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Study on Effect of Uneven Settlement of Foundation on Structure Supported by Foundation with Different Elevations

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ABSTRACT

The structure supported by foundation with different elevations, which the foundation is supported at different elevations, is one of the most commonly used structural types in hillside buildings. In this structure, the uneven settlement of the foundation generates internal forces in the structure. In this paper, the effect of foundation uneven settlement on the internal force of the structure in a hillside building is analyzed. The results showed that even small uneven settlements also can generate large internal forces in the structure, while internal forces mainly occur in the beams connecting the upper and lower support storey, and relatively large internal forces occur in the supporting columns of upper embedding storey. When the uneven settlement occurs, the beam mainly generates shear and bending moments and the axial force is relatively small. The column mainly generates axial and bending moments, and tensile internal force is occurred in the some beams. The results obtained in this paper can be referred to the structural design of the hillside building structure and serve as a basis for further research.

Keywords: hillside building; structure foundation elevations

1. Introduction

Mountainside construction is a distinctive feature of architecture in both cities and villages situated in mountainous regions [1]. The geographical challenges of such locations, such as steep slopes and uneven terrains, require specialized building techniques and innovative design models. As a result, the architectural designs of these structures exhibit unique characteristics that distinguish them from conventional urban or rural buildings. These structures are typically designed to adapt to the topography of the land, incorporating mountain-based models that are specifically tailored to ensure stability and durability on sloping terrains. The foundation and structural systems of buildings in mountainous regions are thus crucial components, as they need to provide adequate support on uneven ground to prevent structural failure [2] [3].

A common design approach used in the construction of buildings on slopes is the implementation of a floor-support structure, in which the building's foundation is raised and supported on ground at varying heights. This technique is often referred to as a stepped or tiered foundation system, and it is particularly effective in balancing the weight distribution of the building. The foundation's varying elevation levels are crucial in maintaining the stability of the structure, but they also introduce complex engineering challenges, especially in seismic-prone areas. The construction of such structures requires precise engineering and a deep understanding of the interaction between the foundation and the underlying slope, as well as the dynamic forces at play during earthquakes.

The seismic vulnerability of hillside buildings became a significant concern after the 2008 Wenchuan earthquake in China, where the failure of hillside structures was notably more severe compared to conventional buildings. This catastrophic event highlighted the need for more comprehensive seismic design methods tailored to buildings situated on sloping grounds. The failure of hillside buildings [4] [5] [6] during the earthquake emphasized the critical role of factors such as seismic wave propagation, foundation settlement, and structural design in determining the safety and resilience of these structures. In particular, it became evident that existing seismic calculation methods and structural design approaches were inadequate for hillside buildings, as they often failed to account for the unique challenges posed by uneven foundations and slope instability [7] [8] [9].

Among the various factors contributing to the failure of hillside structures, the uneven settlement of foundations is one of the most critical. When the foundation settles unevenly due to differential soil conditions or seismic forces, it can lead to significant internal stresses and imbalances within the structure [10] [11] [12]. These stresses, if not properly accounted for in the design, can cause severe structural damage or even collapse. Therefore, understanding and mitigating the effects of uneven foundation settlement is essential for improving the seismic resilience of hillside buildings. Previous studies have highlighted the importance of considering the impact of uneven foundation settlement on the internal forces and behavior of buildings, especially in seismic design.

In response to this challenge, this paper aims to investigate the effects of uneven settlement on the internal forces in hillside structures. The study employs finite element analysis (FEA) to model and analyze the behavior of buildings supported by foundations at varying elevations, also referred to as structures supported by foundation with different elevations (SSFDL). By establishing analytical models of SSFDL and simulating the effects of foundation settlement under seismic loading, this paper seeks to provide valuable insights into the internal force distribution and structural response of these buildings. The findings of this study will inform future seismic design practices and contribute to the development of more robust and reliable design methodologies for hillside structures. Based on the analysis, several recommendations are presented to address the challenges posed by uneven foundation settlement and enhance the earthquake resistance of hillside buildings.

