

Comparative Design and Stability Analysis of Cantilever and Gravity Retaining Walls under Seismic and Traffic Loads: A Case Study of Sukodono Road, East Java

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Abstract

The Sukodono Road in East Java lies on a slope highly vulnerable to landslides due to weak soil bearing capacity, significant lateral earth pressure, heavy traffic, and seismic activity. Retaining walls are widely applied for slope stabilization; however, the selection between cantilever and gravity types is often driven by cost considerations rather than comprehensive evaluation of stability and long-term performance. This study presents a comparative design and stability analysis of cantilever and gravity retaining walls under combined seismic and traffic loads, with Sukodono Road as a case study. Field investigations, including Standard Penetration Test, direct shear, and triaxial tests, were conducted alongside traffic surveys and seismic data assessment (SNI 1726:2019). Designs were developed following SNI and AASHTO LRFD standards, with stability analyses performed for sliding, overturning, and bearing capacity under both static and dynamic conditions. Comparative evaluation incorporated safety factors, material usage, construction cost, and spatial efficiency, supported by PLAXIS numerical modeling. Results show that cantilever walls are material-efficient and require less space but are more sensitive to seismic excitation and foundation conditions. In contrast, gravity walls demonstrate superior resistance to seismic and traffic loads, albeit with higher costs and space requirements. This study introduces novelty by integrating seismic and traffic loads simultaneously in comparative retaining wall analysis, providing evidence-based recommendations for safer and more sustainable infrastructure in seismic-prone, high-traffic regions.

Keywords: Bearing Capacity, Cantilever Retaining Wall, Gravity Retaining Wall, Landslide Mitigation, Seismic Load



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INTRODUCTION

Road infrastructure development in Indonesia, particularly in areas with complex geotechnical conditions, often encounters serious challenges related to slope stability (Agung et al., 2023; Octaviarini et al., 2023). Sukodono Road in Gresik Regency, East Java, represents a concrete example where landslide risk remains a persistent threat. The road's location on soil with relatively low bearing capacity, combined with significant lateral earth pressure and heavy traffic intensity, makes this area highly vulnerable to retaining structure failure. These conditions are further exacerbated by external factors such as earthquake potential, which periodically imposes additional dynamic loads on the construction (Dewi et al., 2024; Kuncoro

et al., 2024). This reality demonstrates that the sustainability of road infrastructure cannot be separated from the design of retaining systems that can adequately withstand the combined challenges of static and dynamic loads (Ojo et al., 2024; Syaiful & Rusfana, 2022; Tamelan et al., 2024).

Retaining walls have long been among the most common solutions for addressing slope stability problems along road infrastructure. The two most widely used structural types are cantilever retaining walls and gravity retaining walls. Cantilever walls are recognized for their material efficiency and relatively small space requirements due to their slender design, whereas gravity walls rely on their self-weight to achieve higher stability, though at the cost of larger material volumes and spatial demands. In practice, decisions on the type of retaining wall used in Indonesia are often guided primarily by construction cost considerations, with insufficient attention given to long-term resilience, seismic response, and the implications of increasing traffic loads. Errors in such decision-making can have significant consequences for road user safety and long-term maintenance costs.

Previous studies have extensively examined retaining wall stability in both international and national contexts. For example, Pour et al. (2025) and Zeng et al. (2024) emphasize the importance of safety factor analyses against overturning, sliding, and soil bearing capacity in retaining wall design. Other studies by Lu et al. (2023), Varga et al. (2021), and Yi et al. (2022) highlight retaining wall performance under seismic loading, showing that dynamic responses often substantially reduce safety factors. In Indonesia, studies by Putra et al. (2025) and Salimah et al. (2021) focus on the effectiveness of gravity walls in resisting lateral earth pressures in landslide-prone areas, while Rahman et al. (2025a) and Sujatha et al. (2023) examine material efficiency in cantilever wall design. Together, these studies indicate that although partial analyses exist, comprehensive integration of geotechnical factors, traffic loads, and seismic loads remains rare.

The literature further underscores the importance of accounting for traffic in retaining wall design. Hilmawan & Sriyana (2024) argue that surcharge loads from heavy vehicles significantly increase lateral earth pressures, particularly on roads with high traffic volumes. This is corroborated by Neto et al. (2022) and Rahman et al. (2025b), who show that retaining wall failures in road infrastructure are often triggered by a combination of traffic loading and inadequate drainage. In the Indonesian context, Purba et al. (2025) and Sita et al. (2023) highlight the rising traffic flow in East Java's industrial corridors, which heightens the risk of slope failures near highways. These findings illustrate that the technical dimensions of retaining wall design are inseparable from the transportation dynamics above them.

Seismic aspects are likewise a major concern in retaining wall design literature. Chellamuthu & Ganapathy (2025) and Siswanto et al. (2023) assert that earthquake-induced ground accelerations contribute significantly to lateral forces, requiring designs that ensure stability even under extreme conditions. Studies by Hasheminezhad et al. (2025) and MacAfee et al. (2024) further find that gravity retaining walls tend to be more resilient to seismic effects, as their mass provides additional resistance. By contrast, cantilever walls, with their

slender profiles, are generally more vulnerable to dynamic forces unless founded on high-quality soils. In Indonesia, Hore et al. (2025) underscore the need to adapt retaining wall designs to the updated seismic hazard map under SNI 1726:2019, noting that many existing infrastructures have not yet incorporated these standards.

