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Research Article

The Influence of Vertical Distance of Tie Beams in Building Substructures on Structural Response and Soil Behavior

Rico Daniel Sumendap [1]*, Dody M.J. Sumajouw [2], Fabian J. Manoppo [3]

[1] Graduate Program in Civil Engineering, Faculty of Engineering, Universitas Sam Ratulangi, Manado, Indonesia; email : rdsumendap1994@gmail.com
[2] Graduate Program in Civil Engineering, Faculty of Engineering, Universitas Sam Ratulangi, Manado, Indonesia; email : dody_sumajouw@unsrat.ac.id
[3] Graduate Program in Civil Engineering, Faculty of Engineering, Universitas Sam Ratulangi, Manado, Indonesia; email : fabian_jm@unsrat.ac.id
* **Corresponding Author** : Rico Daniel Sumendap

Abstract: Indonesia, located in a high seismic zone, requires building structures to be designed with strong earthquake resilience. Tie beams are commonly used in pile foundation systems to improve substructure stability, yet their vertical positioning is rarely analyzed in relation to overall building performance. This study investigates the influence of vertical distance of tie beams in reinforced concrete substructures on both structural response and soil behavior under seismic loading. A seven-story educational building was modeled using SAP2000 with varying tie beam elevations (−1.30 m to 0.00 m). Structural parameters analyzed included inter-story displacement, drift ratio, and stability index (θ), while subsoil behavior was evaluated through soil displacement in X, Y, and Z directions. The results showed that placing the tie beam at 0.00 m significantly reduced structural drift and improved overall stability. Meanwhile, the smallest soil displacement in the X and Z directions occurred when tie beams were placed at −1.00 m. However, in the Y direction, tie beams at 0.00 m produced slightly higher soil movement than configurations without tie beams. These findings highlight the importance of vertical tie beam placement in optimizing both structural and geotechnical performance in seismic design.

Keywords: Tie Beam Elevation; Seismic Response; Drift Ratio; Structural Stability; Soil-Structure Interaction.

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1. Introduction

An earthquake is a vibration originating from within the Earth, caused by the sudden movement or dislocation of rock masses along fault lines. The energy released during an earthquake generates seismic waves that propagate in all directions [1]. Indonesia is one of the countries most frequently affected by earthquakes, as it lies within the Pacific Ring of Fire and near the convergence of three active tectonic plates: the Eurasian Plate, the Pacific Plate, and the Indo-Australian Plate [2]. According to the Indonesian Meteorology, Climatology, and Geophysics Agency (BMKG), as reported on August 19, 2024, the Sunda Strait and Mentawai-Siberut regions are part of a major seismic gap, where no large earthquakes have occurred in centuries. This condition raises concern due to the potential for massive energy release. The megathrust seismic source map released by BMKG indicates that large earthquakes could strike almost anywhere in the Indonesian archipelago.

Improving the earthquake resistance of buildings is one of the most effective strategies to reduce casualties and property damage during seismic events. In seismic-resistant design, it is essential to understand the structural stiffness, the building's response to dynamic loads, and the interaction with ground conditions. Adequate stiffness in a building's structure is necessary to achieve structural performance and to limit excessive deformation under seismic loads. The stiffness characteristics of a building significantly influence its capacity to resist both vertical and horizontal seismic forces [3]. These influences are reflected in structural response parameters such as displacement, inter-story drift ratio, and internal forces. If the building's lateral displacement under seismic loading exceeds permissible limits, structural failure may occur [4].

During an earthquake, both the superstructure and substructure components of a building undergo movement. To maintain the building's stability—particularly against lateral forces—the foundation system must ensure proper integration and continuity among its elements. One such structural component commonly used in pile foundation systems is the tie beam. Installed at the pile cap level, tie beams prevent column rotation and help distribute loads and settlements evenly throughout the foundation system. Nashaat investigated the effect of tie beam dimensions on settlement, lateral displacement, and internal forces using Plaxis 3D software [5]. The study found that increasing the thickness and width of the tie beam effectively reduced all observed parameters. However, the addition of tie beams did not significantly affect the structural analysis results of the superstructure, as the foundation in the model was idealized as fully fixed, which nullified internal moment and shear forces in the upper structure [6].

Almasmoum examined the behavior of tie beams placed at the top elevation of pile caps—often referred to as strap beams—and found that placing tie beams at the same elevation as the pile cap results in more effective transmission of column loads compared to those placed above the foundation level [7]. This indicates that the vertical alignment between tie beams and pile caps is critical in achieving optimal soil-structure interaction. However, in many structural designs, the foundation nodes are idealized as fully fixed supports, and the influence of tie beam elevation is not explicitly considered, even though its position may vary in the field due to site constraints or construction practices. The closer the tie beam is to the pile cap elevation, the better the structural and geotechnical performance.

Therefore, this study aims to investigate the effect of the vertical distance between tie beams and pile caps in reinforced concrete buildings on both structural response and soil behavior. This research is particularly relevant for optimizing the substructure design of buildings located in earthquake-prone regions such as Indonesia.

2. Theoretical Studies

2.1. The Role of Tie Beams in Foundation Systems

Tie beams are essential horizontal components in foundation systems that connect footings and assist in distributing structural loads uniformly. They help prevent differential settlements and enhance the stiffness of the substructure, particularly in seismic zones. Several researchers have investigated the role of tie beams in seismic performance. Elsamny found that increasing the width of tie beams significantly reduces both vertical and horizontal displacements of footings during seismic events, especially when analyzed using Plaxis [8]. However, his study modeled tie beams at a fixed elevation and focused primarily on soil responses without addressing the superstructure. Likewise, Nashaat demonstrated that increasing the size of tie beams reduces bending moments and shear forces under eccentric loading conditions, but the vertical position of the beams remained constant throughout the study [5]. Almasmoum added that strap beams aligned with the top of pile caps more effectively transfer loads compared to those located at higher or lower elevations [7]. While these studies contribute valuable insights, they share a common limitation: the absence of vertical variability in tie beam placement and the exclusion of full structural response parameters such as inter-story drift and θ-index.

2.2. Structural Behavior Under Seismic Loading

In seismic design, structural performance is largely governed by parameters such as inter-story displacement, drift ratio, and stability index, as stipulated by standards like SNI 1726:2019 [9]. These metrics are essential to ensure safety under dynamic loading conditions. Patil, in his study comparing structures with and without seismic loads, showed that moments and shear forces increased significantly under seismic excitation [10]. The need for accurate dynamic analysis using methods like Response Spectrum Analysis (RSA) was therefore emphasized. Meanwhile, Amalia investigated the use of tie beams in moment-resisting frames and found that their presence enhanced lateral stiffness and reduced drift [6]. However, her analysis was limited to the superstructure and did not explore their impact on the foundation or soil behavior. This underscores the need for studies that assess the influence of tie beam positioning not only on structural members but also on substructure interaction during seismic loading.