2. Methods

This study aims to analyze the effect of uneven settlement of foundations on the internal forces of a structure supported by foundations with different elevations, particularly in hillside buildings. The research adopts a quantitative and experimental approach, utilizing numerical simulation to assess the impact of uneven settlement on the mechanical performance of hillside buildings. The method chosen for this study is the finite element method (FEM), which allows for detailed analysis of the internal force distribution in the structure due to uneven foundation settlement.

The computational model used in this study is a simplified single-span frame structure, designed to model the effects of uneven settlement at the foundation on both horizontal and vertical displacements at the upper embedding end. The structure is modeled with parameters such as a 6-meter height for AC columns, a 3-meter height for BD columns, and a 6-meter span for the beams. The elastic modulus of concrete is set at 3.0×10^{10} N/m^2. The model is then adjusted to account for variations in beam length and column height to observe how these factors affect the internal forces within the structure. The foundation is assumed to undergo a uniform displacement of 1 mm at the column foundations of the upper embedding end, and the impact of this displacement on internal forces is analyzed.

The data collection process involves running simulations using the FEM model, with variations in the parameters such as beam length and column height to assess the corresponding changes in internal forces. These simulations focus on the distribution of internal forces such as bending moments, shear forces, and axial forces, particularly in the beams connecting the upper and lower support layers, and the columns of the upper support layer. The study aims to identify how small changes in foundation settlement can result in significant internal forces, especially at the connections between beams and columns.

To ensure the validity and reliability of the results, the FEM model will be compared with empirical data or previous studies to verify the accuracy of the simulated outcomes. The use of FEM is considered appropriate due to its ability to model complex interactions within the structure, including the response to uneven foundation settlement. This methodology also enables the study of the effects of different structural parameters on the internal forces, which can provide valuable insights for the design of hillside buildings that are more resilient to foundation settlement.

This research methodology is expected to provide essential findings on the behavior of structures affected by uneven settlement of foundations. The results will offer a scientific basis for improving the structural design of hillside buildings, helping to mitigate potential risks and ensuring the safety of buildings located in mountainous areas where uneven settlement is a common issue.

3. Result and Discussion

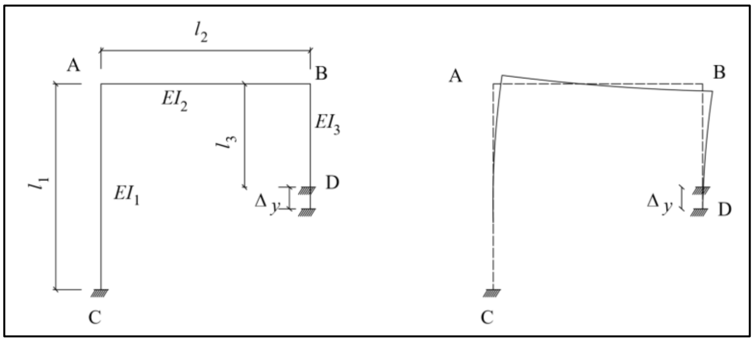
To analyze the effect of uneven settlement at the edge of the foundation on the mechanical performance of the SSFDL, the building structure was simplified into a single-span frame structure. In the case of uneven settlement at the foundation, displacements can occur in both the horizontal and vertical directions of the upper embedding end.

To consider the load-bearing behavior of the model, the model is described as a model with a height of 6 m AC column, height of 3 m BD column, length of frame beam AB 6 m, section of column 450 mm × 450 mm, section of beam 250 mm × 500 mm. Elastic modulus of concrete is $3.0 \times 10^{10} N/m^2$, considering the role of slab in the frame beam set span width 2 m, span thickness 120 mm.

In the computational model shown in Figure 1(a), the building structure is simplified into a single-span frame with two columns (AC and BD) of different heights to represent the sloped terrain condition. Column AC has a height of 6 m, while column BD has a height of 3 m. The connecting beam AB is 6 m long and represents the floor beam subjected to the effects of uneven ground settlement. A vertical settlement Δ_y1 at point D is simulated to evaluate the structural response to differential foundation displacement.

