

Analysis of earthquake impact on market buildings in North Bengkulu using the soil response and finite element method

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Abstract

The vulnerability of market buildings in active seismic zones, such as North Bengkulu which is surrounded by the Sumatran subduction zone and active faults presents a critical research challenge due to the lack of integrated soil-structure seismic assessments for commercial infrastructure. The aim of this study is to evaluate the effects of earthquakes on the Purwodadi Market Building through the integration of soil response analysis and structural dynamics. The methods employed involved calculating soil response based on historical earthquake records of the 2007 Bengkulu–Mentawai Earthquake (subduction, Mw 8.4) and the 1952 Ketahun Earthquake (active fault, Mw 6.8), followed by structural modelling using the Finite Element Method (FEM). The main quantitative results show that the local clay layer significantly amplifies ground motion, with a Peak Ground Acceleration (PGA) at the surface of 0.485 g for the subduction earthquake and 0.389 g for the fault earthquake. The amplification factors at the surface are 1.95 and 1.73, respectively. Structural simulations recorded a substantial increase in internal forces; for example, the bending moment in beam B1 increased from 0.82 kNm to 61.01 kNm, and the shear force at the head of the pile cap PC increased from 2.15 kN to 65.12 kN. Nevertheless, all structural components maintained stress ratios below 1.0, confirming that the building meets the safety standards of SNI 1726:2019. It is concluded that the integration of site-specific ground response with FEM-based structural dynamics is crucial for improving seismic resistance assessment. This study recommends the continued application of this combined method for buildings in earthquake-prone areas and the expansion of earthquake data coverage to improve future risk mitigation strategies.



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Introduction

Disasters with the potential to cause severe damage and pose a threat to safety have been identified as earthquakes (Mavrouli et al., 2023). As a country located in the Pacific Ring of Fire, Indonesia often experiences earthquakes due to the movement of tectonic plates. This condition makes the design of earthquake-resistant buildings a necessity for the safety of building users.

Bengkulu is situated in an area surrounded by several earthquake sources (Hasanah et al., 2024). According to Mase et al. (2024), this region borders the Sumatra Subduction Zone

and is traversed by two active faults, namely the Sumatra Fault and the Mentawai Fault, as shown in Figure 1. This tectonic configuration has triggered major earthquakes, such as the Bengkulu–Mentawai Earthquake (Mw 8.4) in 2007 and the Ketahun Earthquake (Mw 6.8) in 1952.

The movement of tectonic plates in subduction zones is the primary cause of earthquakes in Bengkulu; the resulting tremors have the potential to damage infrastructure and threaten human safety (Mase et al., 2021). Coastal areas such as North Bengkulu and Enggano Island face the

additional risk of tsunamis that may form as a result of offshore earthquakes. Given the history of major earthquakes in the Bengkulu region, recommended risk reduction measures include the implementation of disaster mitigation programmes, the enhancement of early warning systems, and the adoption of earthquake-resistant building designs in accordance with SNI 1726:2019 (Pribadi et al., 2021). SNI 1726:2019 establishes national requirements for the design of building and non-building structures to withstand seismic loads (Hukama & Erizal, 2023).

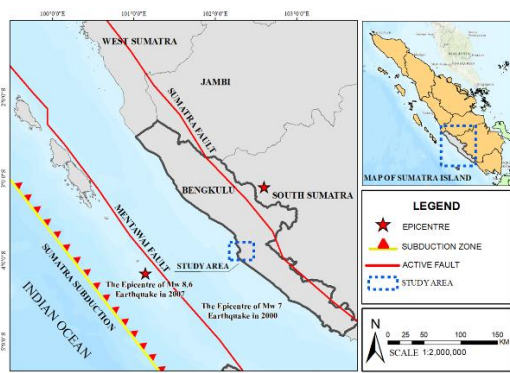


Figure 1. Seismotectonic conditions

Although previous studies have analysed earthquake hazards in Bengkulu in depth using deterministic or probabilistic approaches (Mase, 2020; Mase & Likitlersuang, 2021), and other studies have evaluated structural performance using FEM (Swasdi et al., 2024; Syed & Manzoor, 2022), the majority of existing research treats soil response and structural dynamics separately. Furthermore, previous research has often relied on design response spectra instead of actual time-history records from major past earthquakes. This separation limits the accuracy of predictions regarding building performance in realistic seismic scenarios, particularly for commercial buildings such as traditional markets, which are vital to the local economy but remain understudied.

To date, there has been no comprehensive study combining site-specific soil response analysis with full 3D time-history structural modelling using the finite element method (FEM) for a two-storey reinforced concrete market building still in operation in North

Bengkulu, particularly one that compares two different earthquake source mechanisms. The lack of empirical integration between local soil amplification effects (a profile dominated by clay) and non-linear structural behaviour based on actual historical earthquake records represents a clear research gap.

The uniqueness of this research lies, firstly, in the combined application of soil response analysis and FEM-based time-history structural simulation for an operational market building, secondly, the use of actual historical earthquake records as motion input, representing subduction and fault mechanisms, and thirdly, the quantitative evaluation of internal force amplification in all structural components under two different earthquake sources, validated in accordance with SNI 1726:2019.

This study aims to analyse the impact of earthquakes on the Purwodadi Market Building by integrating soil response analysis and structural dynamics. Specifically, this study aims to: determine the Peak Ground Acceleration (PGA) and amplification factors at ground level and at foundation depth for subduction and fault earthquake scenarios; measure the increase in internal forces in all structural elements due to seismic loads; and verify whether the building meets the safety requirements of SNI 1726:2019. This method involves combining soil characteristic analysis with structural behaviour simulation to demonstrate that this integrated approach can serve as an effective preliminary evaluation method for earthquake resistance.

