from limestone. Secondly, the impermeable layer which consists of marl and clay (loam). Groundwater will be stored or collected at the aquifer zone. The aquifer is a soil layer that can contain and release groundwater. According to Fig. 6, the aquifer zone at Brau Village can be established by rock layers, such as volcanic breccia (containing limestone flakes), tuff and/or tuffaceous breccia (containing pumice flakes), and lava (forming the gravel or sand layers) (Yun et al., 2022).

3.4 Prediction of pore-water pressure

According to several references, there are 4 (four) types of aquifer zones, such as unconfined; confined; semi-confined; and semi-unconfined. An aquifer layer can be assumed by the unconfined saturated layer and has a groundwater table or a phreatic line level. A phreatic line level has a hydrostatic pressure equals to the atmosphere pressure. Bottom of an unconfined aquifer is bounded by the aquitard. Aquitard is a saturated layer that only allows to release of a little volume of groundwater. Some water in a confined aquifer is limited by the aquitard layers at above and below, and a degree of saturation pressure of the aquifer is larger than atmospheric pressure. A semi-confined aquifer is an aquifer that is completely saturated by groundwater. The upper part is limited by a semi-permeable layer, while the lower part is an impermeable layer. The bottom layer of a semi-unconfined aquifer is impermeable, while the top layer is a fine-grained material that allows a groundwater movement. This aquifer is also called the transition between an unconfined and a semi-confined aquifer. Potential ground movement at Brau Village is more caused by high pore water pressure from confined aquifer zones with deeper elevations. Preloading and/or upper infrastructure loading can also be a trigger to change hydrostatic pressure in an aquifer zone and stability of soil water content. An uncontrolled increase of the pore water can exceed the effective stress of soil layers, and finally, the soil shear strength decreases and the soil layers will move in all directions (Guerriero & Mazzoli, 2021). The slip line or collapse line at the slope area can be concerned with the tuff layer based on Fig. 6. Some previous study mentioned that these layers formed by a composed of weathered soil, fine tuff, and lapilli tuff. These layers are not only as a porous media, but also they can store water, however sometimes they act as a barrier to groundwater flow. And, the same time they will create the pore water pressure in these layers (Lin et al., 2015; Azahar et al., 2018).

High pore water pressure caused by an alternating water volume at the aquifer zone level can also generate landslides. Changes in groundwater level can affect physical properties of the soil, such as strength and stability. High groundwater levels can cause the soil to become soft and unstable, besides the specific soft soil also containing montmorillonite. Ground surface at the slope will move towards lower elevations which is initiated by erosion condition (Al-Yaqoub et al., 2017; Devkota et al., 2022).

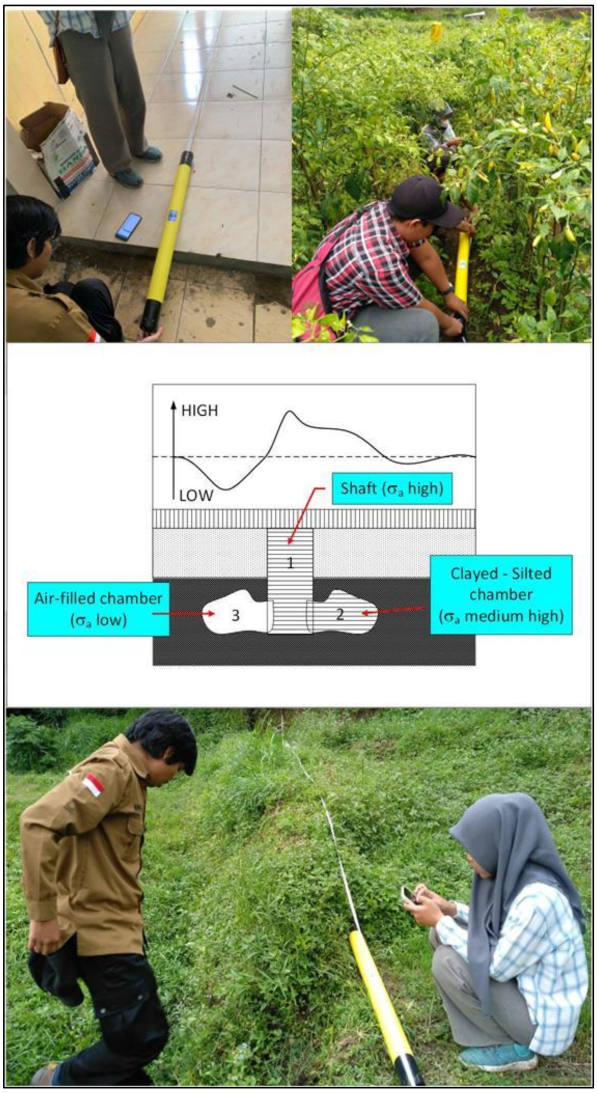


Fig. 7. Field measurement uses electromagnetic devices

3.5 Actual measurement of pore-water pressure

Geophysical method was used for actual measurement of pore water pressure at the aquifer zone in subsurface conditions using the electromagnetic instrumentation. The measurement parameters are responses to electromagnetic radiation based on conductivity and inductance properties. This method has the advantage because this instrumentation can transmit reflected waves deeper than other methods (Vozoff, 1980). Schematically measurement actual pore water pressure at the field is shown in Fig. 7 (Heimovaara et al., 1995; Brovelli & Cassiani, 2008). Some patterns of actual measurement were carried out at this study site were aimed at understanding the nature of soil water and pore water pressure model at aquifer based on energy balance between soil layers and atmosphere boundary conditions. There were 4 (four) tracks of trajectory conducted during measurement (Tao et al., 2021). Ground movement at building school and road construction areas were not influenced by T1 and T4 tracks. Trajectory T2 and T3 were selected at the location where a landslide occurred in a school building closing to road construction areas. Data processing from actual field measurement used the electromagnetic application software (AIDU-Prospecting application). This software could describe in a two-dimensional view depth of the groundwater table and pore water pressure at an aquifer zone (Maggirwar & Umrikar, 2011).