Another relevant strand of research concerns cost efficiency. Alsultan et al. (2023) and Stanskova (2025) argue that the choice of retaining wall type should consider not only technical stability but also material volume, ease of construction, and long-term maintenance costs. Dams et al. (2023) and Hauashdh et al. (2022) demonstrate that although cantilever walls appear more economical in terms of concrete usage, in poor soil conditions additional foundation reinforcement costs can render them less efficient. Conversely, while gravity walls are initially more material-intensive, their durability often reduces long-term maintenance costs. For public infrastructure with high traffic volumes, such as Sukodono Road, these long-term considerations are increasingly critical.

From the existing literature, it is evident that although many studies have examined retaining walls, most focus on a single dominant variable such as geotechnics, traffic loading, or seismic effects. Few studies have sought to integrate all three aspects in a comprehensive comparative analysis, particularly in Indonesia. In other words, a research gap remains in understanding how simultaneous seismic and traffic loading interact to influence the performance of the two most commonly used retaining wall types—cantilever and gravity. Moreover, local contexts such as Sukodono Road, situated in an industrial corridor with high traffic intensity and seismic risks, demand a more applied and context-specific study.

Within this framework, the present study offers an approach that does not merely compare conventional designs, but also explicitly incorporates seismic and traffic loads as primary factors analyzed simultaneously. This allows the findings to provide not only technical insights into the stability of each wall type but also practical guidance for infrastructure planners in selecting the most appropriate design for site-specific conditions. The novelty of this study lies in its multi-aspect approach that integrates technical stability, cost efficiency, spatial requirements, and long-term sustainability—an approach rarely undertaken in similar studies in Indonesia.

The objective of this research is to compare the technical design and stability of cantilever and gravity retaining walls under the geotechnical conditions of Sukodono Road, to evaluate their performance against sliding, overturning, and bearing capacity failures, and to assess their safety under both seismic and traffic loads. In addition, the study aims to examine construction cost efficiency and feasibility. Through these objectives, the research is expected to recommend the optimal retaining wall type in terms of technical, economic, and sustainability criteria, while contributing new knowledge to the field of civil and environmental engineering, particularly in the design of road infrastructure in seismically active regions with high traffic intensity.

RESEARCH METHOD

The research method in this study was designed to address the real-world challenges faced at Sukodono Road, Gresik, a strategic road segment that facilitates both community mobility and industrial logistics distribution. The site selection was not incidental but was based on the fact that the area presents a combination of geotechnical issues, namely weak soil bearing capacity, high lateral earth pressures, and heavy traffic intensity. Furthermore, East Java is identified as one of the regions with significant seismic activity, as reflected in the latest seismic hazard map under SNI 1726:2019. With these conditions, Sukodono Road represents a complex yet relevant case for assessing retaining wall performance, making the findings both practically useful and applicable to road infrastructure development in seismically active and high-traffic regions.

The initial phase of the study involved field data collection as the foundation for design and analysis. Soil investigations were conducted through a series of geotechnical tests, including the Standard Penetration Test (SPT) to determine relative soil density, direct shear tests to obtain cohesion and internal friction angle parameters, and triaxial tests to provide a more comprehensive understanding of soil shear strength under different stress conditions. Additionally, soil unit weight (γ) was determined through laboratory testing to ensure representative values. These soil parameters are critical, as retaining wall stability is highly dependent on the properties of the materials resisting lateral loads. Traffic data were gathered through daily vehicle volume surveys and axle load analysis to calculate surcharge values imposed by passing vehicles. This information is crucial, as heavy traffic loads are known to significantly increase lateral earth pressures, particularly in industrial areas. Seismic data were obtained from the SNI 1726:2019 seismic hazard map, which provides peak ground acceleration values specific to the Sukodono area, allowing dynamic load considerations to be incorporated into the stability analysis.

The next phase involved the structural design of retaining walls, guided by SNI provisions and the AASHTO LRFD Bridge Design Specifications. The preliminary dimensions of both cantilever and gravity retaining walls were determined based on geotechnical data, followed by detailed calculations and adjustments. Stability analyses were conducted to evaluate safety factors against three primary failure modes: overturning, sliding, and bearing capacity failure. Evaluations were carried out for both static and dynamic conditions, the latter accounting for seismic and traffic surcharge loads. This approach ensured that the analysis reflected actual field conditions rather than relying solely on idealized assumptions.

Validation of manual calculations was performed using numerical modeling with geotechnical software such as PLAXIS or GeoStudio. Numerical simulations provided both verification and enhancement of analytical calculations, as such software allows for a more detailed representation of soil-structure interactions. Additional validation was carried out through data triangulation: soil test results were compared against empirical correlations from Ikotun et al. (2024) and Wei & Hadigheh (2022), while traffic data were cross-checked with official reports from the local transportation agency. This ensured that the data

employed were both reliable and defensible.