2.3. Soil-Structure Interaction (SSI) and Vertical Tie Beam Positioning

Soil-Structure Interaction (SSI) is a critical component in foundation design, especially under seismic loading. Prior studies by Karyanto and Sideek emphasized that soil stiffness and confinement significantly influence seismic responses, where insufficient confinement increases base shear and displacement [11], [12]. Karyanto further noted that non-uniform ground motion due to soil variability may not greatly affect the superstructure, but it does intensify shear forces at column bases and axial forces in tie beams, compared to uniform ground movement.

Nashaat investigated the effect of tie beam dimensions and found that improper length configurations could result in uneven stress distribution and inefficient load transfer in isolated footings [5]. Moreover, ground instability due to liquefaction potential—as discussed in studies by Mario and Alfaqikh—further complicates SSI, particularly in loose, saturated sandy soils with uniform grain size and stable void ratios under high ground acceleration and shallow water tables [13], [14].

Despite these insights, the influence of vertical positioning of tie beams in SSI remains largely unexplored. This study addresses this gap by examining how variations in tie beam elevation (−1.30 m to 0.00 m) affect the interaction between substructure and soil under seismic loading conditions.

2.4. Research Gap and Contribution

Several previous studies have examined the role of tie beams in improving foundation or structural performance. Elsamny and Nashaat highlighted that increasing the width and thickness of tie beams can reduce vertical and horizontal soil displacement and contact pressure under both static and dynamic loads, using Plaxis simulations [5], [8]. However, both studies analyzed only substructure behavior, without considering variations in tie beam elevation, nor evaluating superstructure responses such as inter-story drift or structural stability (θ).

Almasmoum investigated tie beam position relative to foundation level and found that lower tie beams transmitted more column load, yet the study lacked dynamic loading and superstructure modeling [7]. Adityawan simulated sloof behavior using SAP2000 and observed differences in settlement and angular distortion, though his focus was solely on the substructure without considering inter-story behavior [15].

Other researchers such as Amalia, Barus, Supit, Karundeng, and Patil emphasized the drift and seismic response of the superstructure but did not examine the soil interaction or tie beam variation [6], [10], [16], [17], [18], [19]. Only Barus combined numerical and experimental validation, yet not on tie beams.

In response to these limitations, the present study offers a comprehensive 3D dynamic analysis using SAP2000, evaluates 10 variations of vertical tie beam position (from –1.30 m to 0.00 m), and integrates both superstructure and substructure responses (drift, θ-index, and soil deformation), thus providing a more holistic understanding of tie beam influence in seismic design.

3. Research Method

This study adopts a **quantitative research approach** that seeks to examine causal relationships between variables through objective and measurable data, processed using numerical analysis techniques. The primary objective is to investigate how variations in the vertical position of tie beams influence both superstructure and substructure performance. The independent variable in this research is the vertical distance of the tie beam (in meters), while the dependent variables include inter-story displacement (mm), stability index (θ), and drift ratio (%) for the superstructure, as well as foundation reactions and ground displacement (mm) for the substructure. These variables are analyzed to understand the structural and soil responses under dynamic seismic loading.

The object of the study is the Faculty of Law building at Sam Ratulangi University in Manado, a new reinforced concrete structure under construction from 2023 to 2024. The building consists of seven floors, each with a height of 4 meters, spanning a total length of 60 meters and a width of 15 meters. It functions as an educational facility and is supported by bore pile foundations with interconnected pile caps and tie beams. The model was created based on architectural and structural drawings, with detailed configurations of beams, columns, slabs, and foundations. Concrete quality is specified as 35 MPa for columns and 30 MPa for other structural components. The reinforcement consists of BjTP 280 plain bars and

BjTS 420B deformed bars. The unit weight of reinforced concrete is assumed to be 24 kN/m^3, and the modulus of elasticity is set at 25,700 MPa.

The structure was modeled using SAP2000 software, which allows for comprehensive 3D modeling and seismic response simulation. The model incorporates detailed structural elements such as columns, beams, slabs, and pile caps, as well as soil masses using solid elements. The modeling includes three tie beam elevation scenarios: −1.30 m, −0.65 m, and 0.00 m relative to the top of the pile cap. Loadings consist of dead loads, live loads, and earthquake loads, defined according to Indonesian standards (SNI 1727:2013 and SNI 1726:2019) [9], [20]. The seismic loading was applied using the Response Spectrum Analysis (RSA) method, with site-specific spectra scaled by a factor of 1.8394.

The soil parameters were based on a geotechnical investigation conducted by PT. Dayana Cipta using the Standard Penetration Test (SPT) at two borehole locations. Based on the results, the subgrade was modeled as four layers with varying properties: unit weight (γ), cohesion (C), and internal friction angle (θ_0). These parameters were then integrated into SAP2000 to simulate soil-structure interaction in a simplified elastic model. Vertical and horizontal displacements of the soil were recorded for each tie beam elevation configuration to assess substructure behavior.

The research was conducted in several stages. First, the research problem and variables were identified and formulated. Then, data collection was carried out, including structural drawings, soil data, and building functions. A theoretical review was performed to support the modeling, covering reinforced concrete behavior, seismic standards, soil mechanics, and SAP2000 software usage. After that, the structural model was developed and analyzed by applying loads and running simulations. The main variable tested was the vertical position of the tie beam, which was varied across three scenarios. The results of each simulation were used to evaluate inter-story drift, displacement, stability index, foundation reactions, and soil movement. Finally, the findings were interpreted and used to draw conclusions and formulate design recommendations.

This methodology allows for a comprehensive understanding of how tie beam elevation affects overall building behavior under seismic loading. Although the soil model uses simplified elastic assumptions and ideal boundary conditions, the study offers valuable insights for foundation design and structural optimization in earthquake-prone regions.

4. Result and Discussion

4.1 . Structural Modeling in SAP2000

4.1.1. Defining Coordinate System and Units

The structural analysis began by creating a building model using SAP2000 software. The dimensions of the building and its structural elements were modeled based on detailed construction drawings and technical specifications. Soil characteristics were defined using correlated data from the Soil Investigation Report, as summarized in the *Soil Parameter Table*. Overall, modeling in SAP2000 consists of two main stages: the Define stage, where materials, section properties, load patterns, and load combinations are established; and the Assign stage, where these definitions are applied to the structural elements.