In the computational model shown in Figure 1(a), the building structure is simplified into a single-span frame with two columns (AC and BD) of different heights to represent the sloped terrain condition. Column AC has a height of 6 m, while column BD has a height of 3 m. The connecting beam AB is 6 m long and represents the floor beam subjected to the effects of uneven ground settlement. A vertical settlement Δ_y1 at point D is simulated to evaluate the structural response to differential foundation displacement.

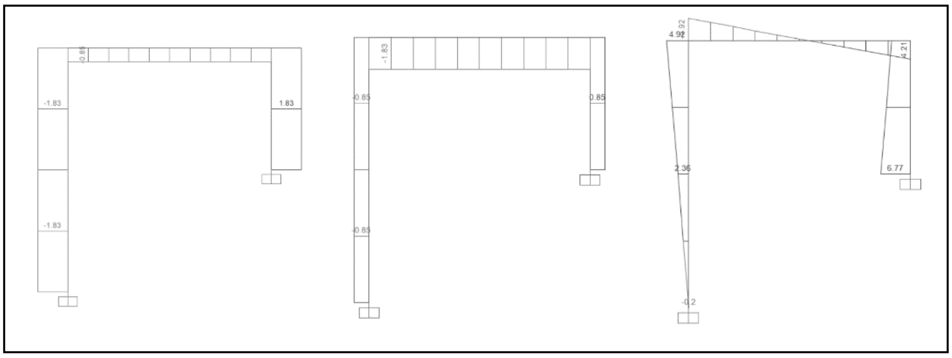
This model enables the analysis of structural parameters such as bending moments, shear forces, and deformations, in order to assess the sensitivity of the structural system to localized foundation settlement and to evaluate the structural integrity of buildings located on hillside terrains.



a) Computational model b) Deformed shape

Figure 1. Computational model of a hillside building structure under vertical displacement

As can be seen in Fig. 2, even with a horizontal displacement difference of 1 mm, large internal forces are generated in the frame structure, large bending moments are generated at the lower part of the short column and at the connections of the beam connected to the column, large shear forces are generated in both columns and large axial forces are applied in the frame beam.



(c) Axial force(kN) (b) Shear force(kN) (c) Bending Moment(kN·m)

Figure 2. Internal force distribution with 1 mm uneven settlement in the model.

Based on the above computational model, other parameters were not modified and only the length of the beam was varied from 3 to 12 m. With increasing the length of the beam, the stiffness of the beam decreases and the beam softens, thus weakening the restraint on the column of the beam [13] [14] [15]. The internal forces at the nodal points of the structure vary as the length of the beam varies. With the increase of the length of the beam, the bending moment of the beam and column decreases and the shear force decreases, indicating that the less the stiffness of the beam, the less the effect of the non-uniform settlement on the structure.

