INSOLOGI

INSOLOGI: Jurnal Sains dan Teknologi
https://journal.literasisains.id/index.php/INSOLOGI
ISSN 2828-4984 (Media Online) | ISSN 2828-4992 (Media Cetak)
Vol. 5 No. 3 (Juni 2026) 862-874
DOI: 10.55123/insologi.v5i3.8017
Submitted: 25-04-2026 | Accepted: 05-05-2026 | Published: 15-06-2026

Interpreting Masonry Wall Cracking through Moisture-Induced Ground Movement and Soil–Structure Interaction in Fine-Grained Soils

Fachri Fachri[1*], Jumelia Ardika[2], Reza Pahlevi Munirwan[3], Munawir Munawir[4], Fitri Zaitun Nurnalisa[5]
[1,2,3,5]Program Studi Teknik Sipil, Fakutas Teknik, Universitas Syiah Kuala, Banda Aceh, Indonesia
[4]Program Studi Teknik Sipil, Fakultas Teknik, Universitas Muhammadiyah Aceh, Banda Aceh, Indonesia
Email: [1]fachri@usk.ac.id

Abstract

This study investigates low rise construction located in Aceh Besar, Aceh Province – Indonesia, with shallow strip masonry foundation system exhibiting wall cracking on their wall sections. The damage is suspected caused by the shrink – swell behaviour in fine-grained moisture sensitive soil. Laboratory testing was conducted to obtain soil properties including water content, unit weight, Atteberg Limits and sieve analysis for soil gradation. Further, by using the soil mechanic framework, the analysis shows that seasonal change in moisture content leads to shrink-swell behaviour and volumetric change. The volumetric change was spatially non-uniform causing differential local movement in the supporting ground beneath foundation. The observed crack patterns are in agreement with this local ground settlement inducing tensile stress in masonry infill wall due to this differential movement of ground support. The findings reflect that even soil with moderate plasticity and activity can caused significant structural stress upon subjected to drying-wetting cycle. The study also indicates that the main cause of this damage is the incompatibility between supporting ground with the above rigid body of structure due to non-uniformity volumetric change in supporting ground induced by shrink-swell behaviour of soil. In general, several essential things to highlight for this study are environmental condition change, soil behaviour and structural response/soil structure interaction in low rise construction with shallow foundation system.

Keywords: *Expansive Soil, Shrink-Swell Behaviour, Ground Movement, Soil-Structure Interaction.*

1. INTRODUCTION

Many constructions around the globe are founded on rocks and clay-rich soil (Hobbs et al., 2019) which is the main content of expansive soils. This kind of soil are sensitive to moisture content and volume change during environmental fluctuations (Sadeghi et al., 2025). The environmental processes such as wetting-drying may change the soil performance subsequently giving detrimental effect to subjected soil (Chabrat et al., 2024; Sadeghi et al., 2025). This changes performance of soil particularly concerning for light loaded structures like low rise buildings and pavements which are commonly built on shallow foundation system and sensitive to minor ground movement (Mishra et al., 2008). Such issues has widely reported occurs in many countries like Australia (Zhou et al., 2013), the United States of America (Khan et al., 2018), China, India, South Africa, the United kingdom (Assadollahi & Nowamooz, 2020) including tropical countries like Indonesia (Fauzi et al., 2018; Iqbal et al., 2020; Putri et al., 2025; Ramadhika et al., 2018) and Malaysia (Zakaria et al., 2025) have also reported the similar issue. For some cases reported, deals even greater damage in term of economic impact due to its recurring and pervasive nature (Pedarla et al., 2016).

Indonesia is one of country with huge clay-rich soil distribution with one of its developing province, Aceh. Located on Sumatra Island, this region offers pertinent but under investigated problem. The combination factors of fluctuating annual rainfall, rich-clay soil distribution and increasing infrastructure development propose a criteria of expansive soil behaviour where it may influence building performance. Reports of damage in low rise buildings, especially on educational facilities like school compound buildings, speaks of the necessity for specific investigation in this particular area. However, studies linking to environmental variation, soil properties and damage observation on building construction in this region remain limited. This study addresses this gap by examining the possible mentioned factors in producing expansive soil issue induced within school compound in Aceh Province. The aim of this study is to identifying the primary mechanism responsible for the observed cracks on the wall section of building by integrating annual precipitation data and crack pattern within analytical framework in correspond to moisture variation, soil properties and foundation response. Particularly, this study interprets the exhibit damage as a result from cyclic soil "breathing" behaviour where fluctuation in moisture content, reflected in precipitation trend, induced volumetric soil loss which lead to spatial ground movement and ultimately cracking on wall section. This study also try to introduce a different angle of understanding to this expansive soil issue by presenting data-based evidence of annual tropical humidity setting.

This paper is organized as follows: the introduction presents the research background and problem context, followed by the methods section which outlines the data collection and analytical approach. The results and discussion section provides elaboration the interaction between environmental conditions, soil behaviour, and structural response; and the final section provides conclusions, implications of the study., and suggestion for further research.

2. RESEARCH METHODS

2.1 Field Investigation

This research was conducted in an elementary school compound, located in Aceh Besar region, Aceh province, Indonesia. The information and history about this school were obtained during interview session with the school headmaster and locals.

