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Performance evaluation of the structural system using the pushover analysis method on the DPRD Bojonegoro building based on SAP2000

Sujiat, Firna Faridatun Nisa

[12]Universitas Bojonegoro, Indonesia

Email: sujiatmaibit@gmail.com

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Abstrak

Indonesia merupakan negara rawan gempa bumi. Hal ini karena Indonesia terletak di wilayah pertemuan tiga lempeng tektonik dunia yang sangat aktif. Pergerakan lempengan bumi tersebut yang menjadi factor utama terjadinya gempa bumi, yang berpotensi besar menyebabkan kerusakan pada struktur gedung. Sehingga dengan merancang bangunan tahan gempa, hal tersebut dapat diminimalisir. Selain itu, dalam pelaksanaan sebuah proyek konstruksi, pondasi juga memiliki peran yang sangat penting. Pondasi harus mampu menahan beban agar tidak melebihi batas aman yang telah ditetapkan. Tujuan dari tugas akhir ini adalah untuk menentukan level kinerja struktur gedung DPRD Bojonegoro dengan metode analisis pushover yang mengacu pada kriteria ATC-40 dan untuk mengetahui daya dukung dari pondasinya. Hasil dari analisis ini menunjukkan bahwa perilaku struktur dimulai dengan munculnya sendi plastis pertama kali pada balok kemudian diikuti oleh kolom. Berdasarkan hasil Analisa spektrum kapasitas, simpangan maksimum total pada arah X sebesar 0,017 mm dan simpangan inelastic maksimum sebesar 0,015 mm. pada arah Y, simpangan maksimum total sebesar 0,013 mm dan simpangan inelastic maksimum sebesar 0,011 mm. mengacu pada ATC (1996), kinerja struktur termasuk kategori Damage Control (DC). Dan berdasarkan hasil analisis daya dukung pondasi tiang pancang berdasarkan N-SPT dengan metode friction menunjukkan bahwa mulai kedalaman 12 m, daya dukung sudah mencukupi. Pada kedalaman 12 m, daya dukung ijinnya sebesar 34,515 ton. Pada kedalaman 13 m, daya dukung ijinnya sebesar 37,818 ton. Dan pada kedalaman 14 m, daya dukung ijinnya sebesar 44,513 ton. Pada kedalaman 12 – 14 m, mampu menahan beban sebesar 34 ton
Kata kunci : Pushover Analysis, Daya Dukung Pondasi Tiang, SAP2000

Abstract

Indonesia is an earthquake-prone country because it is located at the meeting point of three very active world tectonic plates. The movement of the earth's plates is the main factor in the occurrence of earthquakes, which have great potential to cause damage to building structures. So that by designing earthquake-resistant buildings, this can be minimized. In addition, in the implementation of a construction project, the foundation also has a very important role. The foundation must be able to withstand the load so as not to exceed the predetermined safe limit. The purpose of this final project is to determine the structural performance level of the Bojonegoro DPRD building using the pushover analysis method that refers to the ATC-40 criteria and to determine the bearing capacity of the foundation. The results of this analysis show that the behavior of the structure begins with the appearance of plastic joints first in the beam then followed by the column. Based on the results of the capacity spectrum analysis, the total maximum deviation in the X direction is 0.017 mm and the maximum inelastic deviation is 0.015 mm. in the Y direction, the total maximum deviation is 0.013 mm and the maximum inelastic deviation is 0.011 mm. referring to ATC (1996), the performance of the structure is in the Damage Control (DC) category. And based on the results of the analysis of the bearing capacity of the pile foundation based on N-SPT with the friction method, it shows that starting from a depth of 12 m, the bearing capacity is sufficient. At a depth of 12 m, the allowable bearing capacity is 34.515 tons. At a depth of 13 m, the allowable bearing capacity is 37.818 tons. And at a depth of 14 m, the permitted bearing capacity is 44,513 tons. At a depth of 12 - 14 m, it is able to withstand a load of 34 tons
Keywords: Pushover Analysis, Bearing Capacity Of Pile Foundation, SAP2000

Introduction

Indonesia is a country that is highly prone to natural disasters, particularly earthquakes. Every year, earthquakes occur, ranging from small to large magnitudes. This condition is due to Indonesia's location within the Pacific Ring of Fire, commonly known as the Pacific volcanic belt. The Pacific Ring of Fire is a region where three major and highly active tectonic plates converge, namely the Indo-Australian Plate, the Eurasian Plate, and the Pacific Plate. These plates continuously interact and experience friction over time (BMKG, n.d.). The movement of these tectonic plates is the main factor causing earthquakes, which have a high potential to damage building structures.

