

RESEARCH ARTICLE

Analysis of the Effects of Earthquakes on the Pile-Box Culvert System at the Gentos Bridge, Situbondo, Indonesia

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Abstract

Soft soil conditions present significant challenges to the seismic performance of transportation infrastructure, particularly box culverts constructed in earthquake-prone regions. This study evaluates the effectiveness of galam timber piles in improving the stability and reducing the settlement of a pile-supported box culvert at the Gentos Bridge, Situbondo, Indonesia. Three-dimensional numerical analyses were performed using PLAXIS 3D, in which the soil behavior was represented by the Mohr–Coulomb constitutive model. Dynamic loading was applied using the RSN2736 Chi-Chi (CHY101-E) earthquake record from the NGA-West database, which was spectrally matched to the target response spectrum specified in SNI 1726:2019. The matched earthquake motion had a maximum acceleration of 0.20568 g, while the target design spectrum corresponded to a Peak Ground Acceleration (PGA) of 0.307 g. The numerical model incorporated layered soil conditions, staged construction, and soil–structure interaction to evaluate the seismic response of the box culvert foundation system. The results indicate that the installation of galam timber piles reduced elastic settlement from 5.5 cm to approximately 3.0 cm, representing a 45.5% reduction, while increasing the safety factor from 2.55 to 3.02, corresponding to an improvement of 18.4%. These improvements demonstrate a significant enhancement in foundation stiffness, load distribution, and overall structural stability under seismic loading. The main scientific contribution of this study lies in demonstrating the feasibility of utilizing locally available galam timber piles as an effective foundation reinforcement system for pile-supported box culverts subjected to earthquake loading. The proposed approach provides a practical and sustainable alternative for improving the seismic performance of transportation infrastructure constructed on soft soils in earthquake-prone regions.

Keywords: Box Culvert, Dynamic Analysis, Earthquake, Galam Timber Piles, Soft Soil,

1. Introduction

The construction of box culverts on soft soil often faces challenges such as low soil bearing capacity and a high potential for settlement, which can affect the stability of the structure (Basoka, 2020). These conditions become even more critical in earthquake-prone areas because seismic loads can increase soil deformation, changes in pore water pressure, and the dynamic response of the structure, which can potentially cause damage to the foundation system and box culvert elements (Solin, 2022). If these conditions are not anticipated through proper planning, they can lead to reduced structural performance, cracks in concrete elements, and even structural failure, which can disrupt the function of the infrastructure (Alfaries et al., 2026).

In addition to being influenced by soil characteristics, the behavior of box culverts is also influenced by soil–structure interaction (Sagita et al., 2020). This interaction determines the magnitude of stress distribution, deformation, and displacement patterns that occur when the structure is subjected to traffic or seismic loads. During an earthquake, the resulting dynamic response can increase internal forces within the structure; therefore, a support system is required that can reduce stress concentrations and maintain the stability of the soil surrounding the structure (Gumilar P et al., 2022).

One commonly used method is the installation of piles. Piles serve to increase soil stiffness, reduce settlement, improve load distribution on the structure, and enhance the interaction between the soil and the foundation so that deformation response can be minimized (Yang et al., 2025). The use of piles can also increase the soil's bearing capacity through the

mechanisms of skin friction and local compaction around the pile elements (Mujtaba et al., 2018). Furthermore, this method is relatively economical, easy to implement, does not require complex heavy equipment, and is suitable for construction work at sites with limited access (Roschedy et al., 2019). However, there are still few studies reporting on the effectiveness of piles in improving the seismic behavior of soil–box culvert systems, particularly those using a three-dimensional numerical analysis approach based on the finite element method (Rokhman et al., 2023). Although previous studies have investigated pile-supported foundations and numerical analyses of soft soils, most have focused on static loading conditions or conventional concrete and steel piles. Limited attention has been given to the seismic behavior of pile-supported box culverts reinforced with locally available galam timber piles using three-dimensional finite element analysis (Rahman et al., 2026). Furthermore, the dynamic soil–structure interaction under spectrally matched earthquake loading has not been comprehensively investigated (Nurmansyah et al., 2026).

Although several previous studies have investigated the behavior of box culverts on soft soil using numerical analysis, most of them focused on conventional pile foundations or static loading conditions (Diana et al., 2026). Limited studies have evaluated the seismic behavior of box culverts supported by galam wood piles through three-dimensional dynamic finite element analysis (Nugroho et al., 2025). Furthermore, information regarding the effectiveness of locally available timber piles in improving the seismic performance of soil–structure systems remains scarce (Suhendi et al., 2025). Therefore, this study addresses this research gap by investigating the dynamic response of a galam wood pile–box

culvert system under earthquake loading using PLAXIS 3D (Diefenderfer et al., 2024). This study contributes to the existing body of knowledge by developing a three-dimensional numerical framework for evaluating the seismic performance of pile-supported box culverts founded on soft soils using galam timber piles (Bu et al., 2023). Beyond presenting a site-specific case study, the proposed modelling approach demonstrates the potential of locally available timber piles as a sustainable foundation reinforcement alternative for transportation infrastructure in earthquake-prone regions (Lei et al., 2026).

This study aims to analyze the effect of earthquakes on the soil–pile–box culvert system at the Gentos Bridge in Situbondo Regency using finite element method-based dynamic analysis (Sunariyono et al., 2019). The analysis was conducted to evaluate the soil–structure interaction behavior under seismic loading by comparing conditions before and after pile installation (Asrar, 2021). The parameters evaluated include displacement, settlement, lateral deformation, stress distribution, strain, and the overall response of the soil–structure system during the dynamic loading process (Azizi et al., 2020). The research results are expected to provide scientific information on the effectiveness of using piles as a soil improvement method, serve as a reference for planning box culverts on soft soil in earthquake-prone areas, and support the development of safer, more reliable, economical, and sustainable infrastructure designs (Prima et al., 2019). The findings are expected to provide practical guidance for the design and assessment of pile-supported box culverts constructed on soft soils in earthquake-prone regions (Esposito et al., 2026). Furthermore, the proposed modelling framework may serve as a reference for the application of locally available galam timber piles as an economical and sustainable foundation reinforcement alternative (Khalifa et al., 2025).