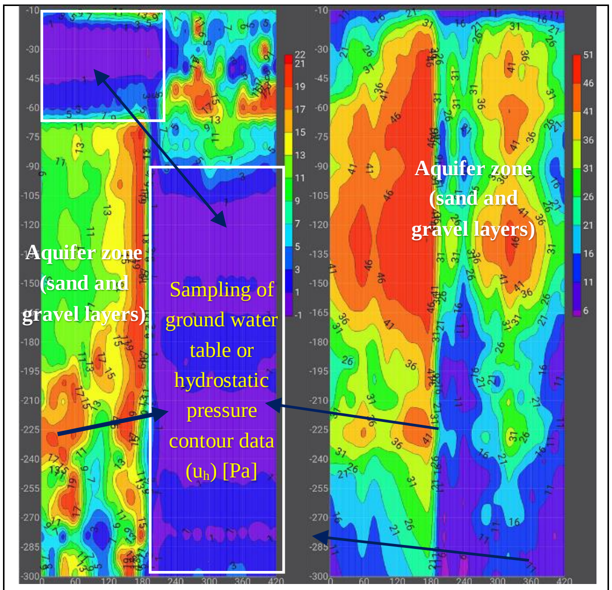
3.6 Ground movement potential analysis using FEM

Ground movement can be caused by a groundwater flow pooling into aquifer zone and infiltration from surface water into the ground. The potential of ground movement can be occurred by water seepage to increase the weight of soft soil layers. Water seepage from aquifer zone can increase pore water pressure and the soil layers become swelling. The pore water pressure can make unstable condition of the slope. There are 6 (six) types of slope sliding in the study area continually occurred, namely: translational, rotational, block movements, rockfalls, soil creep, and debris flows. General conditions when the ground movement first begins can be explained by the appearance of cracks or fractures or fissures on the slopes parallel to the direction of the cliff; usually, ground movement occurs during the rainy season; the sudden appearance of new water springs; the cliffs at the slope were fragile and/ or weathered and gravel started to move.

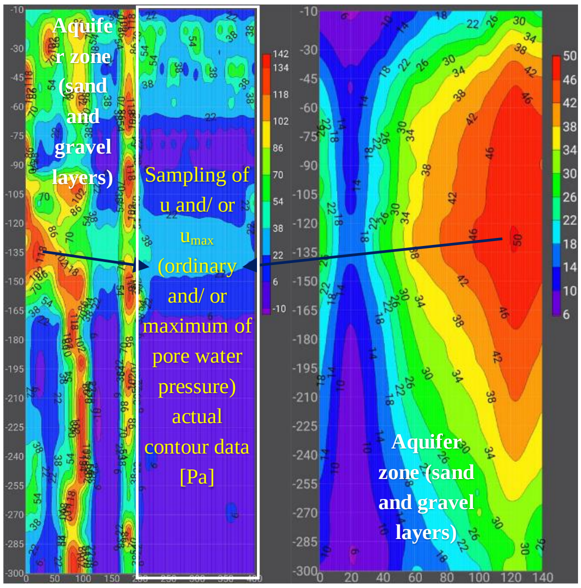
One of the causes of landslides is the existence of ground movement potential. Slope stability can be disturbed by water seepage coming from the aquifer zone and several combination external loads from the superstructure. Some simulations of seepage and slope stability during rainy seasons individually and/or combination were analyzed by 2D-FEM (Geostudio-application software) in order to predict the magnitude of movement (Yong & Hanna, 1977; Liao et al., 2007). Cross-sectional model was adopted from the Yearly Report of BPBD office (2019). Soil layer and input parameter were input as the geotechnical modeling during 2D-FEM analysis.

4. Results and Discussion

After data processing using the AIDU Prospecting application to obtain a two-dimensional (2D) view depth of the groundwater table. From 2 (two) measurements in the Electromagnetic method, Trajectory T2 & T3 are more focused for this research because groundwater flows were connected with a thick very large aquifer zone. Trajectory T2 & T3 existed at the location of the school building and road construction areas in Brau Village. Results investigation of the groundwater level on the T2 & T3 routes are shown in Fig. 8, the depth of the groundwater level was more and less than 10 m, respectively at the aquifer zone. Some damages at both locations could be ascertained by the thickness and location of the aquifer zone and soil conditions containing montmorillonite particles with a plasticity index (PI) value larger than 30% from physical properties at laboratory work.



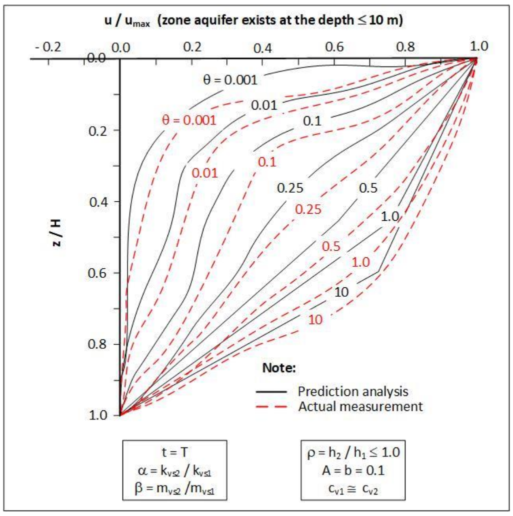
Typical results of track T2: Resistivity estimation at aquifer zone T2:
1. First configuration (0=1-5 mV/nT;
2. Second configuration (1=6-16 mV/nT)