Research Methods

Study Area

The town of Argamakmur, North Bengkulu, Bengkulu, is the location where this study was conducted. As shown in Figure 2, the town is situated in the northern part of the province and lies close to the Sumatra Subduction Zone.

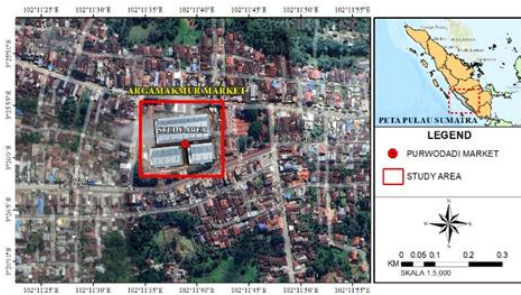


Figure 2. Research Location

The main source of earthquakes originates from the subduction zone, which triggered a major earthquake in 2007 with a magnitude of 8.4 (Handayani et al., 2025). The earthquake struck the western part of Sumatra Island, including the study location in North Bengkulu, which also felt the impact.

Purwodadi Market in North Bengkulu Regency comprises three blocks (A, B and C). Block A is the main two-storey building, designed with a reinforced concrete structural system in accordance with SNI 1726:2019. The building measures 109.27 m × 55.635 m and is used for commercial areas, ancillary facilities and open spaces. Columns, beams, and slabs as structural components are modelled in a 3D representation in Figure 3 to ensure adequate seismic performance. The aim of this analysis is to validate that the structure meets the safety requirements for earthquakes in accordance with national standards.

Earthquake Record Selection Criteria

The two historical earthquake records were selected based on the following explicit criteria:

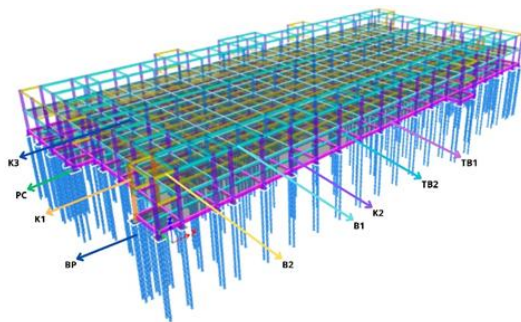


Figure 3. Research building modeling

(1) Magnitude range: Events with $M_w \geq 6.5$ were chosen to represent damaging seismic hazards (Mase, 2020).

(2) Source-to-site distance: The 2007 Bengkulu-Mentawai earthquake (epicentre distance = 142 km) represents the subduction interface events, while the 1952 Ketahun earthquake (31.6 km) represents shallow crustal fault events. This distance variation captures near-field (higher frequency, shorter duration) and far-field (lower frequency, longer duration) ground motion characteristics.

(3) Mechanism compatibility: Both events originate from tectonically active sources that dominate the regional seismic hazard according to Indonesia's seismic hazard map (SNI 1726:2019).

(4) Spectral compatibility: The response spectra of both records were compared against the SNI 1726:2019 design spectrum for North Bengkulu. Both records show reasonable spectral matching (within $\pm 30\%$) in the period range of 0.2–1.0 seconds, which is the fundamental period range of the Purwodadi Market building.

Soil Response Analysis

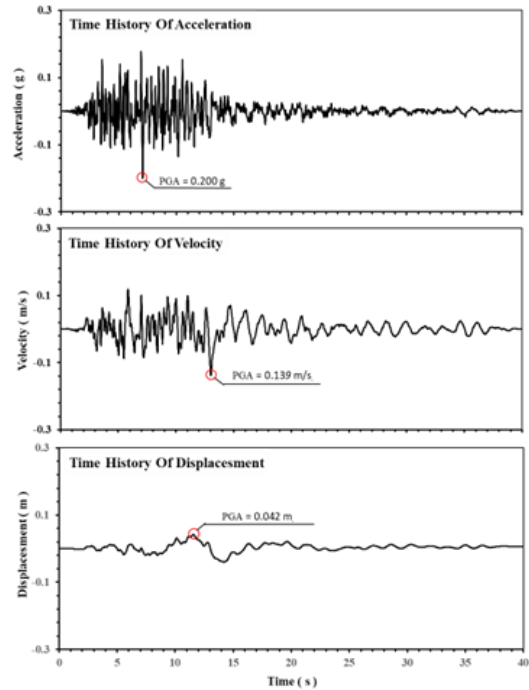
This study includes the 2007 Bengkulu-Mentawai earthquake (M_w 8.4, epicentre distance 142 km), which is widely recognised as the most reliable seismic event for the city of Bengkulu. The peak ground acceleration (PGA), peak ground velocity (PGV) and peak ground displacement (PGD) are 0.280 g, 0.168 m/s and 0.663 m, respectively. In addition to subduction events, this study also includes the 1952 Ketahun active fault earthquake (M_w 6.8, distance 31.6 km) to represent a different source mechanism. The peak ground acceleration (PGA), peak ground velocity (PGV), and peak ground displacement (PGD) are 0.200 g, 0.139 m/s, and 0.042 m, respectively. The two input motion time-history are shown in Figure 4. Mase (2020) states that the selection of earthquake history for hazard analysis must be done carefully and it is necessary to select representative earthquake history as a critical

step before analysing the response of soil to earthquakes.