The novelty of this study lies in the integration of three-dimensional dynamic finite element analysis with the application of locally available galam wood piles as a ground improvement system for box culverts constructed on soft soil (El-bayome et al., 2026). Unlike previous studies that mainly considered conventional pile foundations or static loading, this research evaluates the seismic response of the soil pile box culvert interaction under earthquake loading conditions based on the Indonesian seismic design code (Yatsumoto et al., 2019). The findings provide additional insight into the effectiveness of galam wood piles as an economical alternative foundation system for transportation infrastructure in earthquake-prone soft soil areas (Kheradi et al., 2018).

2. Research Methodology

This study employs a quantitative method using a numerical analysis approach based on the Finite Element Method (FEM) (Santoso and Hartono, 2020). The subject of the study is the soil–pile–box culvert system at the Gentos Bridge in Situbondo Regency. As shown in Fig 1, the soil structure down to a depth of 12 meters consists of soft clay. Modeling was performed using geotechnical software, taking into account soil conditions, pile dimensions, box culvert geometry, as well as gravity and seismic loads in accordance with SNI 1726:2019.

The analysis was conducted under two conditions: without piles and with piles. The parameters evaluated included total displacement, settlement, lateral deformation, and stress distribution (Ereiz et al., 2022). The results of the two models were then compared to assess the effectiveness of using piles in improving the stability and seismic performance of the box culvert on soft soil. For the research methodology, the results of the borehole and Standard Penetration Test (SPT) tests at the Gentos Bridge project site in Situbondo are shown in Fig 1 below.

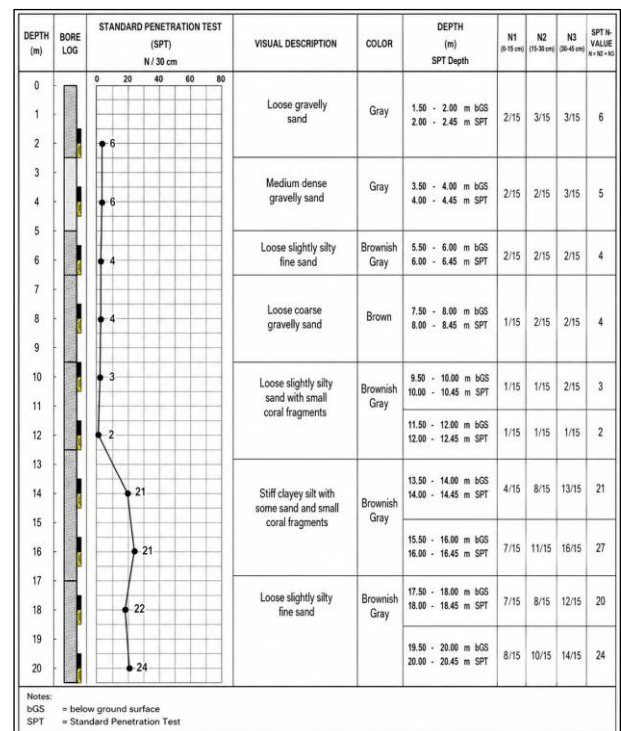


Fig 1. Results of Borehole and SPT Tests at the Gentos Bridge Project Site, Situbondo

2.1 Constitutive Model

The soil layers were modeled using the Mohr–Coulomb (MC) constitutive model in PLAXIS 3D. The Mohr–Coulomb model was selected because it is an elastic–perfectly plastic constitutive model that requires a limited number of engineering parameters, including the elastic modulus (E), Poisson’s ratio (ν), effective cohesion (c'), effective friction angle (ϕ'), dilatancy angle (ψ), and unit weight (γ). These parameters were obtained from the field investigation and laboratory testing conducted at the Gentos Bridge project site.

The selection of the Mohr–Coulomb model is appropriate for the objectives of this study, which focus on evaluating the comparative seismic response of the soil pile box culvert system before and after the installation of galam wood piles. The model provides a practical balance between computational efficiency and engineering accuracy and has been widely applied in finite element analyses of geotechnical structures, particularly for preliminary design and comparative performance assessments (Vinogradov et al., 2017).

It should be noted that the Mohr–Coulomb model assumes linear elastic behavior prior to yielding and perfectly plastic behavior after the failure criterion is reached. Consequently, the model does not explicitly account for stress-dependent stiffness, cyclic degradation, or small-strain stiffness effects that may occur under strong earthquake loading. Nevertheless, for comparative analyses aimed at evaluating the effectiveness of ground improvement, the Mohr–Coulomb model provides sufficiently reliable predictions of settlement, deformation, and overall stability (Sirisonthi et al., 2021).

2.2 Model Validation

Since field monitoring data for the Gentos Bridge box culvert were not available, direct validation against measured displacements or settlements could not be performed. Therefore, the numerical model was validated qualitatively by comparing its predicted behavior with findings reported in previous studies on pile-supported foundations constructed on soft soils (Chen and Zhang, 2021).

The adopted modelling procedure, including the use of field investigation data, staged construction analysis, and dynamic loading based on SNI 1726:2019, provides a reasonable representation of the soil–structure interaction. Therefore, the numerical predictions are considered consistent with previously published findings and suitable for evaluating the seismic performance of the pile–box culvert system. Ince field monitoring data for the Gentos Bridge box culvert were not available, direct validation against measured displacements or settlements could not be performed. Therefore, the numerical model was qualitatively validated by comparing its predicted behavior with findings reported in previous studies on pile-supported foundations constructed on soft soils (Park, 2023).

Table 1. Qualitative Validation of the Numerical Model

Reference	Main Findings	Agreement with the Present Study
Yang et al. (2025)	Pile reinforcement improved foundation stiffness and reduced deformation of structures constructed on soft soil.	Consistent with the present study, where galam wood piles reduced settlement and improved stability.
	Pile foundations enhanced load transfer and increased the bearing capacity of soft soils.	Similar behavior was observed through improved stress distribution and increased safety factor after pile installation. Demonstrates the effectiveness of galam wood piles in improving the seismic performance of the soil–box culvert system.
Mujtaba et al. (2018)	Elastic settlement decreased from 5.5 cm to 3.0 cm, while the safety factor increased from 2.55 to 3.02.	
Present Study		

Previous studies have consistently shown that the installation of pile foundations increases the stiffness of soft soils, reduces settlement, improves load distribution, and enhances the stability of soil–structure systems under static and dynamic loading conditions. The numerical model developed in this study exhibits the same behavior, as indicated by the reduction in elastic settlement and the increase in the safety factor after the installation of galam wood piles. A qualitative comparison between the findings of the present study and those reported in previous literature is presented in Table 1.