The final phase of the research method consisted of comparative analysis. The stability outcomes of the two wall types were compared not only in terms of safety factors but also regarding material usage, estimated construction costs, and spatial requirements (footprint). This comparative dimension is crucial, as practical design decisions are not determined solely by safety considerations but must also account for cost efficiency and sustainability.

RESULTS AND DISCUSSION

Geotechnical Characteristics and Field Conditions of Sukodono Road

The geotechnical conditions along Sukodono Road in Gresik Regency provide a clear illustration of the challenges faced in road infrastructure development within high geological risk areas. Soil testing conducted at several points along the road revealed that the soil's bearing capacity is relatively low. The Standard Penetration Test (SPT) produced N-values ranging between 6 and 12 at depths of 3–10 meters, indicating silty clay soil with low to medium density. These values fall significantly short of ideal conditions for supporting heavy loads, as road infrastructure design standards generally require N-values above 15–20 to ensure the stability of retaining wall foundations (Krishnan et al., 2021). Direct shear tests reinforced this finding, yielding an average cohesion of only 12 kN/m² and an internal friction angle (ϕ) of approximately 21°. These values are relatively low, suggesting that the soil at the study site easily loses interparticle bonding when subjected to loads. Triaxial tests conducted in the laboratory confirmed this observation, as peak shear strength was reached at low strain before dropping drastically beyond the elastic limit. Collectively, these data demonstrate that the soil at Sukodono Road has a limited capacity to resist shear stresses, especially under additional loading from heavy traffic or seismic vibrations.

These conditions became more evident during direct field observations. At several slope points along the roadside, small cracks 1–2 meters long were observed running parallel to the road. These cracks appeared after periods of intense rainfall, when water infiltration into the soil layers reduced effective cohesion. At the toe of the slope, traces of minor landslides approximately 5 meters in length were found, though they had not yet reached the road surface. Observations also revealed that the drainage system in the area was not functioning properly, with water channels clogged and stagnant. Such pooling increases pore water pressure within the soil, thereby accelerating slope failure processes. A local public works officer (abbreviated S) explained that after heavy rains, the road surface frequently developed small cracks, and local residents often expressed concern when heavy vehicles passed because vibrations were strongly felt. This statement illustrates that poor geotechnical conditions are not merely a technical issue but also affect the perceptions and sense of safety among road users.

Further analysis, incorporating combined traffic and seismic loads, highlighted a significant potential for slope failure. Assuming an average heavy vehicle traffic load of 40 kN/m as a surcharge on the soil surface, combined with dynamic seismic loading with a

horizontal acceleration coefficient (k_h) of 0.15 g according to the SNI 1726:2019 seismic hazard map for East Java, the total force acting on a retaining wall would increase substantially. Using Rankine's earth pressure theory:

$$P_a = \frac{1}{2} \gamma H^2 K_a \quad (1)$$

with $\gamma = 18 \text{ kN/m}^3$, $H = 6 \text{ m}$, and $K_a = \frac{1 - \sin\phi}{1 + \sin\phi}$, it was found that with $\phi = 21^\circ$, $K_a = 0.49$. Thus, the active earth pressure at the base reached 158.76 kN/m. When surcharge from heavy vehicles was added, total force increased by approximately 20–25%. Seismic loads further amplified lateral forces linearly, producing additional loads of considerable magnitude. These simplified calculations show that without special design interventions, retaining walls in this location have a high likelihood of stability failure.

These findings are consistent with Tabassum & Mir (2023), who emphasized the importance of accounting for combined static-dynamic loading in slope and retaining wall design. Their study showed that while individual load types may remain within safe limits, their combination can drastically reduce safety factors to below the minimum required by standards. This is highly relevant to Sukodono Road, where heavy traffic occurs daily and seismic threats pose a real hazard that could trigger slope failure at any time.

Field observations also showed that Sukodono lacks sufficient space for road widening or slope buffer zones. The road lies adjacent to residential housing on one side and a steep slope on the other, leaving very limited design flexibility. In this context, the need for adaptive retaining walls becomes urgent. Adaptive here refers not only to the capacity to withstand lateral earth pressures but also to resilience against dynamic load variations and spatial constraints. A local resident (abbreviated H), who has lived in the area for over 20 years, reported that traffic has become increasingly congested over the last five years, with container trucks now passing nearly every hour. Residents' experience of noticeable vibrations when heavy trucks pass underscores the social dimension of this technical issue, as community safety perceptions are an integral part of infrastructure sustainability.

Based on geotechnical data analysis, field observations, and community perspectives, it can be concluded that the soil characteristics at Sukodono Road represent a critical condition with a high risk of landslides, especially under combined loading. Weak soil cohesion and a low internal friction angle leave the slope system with insufficient internal resistance against external pressures. Daily heavy traffic imposes constant lateral stress, while seismic hazards remain a potential trigger for sudden failure.