The first step involved configuring the coordinate system and selecting the unit system for the analysis. SAP2000 uses a three-axis coordinate system: X (longitudinal), Y (transverse), and Z (vertical), with the Z-axis oriented in the direction of gravity. The unit system—kilonewton and meter (kN–m)—was selected at the beginning of the modeling process to ensure consistency. To display the coordinate grid, users selected the Grid Only option in the New Model window.

Figure 1. New Model

The coordinate layout was then customized by right-clicking on the modeling workspace and selecting Edit Grid Data, followed by Modify/Show System. In the Define Grid System Data window, users entered specific values in the spacing columns to adjust the distance between grid lines, enabling alignment with the structural design plan.

Figure 2. Define Grid System Data

4.1.2. Defining Materials

In SAP2000, defining materials is the process of inputting the physical and mechanical properties of the materials to be used in the structural elements, such as concrete, steel, wood, soil, or custom materials. This step is performed by selecting "Materials" from the Define menu bar and then choosing "Add New Material." The user specifies the type of material—whether concrete, steel, or custom—by entering the corresponding specification values.

In this study, the following material properties were defined and applied in the structural model:

- BjTP 280 for plain reinforcing steel with a yield strength of 280 MPa
- BjTS 420A for deformed reinforcing steel with a yield strength of 420 MPa
- Fc 30 for reinforced concrete used in elements other than columns
- Fc 35 for reinforced concrete used specifically for structural columns
- Soil 1 for the first soil layer
- Soil 2 for the second soil layer
- Soil 3 for the third soil layer
- Soil 4 for the fourth soil layer

These materials were later assigned to respective structural and soil elements, ensuring consistency with the structural design and geotechnical data derived from field investigations.

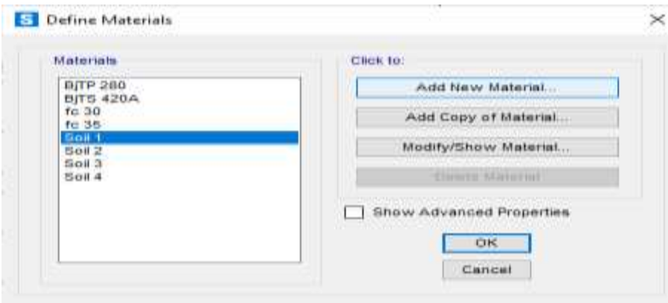

Figure 3. Define Materials

4.1.3. Defining Structural Elements

This stage involves creating or specifying the types of structural elements to be modeled, such as columns, beams, slabs, and foundations. The process begins by selecting "Section Properties" from the Define menu, then choosing the appropriate section type: "Frame Section" for beams and columns, "Area Section" for slabs, and "Solid Properties" for soil and solid foundation elements.

Once the element type is selected, the user assigns the corresponding material properties—previously defined in the material definition stage—to each element type. The structural dimensions and types were defined based on the structural drawings and were consistent with data from the *Structural Element Dimension Table* and the *Soil Parameter Table*. These definitions ensure accurate representation of real structural behavior within the analysis model.

Figure 4. Define Frame

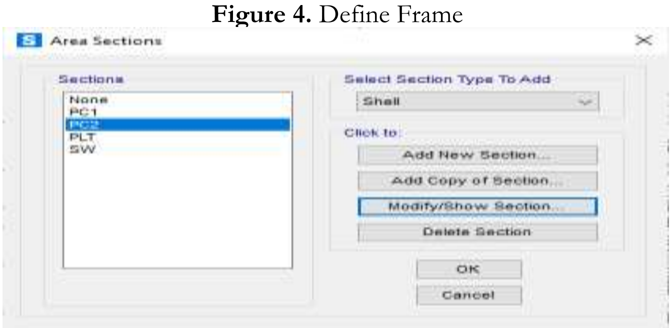

Figure 5. Define Area

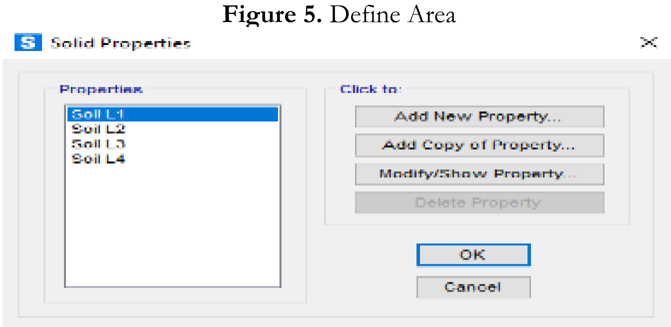

Figure 6. Define Solid

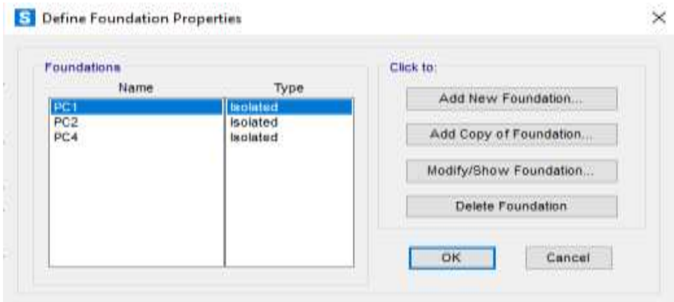

Figure 7. Define Foundation

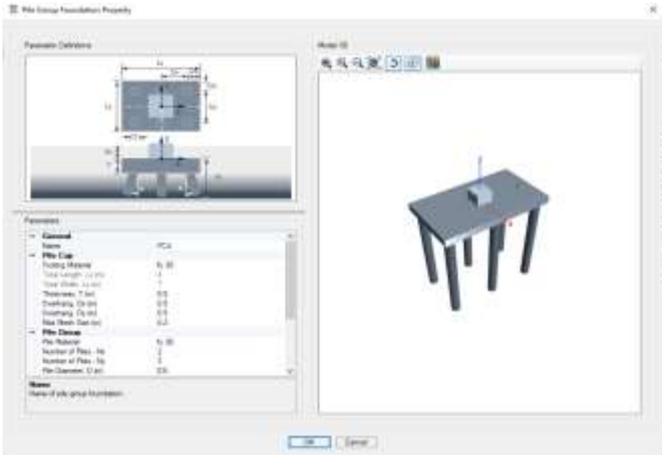

Figure 8. Define Foundation PC4

4.1.4. Drawing Structural Plan

The process of drawing the structural plan involves arranging the previously defined elements—such as columns, beams, floor slabs, foundations, and soil elements—into their respective positions within the SAP2000 model. This is done using the Draw feature, which allows users to manually or automatically place elements according to the architectural and structural design layouts, using the coordinate grid system defined earlier.