The DPRD building functions as a meeting place for legislative institutions or representatives of the people and local communities (at the provincial, regency, or city level), serving as an element of regional governance alongside the local government in carrying out governmental, religious, business, social, and cultural functions. The DPRD Bojonegoro Building is a three-story structure that plays an important role in the governmental and democratic system. As building height increases, structural vulnerability to seismic forces also increases due to the greater effects of earthquake-induced forces. Therefore, the planning of earthquake-resistant multistory buildings is a crucial aspect that must be carefully addressed (Kholil et al., 2023).

Building design must consider aspects of strength, safety, comfort, economy, and earthquake resistance so that the structure can withstand various applied loads, including seismic loads. One structural system capable of resisting lateral, axial, and moment forces caused by earthquakes is the moment-resisting frame system. This system is a structural framework in which the structural components and their joints resist the applied forces. It is divided into three types: the Ordinary Moment-Resisting Frame (OMRF), which has limited ductility and is suitable only for low seismic risk areas; the Intermediate Moment-Resisting Frame (IMRF), which has moderate ductility and is used in regions with moderate seismic risk; and the Special Moment-Resisting Frame (SMRF), which has full ductility and must be used in areas with high seismic risk (Karisoh et al., 2018).

Earthquake-resistant building design aims to minimize casualties resulting from structural damage that can lead to building collapse and loss of life (Laseri, 2017, as cited in Syaputra, 2019). Currently, earthquake-resistant building design commonly adopts a performance-based design approach. This concept emphasizes strength control and adopts structural displacement as a key parameter. Structural response (or structural performance) during earthquakes is the main focus of performance-based design. During seismic events, structures may experience damage or even collapse. The level of damage reflects the extent to which the designed structure performs as intended. To understand the collapse behavior of buildings, pushover analysis, also known as static nonlinear load analysis, is applied.

According to Arum Seto Palupi (2015), pushover analysis or static nonlinear load analysis is a method in which monotonically increasing static lateral loads are applied along the height of a structure until the roof displacement reaches a target value. During the pushover process, plastic hinges initially form and yield at certain locations, followed by the formation of additional plastic hinges. This process continues until the top displacement of the structure reaches an unstable condition (Laresi, 2017). This analysis requires computer software for implementation.

SAP2000 is one of the structural analysis programs that provides built-in pushover analysis features. SAP2000 is a Windows-based software used for structural analysis and design, supporting various types of analyses, including static analysis, dynamic analysis, and finite element analysis. Structural modeling can be performed in both two-dimensional and three-dimensional forms.

The purpose of pushover analysis is to estimate the maximum forces and deformations that occur and to identify critical areas within the structure. Through this analysis, structural components that require special attention in terms of detailing and stability can be identified and improved. In construction projects, soil conditions also play a very important role. Soil not only serves as the foundation supporting the structure but is also a material involved in the construction process itself. Soil and foundations share the same objective: both must be sufficiently strong to support the loads imposed by the structure above. Good soil is characterized by high bearing capacity, and foundations must be able to carry loads without exceeding the established safety limits. Therefore, ensuring foundation stability and adequate soil bearing capacity is essential.

The DPRD Bojonegoro Building is located on soft soil, which is characterized by high water content, low shear strength, low bearing capacity, and high settlement potential. If the subsoil is unable to support the building load, structural failure may occur. Consequently, deep foundations are used to transfer loads to deeper, more competent soil layers and to reduce soil compression. Based on the above discussion, structural performance can be evaluated according to the level of damage after an earthquake and the safety level in accordance with permissible performance categories for specific building types. The bearing capacity of deep foundations can be determined using the friction pile method, in which the load-carrying capacity is derived from soil–pile interaction along the pile shaft as frictional resistance.