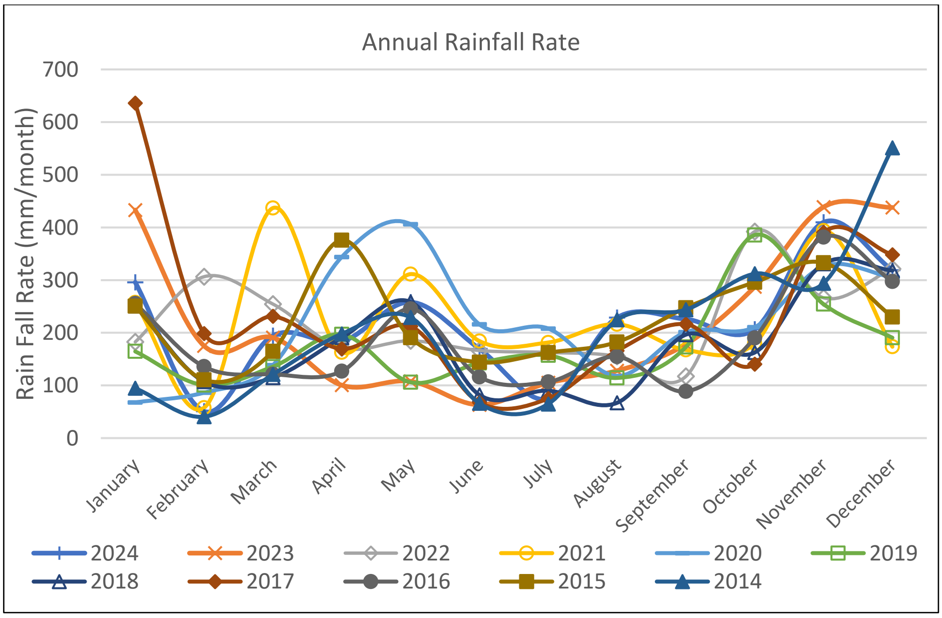
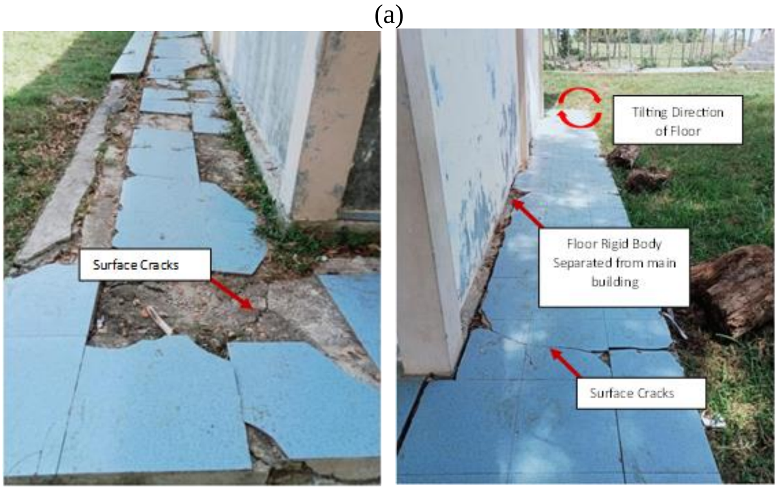


Figure 1. Annual precipitation rate (2014 – 2024)

The school's buildings are a single-story building built in 2015, with shallow continuous stone masonry support foundation. The wall constructions are made from burnt clay bricks as partition wall and acting as infill to the structural reinforced concrete frame which is commonly used in Southeast Asian country (Zerin et al., 2017). During discussion session, it was mentioned that the soil in this area exhibits "breathing" behaviour, referring to its tendency to expand during rainy season and shrunk during low precipitation period. During dry period, occasionally cracks can be visually observed on the ground surface. This aligned well with the climate on this area, with higher rain fall rate at the start and the end of the year before it dropped and relatively drier during the middle season of the year. This fluctuation of moisture content may lead volumetric changes promoted by soil expansion during wet period and shrinkage during dry period in fine-grained soil. The annual rainfall for this site is given in the previous Figure 1 (NASA, 2026).

The cracks exhibit on this building compound developed various forms of wall cracking, from microcracks to significantly splitting cracks with openings around 5~12 mm. Cracks initially generated on the corner infill wall section just below the top beam and propagate diagonally reaching upper corner of window panel. Subsequently, these cracks continue vertically, mid-span of walls, downward beneath window panel before it finally ended upon reaching tie beam. This kind of damage also occurs on the hallway corridor, where it exhibits cracks on the surface area and rigid body of separated-tilting section from the main building. These cracks pattern is shown in Figure 2 (a) to (b). Similar cracks pattern also observed in several buildings within the compound.

(a)



(b)

Figure 2. Cracks patterns on buildings (a) Typical cracks on wall section (b) Cracking and tilting on hallway corridor

2.2 Soil Sampling and Laboratory Testing

Investigation carried on by taking two of undisturbed soil samples. The first sample (S01) was taken just beside the structure with cracks on the wall section and the other (S02) outside the structure perimeter within school compound as shown in Figure 3.