To enhance efficiency, especially for structures with repetitive layouts across multiple floors or bays, the Replicate command was used. This feature enables automatic duplication of structural elements, significantly reducing modeling time and ensuring uniformity throughout the model.

The following images illustrate the completed structural model, including sectional views and the overall 3D model:

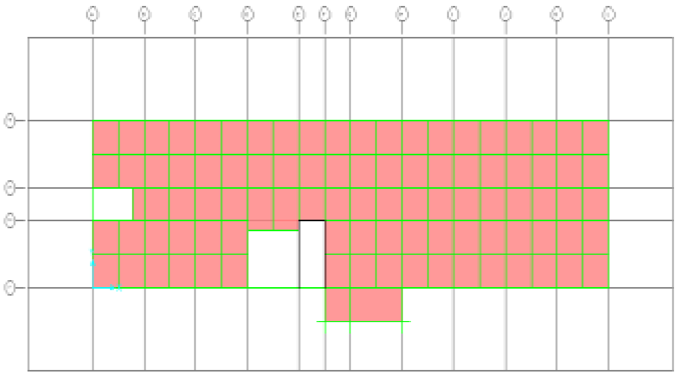

Figure 9. XY Section View

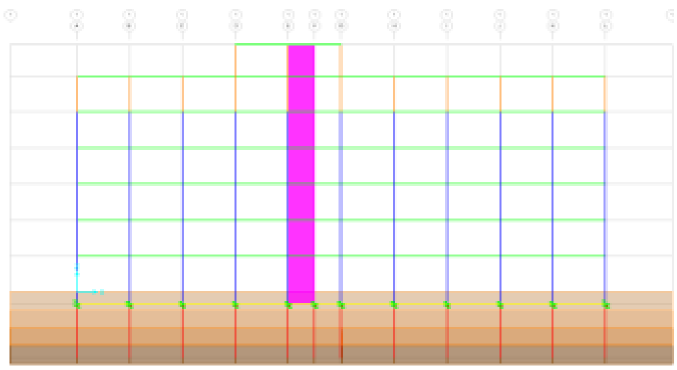

Figure 10. YZ Section View

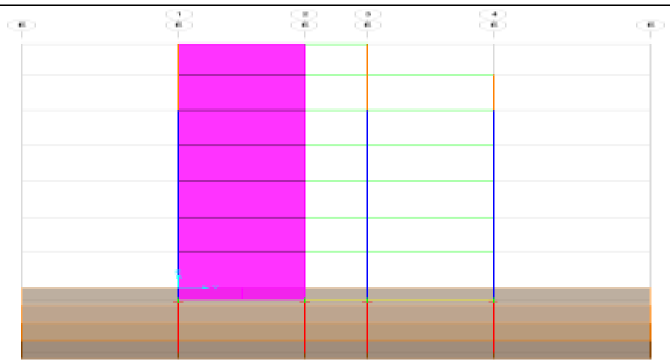

Figure 11. XZ Section View

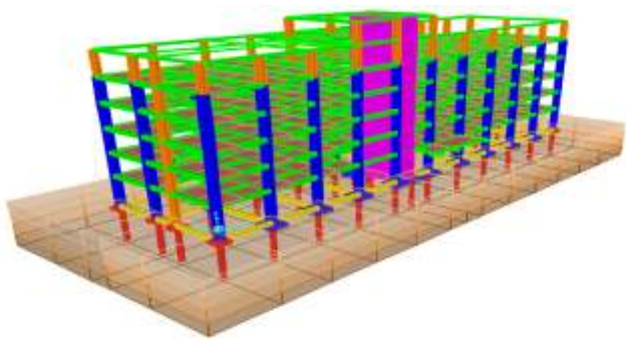

Figure 12. 3D Structural Model

4.1.5. Assigning Dead Load and Live Load to the Model

This stage involves applying both dead loads and live loads to the structural elements that have been modeled in SAP2000. The magnitude and type of loads are determined based on applicable design standards and load regulations. Before assigning the loads, they must first be defined in three hierarchical steps available in the Define menu: Load Pattern, Load Case, and Load Combination.

Load Pattern is used to define the categories of loads acting on the structure, such as dead loads, additional dead loads, live loads, wind loads, earthquake loads, and others. Each load type is given a specific identifier and characteristics.

Figure 13. Define Load Patterns

After defining load patterns, the Load Case step assigns a method of structural analysis to each load pattern. For example, a live load labeled "Live" in the Load Pattern can be analyzed using the Linear Static method under the Load Case named "LL." SAP2000 then calculates structural responses such as internal forces and displacements based on the selected analysis method.

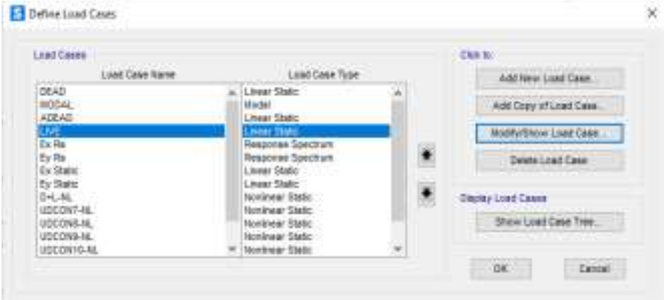

Figure 14. Define Load Cases

Lastly, Load Combinations are defined to simulate real loading scenarios based on design codes. These combinations consist of multiple load cases multiplied by load factors. For instance, a typical load combination for design might include a factor of 1.2 for dead load and 1.6 for live load, summed under a new load case named "D + L."

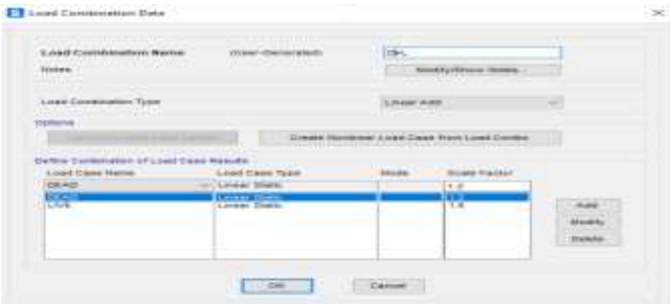

Figure 15. Load Combination Data

4.1.6. Modal Check Test ("Running" the Model)

Before dynamic loads are applied in SAP2000, it is essential to conduct a preliminary modal check, especially for the superstructure. This is done by running the model with self-weight to verify the structure's integrity and to obtain its modal characteristics. The dynamic analysis requires a defined mass, and this step helps identify any disconnected or improperly modeled elements, which can be observed through abnormal displacements or oscillations.