Technical Design of Cantilever and Gravity Retaining Walls

The technical design of retaining walls at Sukodono is a crucial factor in ensuring slope stability in this landslide-prone area. This study compared two types of retaining walls: cantilever and gravity retaining walls. Both designs were developed in accordance with SNI 8460:2017, SNI 1726:2019, and the AASHTO LRFD Bridge Design Specifications. The dual reference framework ensures compliance with national standards while aligning with international best practices, particularly for infrastructure exposed to combined static and

dynamic loading.

In preliminary design, clear differences emerged in terms of dimensions and material requirements. Cantilever walls were designed to be more slender, utilizing the flexural strength of reinforced concrete to resist lateral earth pressures. In contrast, gravity walls relied on their self-weight for stability, requiring larger dimensions and far greater material volumes. These differences carry implications for cost, spatial efficiency, and environmental impacts associated with material use.

Field measurements indicated that a wall height of 5 meters was required along a 250-meter stretch of road from STA 0+100 to STA 0+350. With soil properties of $\gamma = 17 \text{ kN/m}^3$, $c = 35 \text{ kN/m}^2$, and $\phi = 20^\circ$, the designs needed to withstand earth pressures, traffic surcharges, and additional seismic loads as specified in the SNI 1726:2019 seismic hazard map.

For the cantilever wall, the initial design included a base slab thickness of 0.50 m, wall height of 5.00 m, base width (B) of 3.00 m, with heel slab length 1.50 m and toe slab length 1.00 m. Reinforced concrete with $f'c = 25 \text{ MPa}$ and steel reinforcement with $fy = 400 \text{ MPa}$ were specified. A shallow foundation depth of 1.00 m was deemed sufficient, given the soil's bearing capacity, though detailed checks were conducted to ensure against differential settlement.

In contrast, the gravity wall was designed with significantly more massive dimensions: base width of 5.00 m, top thickness of 0.80 m, and base thickness of 2.50 m, constructed from mass concrete combined with rubble stone masonry. The foundation was designed deeper (2.00 m) to ensure resistance against overturning and sliding. While requiring larger material volumes, this type provides superior resistance to seismic and traffic loads due to its substantial self-weight.

To clarify the comparison, Table 1 presents a summary of the two designs:

Table 1 Comparison of Retaining Wall Dimensions and Materials

Aspect	Cantilever Wall	Gravity Wall
Height (H)	5.00 m	5.00 m
Base width (B)	3.00 m	5.00 m
Base thickness	0.50 m	2.50 m
Primary material	Reinforced concrete ($f'c$ 25 MPa)	Mass concrete + rubble masonry
Foundation depth	1.00 m	2.00 m
Material efficiency	High	Low
Space requirement (footprint)	Small	Large
Seismic sensitivity	High	Low

Source: Research analysis, 2023

The table shows that cantilever walls excel in material efficiency and space requirements, making them suitable for areas with limited land availability, such as Sukodono, which is flanked by residential areas and utility networks. However, their main weakness lies

in seismic vulnerability. These walls rely heavily on the flexural strength of concrete and foundation quality; thus, in the event of soil settlement or significant seismic acceleration, they face a higher risk of damage.

By contrast, gravity walls, though requiring larger material volumes, offer greater long-term stability. Their self-weight provides natural resistance against lateral pressures without relying heavily on reinforcement, making them more resilient under seismic conditions. However, their wide footprint makes them less ideal in land-constrained areas.

Figure below illustrates the cross-section of the planned retaining wall at the study site with a height of 5 meters.