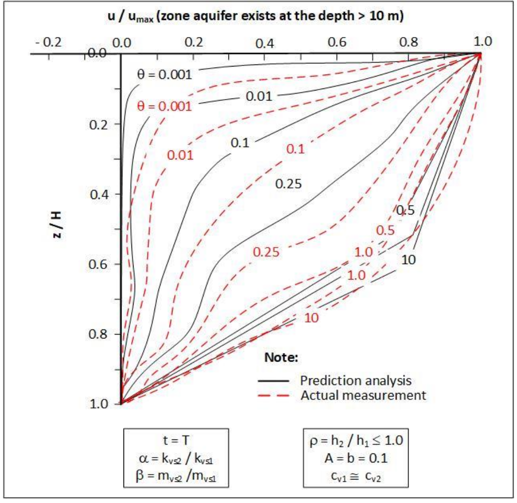
Typical results of track T3, Resistivity estimation at aquifer zone T3:
1. First configuration (0=10-22 mV/nT;
2. Second configuration (1=6-18 mV/nT)

Fig. 8. Typical groundwater level and pore water pressure at T2 and T3 tracks for aquifer zone

Fig. 8 used the results of actual measurement data of pore water pressure at the field and it could be assumed as the distribution of soft soil pore water pressure from the aquifer zone, where the aquifer zone cosnsists of sand and gravel layers. These data were compared to the numerical analysis results from prediction analysis at Fig. 9, where the *(u)* (ordinary or hydrostatistic pore water pressure) were divided by *(u_{max})* (maximum pore water pressure).



Comparison of changes in pore water pressure with changes in thickness and time for 2 (two) aquifer layers



Comparison of changes in pore water pressure with changes in thickness and time with the upper boundary of the aquifer layer and the lower boundary of the impermeable layer

Fig. 9. Dimensionless parameter of pore water pressures between prediction analysis & actual measurement

The pore water pressure distribution pattern from prediction and actual data is very significantly different as shown in Fig. 9. However, the distribution pattern of pore water pressure shows almost similar behavior according the soft soil layers between the aquifer zones at depth of more and less 10.0 m depth. Variation values of pore water pressure in 2 (two) soil layers between the aquifer zone is more caused by some considerations when assessing the parameter of coefficient permeability (k_{vs1} and k_{vs2}) from undisturbed sample in laboratory consoldation test.

Fig. 10 shows the typical results of seepage analysis based on the infiltration soil permeability *(k)* = 8.0.e^{-05} m/day) during average of precipitation potential in every year during the rainy season. In here, permeability values for each layer play an important role with concern near the aquifer zone during analysis. Some cracks occurred at school buildings and road construction areas could be more caused by seepage flow coming from the aquifer zone and through the soil layers with low of permeability values. Initially, the ground movement would be started from lower layers to the ground surface. Infiltration water filled the all pores of soil would change of volumetric water and soil effective stress in several times during the rainy season. This phenomena was always occurred in saturated soil zone or near ground surface. Then, seepage in vertical and lateral directions could push down soil layers near an aquifer zone because pore water pressure increases gradually. A cracked or fissured from below to ground surface in unsaturated zone has been explained by some researchers (Fredlund et al., 2010; Saadeldin & Henni, 2016).

Fig. 10 also explained that alteration water content would cause change desaturation process to the soft soil layers around the aquifer zone. Although determining the water content was easier than determining permeability or shear strength during desaturation, the test is still time-consuming and it was not easy to determine existing pore water pressure level at real time investigation. Besides that, the pore water pressure due to the alteration water content in soft soil layers was difficult to correlate each other. Thus, some cracks or fractures occurred at study area could be explained by the change water content and/or the high pore water pressure. This study was similar to Wu & Zhou (2023), LorellLLa & Schiliro (2018), and Zhang et al. (2024) when simulation process a model of seepage flow at a slope and generated a cracked at the ground surface. This matter requires further research to determine the main cause of cracks or fractures at the study location. However, because the parameter of water content is closely related to the montmorillonite particles, this issue is not discussed in detail on this occasion. Stability pore water pressure due to seepage flow initially was determined by a normal condition of soil. permeability magnitude according to existing area of study, especially during dry season or when the first time a simulation analysis was carried out. Then, large water infiltration into the soil layers from rainfall during rainy season at the ground surface could change the pore water pressure in low permeability due to some flow barriers (e.g. deposits settled at the pore of soil, etc). The soft layers could not completely saturated and the same time it had to drain groundwater in large quantities from the aquifer zone and water infiltration. Besides that, the continually increasing of pore water pressure would exceed the limitation of total stress in the soft soil, and reduce effective stress, so that the soil layers could not retain the high pore water pressure and flow the groundwater during seepage process. Finally, ground movement would be occured and signed by some cracks at the ground surface. Furthermore, some cracks could also arise when a reduction process occurred at soil matric suction of the unsaturated soil zone. In this initial condition, a large water volume could enter the large pores of soil layers with low permeability directly before they went to enter to small pores and water also could flow through or not through cracks or fissures also supported by the high capillary (Kristo et al., 2019).In this way, cracks or fissures could generate wider and push down the nearest soil layers in all directions, eventually has caused soil movement or landslide and pulling out of all foundation layers towards to the toe of slope.

Final report from BPBD (2019) stated that rainfall reaches the average amount of rain 138 days and the rain intensity is around 160 mm/month every year. During the rainy season, ground movement would exist that was initially by the small cracks and/ or fissures. Fig. 11 shows slope stability together with seepage analyses. After returning to normal or lower than before, pore water from aquifer zone was stable, but cracks and/ or fissures still exist because soil layer was already in a plastic condition.