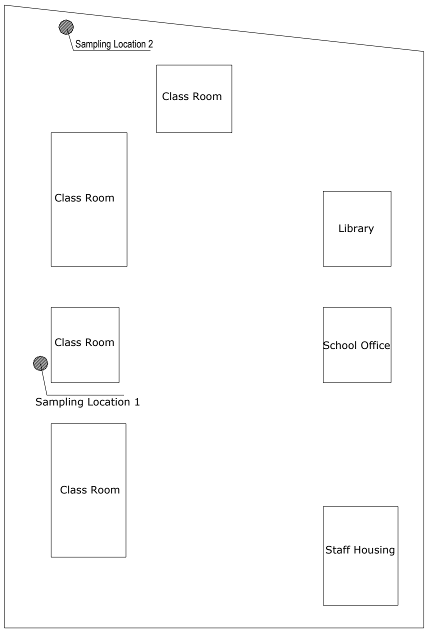


Figure 3. Sampling locations

The samplings were taken from shallow depth, approximately 50 cm from surface soil layer, representative of foundation the bearing layer since the object of this study is a non-rise building with shallow foundation type where the bottom end this foundation located at approximate mentioned depth. This near-surface layer defined as the soil layer subjected to seasonal moisture fluctuation due to environmental conditions such as rainfall fluctuation and evapotranspiration. The locals also mentioned surface cracks during dry season indicating moisture changes predominantly disturb this surface soil layer. Therefore, the sampling depth considered reasonably represent soil layer within the active zone affecting foundation response. Notably, it is acknowledge that no direct measurement suction variation conducted in this study, thus the active zone in this study interpreted qualitatively based on environmental and soil characteristics. The samplings then sealed and transported to geotechnical laboratory for physical and index property analysis. This investigation is to determine the basic soil characteristics relevant to plasticity of the soil, moisture sensitivity, and volume change capacity. The laboratory analysis was conducted using standard soil properties index test. Water content determined to evaluate the moisture condition of soil. Since the sampling were collected during wet season, the unit dry condition was obtained after the sampling dried in oven for 24 hours. Specific gravity was also conducted to evaluate the density of soil. Additionally, the analysis also undertaken Atteberg Limit Test to assess the plasticity and consistency of soil. Liquid limit was obtained using Cassagrande cup method by associating the water content and number of blows required to close the gap in soil sampling.

The plastic limit test performed by rolling the sample into soil-thread like until reach formed around 3 mm diameter and break down into 3-10 parts. Plasticity index, which is the area range soil to remain plastic and therefore susceptible under changing moisture conditions in wet/dry season, introduced by the following equation:

PI = LL – PL ....(1
PI = Plasticity indeks
LL = Liquid limit
PL = Plastic limit

Additionally, shrinkage limit was also analyzed to assess at which point further drying will not give volume reduction. This parameter indicated important insight to this study on soil tendency subjected to shrinkage upon moisture loss during dry season cycle.

Table 1. Laboratory analysis result

NO	Parameter	Unit	S01	S02	Standard Identity
1	Water Content	%	39.45	40.00	SNI 1965-2008
2	Wet Unit Weight		1.46	1.62	SNI 03-3637-1994
3	Dry Unit Weight		1.05	1.16	SNI 03-3637-1994
4	Specific Gravity		2.608	2.596	SNI 1964-2008
5	Liquid Limit	%	42.83	46.58	SNI 1967-2008
6	Plastic Limit	%	24.25	25.53	SNI 1966-2008
7	Plasticity Index	%	18.58	21.05	SNI 1966-2008
8	Shrinkage Limit	%	15.36	12.63	SNI 3422 : 2008
9	Sieve Analysis – Gravel – Sand – Sily – Clay	%	 4.24 19.44 51.82 24.50	 0.14 15.24 54.62 30.00	SNI 3423 : 2008

This parameter indicated important insight to this study on soil tendency subjected to shrinkage upon moisture loss during dry season cycle. Distribution of grain size performed using sieve analysis to identify the proportion of coarse-grained and fine-grained soil fractions. The distribution analysis shows that the soil dominated by fine-grained fractions which are silt and clay fractions. The laboratory samplings results provided in the previous Table 1.

3. RESULTS AND DISCUSSION

3.1 Shrink-Swell Behaviour

In this study, the soil parameters obtained provide a distinct tendency to volume change in corresponding to the loss of moisture content, although it did not directly measured deformation in foundation. The soil classification results indicate that the soil in school compound is fine-grained soil with composition of silt and clay fraction over 75%. Cassagrande Plasticity Chart in Figure 4 draws the soil plasticity, providing analytical basis for understanding its behaviour through simple index value.

