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Influence of Relative Stiffness on Bending Moment in Raft Foundations

P. P. Prabhu[1]*, V. G. Mutalikdesai[2], K.R.Patil[3]
[1] Research Scholar, Civil Engineering Department, K.L.S. Gogte Institute of Technology, Belagavi,
prasadprabhu1983@gmail.com
[2] Professor, Civil Engineering Department, K.L.S. Gogte Institute of Technology, Belagavi,
vgmdesai@git.edu
[3] Assistant Professor , Civil Engineering Department, DY Patil College of Engg & Tech, Kolhapur,
kiranpatil.23@gmail.com

***Abstract*— This research article delves into the impact of raft and soil stiffness on the seismic behavior of soil-structure systems. Understanding soil-structure interaction under seismic loading is crucial for designing and analyzing structures in earthquake-prone regions. The stiffness of both the raft and the underlying soil significantly affects the dynamic response and overall performance of the system. To achieve the research objectives, an extensive numerical study employing advanced finite element analysis is conducted. Various scenarios are explored by systematically varying the stiffness properties of the raft and soil. The seismic response is assessed through structural displacements, accelerations, and stresses, as well as soil settlement and lateral soil pressures. The study's findings highlight the noteworthy influence of raft and soil stiffness on the seismic response of soil-structure systems. Higher raft stiffness tends to reduce structural displacements while increasing stress levels in the structure. On the other hand, softer soil stiffness amplifies the structural response, resulting in larger deformations. The outcomes of this research provide valuable insights for designing and optimizing soil-structure systems subjected to seismic forces. Engineers and researchers can utilize these findings to enhance the seismic performance of structures by appropriately selecting and adjusting the stiffness of the raft and soil, while considering site-specific conditions and design requirements.**

***Index Terms*—soil-structure interaction, seismic response, raft stiffness, soil stiffness, finite element analysis.**

I. INTRODUCTION

Foundations play a crucial role in the safe transfer of loads from the superstructure to the underlying subsoil. Raft foundations, also known as mat foundations, offer an economical solution when faced with low soil bearing pressures, large coverage areas, or potential differential settlements. These rafts are commonly designed as reinforced concrete flat slabs, providing a wide base for load distribution. Traditionally, the design of rafts has been based on assumptions that consider the pressure exerted by the soil on the raft as uniformly upward; assuming the center of gravity of the loads coincides with the centroid of the raft. However, this approach does not account for moments and shears induced by potential differential settlements, resulting in heavily reinforced rafts. In contrast, an alternative method subdivides the raft into a series of continuous strips, considering the shear and moments of each strip for design purposes. This allows for a more accurate design, especially when using an inverted flat slab configuration with a combination of beams and slabs. The determination of contact pressure distribution beneath the foundation is a complex task influenced by the rigidity of the superstructure, the raft itself, and the supporting soil. The pressure distribution is dependent on various factors, including the foundation rigidity and soil characteristics. By understanding the pressure distribution, engineers can calculate the bending moments and shear forces acting on the foundation.

In seismic regions, raft foundations exhibit advantages due to their continuity and inherent rigidity. However, seismic forces introduce additional complexities, leading to significant changes in load distribution and soil pressure. These changes result in large eccentricities of loads relative to the centroid of the raft, inducing additional moments that can cause differential settlement. Therefore, it is crucial to consider the effects of seismic loading when designing raft foundations. This research article aims to investigate the influence of seismic loading on the design of raft foundations. By analyzing the changes in load distribution, soil pressure, and potential differential settlements, a better understanding of the behavior and design considerations of raft foundations under seismic forces will be achieved. This knowledge will assist engineers in developing more effective and reliable design approaches for seismic regions.