The natural period of the structure is one of the key parameters obtained from the modal analysis. Based on the Building Seismic Safety Council [21], the approximate maximum natural period T_u for reinforced concrete structures can be calculated using the formula:

$$T_u = 0.023 \times H_b^{0.9}$$

Where:

- $T_u =$ Natural period (s)
- $H_b =$ Building height (ft) = 90.223 ft

Using this approach, the resulting natural period of the building was found to be 1.3228 seconds, which falls within acceptable theoretical limits.

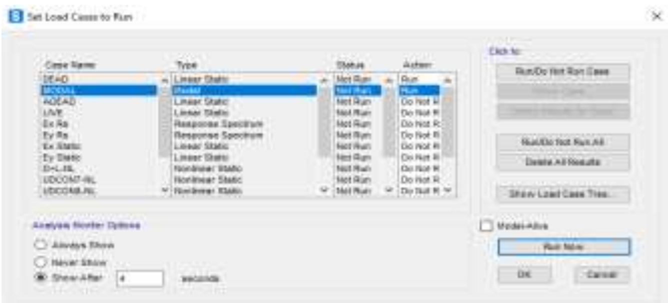

Figure 16. Modal Check Running Cases

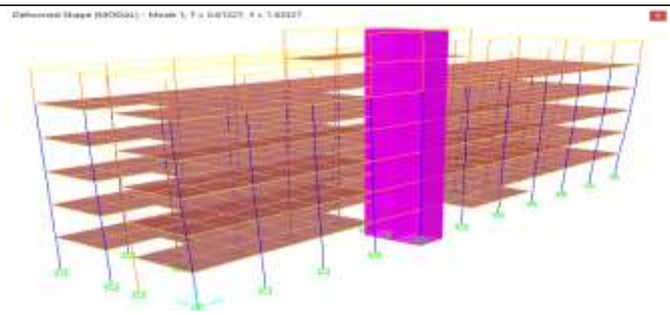

Figure 17. Modal Period and Vibration Mode Review

4.1.7. Defining the Response Spectrum Function

The Response Spectrum Analysis (RSA) method calculates the maximum structural response under seismic loads using a predefined response spectrum curve. In SAP2000, this function is defined by selecting Function > Response Spectrum in the Define menu. Users can choose a code-based response spectrum or input custom data in the *User Defined* mode by specifying period-acceleration values.

In this study, response spectrum data were obtained from the official Indonesian seismic hazard map portal (https://rsa.ciptakarya.pu.go.id/2021/), adjusted to the specific site location of the building. The software automatically generated the response spectrum graph based on the input data.

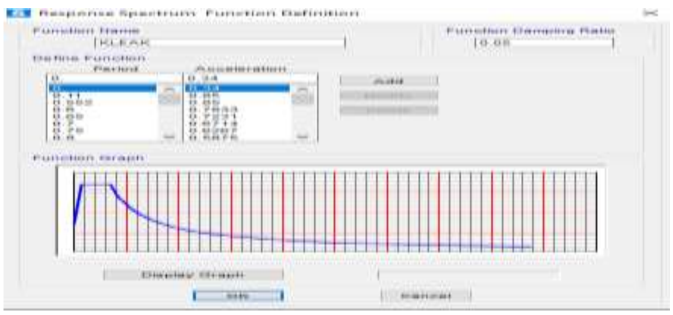

Figure 18. Response Spectrum Function Definition

4.1.8. Response Spectrum Scale Factor Calibration

The defined response spectrum loads were calibrated using a scale factor that reflects the seismic design criteria of the structure. This factor is influenced by several parameters, including building risk category, seismic design category, ground acceleration parameters, and the selected seismic force-resisting system.

The building in this study is classified as a Category IV risk structure due to its educational function, requiring a higher seismic performance level. The importance factor I_e was thus set to 1.50. According to the site's seismic parameters, SDS = 0.64 and SD1 = 0.25, classifying the building into Seismic Design Category D.

A Special Moment Resisting Frame (SMRF) system of reinforced concrete was adopted, with a response modification coefficient R of 8.00. The scale factor α is then calculated as:

$$\alpha = \frac{I_e}{R} \times 9.81 = \frac{1.50}{8.00} \times 9.81 = 1.8394$$

This scale factor was input into the Define Load Case menu for both X-direction (Ex RS) and Y-direction (Ey RS) seismic response cases.

Figure 19. Load Case for Response Spectrum

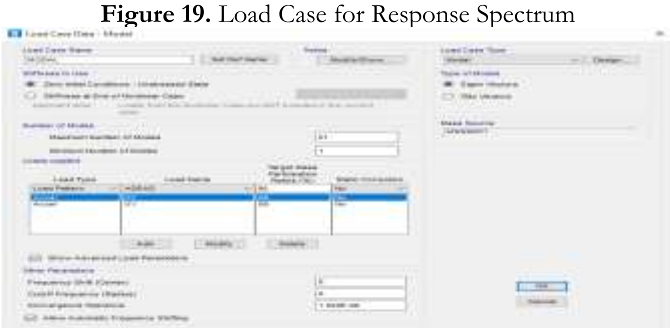

Figure 20. Calibrated Response Spectrum Load Applied to Model

4.1.9. Defining Mass Source and Diaphragm

The mass source defines the accumulation of loads (dead load, live load, etc.) converted into inertial mass for dynamic analysis. In SAP2000, this is defined using the Mass Source option in the Define menu. Proper mass definition ensures accurate seismic response calculations.

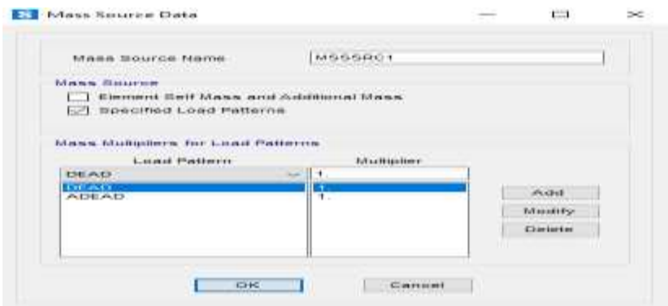

Figure 21. Define Mass Source

Diaphragms are rigid structural components that enable floors to act as horizontal planes, forcing vertical elements (such as columns) to move uniformly. In this model, floor slabs served as diaphragms from the first to the seventh story (elevation 4.0 m to 27.5 m). The joints on these levels were selected using Select > Coordinate Specification > Specified Coordinate Range.

After selecting the joints, diaphragms were assigned via Assign > Joint > Constraints > Define Constraints, and Diaphragm was selected. The option "Assign a different diaphragm constraint to each different selected Z level" was enabled, allowing SAP2000 to automatically assign diaphragms to each floor level.