As shown in Table 1, the numerical predictions obtained from the PLAXIS 3D model exhibit the same general trends reported in previous studies, namely improved soil stiffness, reduced settlement, and enhanced foundation stability following pile installation. Although direct field measurements were unavailable for quantitative validation, the agreement between the numerical results and published literature indicates that the adopted modelling procedure provides a reasonable representation of the soil–structure interaction. Therefore, the developed numerical model is considered sufficiently reliable for evaluating the seismic behavior of the pile–box culvert system.

3. Results and Discussion

3.1 Soil Data and Interpretation

The soil parameters used in the PLAXIS modeling were obtained from soil investigations conducted via Standard Penetration Test (SPT) and laboratory testing. Based on Table 2, the soil layers down to a depth of 20.5 m consist of loose sand, silty clay, and very stiff clay. NSPT values range from 2.5 to 24, indicating that the soil layers are dominated by soft soil

at depths of 5.0–12.5 m with NSPT values of 2.5–4, while deeper soil layers have higher density and stiffness.

The soil physical parameters used in the analysis include saturated unit weight (γ_{sat}), unsaturated unit weight (γ_{unsat}), specific gravity (G_s), porosity (e), and Poisson's ratio (ν). Meanwhile, the shear strength parameters consist of undrained cohesion (C_u), effective cohesion (c'), and internal friction angle (ϕ'). The C_u values range from 20.10 to 24.03 kN/m², while ϕ' ranges from 11° to 20° for cohesive soils.

Table 2. Soil Parameters

Depth (m)	SPT N-Value	Soil Type	Consistency	Water Content (%)	γ_{sat}	γ_{unsat}
0.0–2.5	6	Sand	Loose	15.88	21.47	20.39
2.5–5.0	5	Sand	Loose	51.55	16.71	14.49
5.0–6.5	4	Silty Clay	Soft	46.98	17.00	14.74
6.5–9.5	4	Clayey Silt	Soft	57.32	16.21	13.61
9.5–12.5	2.5	Silty Clay	Soft	47.79	16.97	14.61
12.5–17.0	24	Clay	Very Stiff	52.63	16.66	14.08
17.0–20.5	22	Sand	Medium Dense	45.15	17.29	15.08

The results of the Atterberg limit tests showed a Liquid Limit (LL) of 71.87–79.29% and a Plasticity Index (PI) of 38.65–41.15%, indicating that the silty to clayey silt layer has high plasticity. The elastic modulus (E_s) values ranged from 3,830 to 16,852 kN/m², which were used as soil stiffness parameters in finite element method (FEM) modeling using PLAXIS. All of these parameters served as the basis for analyzing deformation, stress distribution, and the stability of the soil–pile–box culvert system. Although the Mohr–Coulomb constitutive model adequately captured the overall response of the soil–structure system in this study, more advanced constitutive models such as the Hardening Soil (HS) or Hardening Soil with Small-Strain Stiffness (HSsmall) may provide more accurate predictions of nonlinear soil behavior under strong seismic loading. Future studies are therefore encouraged to investigate the influence of different constitutive models on the dynamic response of pile-supported box culverts. All data are presented in Tables 2, 3, and 4.

Table 3. Strength Parameters

Depth (m)	G_s	Void Ratio	Poisson Ratio	C_u (kN/m ²)	C (kN/m ²)	C' (kN/m ²)
0–2.5	2,7	0,43	0,3		16,67	11
2,5–5	2,67	1,38	0,3		23,54	16
5–6,5	2,64	1,24	0,2	20,59	30,40	20
6,5–9,5	2,64	1,51	0,2	20,10	31,38	21
9,5–12,5	2,65	1,27	0,2	22,06	27,95	19
12,5–17	2,65	1,39	0,4	24,03	28,93	19
17–20,5	2,67	1,21	0,4		21,57	14

Table 4. Index Properties and Stiffness Parameters

Depth (m)	ϕ	ϕ'	LL (%)	PL (%)	IP (%)	E_s
0–2,5	23	15				4596
2,5–5	23	15				3830
5–6,5	17	11	73,43	43,14	39,29	5148
6,5–9,5	19	13	79,29	35,14	41,15	5026
9,5–12,5	18	12	71,87	33,22	38,65	5516
12,5–17	18	12	72,91	34,20	38,71	6007
17–20,5	21	14				16852

3.2 Modeling

Modeling was performed to analyze the behavior of the soil–galam wood pile–box culvert system under applied loads using the Finite Element method in PLAXIS software. The model consists of a box culvert structure supported by a group of galam wood piles installed vertically in soft soil.

As shown in Fig 2, the box culvert has a span of 6.90 m and a height of 4.0 m, equipped with a deck slab and wingwalls. The galam wood piles are evenly spaced beneath the box culvert's base slab, forming a composite foundation system that serves to increase soil stiffness and distribute the structural load to deeper soil layers.

In the modeling, soil layers were incorporated based on geotechnical parameters derived from field investigations and laboratory tests. The analyzed loads included the structure's self-weight, the fill above the box culvert, and traffic loads. The analysis was conducted in stages (staged construction), beginning with the original soil conditions, followed by the installation of galam wood piles, the construction of the box culvert, and finally the application of the final load.

The modeling results were used to evaluate settlement, stress distribution, deformation, and the safety factor. A comparison between conditions without reinforcement and those with galam wood pile reinforcement demonstrates the effectiveness of the soil improvement method in enhancing stability and reducing settlement in the box culvert structure. Fig 2. Model of a soil improvement system using galam wood piles on a box culvert foundation for finite element method (FEM) analysis.