Based on this background, the author aims to conduct an analysis of the DPRD Bojonegoro Building. Therefore, this undergraduate thesis is entitled "Performance Evaluation of Structural Systems Using the Pushover Analysis Method on the DPRD Bojonegoro Building Using SAP2000."

Method

This study is a quantitative research employing an engineering analysis approach, aimed at evaluating the seismic performance of the DPRD Bojonegoro Building using the pushover analysis method and analyzing the bearing capacity of pile foundations. The structural performance evaluation is conducted based on the performance-based design concept, referring to the ATC-40 performance criteria. All analytical procedures are carried out numerically using SAP2000 version 22, in accordance with the provisions of SNI 1726:2019 and other relevant standards. The object of this research is the DPRD Building of Bojonegoro Regency, a three-story government building. The analyzed structural components include the superstructure, consisting of beams, columns, and floor slabs, as well as the substructure, comprising pile foundations and pile caps. The structural system adopted is a reinforced concrete moment-resisting frame, designed to withstand both gravity loads and lateral seismic loads.

The data used in this study consist of primary data and secondary data. Primary data include structural drawings, dimensions of structural elements, material specifications for concrete and reinforcing steel, and soil data obtained from N-SPT test results. Secondary data are derived from the Indonesian seismic hazard map, seismic acceleration parameters, loading regulations, and relevant literature and previous studies related to pushover analysis and pile foundation design. Data collection techniques involve document review and literature study to ensure the accuracy and relevance of the data for analysis. The research stages begin with three-dimensional (3D) structural modeling using SAP2000. The modeling process includes the definition of grid systems, material properties, cross-sectional properties of structural elements, and boundary conditions in accordance with the existing conditions of the building. Subsequently, load calculations are performed, including dead loads, live loads, and seismic loads. Seismic loads are analyzed using both the equivalent static method and the dynamic response spectrum method to determine the seismic forces acting on the structure.

After completing the linear analysis, the next stage involves pushover analysis as a nonlinear static analysis. In this stage, lateral loads are applied incrementally until plastic hinges form within the structural elements. The locations of plastic hinges are defined at the ends of beams and columns based on the provisions of ATC-40. The results of the pushover analysis are presented in the form of a capacity curve, illustrating the relationship between base shear force and roof displacement. This curve is then used to evaluate the structural performance level and to identify the collapse mechanism of the building.

In addition to the superstructure analysis, this study also includes an analysis of the bearing capacity of pile foundations. The bearing capacity analysis is conducted using the friction pile method based on N-SPT data to determine both end-bearing capacity and skin friction resistance. Furthermore, vertical and horizontal spring constants are calculated to represent soil–structure interaction. The pile foundations and pile caps are subsequently modeled in SAP2000 using spring supports to evaluate the ability of the deep foundation system to safely support the structural loads.

The results obtained from all analytical stages are used to draw conclusions regarding the performance level of the DPRD Bojonegoro Building based on the ATC-40 criteria, as well as to assess the adequacy of the pile foundation bearing capacity in safely supporting the building loads. This research methodology is expected to provide a comprehensive understanding of the structural behavior under seismic loading and to serve as a reference for the design and evaluation of similar structures in earthquake-prone regions.

Results and Discussion

The results of this study were obtained from the structural analysis of the DPRD Bojonegoro Building using SAP2000 software through both linear and nonlinear analysis approaches. The building structure was modeled in three dimensions based on geometric data, material properties, and a reinforced concrete moment-resisting frame system. The analysis was conducted to determine the structural response to gravity and seismic loads and to evaluate the structural performance level using the pushover analysis method in accordance with the ATC-40 criteria. The dynamic analysis results indicate that the natural vibration period of the structure falls within the allowable limits specified in SNI 1726:2019. The number of vibration modes considered satisfies the minimum mass participation requirement of 90%, confirming the validity of the response spectrum analysis. A comparison between the equivalent static base shear and the dynamic base shear shows that the dynamic base shear value is not lower than the required minimum limit; therefore, it is acceptable for further evaluation.