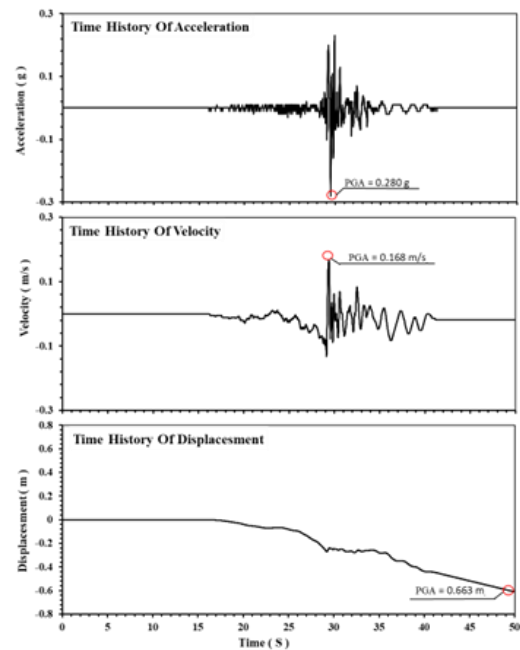
Deepsoil software was used to support this analysis. The output of this analysis will be peak ground acceleration and spectral acceleration profiles. The results of this analysis will be used to determine how buildings respond to earthquakes.

In general, there are three main materials that make up the subsoil in Argamakmur City, namely clay, sandy soil, and sandy rock. Figure 5 presents soil characteristic data from the study site, covering geotechnical parameters including corrected standard penetration test (N-SPT) values, shear wave velocity (V_s), unit weight (γ), and plasticity index (PI). This data play an important role in analysing the mechanical properties of soil and forms the basis for consideration in earthquake risk assessment and foundation structure design.

The soil profile at the study site can be divided into three main layers, namely the clay layer (0-10 m), consisting of organic clay (OH) and sandy clay (CL), the sand layer (11-18 m), consisting of sandy clay (SC) material, and a rock layer (18-30 m) consisting of sandy rock and eroded bedrock. Analysis shows that the average shear wave velocity at a depth of 30 metres below ground level (VS30) is 765.35 m/s.



(a)



(b)

Figure 4. a) Waves caused by active faults, (b) Waves caused by subduction zones

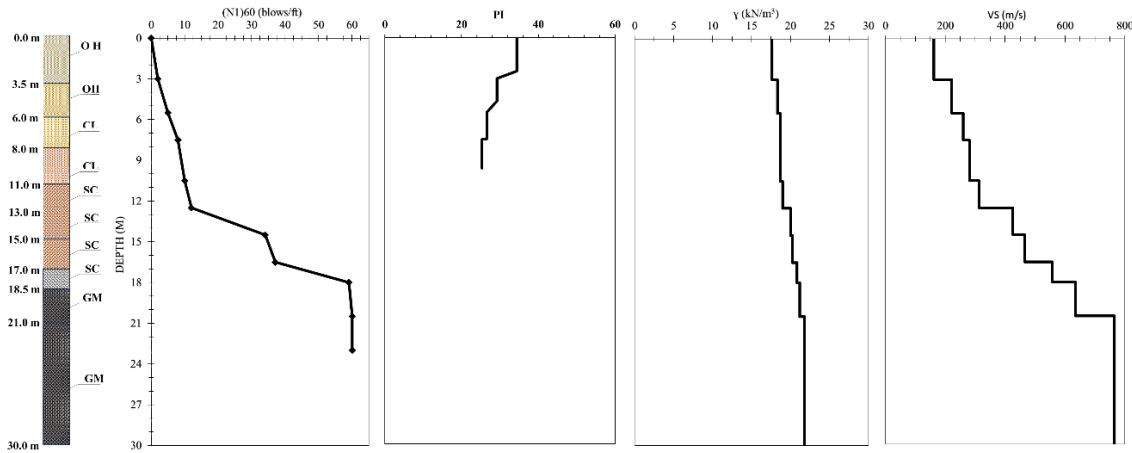


Figure 5. Research location investigation data

From the analysis of the time history of ground acceleration at ground level and at the pile foundation layer, the surface PGA and pile tip PGA values were taken to calculate the amplification factor (AF). The following equation defines AF as the ratio of the PGA at that location to the input PGA (Mase, 2022).

$$AF_{max} = \frac{PGA_{location}}{PGA_{Input}} \quad (1)$$

Structural Dynamics Analysis

In the analysis of soil response to earthquakes, time-history acceleration data is used as the primary reference for modelling structural dynamics. The next step is to evaluate structural performance using the Finite Element Method (FEM), an approach commonly applied in time-history-based structural dynamic analysis. In this study, the soil surrounding the foundations is modelled as a spring system with key parameters such as soil cohesion, the base reaction modulus (Ks), and the ratio of soil pressure to deformation at the contact surface. This spring model has been widely adopted in structural foundation analysis due to its ability to represent soil-structure interaction (Hajian & Attarnejad, 2022). The soil spring constant consists of vertical (Ksv) and horizontal (Ksh)

components, referring to Bowles' equation (1989):

$$K_{SV} = 40FS(Q_a) \quad (2)$$

$$K_{SH} = 2K_{SV} \quad (3)$$

Soil modelling is carried out by integrating spring values determined based on the ultimate bearing capacity of bored piles (Qs) and the safety factor (FS). FS is generally assumed to be 3 to ensure design stability.

Table 1. Input parameters for non-linear seismic ground response analysis

Depth (m)	Soil Type (USCS)	Q_a (kN/m ²)	K_{sv} (kN/m ³)	K_{sh} (kN/m ³)
1	OH	15.63	1875.63	3751.25
2	OH	15.63	1875.63	3751.25
3	OH	39.08	4689.07	9378.13
4	OH	39.08	4689.07	9378.13
5	OH	39.08	4689.07	9378.13
6	CL	62.52	7502.51	15005.01
7	CL	62.52	7502.51	15005.01
8	CL	78.15	9378.13	18756.27
9	CL	78.15	9378.13	18756.27
10	CL	78.15	9378.13	18756.27
11	SC	93.78	11253.76	22507.52
12	SC	93.78	11253.76	22507.52
13	SC	265.71	31885.65	63771.31
14	SC	265.71	31885.65	63771.31
15	SC	289.16	34699.09	69398.19

Table 1. Shows the values of the vertical and horizontal spring constants. These spring constant values will be applied to the building structure, namely to the bored piles columns.