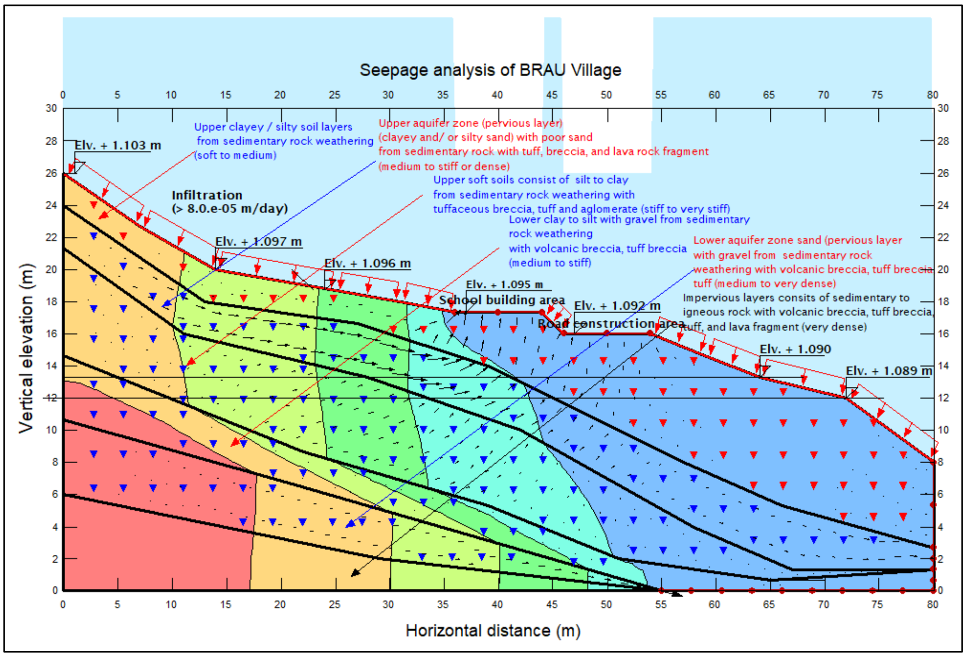


Fig. 10. Typical results of seepage analysis based on the boundary condition during the rainy season

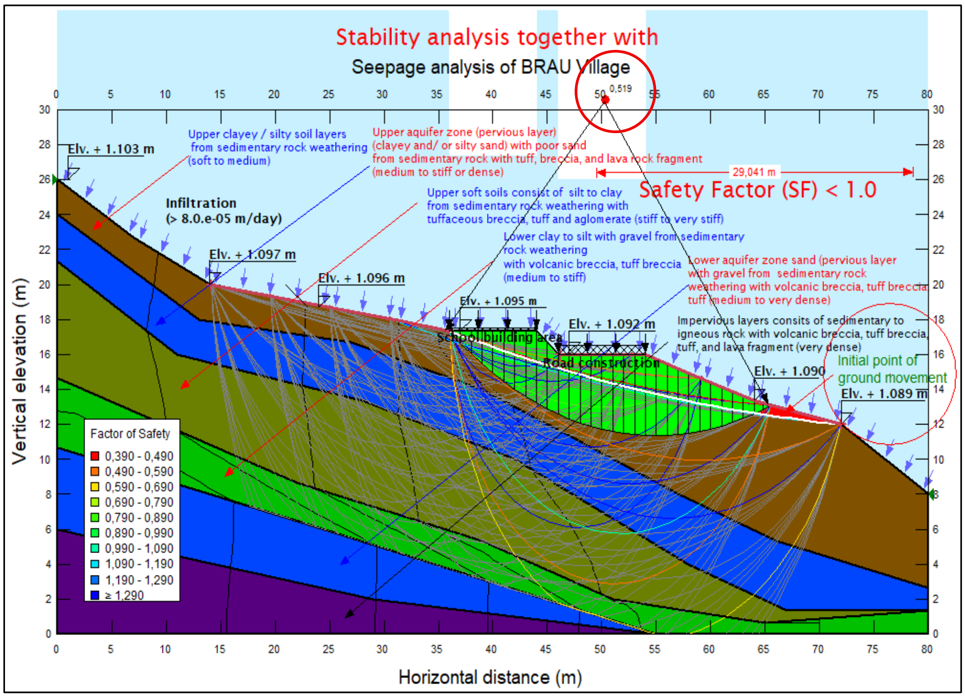


Fig. 11. Typical results of stability analysis based on the boundary condition during the rainy season

The pore water pressure from the aquifer zone, which was initially stable and changed drastically when the rainy season begins. With high rainfall in a long rain periods, pore water pressure continuously increased and started to compress all fine-grained soil particles in all directions (especially for clayey and/or silty layers) from below the soil surface. Fractures and cracks started to appear on the ground surface and shift all infrastructure that was near the concentration of high pore water pressure to the soil layers. The width of fractures and/ or cracks based on some observation during actual measurement at the field indicated a similar result to the analysis in Fig. 11 with a safety factor (SF) < 1.0. These fractures and/ or crackers cumulative increased from year to year during the rainy season. The last actual measurement when the study was carried out showed that the average width of fractures and/ or cracks was more than 15.0 cm at the ground surface. Ground movement would generate cracks > 10 cm width at wall and floor of school building structure; and collapse or differential settlement occurred in road construction > 18 cm depth due to bonding agent separated between soil particles. The length of ground movement in the direction towards the toe of the slope reaches 30.0 m including school building and road construction areas. The similar studies were conducted by some researchers (Schuste et al., 2021; Grimstad et al., 2010; Yin & Tong, 2011; Boyle, 2012). and discussed the potential fractures and/ or cracks caused by the high pore water pressure. They elaborated high pore pressure from a coastal aquifer; a homogeneous porous medium;a multilayer medium; etc. by using theoretically and/ or rheology of soil or rock mass.