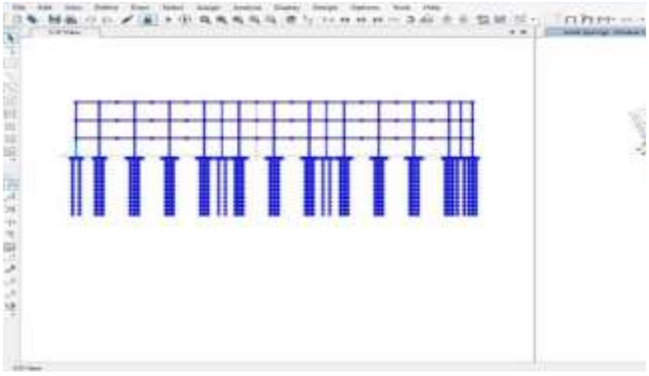
The interstory drift checks reveal that the maximum drift in both the X and Y directions remains below the allowable drift limits stipulated by the SNI provisions. In addition, the stability check considering P–Delta effects indicates that the structure remains stable and does not experience instability due to the combined effects of lateral and gravity loads. The pushover analysis was carried out by applying incremental lateral loads until the structure entered the nonlinear range. The results show that the first plastic hinges formed in the beam elements, followed by the formation of plastic hinges in the columns. This plastic hinge formation pattern indicates that the structural collapse mechanism is governed by beam flexural behavior prior to column failure, which represents the expected and desirable behavior for earthquake-resistant structures.

The pushover curves obtained from the analysis illustrate the relationship between base shear force and roof displacement in both the X and Y directions. Based on the capacity spectrum results, the maximum total displacement of the structure in the X direction is 0.017 mm, with a maximum inelastic displacement of 0.015 mm. Meanwhile, in the Y direction, the maximum total displacement is 0.013 mm, with a maximum inelastic displacement of 0.011 mm. These values indicate that the structure is capable of undergoing deformation without experiencing significant loss of stability.

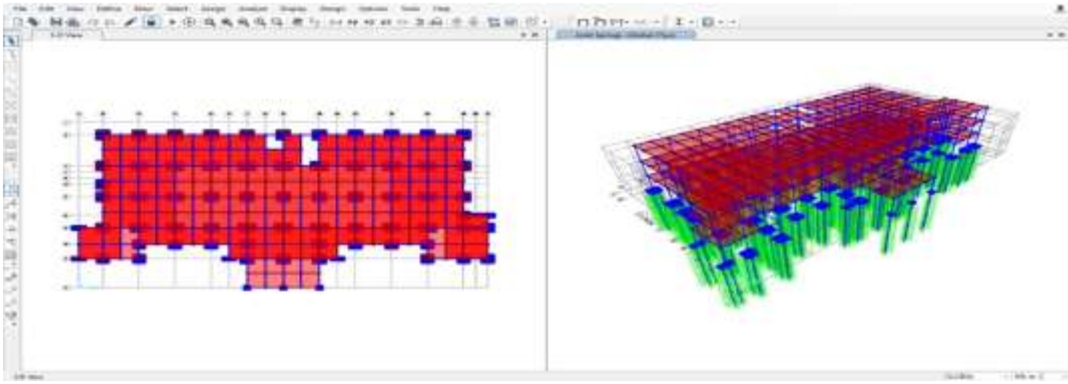
Based on the evaluation of the capacity spectrum curves using the ATC-40 method, the performance level of the DPRD Bojonegoro Building is classified as Damage Control (DC). At this performance level, the structure is able to withstand seismic loads with a relatively low risk of damage and a very low probability of casualties. Although damage occurs in several structural elements, the building does not collapse and still retains residual capacity to resist loads. In addition to the superstructure evaluation, the pile foundation bearing capacity analysis shows that the bearing capacity increases with greater pile depth. Based on calculations using N-SPT data and the friction pile method, the allowable bearing capacity becomes sufficient at a depth of 12 meters. At this depth, the foundation is capable of supporting a load of 34.515 tons, while at depths of 13 meters and 14 meters, the allowable bearing capacities increase to 37.818 tons and 44.513 tons, respectively.