The spring constant values represent the interaction between the bored piles structure and the surrounding soil.

After the geotechnical parameters of the soil have been identified, the structural dynamics analysis stage begins with creating a geometric model of the structural elements to represent the building system numerically (Swasdi et al., 2024).

Structural loading is designed in accordance with SNI 1726:2019 regarding earthquake loads for Building and Non-Building Structures, which regulates dynamic loading patterns, seismic load cases, and load combinations for extreme condition simulations. This process involves load patterns, load cases, and load combinations based on amplification factors in accordance with the ASCE 7-16 standard.

This analysis will produce structural responses in the form of axial force distribution, shear force, and bending moment, which are indicators of structural element performance. Bending moment is used to estimate deformation and bending stress in beams/columns, ensuring that the cross-section capacity meets the serviceability limit criteria (Cancan & Pinar, 2021). Shear forces are examined here to prevent shear failure in non-ductile elements, such as shear walls or beam-column connections (Yang et al., 2017). Axial forces will be evaluated to avoid buckling in columns or other compression components..

Axial forces directly affect the ultimate load capacity and stability of structural elements, particularly in maintaining system integrity when subjected to a combination of axial, shear and bending loads. Understanding the interaction of these forces is important in structural engineering to ensure safety, stability and resistance to varying load scenarios, including earthquakes and extreme winds. Analysis of these forces also forms the basis for considerations in structural design

and reinforcement to meet performance criteria in accordance with SNI 1726:2019.

Combination of Soil Response Analysis and Structural Dynamics

This study integrates soil response analysis and structural dynamics using a sequential (one-way) coupling scheme, as described by Timurağaoğlu (2024). The integration proceeds as follows:

First, surface PGA and spectral acceleration (S_a) from soil response analysis are applied as free-field ground motion at the pile head level. These parameters already incorporate local site amplification, including the effects of the 0–10 m clay layer. Second, vertical (K_{sv}) and horizontal (K_{sh}) spring constants (Table 1), derived from the same soil profile via Bowles' equations, are assigned to the pile elements in the FEM model. These springs represent the stiffness of the surrounding soil and govern the transfer of lateral and vertical loads between structure and ground.

The structural model then calculates internal forces under the amplified motion. This one-way coupling is justified because: (a) the building mass is relatively small; (b) the foundation depth (15 m) is shallow compared to the dominant seismic wavelength (typically > 100 m for the 0.5–2 Hz waves from subduction events); and (c) the soil springs are derived from the same profile, so feedback from structural motion to soil response would be negligible. As noted by Mase et al. (2025) and Silva et al. (2021), for low-to medium-rise buildings on stiff to very dense soil, iterative coupling does not significantly improve accuracy.

The final output axial force, shear force, and bending moment distributions are evaluated against design capacity per SNI 1726:2019. A stress ratio ≤ 1.0 indicates compliance. Figure 6 illustrates the wave propagation pathway from bedrock to surface, and Table 2 summarizes structural element dimensions.

Table 2. Structure element data

No	Elements of structure	Notation	Dimension (mm)	Thickness (mm)
1	Bored Pile	BP	600	-
2	Tie Beam	TB1	300 x 500	-
		TB2	300 x 400	-
4	Beam	B1	350 x 500	-
		B2	300 x 400	-
		K1	500 x 600	-
5	Column	K2	500 x 500	-
		K3	400 x 600	-
		K4	350 x 350	-
6	Slab	Sl	-	125
7	Pile Cap	PC	350 x 350	

Material quality

Concrete quality	$f_c' = 21$ MPa
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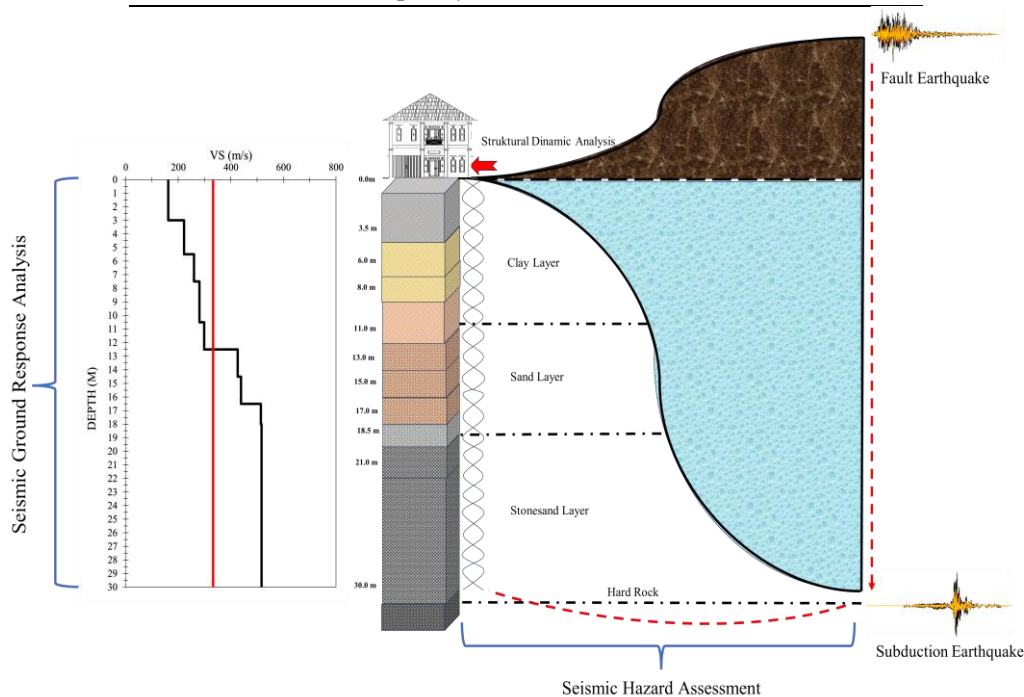


Figure 6. Schematic diagram of the combined method for building assessment

Framework Analysis

The flow diagram in Figure 7 presents a framework for evaluating building performance by combining site soil response analysis with structural dynamics analysis.