II. LITERATURE REVIEW

In the field of raft foundation design, Sharat Chandra Gupta's book on "Raft Foundations Design and analysis with a practical approach" [1] provides valuable insights. This resource offers a practical perspective on the design and analysis of raft foundations, covering essential considerations for engineers. Gupta's book serves as a comprehensive guide, equipping professionals with the knowledge and techniques necessary to tackle challenges related to raft foundation design. A study by Sekhar Chandra Dutta, Rajib Saha, and Sumanta Haldar [2] delves into the inelastic seismic behavior of soil-pile raft-structure systems under bi-directional ground motion. By examining the response of these systems during seismic events, the research sheds light on the behavior and performance of piled raft foundations. Dutta et al.'s study enhances our understanding of soil-structure interaction and provides valuable insights for engineers aiming to design more resilient and robust foundations in seismic regions.

Francesco Basile's study on "Non-linear soil-structure interaction in disconnected piled raft foundations" [3] investigates the behavior of disconnected piled raft foundations under varying loading conditions. This research focuses on understanding the non-linear soil-structure interaction and provides insights into the design and analysis of such foundations. Basile's work contributes to the knowledge base surrounding disconnected piled raft foundations, aiding in their improved design and performance.In their publication, Kyung Nam Kim, Su-Hyung Lee, Ki-Seok Kim, Choong-Ki Chung, Myoung Mo Kim, and Hae Sung Lee [4] explore the optimal pile arrangement to minimize differential settlements in piled raft foundations. Through their parametric study, they investigate the impact of different pile arrangements on the performance of such foundations. This research offers valuable insights into the selection and arrangement of piles, aiming to mitigate potential settlement issues and enhance the stability of piled raft foundations. A parametric study by Dang Dinh Chung Nguyen, Dong-Soo Kim, and Seong-Bae Jo [5] focuses on the optimal design of large piled raft foundations on sand. Through their research, they explore various design parameters and their effects on the behavior and performance of piled raft foundations. Nguyen et al.'s study offers valuable guidance for engineers, contributing to the development of design strategies to ensure the stability and structural response of large piled raft foundations on sand.

Additionally, Jeong and Cho [6] proposed a nonlinear 3-D analytical method for analyzing piled raft foundations, further advancing the understanding of their behavior. Mandolini, Di Laora, and Mascarucci [7] focused on the rational design of piled rafts, considering various design aspects and offering guidance for practitioners. Chaudhari and Kadam [9] explored the effect of piled raft design on high-rise buildings, emphasizing soil-structure interaction. The relevant Indian Standard IS 2950 (Part-I) [10] provides guidelines for the design and construction of raft foundations, while ACI 336.2R [11] offers suggested analysis and design procedures for combined footings and mats.

Jayalekshmi and Chinmayi [12] investigated the soil-structure interaction effect on seismic force evaluation of RC framed buildings with different shear wall shapes, aligning with the broader context of considering soil-structure interaction in seismic design. Collectively, these studies contribute to the understanding of raft foundation design, behavior, and optimization, encompassing aspects such as soil-structure interaction, seismic behavior, pile arrangement, and design guidelines. These insights aid engineers in developing efficient and reliable design approaches for raft foundations in various geotechnical and structural contexts.

The literature review highlights the existing research gap regarding the effects of soil-structure interaction on the seismic response of structures and the practical application of finite element analysis in the design of raft foundations. While significant research has been conducted on the analysis and design of raft foundations, most of it has focused on soil-structure interaction and flexible analysis, neglecting the behavior of the foundation under seismic loading conditions.

The research emphasizes that the current practice of analyzing rafts for gravity loading, following code guidelines, does not fully capture the field conditions. As a result, there is a need for further research to study the seismic/dynamic analysis of raft foundations. This research direction would address the gap in the literature and provide a simple approach to analyzing raft foundations subjected to seismic forces.

III. 3 ANALYSIS OF RCC STRUCTURE

The conventional design and analysis of rafts primarily focus on static loading conditions, while their behavior under seismic conditions requires further investigation. To address this gap, a comprehensive study is conducted, taking into account the insights gained from the literature survey. The study examines a typical concentrically loaded building with a raft foundation under seismic conditions, considering various load combinations, raft thicknesses, and soil conditions.