The box culvert geometry was modeled according to the actual dimensions of the Gentos Bridge structure, with an overall width of 6.90 m, an internal height of 4.14 m, and a top slab thickness of 0.30 m. The galam timber piles were arranged beneath the box culvert to improve the bearing capacity of the soft soil foundation. The layered soil profile represents the site stratigraphy from the ground surface to a depth of 20.5 m, consisting of sand, clayey silt, clay, and medium dense sand layers.

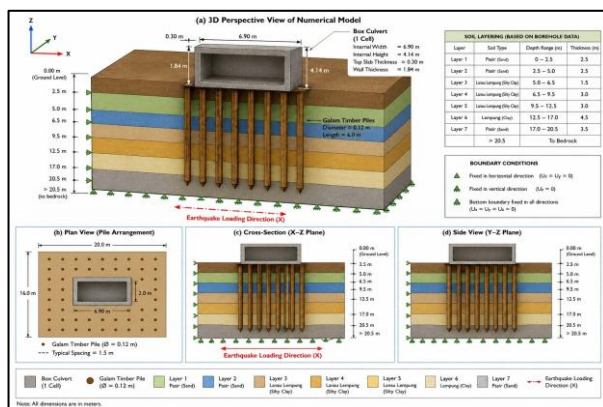


Fig 2. Soft Soil Improvement Model Using Piles

4. Seismic Load

The seismic analysis of this box culvert bridge is based on SNI 2833:2016 regarding Bridge Design for Seismic Loads. Based on the N-SPT test at a depth of 30 m, a value of 24 was obtained, which classifies the site as SD (moderate soil).

4.1 Spectrum Response Analysis

To analyze the spectral response, parameters are required that can be obtained using the Response Spectra Analysis (RSA) Cipta Karya website by entering the coordinates corresponding to the project location. This yields the spectral response parameters and spectral response graphs shown in Table 5 and Fig 3.

Table 5. Spectral response parameters

variable	Value
$PGA_{(g)}$	0,307
$Ss_{(g)}$	0,658
$S1_{(g)}$	0,31

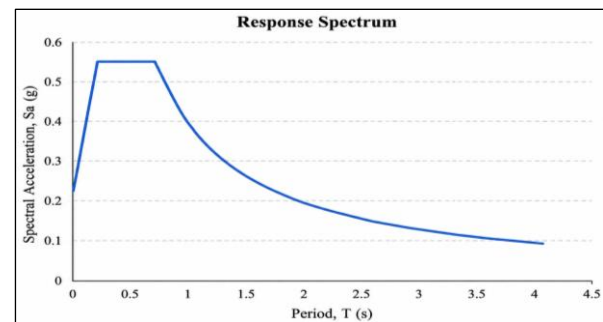


Fig 3. Graph of response spectrum values.

4.2 Earthquake Input Motion

Dynamic analysis in PLAXIS 3D requires earthquake loading in the form of an acceleration time-history record. In this study, the selected earthquake input was the RSN2736 Chi-Chi (CHY101-E) accelerogram obtained from the NGA-West database. The record was selected because it represents a strong earthquake motion and was subsequently modified through a spectral matching procedure to satisfy the target response spectrum specified in SNI 1726:2019 for the Gentos Bridge site.

The target response spectrum was established using seismic hazard parameters obtained from the RSA Cipta Karya application, resulting in Peak Ground Acceleration (PGA) = 0.307 g, $Ss = 0.658$ g, and $S1 = 0.310$ g. Spectral matching was performed using SeismoMatch over a structural period range of 0.072–0.906 s with a tolerance of 10%. The matching process converged successfully after 26 iterations, producing an average spectral misfit of 1.0% and a maximum spectral misfit of 5.1%, both of which satisfy the acceptance criteria of SNI 1726:2019.

Table 6. Characteristics of the Matched Earthquake Input Motion

Parameter	Value
Earthquake record	RSN2736 Chi-Chi (CHY101-E)
Database	NGA-West
Target spectrum	SNI 1726:2019
PGA (Target Spectrum)	0.307 g
Maximum acceleration (Matched record)	0.20568 g
Maximum velocity	17.99549 cm/s
Maximum displacement	9.51506 cm
Approximate duration	60 s
Matching period	0.072–0.906 s
Spectral matching software	SeismoMatch
Number of iterations	26
Average misfit	1.0%
Maximum misfit	5.1%
Arias intensity	0.81973
Scaling factor in PLAXIS	1.0

The matched acceleration record had an approximate duration of 60 s and was directly applied as the seismic input in the PLAXIS 3D dynamic analysis. No additional scaling was applied within PLAXIS because the acceleration record had already been adjusted during the spectral matching process. It should be noted that the PGA value of 0.307 g represents the design seismic parameter from the Indonesian seismic hazard map, whereas the maximum acceleration of the matched accelerogram was 0.20568 g, representing the peak acceleration

of the input record used in the numerical simulation. The principal characteristics of the matched earthquake input motion are summarized in Table 6.

4.3 Spectrum Response Analysis Plaxis 3D

For time-history analysis, spectral response value data is required, which is then subjected to spectral matching. Spectrally matched acceleration records must not deviate by more than 10% from the target spectrum. Time-history analysis is necessary in this study because the Plaxis 3D analysis requires seismic load input in the form of a time history.

The spectral matching results showed a maximum misfit of 9.6%, which is below the 10% threshold. This complies with SNI 1726:2019, which stipulates that the value of the pseudo-acceleration calculated from the spectrally matched records must not exceed 10% of the target spectrum. Therefore, the spectral matching results can be used in the Plaxis 3D analysis.

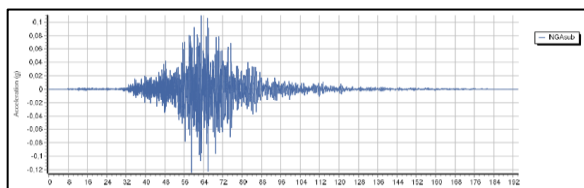


Fig 4. Time-history data used in the Plaxis 3D analysis

5. Analysis

5.1 Stability Analysis of Unreinforced Soil

Fig 5 shows the three-dimensional geometric model (PLAXIS 3D) used to analyze the soil–box culvert–galam wood pile system. The model consists of several soil layers based on the results of geotechnical investigations, with the box culvert placed on the ground surface and reinforced by galam wood piles beneath the foundation.