This process begins with defining the research problem. The next stage is data collection, which includes location investigation data, history of ground movement due to earthquakes, and structural information for the buildings under study.

The earthquake history used in the analysis process is the 2007 Bengkulu-Mentawai earthquake and the 1952 Ketahun earthquake. The second component, structural dynamics analysis, utilises the processed earthquake to evaluate internal forces and stress ratios in structural elements. This analysis provides a quantitative assessment of structural loads due to ground vibrations. The results and discussion will show the output of both

analyses by comparing internal force loads with structural capacity.

This process identifies critical elements at risk of experiencing excessive stress and shows the impact of soil-structure interaction on building performance. The conclusion presents the findings and emphasises the importance of combining soil response with structural modelling to improve building assessment.

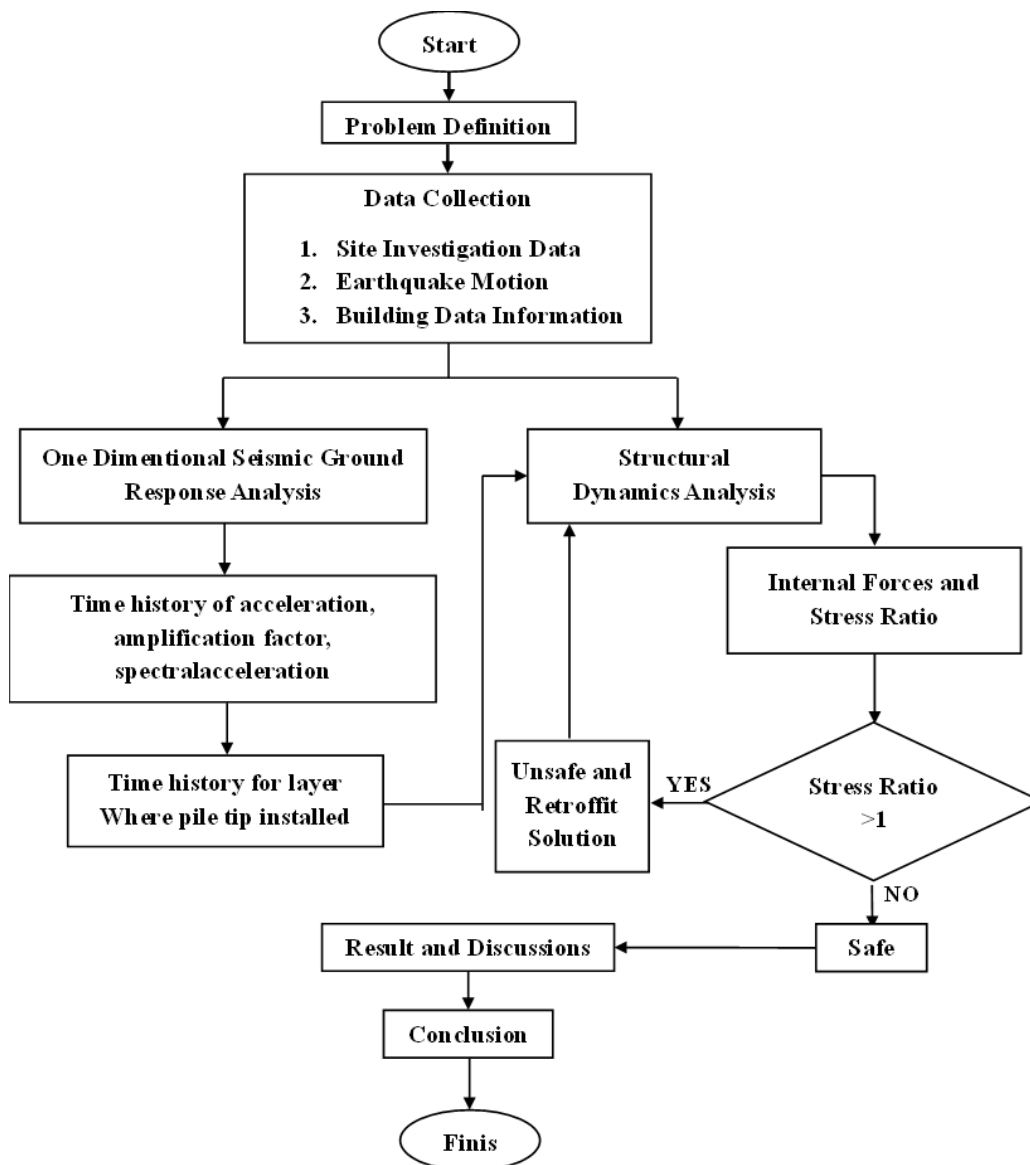


Figure 7. Research flowchart

Results and Discussion

Peak Ground Acceleration Profile (PGA)

Soil response analysis reveals that the local clay layer significantly modifies ground motion. As shown in Figure 8, input motion from bedrock progressively ($PGA_{input} = 0.154$ g for the subduction event) amplifies progressively toward the surface. For the 2007 Bengkulu-Mentawai subduction earthquake (Mw 8.4, distance 142 km), the surface PGA reached 0.485 g, while at the pile tip depth (15 m) it was 0.275 g. For the 1952 Ketahun fault earthquake (Mw 6.8, distance 31.6 km), surface PGA was 0.389 g and pile-tip PGA 0.151 g.