The analysis focuses on a ground plus thirteen-storey RC high-rise residential building with symmetrical plan dimensions. The building's height is 46.5 meters, and it does not have any parking floors. In accordance with Clause 7.8.1 of IS 1893 (Part I):2002, the Response Spectrum method is utilized for dynamic analysis. To conduct the building analysis, software such as ETABS and STAAD.Pro are employed, while the raft is analyzed using SAFE. Through this comprehensive study, the seismic behavior of the building and the response of the raft foundation are thoroughly examined. By considering different load combinations, raft thicknesses, and soil conditions, valuable insights can be gained regarding the structural response and performance under seismic forces. The use of advanced software enables accurate analysis and assessment of the building and raft system, aiding in the development of reliable design approaches for seismic conditions.

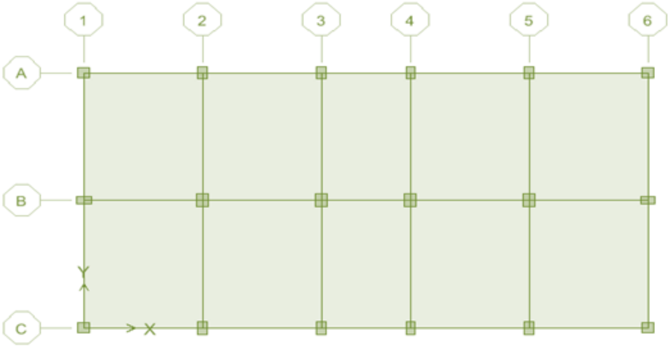

Figure 1: Plan of building

Table 1: Load combinations used for analysis

Factors		DL	LL	EQ
Load Combination	DL+ LL	1.5	1.5	-
	DL+LL*±EQX	1.2	0.25/0.5	1.2
	DL+LL*±EQY	1.2	0.25/0.5	1.2
	DL±EQX	1.5	-	1.5
	DL±EQY	1.5	-	1.5
	DL±EQX	0.9	-	1.5
	DL±EQY	0.9	-	1.5

IV. 4 ANALYSIS OF RAFT

The analysis of the raft foundation is conducted using the SAFE software. The mat is positioned with a 0.5-meter offset from the column face, allowing the vertical loads and moments on the columns to be transferred as column reaction loads onto the mat. Subsequently, the mat is analyzed for various parameters.

To facilitate the analysis, the raft is divided into three strips, namely A, B, and C. Different thicknesses of the raft, ranging from 0.5 meters to 1.5 meters, are considered, along with various Modulus of Subgrade Reactions values ranging from 5000 to 25000 kN/m^2/m. Deflection results are evaluated for different load combinations, identifying the worst load combination for further analysis.

In the preliminary analysis, the raft thicknesses of 0.5 meters, 1 meter, and 1.5 meters are initially considered. However, for a more detailed investigation, the raft thickness is adjusted based on the specific requirements of the soil conditions and the relative stiffness parameter. Different modulus of subgrade reactions are utilized, including values of 5000, 10000, 15000, 20000, and 25000 kN/m^2/m. The bending moment results are analyzed for various load combinations, with the worst load combination being identified and used for subsequent analysis.

Effect of seismic/dynamic loading on solid flat raft provided for symmetrical size and shape building is studied under bending moment and its variation w.r.t. relative stiffness

4.1 Relative stiffness

In conventional design practices, building frames are typically assumed to be fixed at their bases. However, in reality, the soil support exhibits some flexibility, allowing for movement of the foundation. This flexibility decreases the overall stiffness of the building frames in relation to the soil, consequently altering the overall response of the building and its foundation [6].To interpret the results of soil-foundation-structure interaction, the flexural rigidities of superstructure and foundation elements, as well as the stiffness of the soil, serve as defining parameters. Equation (i) in line with IS:2950 Part I 1981 [1] is considered for the study, although the code does not explicitly guide how these factors should be utilized. Furthermore, there has been no significant revision to this code since its reaffirmation in 1987.