Modeling was performed by inputting soil and structural material parameters and applying loads in stages (staged construction). This model was used to evaluate the distribution of stress, deformation, settlement, and the safety factor to determine the effectiveness of using galam wood piles as a method for improving soft soil.

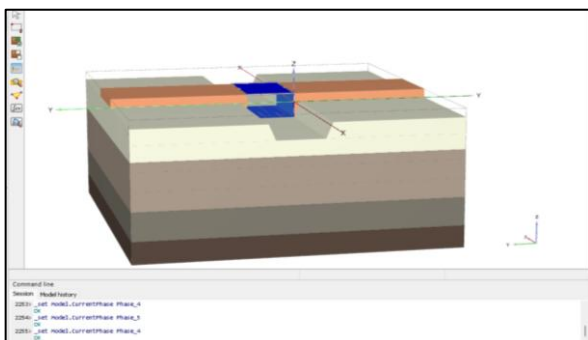


Fig 5. Plaxis 3D Modeling Without Reinforcement

Fig 6 and 7 show the safety factor curves obtained from the PLAXIS analysis for load combinations Extreme 1 and Extreme 2 using the phi-c reduction method. The curves show an increase in the multiplier value (ΣMsf) that continues until convergence is reached, indicating that the model has reached the failure condition to determine the safety factor value.

The curve, which rises sharply in the early stages and then tends to level off, indicates that the soil–structure system remains stable until it reaches the maximum Safety Factor value. These results indicate that the model has sufficient capacity to withstand the extreme load combinations, meaning that the

stability of the foundation system and the box culvert still meets safety requirements based on the results of the finite element method (FEM) analysis.

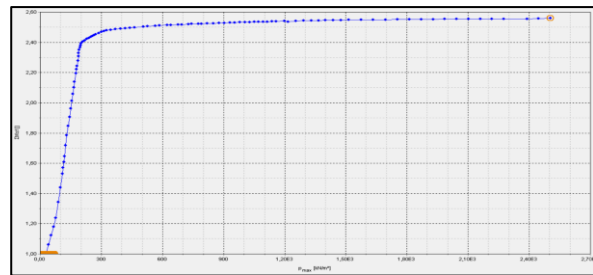


Fig 6. Graph Of The Safety Factor For Extreme 1 Combination

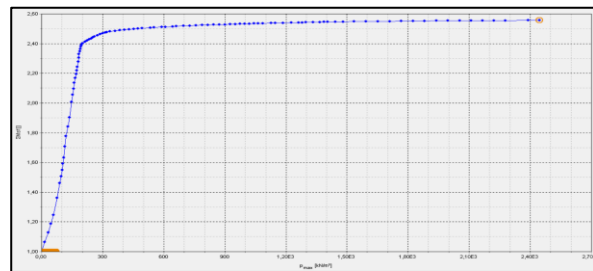


Fig 7. Graph Of The Safety Factor For Extreme 2 Combination

5.2 Analysis of Elastic Settlement in Unreinforced Soil

Fig 8 and 9 show the results of the modeling analysis for extreme combinations 1 and 2; ground settlement is concentrated directly beneath the main structure's foundation in the central part of the surface. This area experiences the highest compression, as indicated by the red-to-orange zones, with the greatest settlement value reaching approximately -55×10^{-3} m. As depth and lateral distance from the load center increase, the magnitude of this settlement gradually decreases and weakens. This is evident from the color gradient transitioning to yellow, green, and finally predominantly dark blue in the deepest soil layers and peripheral areas, indicating that these regions are already in a stable condition or are not affected by the load from the structure above.

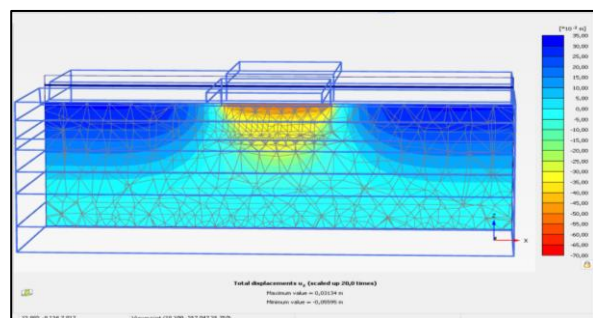


Fig 8. Results Of The Elastic Settlement Of Comb Extreme 1

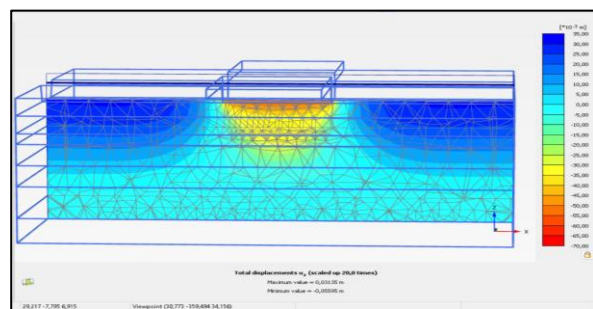


Fig 9. Results of the elastic reduction for Comb Extreme

5.3 Stability Analysis of Soil Reinforced with Galam Wood Piles

Fig 10 shows a three-dimensional model (PLAXIS 3D) of a box culvert system reinforced with galam wood piles spaced at 0.6×1.32 m. In this model, the box culvert is represented as a structural element, while the galam wood piles are modeled as a group of vertically installed piles that are uniformly distributed beneath the base slab to improve the bearing capacity and stiffness of the underlying soft soil. This reinforcement system is intended to reduce excessive settlement and enhance the overall stability of the foundation system under service loads.

The modeling was performed by inputting soil parameters obtained from field investigations, structural material properties, and the interaction between the soil and the piles. The constitutive soil model was selected to represent the actual behavior of the subsoil under loading conditions. The applied loads include the structure's self-weight, backfill, and traffic loads. The analysis was carried out using a staged construction approach so that the numerical simulation closely represents the actual construction sequence in the field, including the gradual application of loads during the construction process.