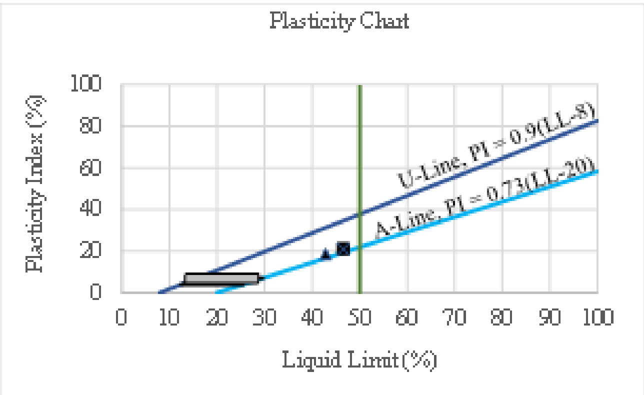


Figure 4. Cassagrande plasticity chart

Even though the chart places the soil within CL classification, it alone cannot fully describe the swelling behaviour as the soil with similar plasticity may give different interpretation based on its composing mineralogy (Cerato & Lutenegger, 2005). Previous study (Nelson et al., 2015) also describe the shrink-swell behaviour itself as a physico - chemical interaction moisture content and clay particle. Moisture variation conditions will modify interparticle stress and density of soil stratum leading to contraction during dry season and expansion during wet condition. Other experimental studies (Shahsavani et al., 2020) and (Zamin et al., 2021) also provide that soil with moderate plasticity category demonstrate significant shrink – swell behaviour under wetting and drying cycles. The water content obtained in current study is around 39%-40% (Table 1) meaning, it is considerably higher than the shrinkage limit which is around 12%-15% (Table 1) pointing, the soil is in the moisture state in which substantial drying contraction can develop prior reaching the limit condition. This broad gap between water content and shrinkage limit indicating, soil shrinkage is expected during drying period in which further moisture content reduction will match the volume change until reaching the obtained limit (Hobbs et al., 2019). This emphasize that shrinkage limit serves as an essential boundary in assessing the potential soil contraction, where drying above this limit will rearranged soil particles hence inducing ground movement due to the soil particles move closer together. Additionally, plasticity index (PI) value obtained ranging 18,58% to 21,05% indicate moderate swell potential (Sridharan & Prakash, 2000). Previous study (Ma et al., 2024; Tong et al., 2021) has shown that the correlation between PI and swelling potential is highly depend on soil mineralogy. Furthermore, identifying soil mineralogy can be done by calculating soil activity (A) introduced by (Shimobe & Spagnoli, 2022) as the following expression:

A = PI/(Percent of Clay Fraction) ....(2

This parameter can be classified into three categories (Iqbal et al., 2020; Ramadhika et al., 2018; Younis et al., 2024) as shown in the following Figure 5.

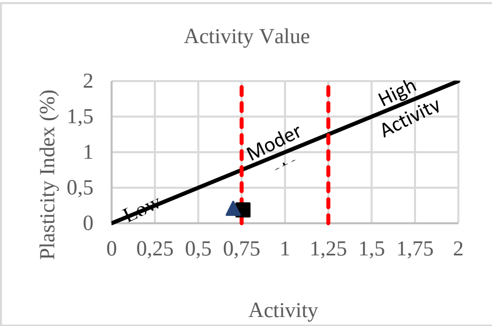


Figure 5. Soil activity value

Obtained sampling shows activity value for each sampling for 0,75 and 0,70 respectively for sampling S01 and sampling S02.

Activity values (A) obtained for soil in this compound are ranging in from 0.70 (S02-outside compound boundary and 0.75 (S01-within compound boundary). Additionally, (Das, 2019) using this index value to identifying minerals contained in soil given in the following table provides mineral content of the soil which is Illite minerals. This agrees well with previous study (Chaerun et al., 2009) that mentioned tsunami-impacted soil in Aceh province contained clay minerals (kaolinite, smectite and illite). Whereas several previous studies (Díaz & Spagnoli, 2024), (Ma et al., 2024), (Tong et al., 2021) and (Fauzi et al., 2018) have conclude that Illite minerals as part of expansive soil minerals.

Table 2. Activities of clay minerals

Mineral	Activity (A)
Smectites	1.0 - 7.0
Illite	0.5 – 1.0
Kaolinite	0.5
Halloysite (4H2O)	0.5
Halloysite (2H2O)	0.10
Attapulgite	0.5 – 0.12
Allophane	0.5 – 0.12

Swelling potential (SP) can also interpret by corresponding PI value by the following expression (Ali et al., 2020).

SP = $0,258e^{0,0838\,(PI)}$ ....(3

This expressed that, soil swelling potential increase exponentially to its PI value. Nonetheless, this empirical swelling potential derived from PI are meant as supporting indicator in-situ behaviour instead of a definitive measurement.

A more comprehensive conclusion develops as multiple parameters assembled. The fine-grained soil enhanced moisture retention and allows water to run within soil matrix, while moderate plasticity defines the existential of clay fraction performing physco-chemical bond with water content. Additionally, considerably low value of shrinkage limit obtained compared to water content confirms that drying can lead to significant volume change. This combined behaviour has broadly reported in shrink-swell studies during drying-wetting cycle lead to soil deformation and structural damage overtime (Punthutaecha et al., 2006).

3.2 Ground Movement and Soil-structure Interaction (SSI)

Expansive soil is commonly known for volume loss correspond to shrink-swell behaviour of soil. Seasonal wetting-drying cycle leads to alternating settlement (shrinkage) or heave (swelling) especially around active area close to the ground surface making the low rise building vulnerable to this behaviour for its shallow foundation embedded within seasonal change active zone (Kirmani et al., 2021; Zamin et al., 2021). This mechanism induces spatial variability due to moisture content, drainage condition and surface cover. Furthermore, soil does not deform as rigid body but instead experiencing differential volumetric change ultimately generates local deformation. This kind differential ground movement will intensified under fluctuated climate, where the prolonged wet-dry cycle alter the depth and scale of suction variation (Devkota et al., 2025; Ramesh & Thyagaraj, 2022). Additionally, (Ito & Azam, 2010) has proven experimentally that shrink-swell behaviour follow nonlinear path, implying that small change in moisture content can produce uneven reduction in soil volume. Consequently, even moderate fluctuation during seasonal change can cause cumulative soil deformation. Moreover, it is reported that displacement in differential movement beyond 30 mm can produce structural integrity problem (Dave & Siddiqui, 2020). Hence, strengthening the sensitivity of structure to local deformation is high despite soil in moderate movement category. Additionally, cracks severity also introduced as shown in the following Table 3.