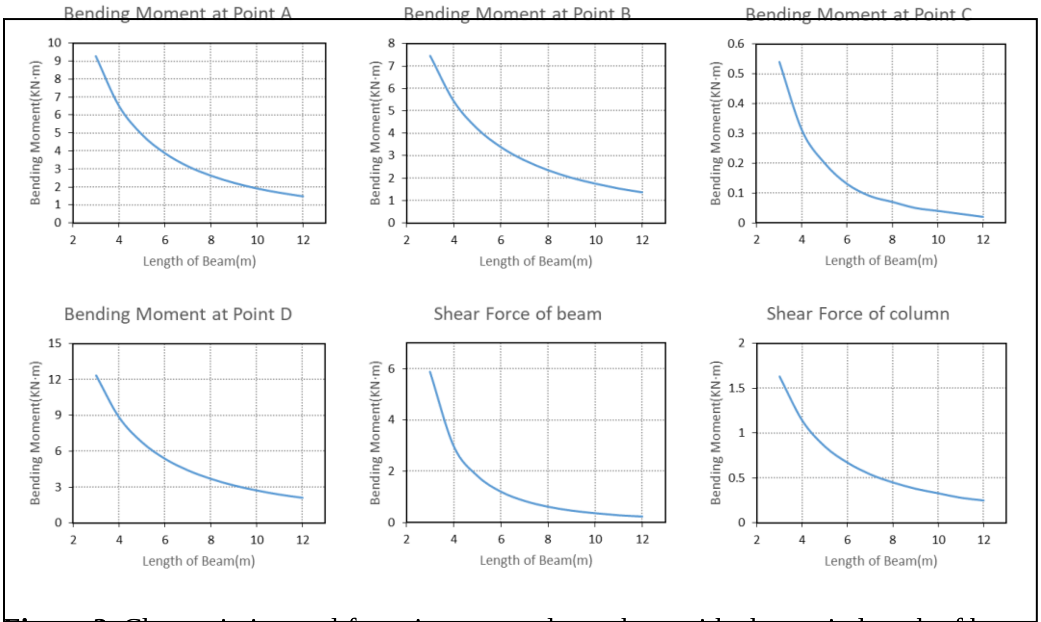


Figure 3. Change in internal force in structural members with change in length of beam

The change in the internal force at various nodes of the structure is shown in Fig. 4. The longer the length of the short column above the slope, the smaller the bending moment and shear force in the members. In other words, the softer the column, the smaller the internal force in the structure due to uneven settlement.

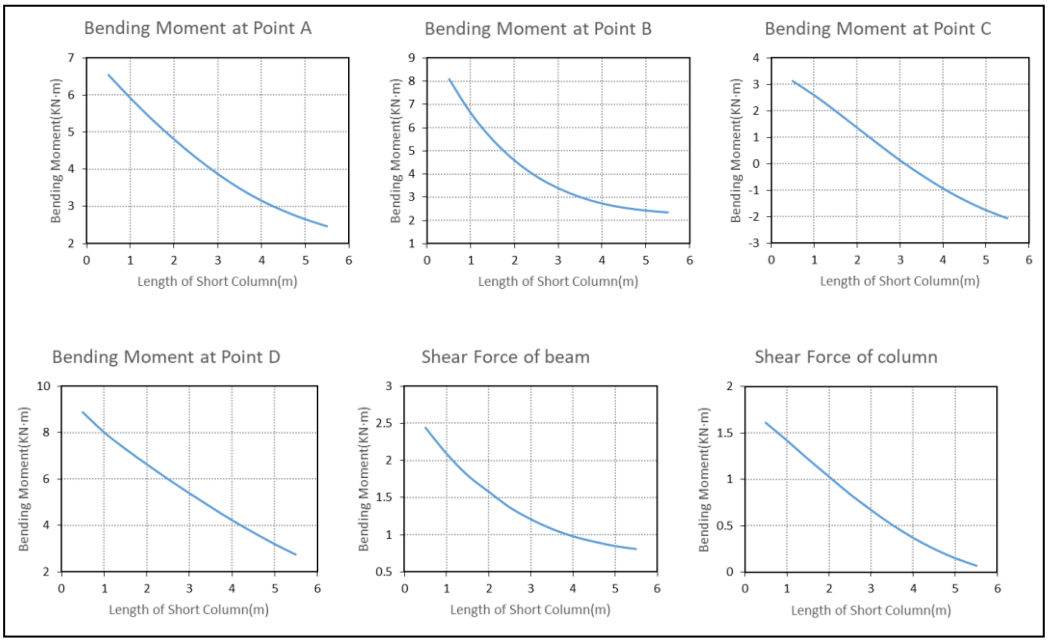


Figure 4. Change in internal force in structural members with variation in column height above the slope

3.1 Analytical model

To analyze the effect of uneven settlement on the SSFDE the model with below parameters are established. The height of the building is 11 stories, the height of the building is 8 stories, the height of the top slope is 3 meters, the height of the structure is 3 meters, the span is 5 meters, the dimensions of the beam are 250 mm × 500 mm, the column dimensions are 550 mm × 550 mm, and 650 mm × 650 mm for the 1-4 stories. The modulus of elasticity concrete is $3.0 \times 10^{10} N/m^2$,