The foundation modeling results using vertical and horizontal spring constants in SAP2000 indicate that the pile foundation system is able to distribute structural loads effectively to the supporting soil. At depths ranging from 12 to 14 meters, the pile foundations are considered safe, as they can support the applied structural loads without exceeding the allowable bearing capacity. Therefore, it can be concluded that both the superstructure and substructure of the DPRD Bojonegoro Building exhibit adequate performance under seismic loading in accordance with applicable standards.

After calculating the spring constants, the pile foundation was subsequently modeled using SAP2000. In this modeling, soil–structure interaction was represented using spring-type supports, with spring constant values applied at intervals of every 1 meter along the pile length.



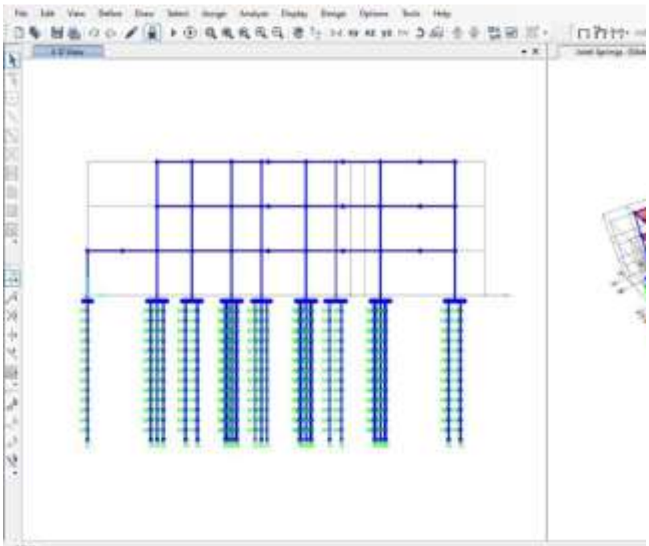
Gambar 4. 68 Portal Pondasi Gedung DPRD XZ



(Sumber : SAP2000)

Gambar 4. 69 Portal Pondasi Gedung DPRD XY

(Sumber : SAP2000)



Gambar 4. 70 Portal Pondasi Gedung DPRD YZ

(Sumber : SAP2000)

Hasil perhitungan setiap lapisan tanah dapat dilihat pada tabel di bawah ini

Tabel 4. 19 Hasil Perhitungan Daya Dukung Pondasi Setiap Lapisan Tanah

Based on Table 4.19, it can be identified that at depths ranging from 1 to 12 meters, the pile foundation is still unable to fully resist the load imposed by the structure. The depth at which the foundation is capable of supporting a load of approximately 34 tons is 12 meters. However, at this depth, the bearing capacity is still close to the minimum allowable limit and may be considered insufficient when an adequate factor of safety is taken into account. Therefore, to ensure that the pile foundation can support the structural load more safely, the pile length may be extended to a depth of 14 meters.

Based on the results of the structural and foundation analyses of the DPRD Bojonegoro Building using SAP2000, it can be concluded that the dynamic response of the structure to seismic loads satisfies the requirements of SNI 1726:2019. The structural mass participation and natural vibration period fall within the permissible limits, and the interstory drifts do not exceed the allowable drift values.

The pushover analysis results indicate that the formation of plastic hinges is dominated by beam elements, reflecting a flexural failure mechanism that is consistent with the principles of earthquake-resistant structural design. The capacity curves in both the X and Y directions show that the structure is capable of undergoing nonlinear deformation without significant loss of stability. Based on the evaluation using the ATC-40 criteria, the structural performance level of the DPRD Bojonegoro Building is classified as Damage Control, indicating that the building remains safe and has a relatively low risk of damage under the design earthquake.

