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Effect of Seismic Analysis Approach and Provision of Shear Walls on Parameters for Raft Foundation Design

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Abstract

The present work attempts to understand the effect of different methods of seismic analysis on the design of building raft foundation. The study also evaluates the role of shear wall on the foundation response. A ten storey building with raft foundation has been analyzed in STAAD Pro using three different seismic analysis methods, viz., Linear static analysis, Linear dynamic analysis and Non-linear dynamic analysis. Furthermore, building with two different arrangements of shear walls (peripheral and core region) are studied by Non-linear dynamic analysis and compared with the model without shear wall. The raft is modeled with plate elements supported by soil springs using Winkler's approach. To consider the effect of different soil and raft stiffness, three different soil spring values and two raft thickness values have been considered. It has been concluded from the study that linear static analysis yields lower values of all foundation design parameters (viz., base pressure, settlement, foundation bending moment and shear stress) as compared to dynamic analysis. Dynamic analysis yields higher variation in base pressure and settlement distribution, which suggests adopting dynamic analysis approach for obtaining more realistic response, especially for settlement sensitive structures. Further the provision of shear wall has negligible influence on base pressure and settlement of foundation, while maximum bending moment and shear stress in foundation increases. Hence, provision of shear wall may increase cost of foundation, however, considering its role in improving structural integrity, shear walls are deemed important. Further, the increase in soil stiffness and reduction in raft thickness yields higher maximum base pressure and variation in base pressure, which confirms the importance of considering the effect of soil-foundation interaction for design of foundation. It is opined that the findings of the study would help in more realistic foundation design to achieve better performance during its life cycle.

Keywords: Seismic analysis, Raft Foundation, Winkler's approach, Shear wall, Foundation design Parameters

1. Introduction

Failure of Civil Engineering structures has been observed during several past earthquakes. In areas which are less prone to seismic activities, design engineers sometimes do not consider earthquake load as it is a transient load and its probability of occurrence is very low with return period of 475 years (for maximum ground acceleration) and with design life of 50 years [1]. But when earthquake strikes it can have catastrophic effect on the structures which are not designed adequately to resist the earthquake. This loss may be very high for the high-rise buildings. Therefore it is important to design for earthquake load and to include structural arrangements such as shear wall and tie beams to improve the integrity of structures. There are different methods to analyze the structure for earthquake load, viz., Linear static analysis, Non-linear static analysis, Linear dynamic analysis and Non-linear dynamic analysis. The use of suitable method depends upon various factors such as importance of the building, seismic zone of the area, project requirements, soil conditions, height of the building, codal recommendations, competency of the designer, etc. In linear static analysis base shear is distributed as an equivalent horizontal loading along the height of the structure. Seismic coefficient method is an example of linear static analysis. In non-linear static analysis the structure is analyzed for gradually increasing horizontal load. Pushover analysis is an example of nonlinear static analysis. Structure is considered as multi degree of freedom (MDOF) system in the linear dynamic analysis. The stiffness matrix to be considered for the linear dynamic analysis is linear elastic in nature. Response spectrum analysis is an example of linear dynamic analysis. In the nonlinear dynamic analysis, the nonlinear elastic properties of the elements are considered. This approach also models the structure with multi degree of freedom. Time history analysis is an example of the nonlinear dynamic analysis.

In order to improve the performance of structures subjected to earthquake induced lateral loads, shear walls are useful structural elements. Shear walls increase the stiffness of the structure and transfers the major part of lateral load during an earthquake event to foundation, thus reducing the impact

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on other parts of the structural system [2]. Generally shear walls are provided around staircase or lift of the building, however, they may be provided in external or internal zone of the structure/building. External walls are more preferred as internal walls may occupy the space to be used by building users.