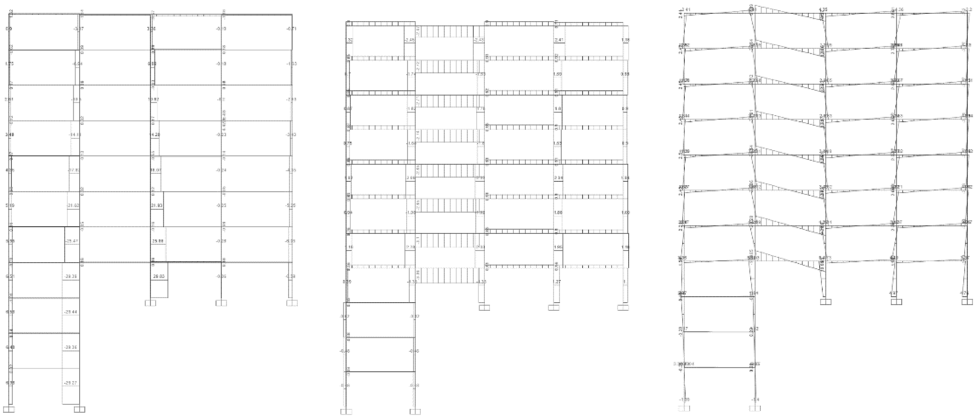
It is difficult to predict quantitatively the magnitude of the uneven settlement in the SSFDL. In this paper, the situation of applying a settlement of 1 mm only on the column foundations on the upper embedding end is simulated.

3.2 Internal force analysis

After applying a displacement of 1 mm to the column at the upper embedding end of the frame structure, the internal force distribution as shown in Fig. 5 was obtained.

Overall, the internal forces mainly occur in the beams connecting the upper and lower support layers and in the support columns of the upper support layers. The internal forces also occur in the upper support layers, but their magnitude is relatively small. Therefore, the support columns of the upper support and the beams connecting the upper support and the lower support layers should be considered as the main influence regions.

The location of relatively large axial forces in the internal force distribution is the adjacent columns on the upper support and lower support, the location of which the largest axial force is the bottom column of the upper support layer and the bottom column of the lower support layer on the upper support layer. The location of the largest shear force is the beam connecting the upper support layer and the lower support layer on the lower support side.



(c) Axial force(kN) (b) Shear force(kN) (c) Bending Moment(kN·m)

Figure 5. Structural internal force distribution under uneven settlement.

The occurrence of uneven settlements in the hillside buildings resulted in relatively large internal forces in the structure and the distribution was not uniform. This was because the main members of the frame structure, beams and columns, used their stiffness to prevent the displacements generated in the foundation after uneven settlement, but different internal forces distribution was observed due to the different contribution of members to them, for example, the beams connecting the upper and lower support layers.

The distribution of the internal forces in the computational model showed that large shear and bending moments occur in the beams and columns connecting the upper and lower support layers, and that in the case of uneven settlements in this structure, the shear and bending moments generated in the beams connecting the upper and lower support layers and in the support columns of the upper support layers should be considered.

4. Conclusion

This study presents a comprehensive analysis of hillside building structures supported by foundations at varying elevations, with a specific focus on the internal force distribution resulting from uneven settlement. By utilizing finite element models and simulating displacement scenarios, the research identifies key patterns in structural behavior under differential settlement conditions.

First, the findings reveal that even minimal uneven settlement can induce significant internal forces within the structure. These forces are especially prominent in the beams connecting the upper and lower support layers, and in the columns situated at the upper embedding end. The severity of these internal forces diminishes with a reduction in stiffness of the corresponding columns and beams, indicating the importance of flexible design in mitigating structural stress.

Second, the study highlights that the internal forces resulting from settlement are not uniformly distributed. The concentration of forces in specific structural members—particularly beams and columns bridging support layers—underscores the necessity for targeted reinforcement and design adaptation in these critical areas.

Third, the analysis of internal force types shows that beams primarily experience shear and bending moments, with axial forces being relatively minor, although localized tensile forces can occur. Columns, on the other hand, are mainly subjected to axial forces and bending moments. This distinction in force behavior emphasizes the need for tailored structural responses in beams versus columns during the design process.

Overall, the insights derived from this research contribute valuable knowledge to the field of hillside architectural design, providing a foundational basis for optimizing structural resilience and informing future investigations. It is recommended that further studies explore more complex settlement patterns and integrate dynamic seismic factors for a more holistic understanding of hillside structural performance.

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6. Conflict of Interest

The authors declare that there is no conflict of interest regarding the publication of this paper.

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