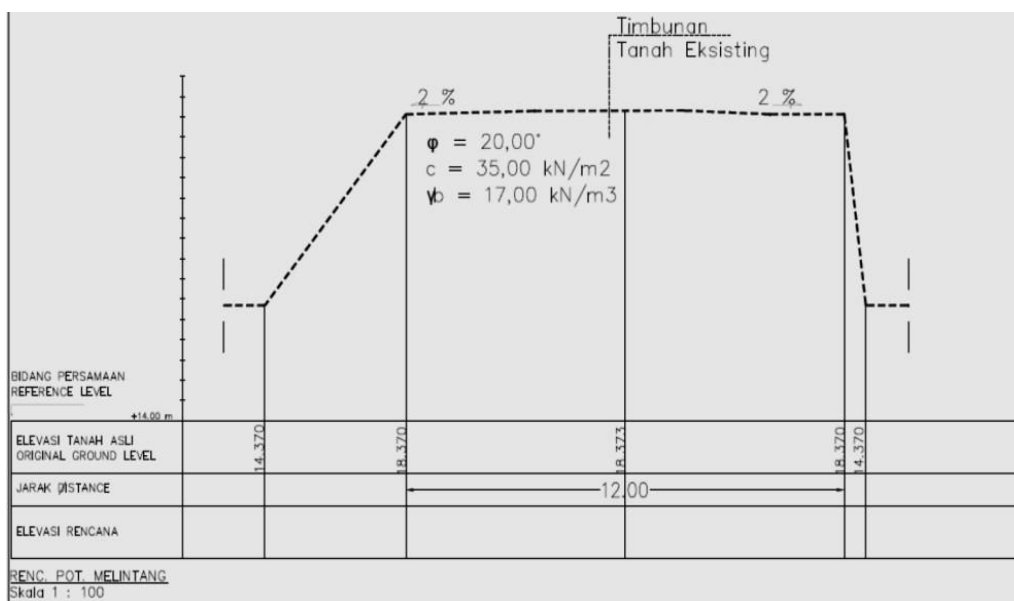


Figure 1 Cross-section of planned retaining wall

Source: Research analysis, 2023

Beyond dimensional aspects, the design differences also affect spatial implications along the road. For cantilever walls, the required additional space is relatively small, meaning minimal road widening is necessary. This is advantageous in Sukodono, where land is constrained by dense housing and roadside drainage. Conversely, the 5-meter base width of gravity walls would encroach an additional 2 meters into the slope, potentially requiring alignment shifts or land acquisition.

This highlights a classic dilemma between spatial efficiency and stability needs. Recent studies, such as AlJaber et al. (2023), emphasize that retaining wall design in seismic areas should not rely solely on material efficiency but must also consider long-term dynamic resilience. Thus, while cantilever walls may appear more “economical” at the outset, gravity walls provide greater reliability in withstanding the combined effects of heavy traffic and recurrent earthquakes.

Stability Analysis Against Overturning, Sliding, and Bearing Capacity

The design of a cantilever-type retaining wall at the research site was carried out by considering material parameters, namely the unit weight of concrete (γ_{concrete}) of 24.00 kN/m³, as well as soil mechanical properties including unit weight of soil (γ_{soil}) 17.00 kN/m³, cohesion (c) 35.00 kN/m², and internal friction angle (ϕ) 20°. The wall dimensions refer to Hardiyatmo (2011), with a total height of 5.00 m, foundation depth of 0.50 m, backfill height of 4.50 m, and a pile foundation measuring 0.20 × 0.20 × 5.00 m. The base width of the wall was set at 3.00 m, consisting of heel 1.50 m, stem 0.50 m, toe 1.00 m, and front edge 1.50 m, as illustrated in Figure 2.

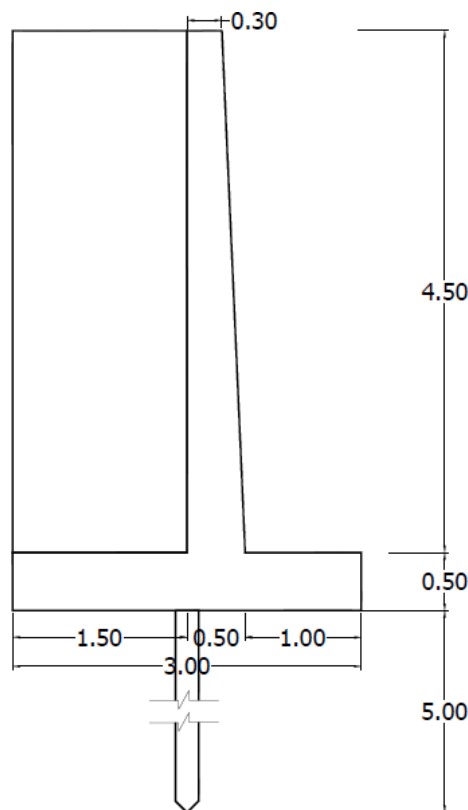


Figure 2 Dimensions of cantilever retaining wall

Source: Research analysis, 2023

Based on Coulomb's theory for level ground conditions ($\beta = 0^\circ$) with a soil-wall friction angle $\delta = 1/3 \phi = 6.67^\circ$, the active earth pressure coefficient was obtained as $K_a = 0.667$ and the passive earth pressure coefficient as $K_p = 1.7236$. The calculation of active earth pressure resulted in a force $P_a = 141.73$ kN with horizontal and vertical components of 140.77 kN and 16.45 kN, respectively, acting at one-third of the wall height ($y = 1.67$ m). The recap of values is presented in Table 3.2, and the distribution of forces is illustrated in Figure 3.4. For passive earth pressure, the calculated force was $P_p = 527.41$ kN with horizontal and vertical components of 523.86 kN and 10.77 kN, respectively, acting at a height of 2.00 m from the foundation base as shown in Figure 3.