Content of montmorillonite of soil layers with plasticity index (PI) larger than 30% also contributes to accelerate the swelling potential due to change of initial water content. All zones of unsaturated soils of study area would have a potential for swelling-shrinkage to generate some cracks.

Some previous special studies from geological and geotechnical engineering of soft soils (clayey and/ or silty deposits) in Brau village, it is believed that soft soil layers formed in Brau Village have a combination with aquifer layers for hundreds of years according to the rock age geologically. Flows of groundwater from the aquifer zone are initially stable because they were supported by vegetation that was able to absorb water (Agung et al., 2023). Pore water pressure of soil layers was not alternated significantly due to land use change, generally, the residents of Brau Village used as agricultural or plantation areas. Thus, the seepage flow from aquifer zone was still maintained, so that the pore water pressure could always stable in the dry season or rainy season. Green open space at the study location and a good surface drainage system were provided. However, the development or addition of infrastructure or buildings in this area has caused many problems with the natural water storage system in the aquifer zone. Land clearing; some additional loadings from new superstructure and foundation systems have damaged the groundwater flow pattern originating from the aquifer zone The soil layer contains many montmorillonite particles which makes the soil layer swell easily (Nelson et al., 2001; El-Garhy & Wray, 2004; Zhou et al., 2023).
. The amount of montmorillonite content should be checked in detailing works using micro-analysis methods in the soil mechanics laboratory (XRF, XRD, etc). In this research, the results of macro testing are provided and indicated that these soft soil layers can be classified as swelling soil (expansive soil type). Apart from that, the handling of fractures and/or cracks on the ground surface is not managed properly, so incoming surface water further increases soil movement. Water surface absorbed by cracks and/or fissures will change the water content of the soil quickly and will exceed its liquid limit, resulting in the potential for faster expansion (swelling-shrinkage potential) and the creep condition will soon be achieved eventhough there is no significant additional load.

The differences in pore water pressure results from predictions and actual measurements in the field that occur are more due to consolidation testing procedures on undisturbed samples and the difficulty of allocating data from field measurements to undisturbed sampling points in the field. Besides that, the parameter values from test results in the consolidated laboratory also vary greatly, so that when analyzing predictions using mathematical equations they are also different from one another. Some plotting of the actual measurement should be exist in dry and rainy seasons, because distribution of the pore water pressure is quite depended on groundwater fluctuation. And, the real-time measurement implementation was difficult to equalize with the testing results at the laboratory of consolidation test. However, the shape of the resulting isochrones remains closing to Terzaghi's theory (1925). After an accurate examination from theory of historical solution, and interpretation of laboratory consolidation data, this research work proposes a solution that can be considered correct as it solves the differential equation and, at the same time, allows correct interpretation of experimental data through actual measurement at the field.

Model of groundwater flow also influenced to the ground movement. Pattern of groundwater flows was depended on an existing aquifer zone model as a part of the subsurface of soil layers. Observation at the field shows that groundwater flows were connected, so that the flows of groundwater could be very large, especially during the rainy season. These big flows of groundwater could create a lot of increments of pore water pressure in various directions. Then, all pore water pressures could change soil shear strength and when they exceed the effective stress, the ground movement would create some potential of ground movement. Furthermore, rising ground movement due to the high pore water pressure could cause fractures or cracks before the entire area experienced landslides; heaving; differential settlement, soil collapse, etc.

5. Conclusion

High pore water pressure coming from the aquifer zone during rainy season is one of the factors causing potential ground movement in Brau village. Besides that, the saturation process of soil layers during a high rainfall can change of physical and mechanical properties and damage school buildings and road construction areas.

Results from prediction analysis using one-dimensional consolidation theory and actual measurement using the electromagnetic instruments are significantly difference. Some errors is more caused when determining soil permeability as the input parameter during prediction analysis. Besides that, the physical properties from laboratory works evaluated the montmorillonite using macro physical properties test, and the results indicated that soil layers (clayey and/ or silty soils) has plasticity index larger than 30%. Thus, the soil layers has also a potential swelling and shrinkage when the initial water content firstly change.

Seepage and slope stability analyses show that the pore water pressure plays important role in potential of ground movement in Brau village. Pore water pressure from aquifer zone increases during the rainy season. High pore water pressure exceeding the total stress will separate the soil particle drastically during desaturation process. Some cracks and/ or fissures start to occur when soil effective stress decrease and change the soil to the plastic condition.

For further advanced study is proposed to use the cone penetration test and pore water pressure (CPTu) and/or piezometer instrumentations. Thus, the implementation of actual measurement in the field can be performed together with the taking of undisturbed samples for a one-dimensional consolidation test at the laboratory.

One of parts as the research output is to evaluate in relocating the school building to more safely place. The research results also encourage the local government of Kota Wisata Batu in finding a new location for school building areas in Brau Village region.

Notation

a_v : A constant over the increment of applied stress
a_{max} : An existing of peak ground acceleration (PGA) at soil layer from the bedrock
$c_{vs1 \text{ or } 2}$: Coefficient of consolidation of the upper layer and the lower layer
e_0 : Initial void ratio of soil element
H : Total thickness of soil layer
k : General cofficient of soil permeability
$h_{1 \text{ or } 2}$: Thickness of first and second soil layers
$k_{vs1 \text{ or } 2}$: Coefficient of permeability in the vertical direction of the upper layer and the lower layer
$m_{vs1 \text{ or } 2}$: Coefficient of volume change of the upper layer and the lower layer

SF : Safety factor
T : Period of time-dependent function describing the pore pressure variation at
T_v : Time factor
t : Time
u : Pore water pressure
u_i : Pore water pressure at depth z and time t when the pore water pressure at the boundary is kept unity in the upper or lower layer (i = 1, 2)
u/u_{max} : comparison of pore water pressure in dimensionless
z : Spatial coordinate or depth variable in the soil element
z/h : Comparison between spatial coordinate and total thickness of soil layer in dimensionless
$\square_w$: Unit weight of water

Acknowledgments

The author would like to gratefully acknowledge for BPBD-Kota Wisata Batu (KWB) office for all the support when carrying out this research and Several colleagues helped relating with soil tests in the soil mechanics laboratory.