Figure 22. Select Points for Diaphragm Assignment

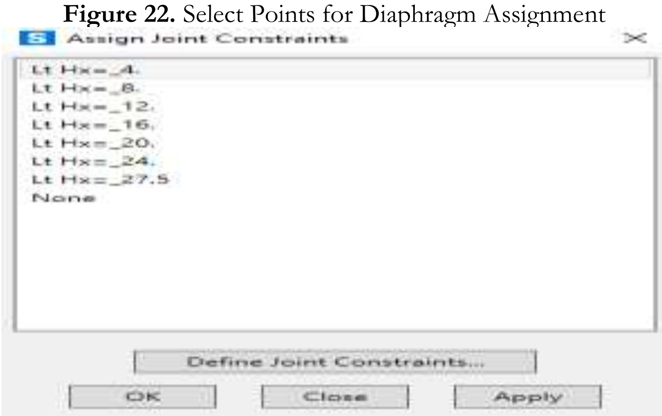

Figure 23. Assign Diaphragm Constraints

4.1.10. Running the Structural Model

The final step involved running the completed structural model and recording the results for further analysis. The process was carried out by selecting the Analyze menu or pressing F5. The output data were accessed through Display > Show Table, where SAP2000's internal force results, displacements, and other response parameters were retrieved.

This process was repeated for each model variation, specifically for different vertical distances between tie beams. The SAP2000 output data were exported to MS Excel for post-processing to evaluate the effect of tie beam elevation on both structural and soil behavior.

4.2 . Structural Response Analysis Results

The output data generated by SAP2000, which included internal forces, support reactions, and displacements, were further processed and analyzed using Microsoft Excel. The influence of variations in vertical tie beam elevation was evaluated based on three primary indicators: inter-story displacement (mm), drift ratio (%), and structural stability value (θ). All evaluations adhered to the seismic design procedures set forth in SNI 1726:2019 for buildings and non-building structures.

4.2.1. Internal Forces in the Structural Model

The internal force diagrams of the structure include shear force and bending moment distributions across the tie beams and foundations.

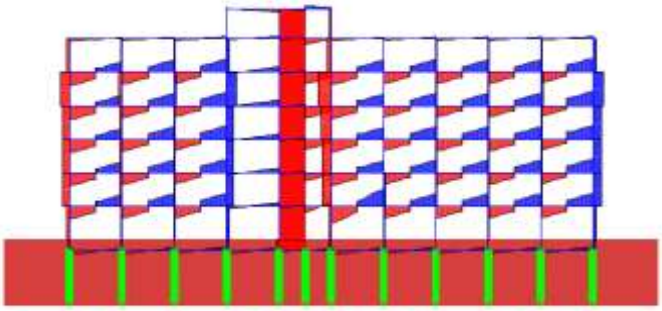

Figure 24. Shear Force Diagram of the Structural Model

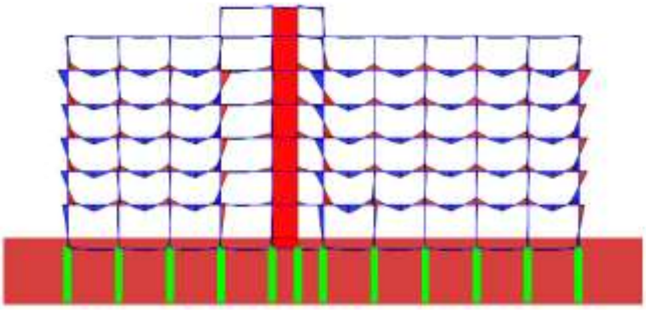

Figure 25. Moment Diagram of the Structural Model

The structural model assumes fixed-end supports, implying a monolithic and rigid connection among all structural elements. The internal moment observed at the foundation is caused by unsymmetrical loading (eccentricity) or lateral forces such as earthquakes or wind. This indicates that tie beams also contribute to resisting moment and lateral forces transferred to the soil. As supported by Vicenzo [22], tie beams can significantly reduce bending moments transmitted to the foundation—by 50% to 70%—compared to moments acting directly on the footing. This reduction lowers eccentric loading and can lead to savings in foundation size and cost, especially in seismic-prone areas.

4.2.2. Inter-Story Displacement

The inter-story displacement in both X and Y directions varied according to the elevation of the tie beams.

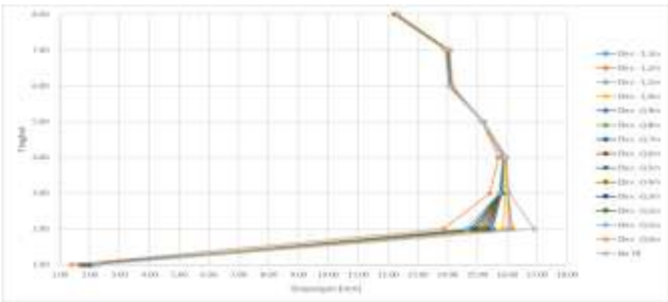

Figure 26. Graph of Inter-Story Displacement in X Direction

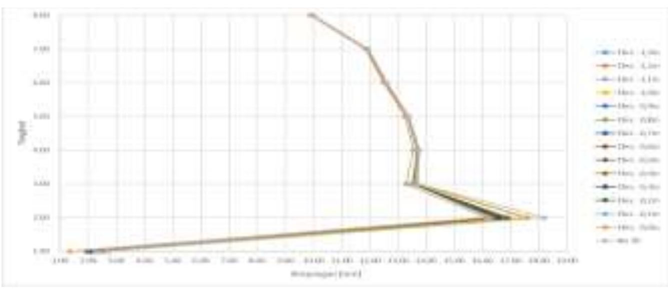

Figure 27. Graph of Inter-Story Displacement in Y Direction

Based on the data, the largest displacement occurred in the Y-axis direction on the second floor under the condition without tie beams, reaching 18.19 mm. The smallest displacement of 1.67 mm was recorded when the tie beam was placed at elevation 0.00 m. The greater displacement in the Y direction can be attributed to the rectangular shape of the structure, which is longer along the X-axis, making the Y-axis the shorter and more flexible direction under lateral loading. The most significant displacement variations were observed between the second and fourth floors, while other levels showed minimal change. Displacement consistently decreased as the tie beam elevation approached 0.00 m.

4.2.3. Inter-Story Drift Ratio

The drift ratio values were analyzed for both directions and presented in percentage form.