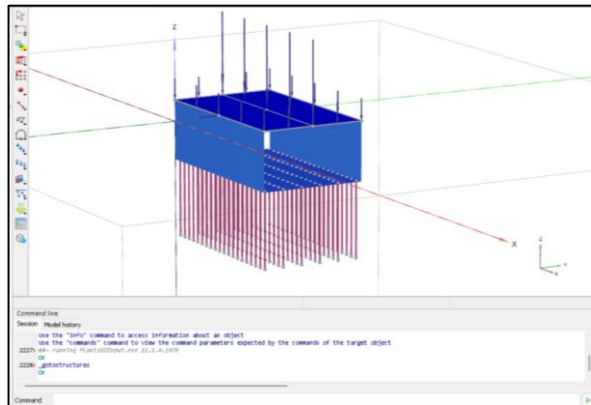


Fig 10. Plaxis 3D Modeling with Galam Wood Piles Spaced 0.6 x 1.32 m Apart

Boundary conditions and mesh generation were carefully defined to ensure numerical stability and improve the accuracy of the finite element analysis. Appropriate interface properties were also assigned to simulate the interaction between the soil and the galam wood piles, allowing the transfer of stresses and deformations to be represented more realistically throughout the analysis.

This PLAXIS 3D model was used to evaluate the behavior of the soil-pile-box culvert system, including stress distribution, deformation, settlement, and the safety factor. The analysis results were then compared with conditions without reinforcement to assess the effectiveness of using galam wood piles in improving foundation stability on soft soil.

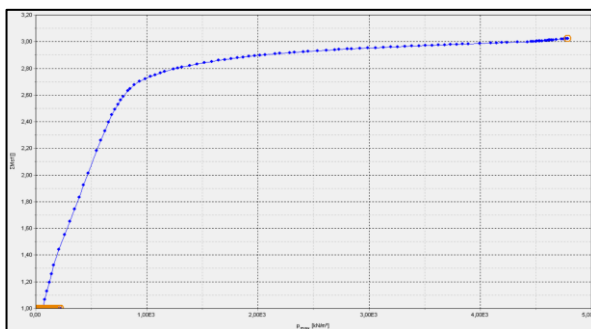


Fig 11. Safety factor graph for galam wood stakes spaced 0.6 x 1.32 m apart

Fig 11 shows the safety factor curve obtained from the PLAXIS analysis for Extreme Load Combination 1 using the phi-c reduction method on reinforced soil. The curve shows an increase in the multiplier value (ΣMsf) until convergence is reached, indicating that the model has reached the failure condition to determine the safety factor value.

5.4 Analysis of Settlement in Soil Reinforced with Galam Wood Piles

Fig s 12 show the results of the modeling analysis for extreme combinations 1 and 2; ground settlement is concentrated directly beneath the foundation of the main structure in the central part of the surface. This area experiences the highest compression, as indicated by the red-to-orange zones, with the greatest settlement reaching approximately -3 cm.

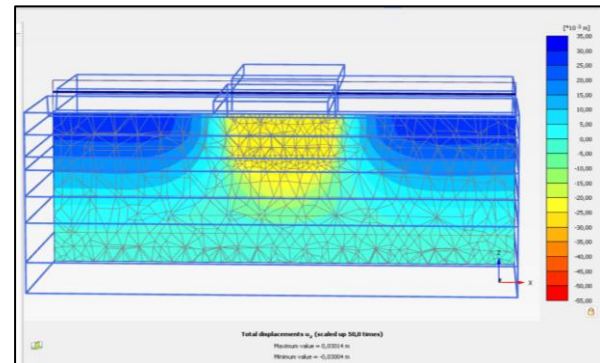


Fig 12. Results of elastic settlement using galam wood piles spaced 0.6 x 0.95 m apart

5.5 Sensitivity Analysis of Galam Timber Pile Configuration

To identify the optimum galam timber pile configuration, a sensitivity analysis was conducted by evaluating several pile arrangements while maintaining the same pile diameter (0.10 m) and pile length (6.0 m). The investigated variable was the pile spacing, which directly influences the number of piles, load distribution, soil stiffness, settlement, and overall foundation stability. Each configuration was analyzed using the same loading conditions and soil properties to ensure a consistent comparison of structural performance.

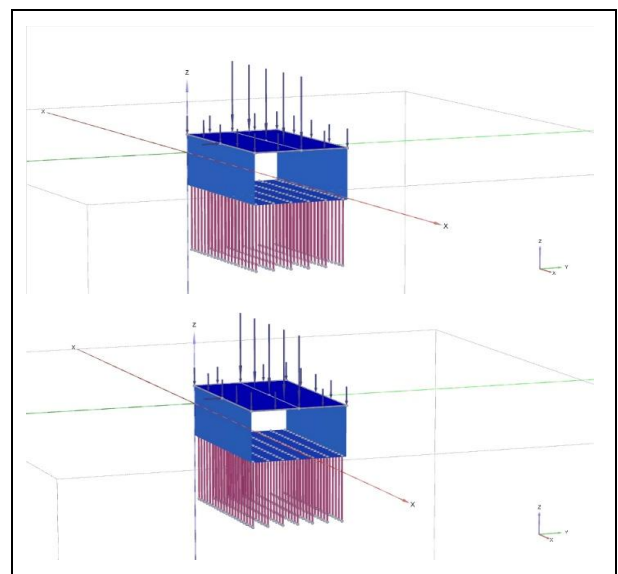


Fig 13. Three-dimensional numerical model of the box culvert reinforced with galam timber piles used in the sensitivity analysis

5.6 Dynamic Response Analysis under Earthquake Loading

To further demonstrate the influence of seismic loading on the reinforced box culvert system, additional dynamic response parameters obtained from the PLAXIS 3D time-history analysis are presented. Unlike the static analysis, which only evaluates settlement and safety factor, the dynamic analysis illustrates the structural response throughout the earthquake duration. The horizontal displacement of the box culvert was monitored during the application of the matched earthquake accelerogram with a peak ground acceleration (PGA) of 0.206 g, allowing the transient and permanent deformation characteristics of the soil pile culvert system to be evaluated.