The pile foundation bearing capacity analysis demonstrates that the foundation is capable of safely supporting the structural loads at a minimum depth of 12 meters. Thus, both the superstructure and substructure of the DPRD Bojonegoro Building are considered to have adequate seismic performance in accordance with the applicable standards.

Discussion

Based on the previously obtained results, it is observed that plastic hinges in both the X and Y directions begin to form at step 4, indicated by pink-colored points at the ends of beam elements, corresponding to the B–IO performance level. In the pushover analysis for both the X and Y directions, a total of 11 steps were applied, and plastic hinges appeared in almost all beam and column elements. In the X direction, the appearance of pink, blue, and green points indicates that the plastic hinges reached the CP–C performance levels, representing severe structural damage accompanied by a significant reduction in stiffness. In the Y direction, the presence of pink, blue, green, and yellow points indicates plastic hinge levels ranging from C–D, where the elements have experienced extensive damage and are approaching collapse.

The pushover analysis in the X direction yields a maximum total displacement ratio of 0.017 mm and a maximum inelastic displacement of 0.015 mm. In the Y direction, the maximum total displacement ratio is 0.013 mm, with a maximum inelastic displacement of 0.011 mm. These values indicate that the DPRD Building achieves a Damage Control performance level, meaning that the structure remains capable of resisting seismic loads with a very low risk of casualties. At this performance level, the building remains habitable and can be reoccupied after an earthquake, as the observed damage is relatively minor.

Furthermore, the results show that plastic hinges initially form in beam elements. This behavior confirms that the structure satisfies the strong column–weak beam principle, in which column strength exceeds beam strength. This principle is essential in earthquake-resistant design, as it ensures that initial damage occurs in beams rather than columns, which serve as the primary vertical load-bearing elements. Consequently, the structure is less likely to experience sudden total collapse, thereby providing a safer evacuation period for occupants during seismic events.

Based on the analysis of pile foundation bearing capacity using N-SPT data and the friction pile method at depths ranging from 0 to 14 meters, it is observed that at depths of 0 to 11 meters, the allowable bearing capacity of the foundation does not meet the structural load demand. At depths between 12 and 14 meters, the allowable bearing capacity is sufficient to resist the applied loads, indicating that the foundation is safe for use at these depths. A depth of 12 meters represents the minimum depth at which the foundation can safely support the load; however, to enhance safety, the pile foundation may be extended to a depth of 14 meters.

Conclusion

After evaluating the DPRD Bojonegoro Building using pushover analysis and analyzing the pile foundation bearing capacity, it can be concluded that the structural performance meets the required seismic criteria. The capacity spectrum analysis in the X direction shows a maximum total displacement of 0.017 mm and a maximum inelastic displacement of 0.015 mm, while in the Y direction the maximum total displacement is 0.013 mm with a maximum inelastic displacement of 0.011 mm. Referring to ATC-40 (1996), these results indicate that the building achieves a Damage Control (DC) performance level, meaning the structure remains capable of resisting the design earthquake with a very low risk of casualties and performs in accordance with the design objectives.

The pushover analysis results also demonstrate a favorable structural behavior. Plastic hinges initially form in the beam elements in both the push-X and push-Y analyses, followed by hinge formation in other structural components. This hinge formation pattern confirms that the structure satisfies the strong column–weak beam principle, which is a fundamental requirement in earthquake-resistant design. By ensuring that damage occurs first in beams rather than columns, the structure avoids sudden collapse and provides a safer condition for occupants during seismic events.

Furthermore, the analysis of the pile foundation bearing capacity indicates that the foundation system is adequate to support the applied structural loads. For pile foundations with a diameter of 40 cm and a depth of 14 m, calculations based on SPT data yield an ultimate bearing capacity of 111.282 tons and an allowable bearing capacity of 44.513 tons. Since the load acting on each pile obtained from SAP2000 is approximately 34 tons, the pile foundation at a depth of 14 meters is considered safe. Overall, both the superstructure and substructure of the DPRD Bojonegoro Building exhibit satisfactory performance under seismic loading in compliance with applicable standards

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