In practice, raft foundations are analyzed based on gravity loading guidelines provided by codes, which do not fully capture the field conditions. Most of the existing research focuses on soil-structure interaction and the flexible analysis of rafts. However, the literature review and provisions of the IS code emphasize static loading conditions. Therefore, a more comprehensive study is required to investigate the seismic/dynamic analysis of rafts, aiming to determine a satisfactory solution for analyzing raft foundations under seismic forces.

$$K_r = \frac{E}{12\,E_s}\left(\frac{d}{b}\right)^3 \quad \text{….(i)}$$

where Kr < 0.5: Flexible and Kr ≥ 0.5: Rigid

For long beams Vesic (1961) proposed an equation (ii) for estimation of sub grade reaction that can be expressed as

$$K = \frac{E_s}{B\,(1-\mu_s^2)} \quad \text{…(ii)}$$

where,

k = modulus of sub grade reaction, Es = modulus of elasticity of soil, μs = Poisson’s ratio of soil

4.2 Relative Stiffness Factor

The relative stiffness [1] values corresponding to thickness and subgrade modules are shown in table 2.

Table 2 Relative stiffness for varying soil modulus and raft stiffness

K in kN/m^3	0.5m	1m	1.5m
5000	0.282(F)	2.25(R)	7.61(R)
10000	0.141(F)	1.128(R)	3.808(R)
25000	0.0564(F)	0.45(SR)	1.523(R)

Where, F- Flexible Raft, R-Rigid Raft.

V. 5 RESULTS AND DISCUSSIONS

The investigation focused on analyzing the behaviour of a divided raft, which comprised three strips labelled as A, B, and C (as shown in Figure 1, with column positions marked with crosses). The key parameters examined were a bending moment in relation to the raft. Additionally, the response of the raft at its threshold thickness was assessed by studying selected parameters. The critical load combination for the raft was determined during the study. It was observed that the load combination 1.5 (DL+EQY) was critical for the edge-strips A and C, indicating a higher vulnerability under seismic loading conditions. Conversely, for the B-strip, the critical load combination was 1.5 (DL + LL), suggesting a greater influence of regular gravity loading.

These findings shed light on the distinct behaviour and response of different strips within the raft system, emphasizing the varying susceptibility of the edges (strips A and C) to seismic forces and the influence of gravity loading on the central strip (B-strip).

Solid raft is analyzed for different thicknesses and soil parameters and results are as below:

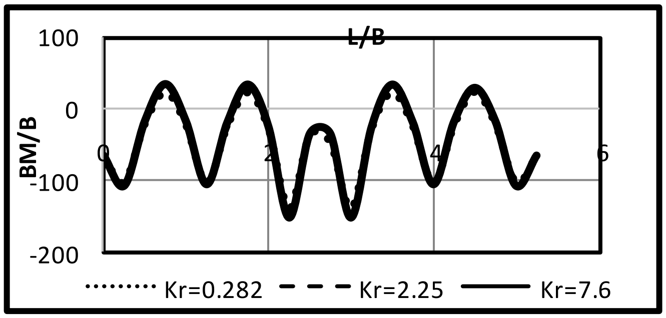

Figure 2 BM results for A and C strip for K=5000kN/m^2/m

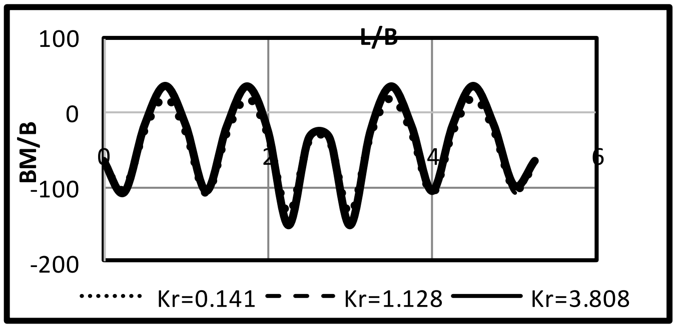

Figure 3 BM results for A and C strip for K=10000kN/m^2/m

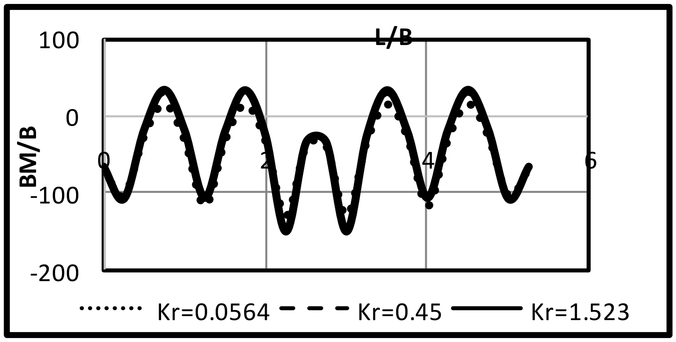

Figure 4 BM results for A and C strip for K=25000kN/m^2/m

Figure 2 – 4 shows that shows the variation of bending moment for different relative stiffness Kr, of the raft in terms of M/B and L/B. From Figure 2-4 it is clear that, there is no substantial variation in bending moment with respect to relative stiffness of raft for strips A & C.

Figure 5 – 7 shows the BM/B and L/B variation for different values of relative stiffness (Kr). For strip B there is

slight increase in bending moment with increase in relative stiffness of raft.

The change in maximum bending moment is substantial for flexible raft (refer figure 8), whereas in case of rigid raft (figure 9) maximum bending moment values are not much altered by changes in relative stiffness.

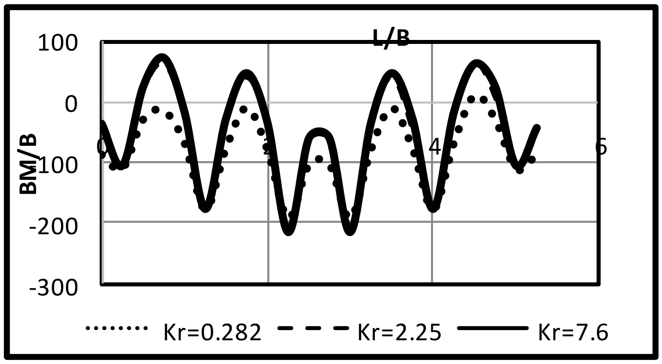

Figure 5 BM results for B strip for K=5000kN/m²/m

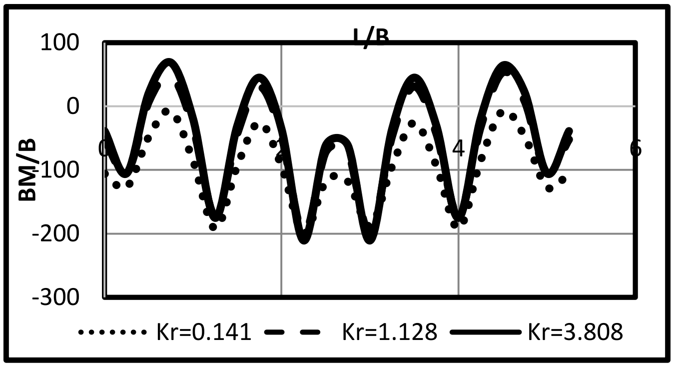

Figure 6 BM results for B strip for K=10000kN/m²/m

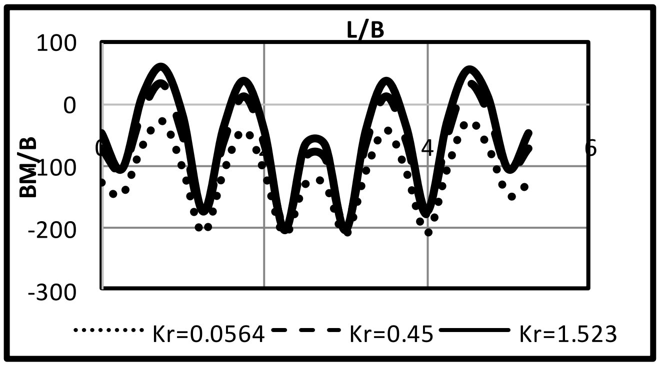

Figure 7 BM results for B strip for K=25000kN/m²/m

These findings demonstrate that the relative stiffness of the raft plays a more substantial role in influencing the bending moment behavior for the mid strip (strip B) compared to the edge strips (strips A and C). Additionally, they indicate that the rigidity of the raft significantly affects the magnitude of the maximum bending moment, with a more pronounced impact observed for flexible raft conditions compared to rigid raft conditions.