References

Agraine, H., Bouali, M. F., & Messameh, A. H., "Numerical Analysis of One-Dimensional Consolidation in Fine-Grained Soils," Key Eng. Mater., vol. 857, pp. 334–340, 2020, doi: http://dx.doi.org/10.4028/www.scientific.net/KEM.857.334.

Agung, P. A. M., Salimah, A., Yatmadi, D., & Hasan, M. F. R., "Ground movement risk analysis of slope with expansive soil for sustainable infrastructure development," in ICOAGPG-2024, T. Sipil_UNS, Ed., Solo: UNS, 2024, pp. 1–11. doi: https://iopscience.iop.org/article/10.1088/1755-1315/1462/1/012028.

Agung, P. A. M., et al., "Compilation of Parameter Control for Mapping the Potential Landslide Areas," Civ. Eng. J., vol. 9, no. 4, pp. 974–989, 2023, doi: https://doi.org/10.28991/CEJ-2023-09-04-016.

Al-Yaqoub, T. H., Parol, J., & Znidarcic, D., "Experimental investigation of volume change behavior of swelling soil," Appl. Clay Sci., vol. 137, no. 7, pp. 22–29, 2017, doi: http://dx.doi.org/10.1016/j.clay.2016.11.018.

Azahar, M. A., Mahadi, N. F. Z., Rusli, Q. N., Narendranathan, N., & Lee, E. C., "Use of geophysics for site investigations and earthworks assessments," in 10th Malaysian Road Conference & Exhibition, P.-L. Publishing, Ed., Malaysian: IOP Conf. Series: Materials Science and Engineering 512 (2019) 012007, 2018. doi: 10.1088/1757-899X/512/1/012007.

Boone, S. J., "Ground-Movement-Related Building Damage," J. Geotech. Eng., vol. 122, no. 11, pp. 886–896, 1996, doi: https://doi.org/10.1061/(ASCE)0733-9410(1996)122:11(886).

Boyle, J. T., "The creep behavior of simple structures with a stress range dependent constitutive model," Appl. Mech., vol. 82, no. 4, pp. 495–514, 2012, doi: https://doi.org/10.1007/s00419-011-0569-1.

Brovelli, A., & Cassiani, G., "Effective permittivity of porous media: a critical analysis of the complex refractive index model," Geophys. Prospect., vol. 56, pp. 715–727, 2008, doi: https://doi.org/10.1111/j.1365-2478.2008.00724.x.

Collins, T. K., "Debris flows caused by failure of fill slopes: Early detection, warning, and loss prevention," Landslides, vol. 5, no. 1, pp. 107–120, 2008, doi: http://dx.doi.org/10.1007/s10346-007-0107-y.

Conte, E., & Troncone, A., "One-dimensional consolidation under general time-dependent loading," Can. Geotech. J., pp. 1107–1116, 2006, doi: https://doi.org/10.1139/t06-064.

Dahal, R., & Hasegawa, S., "Representative rainfall thresholds for landslides in the Nepal Himalaya," Geomorphology, vol. 105, no. 3–4, pp. 429–443, 2008, doi: http://dx.doi.org/10.1016/j.geomorph.2008.01.014.

Devkota, B., Karim, M. R., Rahman, M. M., & Nguyen, H. B. K., "Accounting for Expansive Soil Movement in Geotechnical Design—A State-of-the-Art Review," Sustainability, vol. 14, pp. 1–27, 2022, doi: https://doi.org/10.3390/su142315662.

Di Francesco, R., "Exact Solution of Terzaghi's Consolidation Equation and Extension to Two/Three-Dimensional Cases," Appl. Math., vol. 4, no. 4, 2013, doi: http://dx.doi.org/10.4236/am.2013.44099.

El-Garhy, B. M., & Wray, W. K., "Method for Calculating the Edge Moisture Variation Distance," J. Geotech. Geoenvironmental Eng., vol. 130, no. 9, pp. 945–955, 2004, doi: http://dx.doi.org/10.1061/(ASCE)1090-0241(2004)130:9(945).

Feng, K., et al., "Dynamic evolution and frequency analysis of hydrological drought from a three-dimensional perspective," J. Hydrol., vol. 600, pp. 1–14, 2021, doi: https://doi.org/10.1016/j.jhydrol.2021.126675.

Fredlund, D. D., Houston, S., Nguyen, Q., & Fredlund, M. D., "Moisture Movement Through Cracked Clay Soil Profiles," Geotech. Geol. Eng., vol. 28, no. 6, pp. 865–888, 2010, doi: http://dx.doi.org/10.1007/s10706-010-9349-x.

Gao, W., "Forecasting of landslide disasters based on bionics algorithm (Part 1: Critical slip surface searching)," Comput. Geotech., vol. 61, pp. 370–377, 2014, doi: https://doi.org/10.1016/j.compgeo.2014.06.007.

Grimstad, G., Degago, S. A., Nordal, S., & Karstunen, M., "Modeling creep and rate effects in structure anisotropic soft clays," Acta Geotech., vol. 5, no. 1, pp. 69–81, 2010, doi: http://dx.doi.org/10.1007/s11440-010-0119-y.