The amplification factors (AF) at the surface, calculated using Equation (1), are 1.95 (subduction) and 1.73 (fault). At 15 m depth, AF values drop to 0.76 and 0.98, respectively, indicating that amplification occurs primarily

within the upper 10 m of clay. This depth-dependent behavior is consistent with the shear wave velocity profile: low-impedance clay overlies stiffer sand and rock, creating a strong impedance contrast that traps and amplifies incoming waves.

Two physical mechanisms explain the higher amplification from the subduction earthquake. First, its longer rupture duration and greater source distance generate long-period waves (0.5–2 Hz) that align with the natural period of the clay layer (0.6–1.2 s), inducing resonance. Second, cyclic loading at shear strains exceeding 0.1% causes strain-softening in the clay, reducing its shear modulus and further increasing amplification (Vucetic & Dobry, 1991). The fault earthquake, with shorter-period, higher-frequency waves, experiences more rapid damping within the same clay layer.

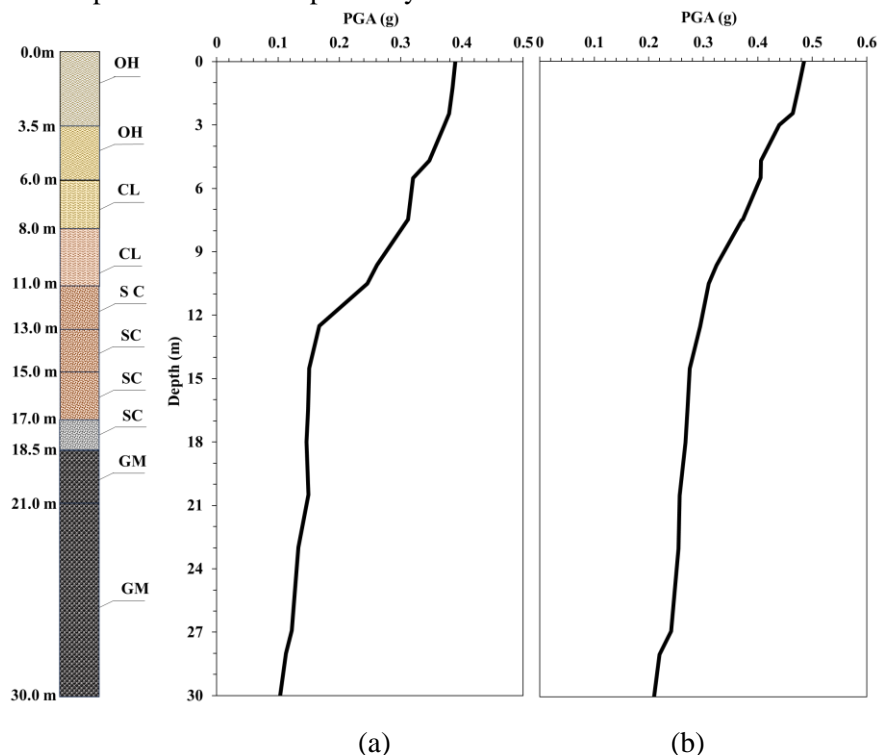


Figure 8. PGA values (a) due to active fault earthquakes, (b) due to subduction zones

Spectral Acceleration Comparison

Figures 9 and 10 show a comparison of spectral acceleration values under three conditions, namely ground surface, pile

foundation layer, and input motion. The analysis results show that the spectral acceleration at the ground surface is consistently higher than the values measured at the pile foundation layer and input motion,

indicating the presence of seismic amplification due to soil-structure interaction. Research by (Qodri et al., 2022) states that spectral acceleration in seismic input motion is lower than on the ground surface. In addition,

the spectral acceleration of the soil response analysis results was also compared with the spectral acceleration design values specified in SNI 1726:2019.

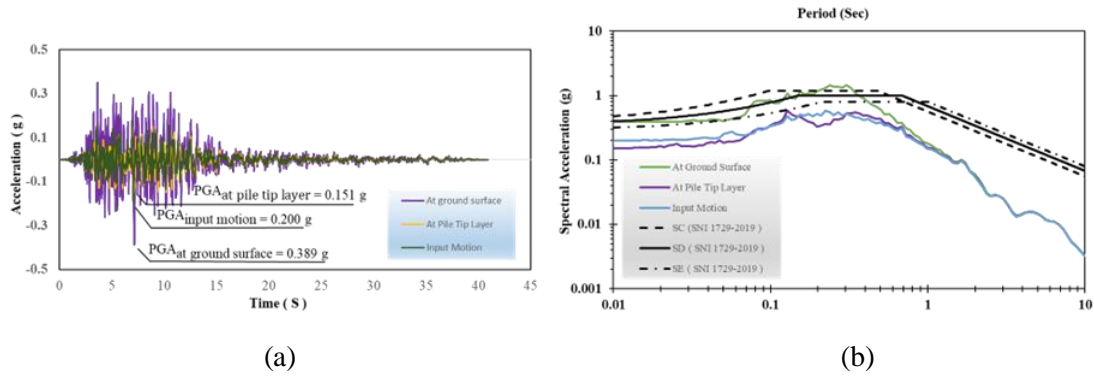


Figure 9. (a) Acceleration time history due to active faults, (b) Spectral acceleration