Table 3. Cracks Severity Category

Approximate Crack Width (mm)	Damage Catagory
< 0.1	Negligible
1	Very Slight
1 – 5	Slight
5 – 15	Moderate
15 – 25	Severe
> 25 and multiple cracks	Very Severe

This aligns well with current study where exhibit cracks width around 5~12 mm and soil activity in moderate range. Based on the observation and information obtained in this study, the damage generated on the infill wall may be associated with ground movement induced by shrinking-swelling behaviour of underlaying soil. This behaviour triggered localized movement in shallow foundation generates vertical and lateral strain in soil leading to cracks in the wall. This strain can extend to considerable magnitude producing vertical deformation that represent volumetric change (Shamrani et al., 2010). Consequently, the failure of masonry prisms is initiated by lateral tensile splitting of the bricks due to stress concentrations arising from mortar–brick interaction (Zerin et al., 2017) induced by this soil deformation movement. Previously figure 5, illustrates the activity value of in-situ soil sampling. It shows that, the soil within compound parameter (S01) exhibits moderate activity while sampling outside parameter (S02) is within normal activity range. This variability between samplings shows that shrink-swell behaviour result is not uniform in the school compound site. This unevenness is critical, since the primary factor governing ground movement beneath shallow foundation differential soil leading to local deformation. Furthermore, this also explain why some building in this compound experience walls cracking while some others are not. Several previous studies (Mzungu et al., 2025) and (Ali et al., 2020) have also described this non uniformity behaviour triggered uneven settlement and heave, leading cracks and damages in low rise building construction. Crack patterns observed showed in Figure 1, reveal that stress distribution developed around infilled opening (window). This is crucial for building with brick infilled masonry, since brick have brittle characteristic meaning it have relatively small capacity to withstand deformation. Originally, the cracks generated in wall section near the top beam and continue further angled downward window corner indicating differential settlement or rotation of footing's support. The cracks the advanced vertically beneath the window demonstrates localized stress concentration in wall section part where brick-mortar integrity compromised. The observed patterns are in line with masonry infill behaviour subjected to non-uniformity support structure, where the tensile stresses generate as result from differential settlement. Similar pattern has also mentioned in previous study (Erguler & Ulusay, 2006) and (Al-Mhaidib, 2006) where typical behaviour contributes to spreading cracks and usability problems. Preceding study also agree and underline this non uniform movement behaviour commonly leads to distortion, differential settlement and misalignment in the opening.

While in term of SSI framework, the main problem here is not settlement or heave. Instead, the differential movement in relatively short distance or local deformation will produce significant tensile stresses as well as unexpected brittle failures damaging infilled masonry (Zerin et al., 2017). Given wider geotechnical understanding, ground movement induced by this phenomenon mechanism exhibits similarities to those influence in seismic environments. Earthquakes is indeed involve sudden energy release however, the after effects such as soil deformation/settlement, soil cracking and soil failure likewise are governed by local soil properties and their reaction against this stress alteration (Dasog & Mermut, 2013). These factors determine how deformation distribution take place, whether it develops as rigid body or spatially leading to local deformation ground movement. This distress problem cause more damage particularly among typical low rise structures (Hussain, 2020), since they commonly built on shallow masonry foundations imposing considerably low contact stress upon supporting ground due to light-wight of structure supported. Furthermore, the stiffness of foundation system is inadequate to restrain soil deformation. In contrast, they tend to join the movement of soil deformation, resulting conflicts between deforming soil mass and relatively brittle structural/non-structural elements.

4. CONCLUSION

This study demonstrates that the structural damage observed in the investigated associated with moisture-induced volume change in the underlying fine-grained soil. While field deformation was not directly measured, the combined evidence from index properties and shrinkage characteristics provides a consistent basis to interpret the observed cracking as a consequence of differential ground movement. These movements generate differential deformation within the active zone, which interacts with structural stiffness to produce internal stresses and damage. Previous discussion suggested that for such cases, even soils of moderate plasticity can generate significant deformation when volumetric strain behaviour is considered, indicating the necessity of interpreting ground movement beyond conventional index-based classification. Thus, ground movement at the site is governed by moisture-induced volume changes in fine-grained soils within the active zone. The study found that the interaction between this ground movement and the structure is explained by local deformation, arising from spatial variability in soil properties and moisture conditions. This interaction forms the basis for understanding the observed damage, which is further elaborated previously in discussion section.

Aceh province has known globally for its coffee commodities (Harnelly et al., 2024; Nasution et al., 2025; Sayuti & Raza, 2018) and also acts as one of the catalyst for economic growth. Naturally, as the demand for this commodity rise, the waste of this by-products are also huge (Munirwan, Taib, et al., 2022). (Rangwala & Prajapati, 2025) mentioned in their study that the used of this kind solid waste shows promising approach for improving expansive soil behaviour.   Taking this into account, several previous study can be implemented for economic solution in this issue (Munirwan, Taha, et al., 2022; Tessema et al., 2023) using coffee husk ash (CHA) for soil stabilization. From a practical perspective, mitigation must address both the material properties of the soil and the moisture dynamics governing its behaviour. Stabilization techniques reported in previous studies offer different but complementary pathways. First, the use of coffee husk ash (CHA), particularly when combined with gypsum, has been shown to reduce plasticity, shrinkage potential, and improve strength through pozzolanic bonding mechanisms. Second, bentonite-based stabilization works through a distinct mechanism by enhancing water retention capacity and modifying soil microstructure. Arguably, this increases optimum moisture content and improves compaction characteristics, reflecting its strong water adsorption capacity and ability to regulate moisture within the soil matrix (Ardika et al., 2025). Hence, this study views that the two approaches could target different aspects of the problem. CHA-based stabilization could improve the strength and reduces deformability, while bentonite-based treatment could also mitigate rapid moisture fluctuations that drive shrink–swell cycles. Nevertheless, it is important to recognise that increasing water retention may also lead to higher moisture demand and requires careful control in field applications. This study argues, effective mitigation also requires an integrated approach that combines soil stabilization with environmental control measures. Surface drainage management, moisture barriers, and appropriate foundation design must be considered alongside material treatment to reduce differential movement. Without controlling moisture variation, even improved soil properties may not fully prevent structural damage.