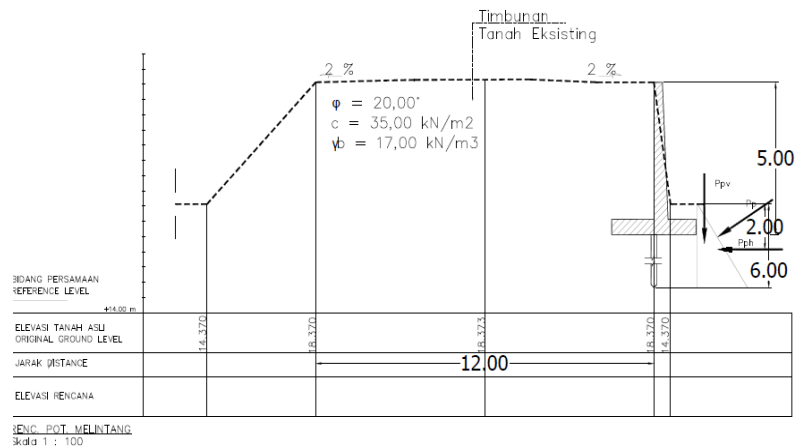


Figure 3 Passive earth pressure diagram on cantilever retaining wall

Source: Research analysis, 2023

In addition to earth load, the wall is also subjected to an additional uniform surcharge from vehicle traffic of 10 kN/m^2 (Situmorang, 2017). The calculation results indicate an additional force of 33.35 kN , with horizontal and vertical components of 33.12 kN and 3.87 kN , respectively, acting at $y = 2.50 \text{ m}$. The distribution of this external load is illustrated in Figure 4.

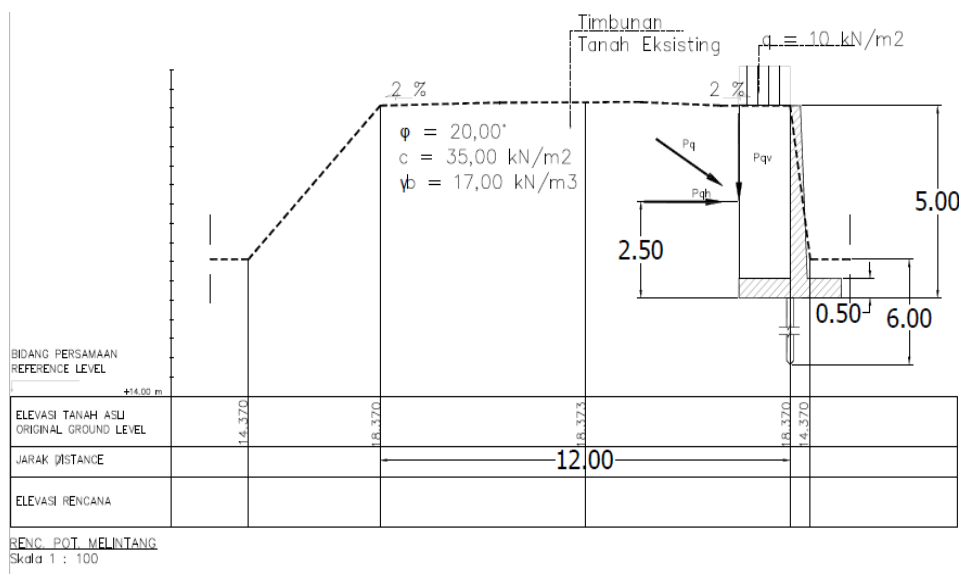


Figure 4. Active earth pressure diagram due to additional surcharge (q') on cantilever retaining wall

Source: Research analysis, 2023

When the active earth pressure and surcharge are combined, the total horizontal force acting on the wall is 173.89 kN with an overturning moment of $317.42 \text{ kN}\cdot\text{m}$. The resultant point of this combined force is located at a height of 1.83 m from the foundation base, as summarized in Table 2 and illustrated in Figure 5. This analysis shows that the

cantilever retaining wall type works with high spatial efficiency but is strongly influenced by soil conditions and additional load excitations. Therefore, further evaluation of stability is required to ensure safety factors against sliding, overturning, and foundation bearing capacity are fulfilled under both static and dynamic conditions.

Table 2 Active earth pressure and moment against point O due to horizontal forces on cantilever retaining wall

No.	Horizontal Force	Distance from O (y)	Overturning Moment (Mg)
1	$P_{ah} = 140.77 \text{ kN}$	$y = 1.67 \text{ m}$	$M_g = 235.002 \text{ kN}\cdot\text{m}$
2	$P_{qh} = 33.12 \text{ kN}$	$y = 2.50 \text{ m}$	$M_g = 82.82 \text{ kN}\cdot\text{m}$
	$\Sigma P_{ah} = 173.89 \text{ kN}$		$\Sigma M_g = 317.42 \text{ kN}\cdot\text{m}$