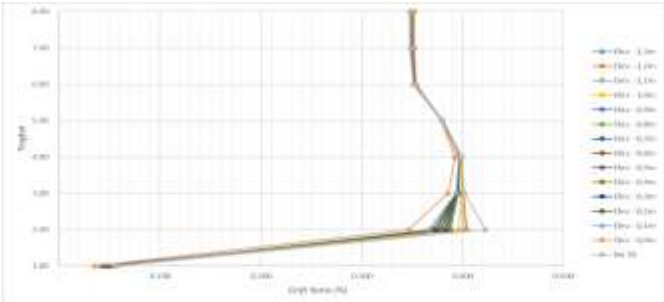

Figure 28. Graph of Inter-Story Drift Ratio in X Direction

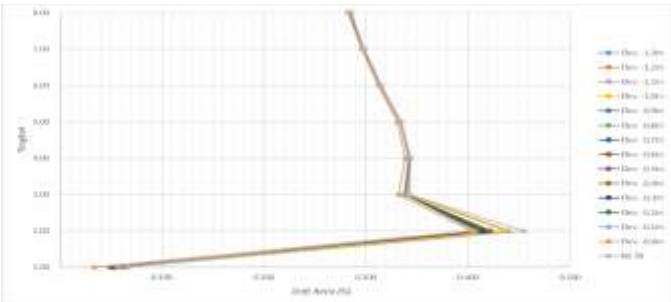

Figure 29. Graph of Inter-Story Drift Ratio in Y Direction

In the X-axis direction, the maximum drift ratio of 0.42% occurred in the model without tie beams, which also showed the highest drift in the Y direction at 0.45%. The smallest drift ratios were observed when tie beams were placed at elevation 0.00 m: 0.04% in the X direction and 0.03% in the Y direction. These results demonstrate that the drift ratio increases as the tie beam elevation deviates further from 0.00 m.

4.2.4. Stability Value (θ)

The structural stability index (θ) was calculated to assess the potential for second-order (P-Δ) effects.

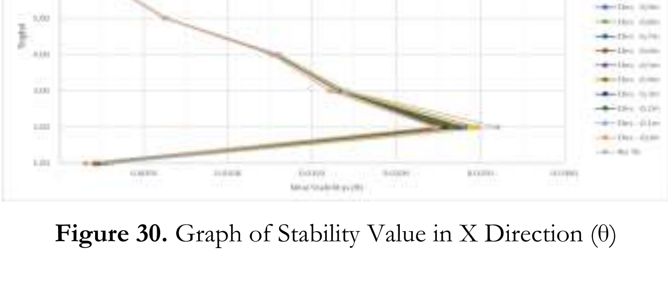

Figure 30. Graph of Stability Value in X Direction (θ)

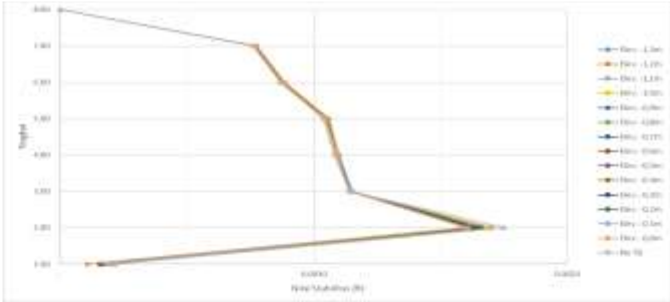

Figure 31. Graph of Stability Value in Y Direction (θ)

The Y-axis stability values were consistently lower than those in the X direction. The smallest value in the Y direction was 0.0017, while the highest in the X direction was 0.0260. A significant variation in stability values was observed with changes in tie beam elevation, particularly in the X-axis. The model with a tie beam placed at 0.00 m elevation showed the best stability performance, while the model without any tie beams had the highest (least stable) values. These results follow the same trend as the displacement and drift ratio findings, where lower tie beam elevations contribute to enhanced structural stability.

4.3 . Soil Behavior Analysis Results

The influence of variations in the vertical elevation of tie beams on soil behavior was analyzed by observing the displacement of the soil. A reference point was selected on one of the foundation elements (bored pile tip) to consistently measure the response of the soil to changes in tie beam elevation. The observed data focused on the maximum displacements in the X, Y, and Z directions at that foundation point.

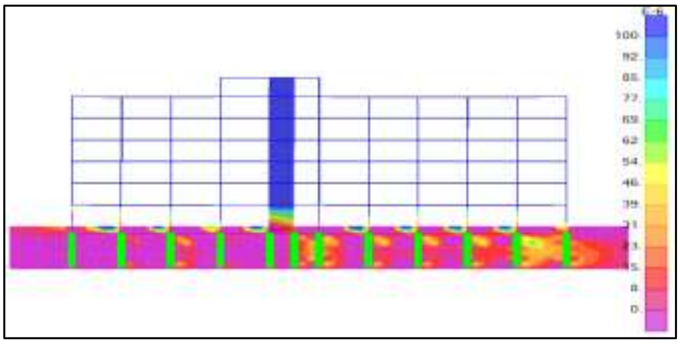

Figure 32. Soil Deformation Diagram in X Direction (m)

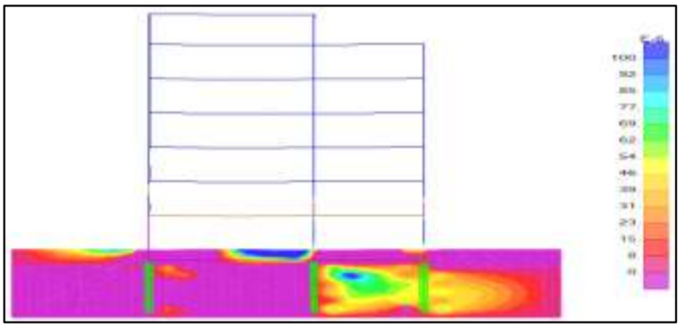

Figure 33. Soil Deformation Diagram in Y Direction (m)

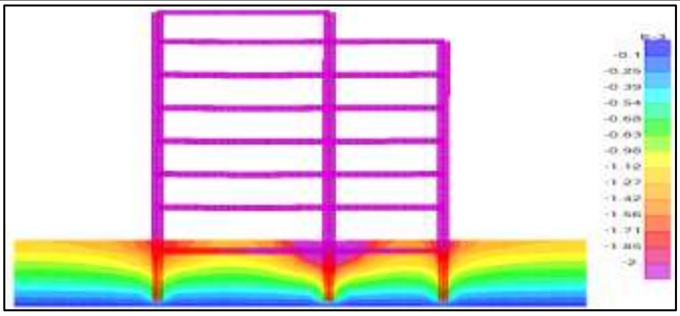

Figure 34. Soil Deformation Diagram in Z Direction (m)

Table 1. Soil Displacement (mm)