This study contributes to the literature by providing an integrated interpretation of building distress within a tropical, clay-rich environment, where empirical evidence remains limited. It frames building damage as an interaction between soil behaviour, environmental variability, and structural response. Then, by linking observable damage patterns with index properties and shrinkage characteristics, the study offers a context-specific explanation of failure mechanisms in low-rise structures and highlights the limitations of relying solely on conventional soil classification. Nonetheless, this study is also subject to several limitations: the proposed mitigation strategies are based on existing literature and were not experimentally validated within this research; the analysis relies on observational evidence without long-term in-situ monitoring; and the focus on Aceh may limit broader applicability. Therefore, future research should prioritise field monitoring and experimental validation of stabilisation techniques under local conditions, as well as comparative studies across different soil and environmental contexts to help refining the applicability of the findings and support more robust mitigation strategies

REFERENCES

Al-Mhaidib, A. I. (2006). Swelling behavior of expansive shale: A case study from Saudi Arabia. In A. A. Al-Rawas & M. F. Goosen (Eds.), *Expansive soils: recent advances in characterization and treatment* (pp. 274-276).

Ali, T. K. M., Khuzaie, H. M. A. A., Abbas, B. J., Allous, M. B., & Abdulsamad, B. Z. (2020). Diagnostic Geotechnical Study of Cracks Experienced by Residential Compound: A Case Study. Key Engineering Materials,

Ardika, J., Elmyra, F. Q., Fachri, F., Munirwan, R. P., Yuliana, Y., Maulida, S. M., & Rahmad, A. (2025). Enhancing Water Retention Capacity and Mechanical Properties of Clay Soils with Bentonite Sand Additives. *Built Environment*, *1*(1), 29-40.

Assadollahi, H., & Nowamooz, H. (2020). Long-term analysis of the shrinkage and swelling of clayey soils in a climate change context by numerical modelling and field monitoring. *Computers and Geotechnics*, *127*, 103763. https://doi.org/https://doi.org/10.1016/j.compgeo.2020.103763

Cerato, A. B., & Lutenegger, A. J. (2005). Activity, relative activity and specific surface area of fine-grained soils. Proceedings of the International Conference on Soil Mechanics and Geotechnical Engineering,

Chabrat, N., Russo, G., Vitale, E., Masrouri, F., & Cuisinier, O. (2024). Long-term characteristics of a stabilized expansive clay exposed to environmental-driven processes. *Transportation Geotechnics*, *46*, 101257. https://doi.org/https://doi.org/10.1016/j.trgeo.2024.101257

Chaerun, S. K., Whitman, W. B., Wirth, S. J., & Ellerbrock, R. H. (2009). Chemical and mineralogical characterization of agricultural soils inundated by the December 26, 2004 Tsunami after intrinsic bioremediation in Banda Aceh, Sumatra Island, Indonesia. 26th Annual Meetings of the American Society of Mining and Reclamation and 11th Billings Land Reclamation Symposium 2009,

Das, B. M. (2019). *Advanced soil mechanics*. CRC press.

Dasog, G. S., & Mermut, A. R. (2013). Expansive Soils and Clays. In P. T. Bobrowsky (Ed.), *Encyclopedia of Natural Hazards* (pp. 297-300). Springer Netherlands. https://doi.org/10.1007/978-1-4020-4399-4_124

Dave, T. N., & Siddiqui, A. K. (2020). A Review of Expansive Soil—Effects and Mitigation Techniques. In *Lecture Notes in Civil Engineering* (Vol. 56, pp. 519-527). https://doi.org/10.1007/978-981-15-0890-5_43

Devkota, B., Karim, M. R., Rahman, M. M., Nguyen, H. B. K., & Beecham, S. (2025). The changing frequency of La Niña cycles and their effect on footing design in expansive soils [Article]. *Journal of Environmental Management*, *393*, Article 127124. https://doi.org/10.1016/j.jenvman.2025.127124

Díaz, E., & Spagnoli, G. (2024). Gradient boosting trees with Bayesian optimization to predict activity from other geotechnical parameters. *Marine Georesources & Geotechnology*, *42*(8), 1075-1085. https://doi.org/doi.org/10.1080/1064119X.2023.2251025

Erguler, Z. A., & Ulusay, R. (2006). Swelling behavior of Ankara Clay Predictive techniques, damage details, and swelling maps. In A. A. Al-Rawas & M. F. Goosen (Eds.), *Expansive soils: recent advances in characterization and treatment* (pp. 166-168).

Fauzi, R. R., Sophian, R. I., Muslim, D., Hendarmawan, & Haryanto, I. (2018). Identification of Expansive Soils as Weathering Product of Volcanic Materials in Jatinangor Area, West Java, Indonesia. In A. Kallel, M. Ksibi, H. Ben Dhia, & N. Khélifi, *Recent Advances in Environmental Science from the Euro-Mediterranean and Surrounding Regions* Cham.