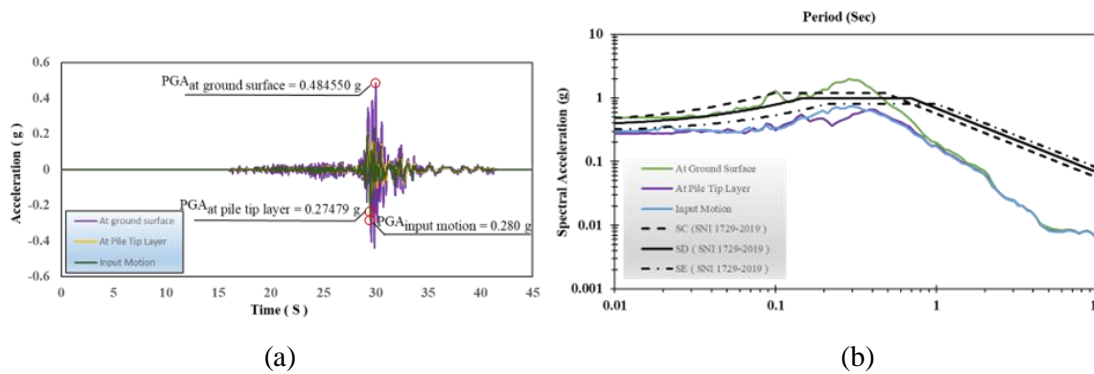


Figure 10. (a) Acceleration time history due to subduction zone, (b) Spectral acceleration

The analysis shows that the spectral acceleration in North Bengkulu City, as calculated in accordance with SNI 1726:2019, is consistently greater than the spectral acceleration in the foundation layer and the input motion.

These findings confirm that the structural design of Purwodadi Market complies with the requirements of SNI 1726-2019, with an adequate safety factor to ensure structural stability and integrity during an earthquake. Figures 9 and 10 also show that both types of earthquake, whether caused by faults or subduction zones, produce spectral acceleration values higher than the SNI standard spectral acceleration values in the 0.1 to 0.5-second period range. This is due to

spectral acceleration amplification, which tends to occur in the 0.3 to 0.5-second period range (Mase et al., 2025).

Dynamic Response of Buildings

Finite element analysis quantified the increases in internal forces for all structural elements under two seismic scenarios, as presented in Table 3a and Table 3b. Overall, seismic loading caused dramatic increases compared to gravity only conditions. Beam B1 (350×500 mm) experienced a bending moment rise from 0.82 kNm to 61.01 kNm under both earthquakes, the highest among all elements, indicating that B1 is the most flexurally stressed component. The pile cap PC recorded a shear force increase from 2.15 kN to approximately 65 - 67 kN, confirming

that significant seismic shear is being transferred from the superstructure into the foundation system. Column K2 showed a shear rise from 0.65 kN to about 58.8 kN, making it the vertical element with the largest absolute shear demand. Meanwhile, tie beam TB1 exhibited the most extreme relative increase in shear from 0.13 kN to about 65.5 kN, which is expected because tie beams are specifically designed for earthquake resistance. In contrast, axial forces in bored piles (BP) remained relatively low compared to their design capacity, indicating that the deep foundation system effectively resists vertical loads without overstressing.

For the structural response, the doubling of bending moments between pre- and post-earthquake conditions is physically determined by lateral inertia forces. The fundamental period of the structure is within the amplified spectral acceleration range (0.3 - 0.5 s) for subduction earthquakes (Figure 10b), leading to near-resonant base shear amplification. However, the simulation results show that all structural components are still capable of withstanding the earthquake load without collapsing. This can be seen from the stress ratio, which is still within safe limits.

Table 3 a). Maximum force values before and after applying the Ketahun earthquake load

Ketahun Earthquake						
Element	Before			After		
	Axial (kN)	Shear (kN)	Moment (kNm)	Axial (kN)	Shear (kN)	Moment (kNm)
BP	0.154	0.0173	0.0379	31.02	1.05	2.47
TB1	0	0.1278	0.1604	0	65.47	43.63
TB2	0	0.0175	0.0389	0	9.25	15.11
B1	0	0.6358	0.8235	0	79.17	61.01
B2	0	0.2476	0.405	0	28.31	20.62
K1	0.2629	0.3102	0.49	-15.38	52.21	41.37
K2	0.725	0.651	1.0892	23.91	58.85	51.30
K3	1.2388	0.4687	0.756	-21.56	43.29	29.78
SI	0.01	0.265	0.033	0.02	14.95	6.28
PC	0.221	2.153	0.401	5.91	66.80	10.42

Table 3 (b). Maximum force values before and after applying the Bengkulu-Mentawai earthquake load

Bengkulu-Mentawai Earthquake						
Element	Before			After		
	Axial (kN)	Shear (kN)	Moment (kNm)	Axial (kN)	Shear (kN)	Moment (kNm)
BP	0.154	0.017	0.0379	35.02	1.02	2.08
TB1	0	0.128	0.1604	0	65.51	43.63
TB2	0	0.018	0.0389	0	9.25	15.11
B1	0	0.636	0.8235	0	79.04	61.01
B2	0	0.248	0.405	0	28.39	20.63
K1	0.263	0.310	0.49	-15.23	55.88	40.67
K2	0.725	0.651	1.0892	23.90	58.84	51.31
K3	1.239	0.469	0.756	-21.73	42.31	30.18
SI	0.01	0.265	0.033	0.01	14.93	6.28
PC	0.221	2.153	0.401	3.91	65.12	10.37

Although the stress ratio for every element remained below 1.0, with a maximum value of 0.87, the distribution of these ratios reveals a hierarchy of critical elements. Beam B1 is closest to the code limit, followed by column K2 with a ratio of approximately 0.78, tie beam TB1 at about 0.75, pile cap PC at around 0.65, and bored piles below 0.30.