Guerriero, V., & Mazzoli, S., "Theory of Effective Stress in Soil and Rock and Implications for Fracturing Processes: A Review," Geosciences, vol. 11, no. 3, pp. 1–35, 2021, doi: https://doi.org/10.3390/geosciences11030119.

Heimovaara, T. J., Focke, A. G., Bouten, W., & Verstraten, J. M., "Assessing Temporal Variations in Soil Water Composition with Time Domain Reflectometry," Soil Sci. Soc. Am., vol. 59, no. 3, p. 689–698, 1995, doi: https://doi.org/10.2136/sssaj1995.03615995005900030009x.

Ho, L. H., Fatahi, B., & Khabbaz, H., "Analytical solution for one-dimensional consolidation of unsaturated soil deposit subjected to step loading," Unsaturated Soils Res. Appl., vol. 2, pp. 1763–1769, 2014, doi: http://dx.doi.org/10.1201/b17034-258.

Huang, Y., Li, T., & Fu, X.-L., "Consolidation of Unsaturated Drainage Well Foundation with Smear Effect under Time-Dependent Loading," KSCE J. Civ. Eng., vol. 2346, 2021, doi: http://dx.doi.org/10.1007/s12205-021-0086-x.

Kim, H.-J., & Mission, J. L., "Numerical Analysis of One-Dimensional Consolidation in Layered Clay Using Interface Boundary Relations in Terms of

Infinitesimal Strain," Int. J. Geomech., vol. 11, no. 1, pp. 72–77, 2011, doi: http://dx.doi.org/10.1061/(ASCE)GM.1943-5622.0000066.

Kristo, C., Rahardjo, H., & Satyanaga, A., "Effect of hysteresis on the stability of residual soil slope," Int. Soil Water Conserv. Res., vol. 7, pp. 226–238, 2019, doi: https://doi.org/10.1016/j.iswcr.2019.05.003.

Lee, P. K. K., Xie, K. H., & Cheung, Y. K., "A study on one-dimensional consolidation of layered systems," Int. J. Numer. Anal. METHODS Geomech., vol. 16, pp. 815–831, 1992, doi: https://doi.org/10.1002/nag.1610161104.

Leroueil, S., "Natural slopes and cuts: Movement and failure mechanisms," Geotechnique, vol. 51, no. 3, pp. 197–243, 2001, doi: http://dx.doi.org/10.1680/geot.51.3.197.39365.

Li, H., He, Y., Xu, Q., Deng, J., Li, W., & Wei, Y., "Detection and segmentation of loess landslides via satellite images: a two-phase framework," Landslides, vol. 19, pp. 673–686, 2022, doi: http://dx.doi.org/10.1007/s10346-021-01789-0.

Liao, H.-J., Liu, J., Zhao, Y.-G., & Xiao, Z. H., "Analysis of Soil-Structure Interaction with Finite Element Method," Comput. Geotech., vol. 340–341, pp. 1279–1284, 2007, doi: https://doi.org/10.1016/j.compgeo.2023.106003.

Lin, C.-P., Lin, C.-H., Wu, P.-L., Liu, H.-C., & Hung, Y.-C., "Applications and challenges of near surface geophysics in geotechnical engineering sedimentary basins," Chinese J. Geophys., vol. 58, no. 8, pp. 2664–2680, 2015, doi: http://dx.doi.org/10.6038/cjg20150806.

Liverman, D., Batterson, M., Taylor, D., & Ryan, J., "Geological hazards and disasters in Newfoundland and Labrador," Can. Geotech. J., vol. 38, no. 5, pp. 936–956, 2001, doi: http://dx.doi.org/10.1139/cgj-38-5-936. LorellLLa, M., & Schiliro, L., "Inferences on modeling rainfall-induced shallow landslides from Experimental Observation on Stratified Soils," Ital. J. Eng. Geol. Environ., vol. 2, pp. 77–85, 2018, doi: 10.4408/IJEGE.2018-02.O-06.

Maggirwar, B. C., & Umrikar, B., "Influence of various factors on the fluctuation of groundwater level in hard rock terrain and its importance in the assessment of groundwater," J. Geol. Min. Res., vol. 3, no. 11, pp. 305–317, 2011, doi: http://www.academicjournals.org/JGMR.

Moore, J. C., et al., "Consolidation patterns during initiation and evolution of a plate-boundary decollement zone: Northern Barbados accretionary prism," Geology, vol. 26, no. 9, pp. 811–814, 1998, doi: http://dx.doi.org/10.1130/0091-7613(1998)026%3C0811:CPDIAE%3E2.3.CO;2.

Mufundirwa, A., Fujii, Y., & Kodama, J., "A new practical method for prediction of geomechanical failure-time," Int. Rock Mech., vol. 47, pp. 1079–1090, 2010, doi: http://dx.doi.org/10.1016/j.ijrmms.2010.07.001.

Ndiaye, C., Fall, M., Ndiaye, M., Sangare, D., & Tall, A., "A Review and Update of Analytical and Numerical Solutions of the Terzaghi One-Dimensional Consolidation Equation," Open J. Civ. Eng., vol. 4, pp. 274–284, 2014, doi: http://dx.doi.org/10.4236/ojce.2014.43023.

Nelson, J. D., Overton, D. D., & Durkee, D. B., "Depth of Wetting and the Active Zone," Fort Collins, Colorado 80523, 2001. doi: http://dx.doi.org/10.1061/40592(270)6.

Paul, J. D., Beare, B., Brooks, Z., Derguti, L., & Sood, R., "An investigation into the physical factors that control slow mass movements," Landslides, vol. 21, pp. 2093–2100, 2024, doi: 10.1007/s10346-024-02280-2.
Pei, X., et al., "On the initiation, movement and deposition of a large landslide in Maoxian County, China," J. Mt. Sci., vol. 15, no. 2, pp. 1–13, 2018, doi: http://dx.doi.org/10.1007/s11629-017-4627-1.