Harnelly, E., Heriansyah, F., & Ramlan, R. R. (2024). Morphological relationship of coffee varieties (Coffea spp.) arabica and robusta in Pondok Gajah Experimental Garden Bener Meriah. IOP Conference Series: Earth and Environmental Science,

Hobbs, P. R. N., Jones, L. D., Kirkham, M. P., Gunn, D. A., & Entwisle, D. C. (2019). Shrinkage limit test results and interpretation for clay soils. *Quarterly Journal of Engineering Geology and Hydrogeology*, *52*(2), 220-229. https://doi.org/10.1144/qjegh2018-100

Hussain, M. (2020). Effect of Lime and Cement on Strength and Volume Change Behavior of Black Cotton Soil. In A. Prashant, A. Sachan, & C. S. Desai, *Advances in Computer Methods and Geomechanics* Singapore.

Iqbal, P., Muslim, D., Zakaria, Z., Permana, H., Satriyo, N. A., Syahbana, A. J., Yunarto, Khoirullah, N., & Asykarullah, A. W. (2020). Swelling potential of volcanic residual soils in Sumatra (Indonesia) in relation to environmental issues. *Environmental & Socio-economic Studies*, *8*(4), 1-10. https://doi.org/10.2478/environ-2020-0019

Ito, M., & Azam, S. (2010). Determination of swelling and shrinkage properties of undisturbed expansive soils [Article]. *Geotechnical and Geological Engineering*, *28*(4), 413-422. https://doi.org/10.1007/s10706-010-9301-0

Khan, M. A., Wang, J. X., & Patterson, W. B. (2018). Swelling–shrinkage properties of expansive Moreland clay. In *PanAm Unsaturated Soils 2017* (pp. 100-109). https://doi.org/https://doi.org/10.1061/9780784481707.011

Kirmani, K., Ali, K., & Khan, M. A. (2021). Swelling Behavior of the Expansive Soil Prepared with Calcium Bentonite. Lecture Notes in Civil Engineering,

Ma, T. T., Yu, H. W., Wei, C. F., Yi, P. P., & Yao, C. Q. (2024). Mechanism of physicochemical effect on the shrinkage of expansive soil [Article]. *Yantu Lixue/Rock and Soil Mechanics*, *45*(3), 697-704. https://doi.org/10.16285/j.rsm.2023.0508

Mishra, A. K., Dhawan, S., & Rao, S. M. (2008). Analysis of Swelling and Shrinkage Behavior of Compacted Clays. *Geotechnical and Geological Engineering*, *26*(3), 289-298. https://doi.org/10.1007/s10706-007-9165-0

Munirwan, R. P., Taha, M. R., Mohd Taib, A., & Munirwansyah, M. (2022). Shear Strength Improvement of Clay Soil Stabilized by Coffee Husk Ash. *Applied Sciences*, *12*(11), 5542. https://www.mdpi.com/2076-3417/12/11/5542

Munirwan, R. P., Taib, A. M., Taha, M. R., Abd Rahman, N., & Munirwansyah, M. (2022). Utilization of coffee husk ash for soil stabilization: A systematic review. *Physics and Chemistry of the Earth, Parts A/B/C*, *128*, 103252. https://doi.org/https://doi.org/10.1016/j.pce.2022.103252

Mzungu, N. P., Negulescu, C., Bertrand, E., Perringaux, A., Boissier, L., Gourdier, S., Colas, B., Leone, F., & Grandjean, G. (2025). A novel clay shrink-swell buildings damage model: From unstructured insurance data to the creation of buildings database, and the proposition of damage severity scale [Article]. *International Journal of Disaster Risk Reduction*, *127*, Article 105636. https://doi.org/10.1016/j.ijdrr.2025.105636

NASA. (2026). *Time Series, Area-Averaged of Daily mean precipitation rate (combined microwave-IR) estimate - Early Run daily (daily)*. Earthdata. Retrieved 09/03/2026 from https://giovanni.gsfc.nasa.gov/giovanni/#service=ArAvTs&starttime=1998-01-

01T00:00:00Z&endtime=2025-08-31T23:59:59Z&bbox=95.5316,4.8065,96.1359,5.6525&data=GPM_3IMERGDE_07_precipitation&portal=GIOVANNI&format=json

Nasution, Z., Lubis, S. N., & Aritonang, E. Y. (2025). The Impact of Sustainable Certification on, Arabica Coffee's Competitiveness and Regional Development in Aceh, Indonesia [Article]. *Journal of Ecohumanism*, *4*(1), 76-85. https://doi.org/10.62754/joe.v4i1.4089

Nelson, J. D., Chao, K. C., Overton, D. D., & Nelson, E. J. (2015). Nature of Expansive Soils. In *Foundation Engineering for Expansive Soils* (pp. 9-58). https://doi.org/https://doi.org/10.1002/9781118996096.ch2

Pedarla, A., Acharya, R., Bheemasetti, T., Puppala, A. J., & Hoyos, L. R. (2016). Influence of mineral montmorillonite on soil suction modeling parameters of natural expansive clays. *Indian Geotechnical Journal*, *46*(3), 291-298. https://doi.org/10.1007/s40098-015-0175-1