The numerical model shown in Fig 13 was employed for all trial configurations. Only the pile spacing was modified during the sensitivity analysis, whereas the geometry of the box culvert, soil stratification, constitutive model, boundary conditions, and loading remained unchanged.

a.) Configuration A (Spacing 0.60×1.32 m)

The first configuration employed a pile spacing of 0.60 m in the longitudinal direction and 1.32 m in the transverse direction, resulting in a total of 120 galam timber piles.

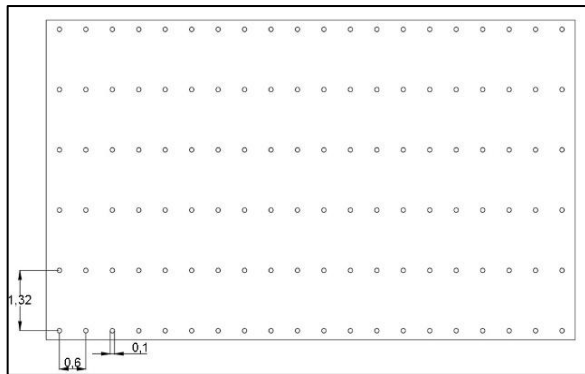


Fig 14. (Spacing 0.60×1.32 m)

The analysis results for Trial 1, with a galam wood pile spacing of 0.6×1.32 m, yielded the following values for the factor of safety, elastic settlement, and consolidation settlement (366 days):

Factor of safety = 3.02
Elastic settlement = 3.0 cm
Consolidation settlement = 11.6 cm

b.) Configuration B (Spacing 0.60×0.95 m)

The second configuration reduced the transverse pile spacing to 0.95 m while maintaining the longitudinal spacing at 0.60 m. Consequently, the total number of piles increased to 140, producing a denser pile group beneath the box culvert.

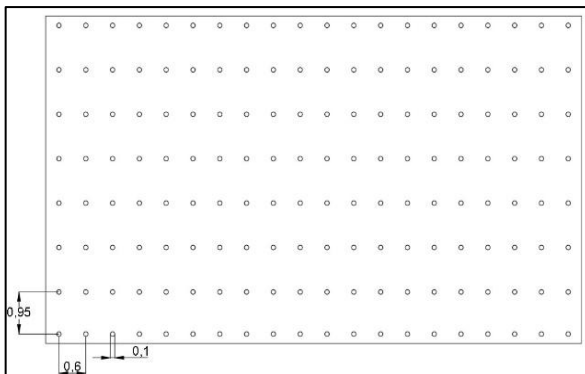


Fig 15. (Spacing 0.60×0.95 m)

The analysis results for Trial 2, with a galam wood pile spacing of 0.6×0.95 m, yielded the following values for the factor of safety, elastic settlement, and consolidation settlement (366 days):

Factor of Safety = 3.03
Elastic Settlement = 3.0 cm
Consolidation Settlement = 11.5 cm

c.) Comparison of Sensitivity Analysis Results

To evaluate the influence of pile spacing on the structural performance of the reinforced box culvert, the results obtained from each trial configuration are summarized and compared in Table X. The comparison focuses on the number of piles, elastic settlement, consolidation settlement, and safety factor, allowing the effectiveness of each pile arrangement to be objectively assessed. This comparison also facilitates the selection of the optimum pile configuration that provides the best balance between settlement reduction, structural stability, and practical implementation.

Table 7. Comparison of sensitivity analysis results for different galam timber pile configurations.

Configuration	Pile Spacing (m)	Number of Piles	Elastic Settlement (cm)	Consolidation Settlement (cm)	Safety Factor
Trial 1	0.60×1.32	120	3.00	11,60	3.02
Trial 2	0.60×0.95	140	3,00	11,50	3,03

As shown in Table 5, reducing the pile spacing increases the number of galam timber piles supporting the box culvert, resulting in a stiffer foundation system and more efficient load transfer to the underlying soil layers. Consequently, the safety factor generally increases, while both elastic and consolidation settlements tend to decrease. Although the improvements between some configurations are relatively small, the overall trend indicates that closer pile spacing enhances the mechanical performance of the soil-pile-structure system. Therefore, the optimum configuration was selected by considering both the engineering performance and the practicality of construction.

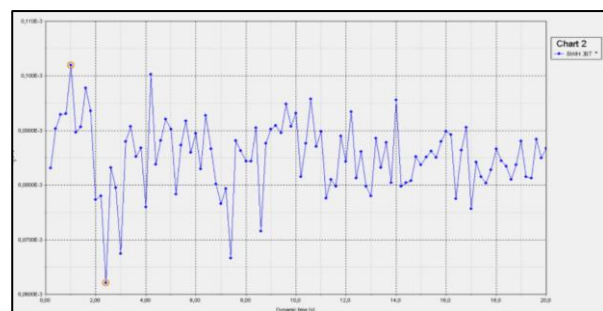


Fig 16. Time-history horizontal displacement of the reinforced box culvert during earthquake loading

Figure 16 presents the horizontal displacement response of the reinforced box culvert during the earthquake excitation. The displacement fluctuates continuously following the characteristics of the input ground motion, indicating that the soil-pile-culvert system dynamically responds to cyclic seismic loading. The maximum displacement occurs during the strongest portion of the earthquake record, after which the response gradually decreases as the earthquake intensity diminishes. This behavior indicates that the galam timber pile foundation effectively increases the stiffness of the supporting soil and limits excessive lateral movement during seismic excitation. Although oscillatory displacement is observed throughout the loading duration, no progressive instability or

excessive deformation develops, demonstrating that the reinforced foundation system remains stable under the applied earthquake loading.