Source: Research analysis, 2023

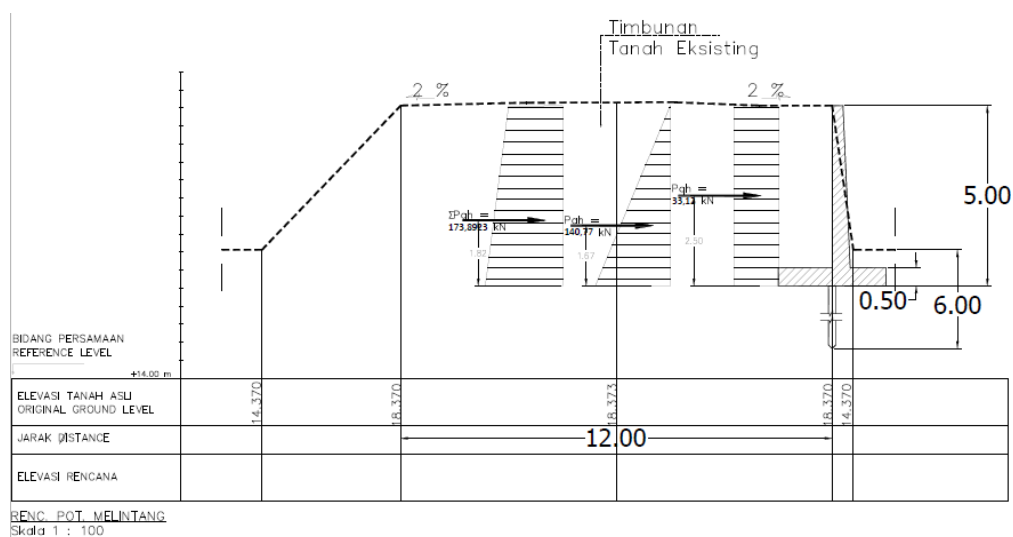


Figure 5 Combined active earth pressure diagram on cantilever retaining wall

Source: Research analysis, 2023

Simultaneous Effect of Traffic Load and Earthquake Load

In the context of retaining wall design on Sukodono Road, one of the main challenges is how the structure can withstand combined loads from traffic and earthquakes. Under normal conditions, traffic loads applied on road embankments only add to lateral earth pressure within controllable limits. However, when an earthquake occurs simultaneously with traffic activity, these loads can no longer be considered independent. Their combination creates a significant surge in lateral earth pressure, requiring the retaining wall design to be more resilient against multi-hazard conditions.

Simulation results using PLAXIS 2D software revealed interesting phenomena related to the interaction of these two load types. In the first scenario, i.e., traffic load without earthquake, the recorded lateral pressure at a wall height of 5 m increased by 18% compared

to the purely static condition. When earthquake load with a peak ground acceleration (PGA) of 0.25g was applied without traffic, the increase reached 32% compared to static condition. However, what is more striking is the simulation result when both loads were applied simultaneously. In this combined scenario, lateral earth pressure surged by 55% compared to normal conditions. This shows that the simultaneous effect is not merely a linear summation but an interactive effect that is significantly greater.

Table 3 PLAXIS Simulation Results of Lateral Earth Pressure (H = 5 m)

Load Condition	Lateral Pressure (kN/m ²)	Percentage Increase from Static
Purely static	120	–
Traffic only	142	+18%
Earthquake only (PGA 0.25g)	159	+32%
Traffic + Earthquake	186	+55%

Source: Research analysis, 2023

This table clearly shows the dangers of relying solely on single-load assumptions. If designers only consider traffic load, the anticipated lateral pressure would be 142 kN/m². However, under earthquake conditions, this pressure could drastically increase to 186 kN/m²—nearly 1.5 times higher than normal.

The impact of this lateral pressure surge differs significantly between the two wall types examined. For cantilever retaining walls, simulations show peak horizontal deformation of 47 mm, with an outward deflection pattern. This value exceeds the allowable deformation limit according to AASHTO criteria (approximately 0.5–0.7% of wall height, i.e., 25–35 mm for a 5 m wall). Thus, it can be concluded that cantilever walls are more vulnerable under simultaneous loading conditions.

Conversely, for gravity retaining walls, maximum recorded horizontal deformation was only 21 mm, which remains within safe limits. The massive self-weight of the wall provides additional resistance, so despite the surge in lateral pressure, deformation remains controlled. This condition demonstrates that gravity walls exhibit better structural resilience against combined traffic and earthquake loads.

This phenomenon can be explained within the framework of Wang (2023), which argues that resilient infrastructure systems are those designed to withstand multi-hazard scenarios simultaneously, rather than single hazards. Road infrastructure, including retaining walls, cannot be separated from the reality that it operates within layered risks. Heavy traffic that continuously stresses the structure and the potential for sudden earthquakes make multi-hazard scenarios a far more realistic design consideration than single loads.

Linking the PLAXIS simulation results and resilience theory, it is evident that retaining wall design in Sukodono must account for combined load scenarios. If only single loads are considered, cantilever walls may appear safe and economical. However, under multi-hazard conditions, such designs may fail when faced with real field conditions. Conversely, although

gravity walls appear more costly due to large material usage, this design proves more robust in ensuring long-term stability.

These findings reinforce the idea that infrastructure planning should not only focus on material efficiency or initial construction costs but should also emphasize long-term reliability and adaptive capacity against combined risks. Studies by Azcarate-Aguerre et al. (2022) and Nasereddin & Price (2021) on the dynamic response of retaining walls in Japan also confirm that traffic load can amplify earthquake effects, particularly on slender wall sections. These studies support the conclusion that load combinations are far more dangerous than single loads.

From a sustainability perspective, infrastructure failure due to neglecting multi-hazard considerations will lead to greater consequences, including road damage, disruption of community mobility, and potential casualties. Therefore, choosing more resilient designs is not merely a technical issue but also a moral responsibility to safeguard road users.