Punthutaecha, K., Puppala Anand, J., Vanapalli Sai, K., & Inyang, H. (2006). Volume Change Behaviors of Expansive Soils Stabilized with Recycled Ashes and Fibers. *Journal of Materials in Civil Engineering*, *18*(2), 295-306. https://doi.org/10.1061/(ASCE)0899-1561(2006)18:2(295)

Putri, C. A., Prakoso, W. A., Rahayu, W., & Zulys, A. (2025). Effect of Wetting-Drying Cycles on Swelling-Shrinkage Behavior and Microstructures of Tropical Residual Expansive Soil [Article]. *International Journal of Technology*, *16*(4), 1408-1420. https://doi.org/10.14716/ijtech.v16i4.7005

Ramadhika, F., Kristyanto, T. H. W., Indra, T. L., & Syahputra, R. (2018). The responsibility of high activity clay mineral toward landslide occurrence in volcanic sediment area, Cianjur. AIP Conference Proceedings,

Ramesh, S., & Thyagaraj, T. (2022). Effect of Sand Content and Plasticity on Swell and Hydraulic Behaviour of Expansive Soils. Lecture Notes in Civil Engineering,

Rangwala, H. M., & Prajapati, A. (2025). Effect of Solid Waste on Swell–Shrink Behaviour of Clay with Intermediate Plasticity [Article]. *Geotechnical Engineering*, *56*(1), 1-5. https://doi.org/10.14456/seagj.2025.5

Sadeghi, H., Darzi, A. G., Mirpanji, A., & Garakani, A. A. (2025). A hybrid saturated-unsaturated framework for modeling land subsidence under the combined effects of water exploitation and environmental conditions. *Engineering Geology*, 108322. https://doi.org/10.1016/j.enggeo.2025.108322

Sayuti, M., & Raza, H. (2018). Analysis the competitive advantage of arabica gayo coffee organic in Indonesia [Article]. *Indian Journal of Public Health Research and Development*, *9*(12), 1880-1884. https://doi.org/10.5958/0976-5506.2018.02264.7

Shahsavani, S., Vakili, A. H., & Mokhberi, M. (2020). The effect of wetting and drying cycles on the swelling-shrinkage behavior of the expansive soils improved by nanosilica and industrial waste. *Bulletin of Engineering Geology and the Environment*, *79*(9), 4765-4781. https://doi.org/10.1007/s10064-020-01851-6

Shamrani, M. A., Mutaz, E., Puppala, A. J., & Dafalla, M. A. (2010). Characterization of problematic expansive soils from mineralogical and swell characterization studies. Geotechnical Special Publication,

Shimobe, S., & Spagnoli, G. (2022). A General Overview on the Correlation of Compression Index of Clays with Some Geotechnical Index Properties. *Geotechnical and Geological Engineering*, *40*(1), 311-324. https://doi.org/10.1007/s10706-021-01888-8

Sridharan, A., & Prakash, K. (2000). Classification procedures for expansive soils. *Proceedings of the Institution of Civil Engineers-Geotechnical Engineering*, *143*(4), 235-240.

Tessema, A. T., Wolelaw, N. M., Abebe, A. E., Alene, G. A., & Abeje, B. T. (2023). Utilization of Coffee Husk Ash on the Geotechnical Properties of Gypsum-Stabilized Expansive Clayey Soil. *Advances in Civil Engineering*, *2023*(1), 3101774. https://doi.org/https://doi.org/10.1155/2023/3101774Digital Object Identifier (DOI)

Tong, K., Guo, J., Chen, S., Yu, F., Li, S., & Dai, Z. (2021). A Simulation Study on the Swelling and Shrinking Behaviors of Nanosized Montmorillonite Based on Monte Carlo and Molecular Dynamics [Article]. *Geofluids*, *2021*, Article 1038205. https://doi.org/10.1155/2021/1038205

Younis, S. N., Mahmood, R. A., & Al-Saad, H. A. (2024). Swelling Potential and Mineralogy of Al-Hartha City Soil in Basrah-Southern Iraq [Article]. *Iraqi Journal of Science*, *65*(4), 2020-2030. https://doi.org/10.24996/ijs.2024.65.4.20

Zakaria, N. S. S., Jusoh, S. N., Mohd Yunus, N. Z., Zolkepli, M. F., Saleh, S., Salleh, S. N., Ismail, N. S., Mohd Rasoll, M. A. B., & Mamat Jailani, M. Z. (2025, 2025//). Durability Performance of Lime-Laterite Stabilised Soil Towards Malaysia Tropical Weather. Proceedings of the 13th International Conference on Geotechnical Engineering in Tropical Regions (GEOTROPIKA 2024), Singapore.

Zamin, B., Nasir, H., Mehmood, K., Iqbal, Q., Farooq, A., & Tufail, M. (2021). An Experimental Study on the Geotechnical, Mineralogical, and Swelling Behavior of KPK Expansive Soils [Article]. *Advances in Civil Engineering*, *2021*, Article 8493091. https://doi.org/10.1155/2021/8493091

Zerin, A. I., Hosoda, A., Salem, H., & Amanat, K. M. (2017). Seismic Performance Evaluation of Masonry Infilled Reinforced Concrete Buildings Utilizing Verified Masonry Properties in Applied Element Method. *Journal of Advanced Concrete Technology*, *15*(6), 227-243. https://doi.org/10.3151/jact.15.227

Zhou, Y. Y., Zhao, F. H., Shi, W. C., & Li, J. (2013). A general discussion of soil-water interaction in expansive soil. Applied Mechanics and Materials,