Elev. (m)	X (mm)	Y (mm)	Z (mm)
-1.30	0.0033	0.0092	0.4750
-1.20	0.0033	0.0093	0.4750
-1.10	0.0033	0.0093	0.4740
-1.00	0.0030	0.0100	0.4650
-0.90	0.0034	0.0092	0.4750
-0.80	0.0033	0.0092	0.4750
-0.70	0.0033	0.0092	0.4750
-0.60	0.0033	0.0092	0.4750
-0.50	0.0033	0.0092	0.4750
-0.40	0.0033	0.0092	0.4750
-0.30	0.0033	0.0092	0.4750
-0.20	0.0033	0.0092	0.4750
-0.10	0.0033	0.0092	0.4750
+0.00	0.0031	0.0110	0.4660
No Beam	0.0036	0.0084	0.4650

Based on the analysis results presented in Table 19, the maximum soil displacement in the X direction was 0.0036 mm, occurring under the condition without tie beams. The minimum value was 0.0030 mm when the tie beam was placed at an elevation of –1.00 m. In the Y direction, the maximum soil displacement of 0.0110 mm occurred when the tie beam was located at elevation 0.00 m, while the smallest displacement of 0.0084 mm was found in the model without tie beams.

In the Z direction (vertical), displacement values were more consistent, with the highest value being 0.4750 mm and the lowest being 0.4650 mm. The results indicate that the vertical elevation of tie beams influences soil response, albeit slightly. The presence and elevation of the tie beam subtly affect the stiffness and load transfer mechanisms between the structure and the ground.

4.4 . Discussion

Based on the results of structural analysis, the largest displacement occurred along the Y-axis, particularly on the second floor of the model without tie beams. In contrast, the smallest displacement was observed along the X-axis when the tie beam was placed at an elevation of 0.00 m. Tie beams significantly contributed to reducing both displacement and inter-story drift, especially between the second and fourth floors. The greatest values for both displacement and drift ratio were consistently found in the model without tie beams, while the smallest values were recorded when the tie beam was positioned at 0.00 m elevation.

In terms of structural stability (θ), the model without tie beams exhibited the highest θ value, indicating reduced stability. Conversely, the model with the tie beam at elevation 0.00 m had the lowest stability index, showing a more stable configuration. The θ value in the model without tie beams approached the maximum allowable stability limit (θ_{max}), suggesting a higher risk of structural instability compared to the configuration with a well-placed tie beam.

From the soil behavior analysis, tie beams were found to reduce soil displacement in the X direction, with the smallest displacement recorded at elevation –1.00 m. The model without tie beams, in contrast, exhibited the greatest displacement in this direction. Interestingly, in the Y direction, the largest soil displacement occurred at elevation 0.00 m, while the model without tie beams produced a smaller value. This inverse relationship between the X and Y axes is likely influenced by the difference in tie beam span lengths along each direction.

A study by Nashaat investigated the effect of tie beam length on soil displacement in shallow foundations on non-cohesive soils [5]. By varying the beam length (1.0 m, 1.5 m, and 2.0 m), the research found that short tie beams allowed foundations to behave as combined footings, distributing loads more evenly. However, when tie beams were excessively long, the foundations acted independently, reducing the effectiveness of load sharing and increasing settlement.

In the Z direction, the largest vertical displacement (settlement) reached 0.4750 mm and was consistent across tie beam elevations from –1.30 m to –0.10 m. The smallest vertical displacement, 0.4650 mm, occurred in two scenarios: when the tie beam was at elevation –1.00 m and when it was absent altogether. This finding implies that vertical ground movement can be better controlled either at specific tie beam elevations or in some cases, even without a tie beam.

Sideek supports this observation by stating that tie beams can effectively reduce foundation settlement, particularly when their width is increased [12]. However, when tie beams are excessively long, their efficiency diminishes due to overlapping stress zones beneath the foundation. These *overlap stress zones* occur when the pressure bulbs from adjacent footings interact, creating a zone in the soil where stress distributions overlap and potentially amplify. This zone typically extends 1.6 to 1.75 times the width of the tie beam and may reduce the effectiveness of the beam in redistributing loads, thereby increasing local settlement under certain configurations.

5. Conclusion

Based on the structural analysis conducted on the Faculty of Law building at Sam Ratulangi University in Manado, this study concludes that the presence and vertical positioning of tie beams significantly affect both structural response and soil behavior under seismic loading. The building model was found to meet the displacement and stability requirements of the Indonesian seismic design code (SNI 1726:2019). The inclusion of tie beams in the substructure of reinforced concrete buildings effectively reduced inter-story displacement and drift ratio. Conversely, the absence of tie beams resulted in higher displacement values and drift ratios, with a stability index closer to the critical threshold. Among all configurations analyzed, placing the tie beam at the 0.00 m elevation proved to be the most effective in minimizing both drift and displacement, while also providing the highest structural stability.

Regarding subsoil behavior, the results showed that tie beams contributed to reducing ground displacement in the X-direction, particularly at an elevation of −1.00 m. In the Y-direction, however, some configurations with tie beams caused an increase in lateral displacement. The smallest vertical settlement (Z-direction) was also observed when the tie beam was located at −1.00 m. Overall, the elevation of −1.00 m was considered most effective in improving soil performance, although the influence of tie beam elevation on soil movement was relatively minor or negligible under certain conditions.

In conclusion, it is recommended that, for similar building types and site conditions, tie beams be placed at the 0.00 m elevation to optimize structural stability and reduce inter-story deformation. For future studies, further investigation is advised on the effects of tie beam depth, span, width, and direction, in order to determine more precise proportions that benefit both structural and geotechnical performance.

Author Contributions: Conceptualization: Rico Daniel Sumendap and Prof. Ir. Marthin Dody J. Sumayouw, M.Eng., Ph.D; Methodology: Rico Daniel Sumendap; Software: Rico Daniel Sumendap; Validation: Rico Daniel Sumendap, Prof. Ir. Marthin Dody J. Sumayouw, M.Eng., Ph.D, and Prof. Dr. Ir. Fabian J. Manoppo, M.Agr; Formal Analysis: Rico Daniel Sumendap; Investigation: Rico Daniel Sumendap; Resources: Rico Daniel Sumendap; Data Curation: Rico Daniel Sumendap; Writing – Original Draft Preparation: Rico Daniel Sumendap; Writing – Review and Editing: Prof. Ir. Marthin Dody J. Sumayouw, M.Eng., Ph.D, and Prof. Dr. Ir. Fabian J. Manoppo, M.Agr; Visualization: Rico Daniel Sumendap; Supervision: Prof. Ir. Marthin Dody J. Sumayouw, M.Eng., Ph.D; Project Administration: Rico Daniel Sumendap; Funding Acquisition: Not applicable.

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