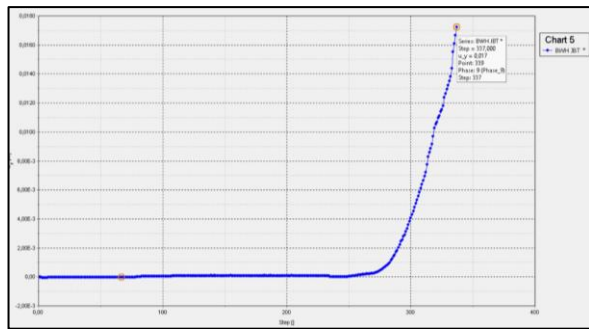


Fig 17. Permanent horizontal displacement after completion of the earthquake analysis

Figure 17 illustrates the evolution of horizontal displacement throughout all calculation steps until the completion of the dynamic analysis. The displacement remains relatively constant during the initial calculation stages and increases significantly only when the earthquake loading phase is activated. At the end of the analysis, the residual horizontal displacement reaches approximately 0.017 m (17 mm), representing the permanent deformation remaining after the earthquake motion has ceased. This residual displacement is relatively small compared with the overall dimensions of the box culvert, indicating that the reinforced system maintains adequate structural stability and serviceability after seismic loading. The limited permanent displacement also confirms that the galam timber piles effectively reduce irreversible soil deformation and improve the overall seismic performance of the soil–structure system.

The additional dynamic response results presented in Figure 13 and 14 complement the static settlement and safety factor analyses by providing direct evidence of the seismic behavior of the reinforced foundation system. The combination of limited transient displacement, small permanent deformation, and improved stability demonstrates that the galam timber pile reinforcement performs effectively in mitigating earthquake-induced ground deformation beneath the box culvert. These findings strengthen the reliability of the proposed reinforcement method for transportation infrastructure constructed on soft soil deposits located in seismic regions.

6. Result and Discussion

A numerical analysis using the finite element method implemented in PLAXIS 3D was conducted to evaluate the influence of galam timber pile reinforcement on the seismic performance of the box culvert foundation system. The numerical results indicate that the installation of galam timber piles reduced the elastic settlement from 5.5 cm to approximately 3.0 cm, corresponding to a reduction of 45.5%. Furthermore, the safety factor increased from 2.55 to 3.02, representing an improvement of approximately 18.4%. These results demonstrate that the reinforcement system significantly enhances the geotechnical performance and overall stability of the foundation under seismic loading.

The observed improvement is primarily attributed to the load transfer mechanism provided by the galam timber piles. Under seismic loading, a substantial portion of the structural load from the box culvert is transferred through the timber piles into deeper soil layers with higher bearing capacity. As a result, the stress acting on the upper soft soil layer is reduced, decreasing soil compression and limiting excessive settlement.

This load-sharing mechanism allows the foundation system to respond more efficiently to both static and dynamic loading conditions.

The installation of galam timber piles also increased the composite stiffness of the soil–foundation system. The pile reinforcement modified the stress distribution beneath the box culvert by transferring concentrated loads over a wider area, thereby reducing stress concentration within the soft soil. Consequently, the deformation became more uniform, leading to lower elastic settlement and an increase in the overall safety factor. These findings indicate that the reinforcement system effectively improved the load-bearing behavior of the foundation.

Soil–pile interaction played a significant role in improving the seismic response of the foundation system. During loading, shear resistance developed along the interface between the galam timber piles and the surrounding soil, enabling loads to be transferred efficiently to deeper soil layers. In addition, the closely spaced pile group acted as a composite foundation element rather than as individual piles. This pile group effect increased the overall stiffness of the reinforced ground, minimized differential settlement, and improved the stability of the box culvert under earthquake loading.

The numerical response obtained in this study is consistent with previous investigations on pile-supported foundations in soft soils. Similar studies have reported that pile reinforcement increases foundation stiffness, reduces settlement, improves stress redistribution, and enhances overall stability. The reduction in settlement and increase in the safety factor observed in this study therefore demonstrate behavior that is consistent with published findings, supporting the reliability of the developed PLAXIS 3D numerical model.

Table 8. Comparison of Numerical Results Before and After Galam Timber Pile Reinforcement

No	Description	Without Reinforcement	With Reinforcement	Change
1	Elastic Settlement (cm)	5,5	3,	Ups ±45,5%
2	Safety Factor	2,55	3,02	Down ±18,4%

Although the numerical analysis demonstrates that galam timber piles effectively improve the seismic performance of the soil–box culvert system, their long-term performance should also be considered. The durability of timber piles is highly dependent on groundwater conditions. Timber that remains continuously submerged below the groundwater table generally exhibits good durability because biological deterioration caused by fungi and insects is minimized. However, fluctuations in groundwater levels may accelerate timber degradation and gradually reduce the structural capacity of the piles over time. In addition, timber may experience creep under sustained loading, contributing to gradual increases in settlement during the service life of the structure. These long-term effects were beyond the scope of the present study and should be investigated in future research.

7. Conclusions and Recommendations

Conclusion

This study demonstrates that the installation of galam timber piles effectively improves the seismic performance of box culverts constructed on soft soils. The numerical analysis confirms that the pile group reduces foundation settlement, increases the overall safety factor, and enhances the stiffness of the soil–structure system under seismic loading conditions. The main scientific contribution of this study lies in the development of a three-dimensional finite element modelling

framework for evaluating the interaction between box culverts, timber pile foundations, and layered soft soils subjected to earthquake loading. The results demonstrate that locally available galam timber piles can serve as an economical alternative reinforcement system for buried structures in soft-soil regions.

From an engineering perspective, the proposed reinforcement system may be considered for bridge approaches and culvert foundations located in areas with similar geotechnical and seismic conditions. Nevertheless, this study is limited to one pile configuration and one earthquake loading scenario using the Mohr–Coulomb constitutive model. Future studies should investigate different pile geometries, constitutive soil models, groundwater variations, liquefaction effects, and multiple earthquake records to further improve the reliability of the proposed design methodology.

Recommendations

1. The results of numerical analyses using PLAXIS should be validated with data from field tests or observations during construction to achieve a higher level of accuracy.
2. Future research is recommended to analyze variations in the dimensions, lengths, and spacing of the reinforcement elements to determine the most efficient and economical configuration.
3. The analysis can be expanded to account for the effects of dynamic loads, such as traffic and seismic loads, so that the behavior of the soil–foundation system can be evaluated more comprehensively.
4. The use of more representative soil constitutive models, such as Hardening Soil (HS) or Hardening Soil with Small Strain (HSSmall), is recommended to improve the accuracy of deformation and stress distribution predictions.
5. Further studies should also incorporate construction costs and life cycle cost analysis to ensure that the selected reinforcement method not only meets technical requirements but also provides economic efficiency.

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