Figure 11 shows the distribution of structural stress ratios when subjected to seismic loads. If the stress ratio exceeds 1, an evaluation is required to modify the dimensions of the structural elements. The evaluation results also prove the stable performance of the structure in withstanding earthquake loads, both in the upper components and lower components, both before and after the earthquake simulation.

The building's 15m deep foundations are still considered structurally sound enough to support the building's function. However, as this study used actual earthquakes with an MMI VIII exposure, there is the potential for

long-term dynamic load accumulation, requiring proactive mitigation measures.

Study Contribution and Limitations

This study does not introduce any new theoretical or numerical modelling innovations. Its main contribution lies in the integrated and site-specific application of existing methods to a real operational market building in a poorly documented region. The added value provided includes: (a) a comparative assessment under two different source mechanisms, (b) explicit validation of compliance with SNI 1726:2019, and (c) the identification of critical structural elements requiring priority repair. This case study provides a replicable framework for the seismic assessment of similar market buildings in developing countries, where local ground amplification is often overlooked in design. Future work should include non-linear soil behaviour and two-directional input motions, which are beyond the scope of this study.

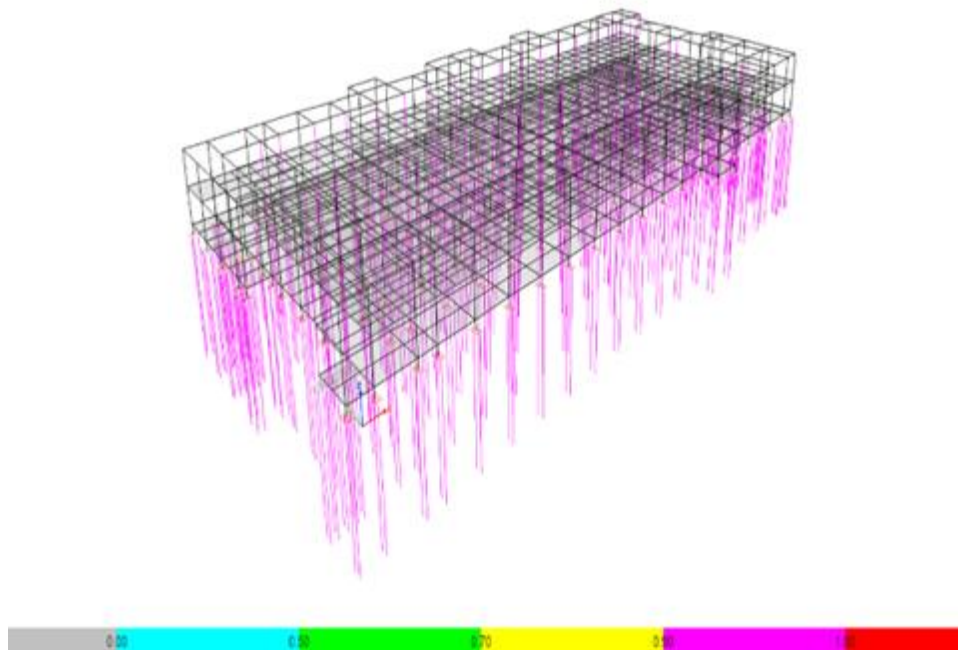


Figure 11. Stress ratio of concrete structure

Conclusion And Recommendations

Conclusion

This study indicates that local soil conditions, particularly the 0–10 m thick clay layer, contribute to ground motion amplification at the Purwodadi Market site. For the 2007 Bengkulu-Mentawai subduction earthquake, the calculated Peak Ground Acceleration (PGA) at the surface reached 0.485 g with an amplification factor of 1.95 relative to bedrock. For the 1952 Ketahun fault earthquake, the surface PGA was 0.389 g with an amplification factor of 1.73. The higher amplification observed for the subduction event may be attributed to the alignment between longer-period waves and the natural period of the clay layer.

Based on the criteria of SNI 1726:2019 stress ratio ≤ 1.0 , all structural components analyzed met the safety requirements. The maximum stress ratio recorded was 0.87 beam B1 under subduction earthquake. However, internal forces increased considerably under seismic loading; for example, the bending moment in beam B1 increased from 0.82 kNm to 61.01 kNm, and the shear force at the PC pile cap increased from 2.15 kN to 65.12 kN. Elements B1 and K2 experienced the highest force increases, suggesting potential locations for closer inspection.

Buildings with a natural period in the range of 0.3–0.5 s, such as Purwodadi Market ($T = 0.48$ s), may be more susceptible to subduction earthquakes due to spectral acceleration amplification. Foundation systems that penetrate beyond 10 m depth appear to reduce amplification effects.

For existing buildings in North Bengkulu, priority retrofitting or detailed evaluation could focus on beam B1 and column K2. For new construction, deeper foundations or soil improvement might be considered to mitigate amplification. Future studies should incorporate two-way input motions and non-linear soil behavior to improve the accuracy of evaluations.

Recommendations

The author suggests that future research should incorporate new parameters to support the analysis of a building's response to seismic waves.

Declaration Statement

The authors declare that ChatGPT (OpenAI) was used solely for language proofreading, grammar correction, and improvement of writing clarity during the preparation of this manuscript. All scientific content, including the study design, methodology, data analysis, interpretation of findings, and conclusions, were developed and verified exclusively by the authors. The authors take full responsibility for the accuracy, originality, integrity, and validity of the manuscript's content.

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