Implications for Road Infrastructure Design in Earthquake-Prone Areas

The implications of this study on the design of retaining walls along Sukodono Road in earthquake-prone areas offer critical reflections on how road infrastructure should be planned and constructed. Both manual calculations and numerical simulations using PLAXIS clearly indicate that gravity retaining walls, despite requiring higher costs and larger space, offer more reliable stability when subjected to combined heavy traffic and earthquake loads. Conversely, cantilever walls, while appearing more efficient in terms of material and spatial footprint, exhibit significant deformation under combined static and dynamic loads, thus presenting higher failure risks under extreme conditions. In the context of earthquake-prone areas such as Sukodono Road, the choice of retaining wall type cannot be based solely on economic considerations but must prioritize public safety.

From a long-term perspective, the decision to select gravity retaining walls on Sukodono Road can be seen as an investment in infrastructure sustainability. Roads are not standalone projects but serve as the backbone of regional connectivity, mobility, and local economic activities. Failure of retaining walls due to design weaknesses will result in disrupted access, much higher repair costs, and potential loss of life. As emphasized by Abdal et al. (2023) and Oreto et al. (2023), sustainable infrastructure in disaster-prone regions requires planning based on multi-hazard risk mitigation rather than merely construction cost control. Thus, the additional costs for building gravity walls are justified by the benefits of greater resilience to earthquakes and long-term traffic loads.

Beyond technical aspects, the implications of this study also relate to a paradigm shift in infrastructure design decision-making. Many road and retaining wall projects in Indonesia have traditionally prioritized short-term cost efficiency. However, empirical evidence from Sukodono Road demonstrates that low-cost designs prone to failure may eventually generate higher social and economic costs. Life-cycle cost analysis, which accounts for construction, maintenance, and failure risks, should therefore become the standard for determining wall type selection (Chukwunweike et al., 2024; Sathkumara et al., 2025). This aligns with the

global push to integrate sustainability principles into civil engineering, especially in high-seismic-risk regions.

From a policy perspective, this research contributes to the knowledge base that decision-makers in civil and environmental engineering can reference. Evidence-based design decisions not only enhance infrastructure reliability but also strengthen the legitimacy of development policies in the eyes of the public. The finding that gravity walls are more stable against combined earthquake and traffic loads provides a strong technical argument for local governments and project planners to choose safer designs, even if they require larger budget allocations. This resonates with Sathkumara et al. (2025), who emphasize that resilient infrastructure systems require adaptive designs that consider the interaction of multiple loads simultaneously.

This research also implicitly indicates that road infrastructure in earthquake-prone areas requires a more interdisciplinary approach. Geotechnical factors, traffic loads, seismic activity, and environmental aspects must be viewed as a unified system. A weakness in one aspect, such as low soil bearing capacity, may be exacerbated by other factors like heavy vehicle surcharges or seismic shocks. Therefore, the decision to adopt gravity walls on Sukodono Road is not merely a technical choice but also a systemic approach prioritizing safety and sustainability. Research by Ghimire et al. (2024) and Onukwulu et al. (2023) supports this by stressing the need for slope stability and retaining wall planning that simultaneously considers combined static–dynamic loading.

Furthermore, these implications can inform the development of national design guidelines in Indonesia. While SNI and AASHTO LRFD standards already provide comprehensive calculation frameworks, field findings from Sukodono Road highlight the importance of explicitly emphasizing simultaneous load evaluation in stability analyses. In other words, technical guidelines should not stop at single-load safety factors but should also encourage dual-load simulations that more realistically represent field conditions. Integrating these findings into national standards would strengthen the resilience of Indonesian infrastructure against increasing earthquake and traffic risks.

CONCLUSION

The findings of this study affirm that the selection of retaining wall types in earthquake-prone and heavily trafficked areas such as Sukodono Road cannot be determined solely by cost and spatial efficiency considerations but must be based on a comprehensive evaluation of long-term stability and multi-hazard resilience. Comparative analysis between cantilever and gravity retaining walls shows that although cantilever walls are more material-efficient and require less space, their performance is much more sensitive to seismic vibrations and weak soil conditions. In contrast, gravity retaining walls, despite requiring higher cost and space, provide superior resistance against combined earthquake and traffic loads, thus ensuring structural safety and road infrastructure sustainability. By integrating simultaneous load analysis—earthquake and traffic—into the design framework, this study

offers an evidence-based approach to support technical decision-making in civil and environmental engineering. These findings also emphasize that infrastructure design in disaster-prone regions must be positioned as a long-term investment in public safety and transport system sustainability, rather than short-term construction efficiency.

ETHICAL STATEMENT AND DISCLOSURE

This study was conducted in accordance with established ethical principles, including informed consent, protection of informants' confidentiality, and respect for local cultural values. Special consideration was given to participants from vulnerable groups to ensure their safety, comfort, and equal rights to participate. No external funding was received, and the authors declare no conflict of interest. All data and information presented were collected through valid research methods and have been verified to ensure their accuracy and reliability. The use of artificial intelligence (AI) was limited to technical assistance for writing and language editing, without influencing the scientific substance of the work. The authors express their gratitude to the informants for their valuable insights, and to the anonymous reviewers for their constructive feedback on an earlier version of this manuscript. The authors take full responsibility for the content and conclusions of this article.

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