Petley, D., "Global patterns of loss of life from landslides," Geology, vol. 40, pp. 927–930, 2012, doi: 10.1130/G33217.1.

Putra, M. A. A., & Cupasindy, D. A. R., "A Numerical Model of Rainfall-Induced Landslide for Slope Stability Analysis," in 27th Annual National Conference on Geotechnical Engineering, HATTI, Ed., Jakarta Indonesia: HATTI, 2023, pp. 68–74. [Online]. Available: https://www.researchgate.net/publication/379835037_A_Numerical_Model_of_Rainfall-Induced_Landslide_for_Slope_Stability_Analysis/figures

Saadeldin, R., & Henni, A., "A novel modeling approach for the simulation of soil–water interaction in a highly plastic clay," Geomech. Geophys. Geo-Energy Geo-Resources, vol. 2, pp. 77–95, 2016, doi: 10.1007/s40948-016-0023-5.

Santos, V. dos A., Romanel, C., & Carneiro, R. F., "Primary consolidation settlement due to ramp loading: Terzaghi (1943) method revisited," Int. J. Geotech. Geoenvironmental Eng., vol. 47, no. 1, pp. 1–5, 2023, doi: https://doi.org/10.28927/SR.2024.003522. Schiffman, R. L., & Stein, J. R., "One-Dimensional Consolidation of Layered Systems," J. Soil Mech. Found. Div., vol. 96, no. 4, 1970, doi: https://doi.org/10.1061/JSFEAQ.0001453.

Schuste, V., Rybacki, E., Bonnelye, A., Herrmann, J., Schleicher, A. M., & Dresen, G., "Experimental Deformation of Opalinus Clay at Elevated Temperature and Pressure Conditions: Mechanical Properties and the Influence of Rock Fabric," Rock Mech. Rock Eng., doi: https://link.springer.com/article/10.1007/s00603-021-02474-3.

Spudich, P., Cirella, A., Scognamiglio, L., & Tinti, E., "Variability in synthetic earthquake ground motions caused by source variability and errors in wave propagation models," Geophys. J. Int., vol. 219, no. 1, pp. 346–372, 2019, doi: https://doi.org/10.1093/gji/ggz275.

Suwa, H., Mizuno, T., & Ishii, T., "Prediction of a landslide and analysis of slide motion with reference to the 2004 Ohto slide in Nara, Japan," Geomorphology, vol. 124, no. 3–4, pp. 157–163, 2010, doi: https://doi.org/10.1016/j.geomorph.2010.05.003.

Tao, Y., et al., "A comparative analysis of trajectory similarity measures," GIScience Remote Sens., vol. 58, no. 5, pp. 63–69, 2021, doi: https://doi.org/10.1080/15481603.2021.1908927. Vozoff, K., "Electromagnetic Methods in Applied Geophysics," Geophys. Surv., vol. 4, pp. 9–29, 1980, [Online]. Available: chrome-extension://efaidnbmnnnibpcajpcglclefindmkaj/https://www.mtnet.info/division/papers/EMWKSHP_ReviewVolumes/1978Murnau/Vozoff_1978Murnau

Review_SG_1980.pdf

Wu, L., & Zhou, J., Rainfall Infiltration in Unsaturated Soil Slope Failure, 1st ed. Chongqing, China: SpringerBriefs, 2023. doi: http://dx.doi.org/10.1007/978-981-19-9737-2.

Yin, J.-H., & Tong, F., "Constitutive modeling of time-dependent stress–strain behaviour of saturated soils exhibiting both creep and swelling," Can. Geotech. J., vol. 48, no. 12, pp. 1870–1885, 2011, doi: http://dx.doi.org/10.1139/t11-076.

Yong, R. N., & Hanna, A. W., "Finite Element Analysis of Plane Soil Cutting," J. Terramechanics, vol. 14, no. 3, pp. 103–125, 1977, doi: https://doi.org/10.1016/0022-4898(77)90010-6.

Yuan-qiang, C., Xu, C., & Hai-ming, Y., "One-dimensional consolidation of layered and visco-elastic soils under arbitrary loading," Appl. Math. Mech., vol. 22, no. 3, pp. 353–360, 2001, doi: http://dx.doi.org/10.1023/A:1015570806849.

Yun, H.-S., Moon, S.-W., & Seo, Y.-S., "Effects of breccia and water contents on the mechanical properties of fault-core-zone materials," Republic of Korea, 2022. doi: http://dx.doi.org/10.1038/s41598-022-10995-2.

Zhang, J., et al., "Evaluation of the Effects of Rainfall Infiltration Boundaries on the Stability of Unsaturated Soil Slopes Using the Particle Flow Code," Water, vol. 16, no. 24, pp. 1–15, 2024, doi: https://doi.org/10.3390/w16243704.

Zhang, S., et al., "A new forecasting method for failure time of creep landslide based on nonlinear creep behavior and new pre-warning criterion," Front. Earth Sci., vol. 10, pp. 1–23, 2022, doi: http://dx.doi.org/10.3389/feart.2022.1018432.

Zheng, C., Franza, A., & Jimenez, R., "Analytical prediction for ground movements due to deep excavations in soils," Tunn. Undergr. Sp. Technol., vol. 141, 2023, doi: https://doi.org/10.1016/j.tust.2023.105316.

Zhou, C.-B., Chen, Y.-F., Hu, R., & Yang, Z., "Groundwater flow through fractured rocks and seepage control in geotechnical engineering: Theories and practices," J. Rock Mech. Geotech. Eng., vol. 15, no. 1, pp. 1–36, 2023, doi: https://doi.org/10.1016/j.jrmge.2022.10.001.