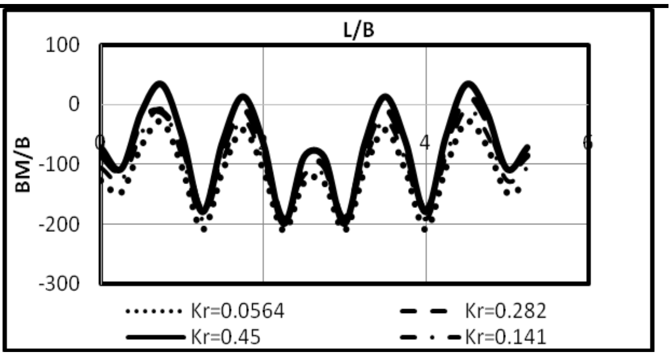

Figure 8 BM results for B strip for flexible raft conditions

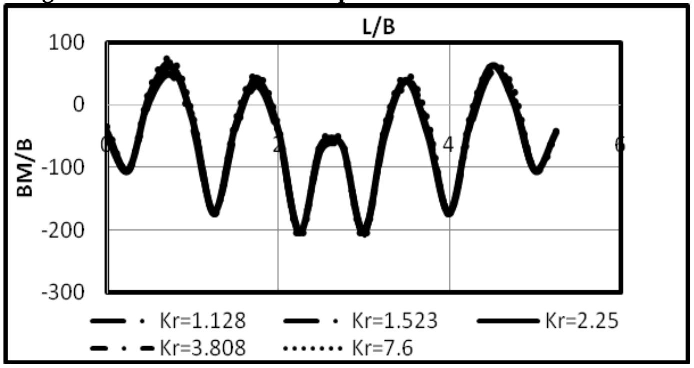

Figure 9 BM results for B strip for rigid raft conditions

VI. CONCLUSIONS

1. The investigation reveals that the bending moment per meter width (BM/B) can be effectively expressed in terms of the relative stiffness factor for different L/B ratios across all three strips.
2. The magnitude of the bending moment exhibits little variation with changes in the relative stiffness of the raft for strips A and C. However, for strip B, there is a noticeable increase in the maximum bending moment (sagging or hogging) with higher relative stiffness values (> Kr = 0.5) of the raft.
3. As the relative stiffness factor (Kr) approaches 0.5, indicating a rigid condition, the bending moment values tend to stabilize at higher levels of relative stiffness (Kr > 0.5).
4. The observed pattern of bending moment variation remains consistent for both rigid and flexible foundations, with the intensities varying based on the relative stiffness. Notably, this pattern is independent of the stiffness of the raft or the stiffness of the soil.
5. The bending moment pattern remains unchanged regardless of whether the loading is static or dynamic.
6. In a flexible foundation, an increase in the relative stiffness leads to a substantial increase in the maximum bending moment (sagging or hogging), whereas in a rigid foundation, the impact of increasing relative stiffness on the maximum bending moment is less pronounced. Once the foundation reaches a rigid state, changes in Kr values have minimal influence on the bending moment values, regardless of the specific strip being analyzed.

Overall, these findings contribute to a better understanding of the behavior of raft foundations and their response under varying degrees of rigidity, providing valuable insights for the design and analysis of such foundations under dynamic loading conditions.

DECLARATION OF COMPETING INTEREST

The authors declare that they have no know competing financial interest or personal relationships that could have appeared to influence the work reported in this paper.

FUNDING DECLARATION

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