Static analysis of a similar building foundation has been presented in past study by authors [3]. The present study focuses on studying the effect of different seismic analysis methods and provision of shear wall on design of raft foundation provided for a multistoreyed building. Three different methods are considered for evaluation of the effect of earthquake load: Seismic response method as per IS code [4], Response spectrum method as per IS code [4] and Time history analysis (based on site specific spectra), as these are the most widely used methods. The study also evaluates the role of shear walls (provided in periphery and core region of the building) on design of raft foundation. STAAD Pro. has been utilized to model and analyze the building with raft foundation as well as with shear walls. In STAAD Pro software, the soil can be modeled as number of linear discrete elastic springs (uncoupled) based on the Winkler approach. The modulus of subgrade reaction is used to define the stiffness of the springs. The methodology of the study, results and its discussion is presented in following sections.

2. Methodology

2.1 Modeling of the Building with raft foundation in STAAD Pro.

In STAAD Pro. V8i software, a ten storey building has been modeled and the details are provided below. The building is symmetric in plan and the type of building is institutional building with 10 storeys with each storey height of 4 m. The frame type of building is Ordinary Moment Resisting Frame (OMRF). The base area of building is 25 m x 25 m which includes five bays along both the length and width. Initial beam size selected was 230 mm x 350 mm and column size was 600 mm x 600 mm for the analysis.

Building was provided with raft foundation. Size of the Raft is 27 m x 27 m. As per the IS code [5] the raft is flexible raft. The thickness of the raft was varied as 0.5 m and 0.9 m. Depth of foundation below ground level was considered as 2m. The raft foundation was modeled using plate elements of size 0.5m x 0.5m. Every node of plate mesh has been assigned as the foundation support using soil springs, which are defined using the values of modulus of subgrade reaction. Three different values of modulus of subgrade reaction were used in the study to represent the different compaction states (stiffness) of the soil. The plan view and isometric view of the STAAD model is shown in Figure 1.

2.2 Loading on the building

The building-foundation model is subjected to dead load as per IS code [6], which includes the self weight of RC elements of building as well as a member load of 20 kN/m on each beam as wall load, and live load of 4kN/m^2 for an institutional building as per IS code [7] was considered. The earthquake load has been applied by three different methods.

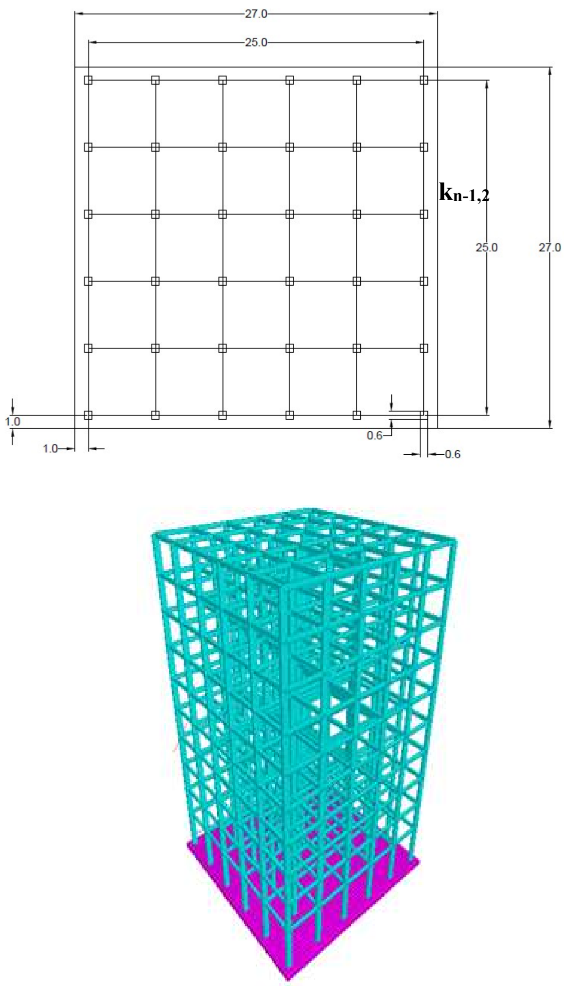


Figure 1 Plan view (dimensions in m) and Isometric view of the modelled building

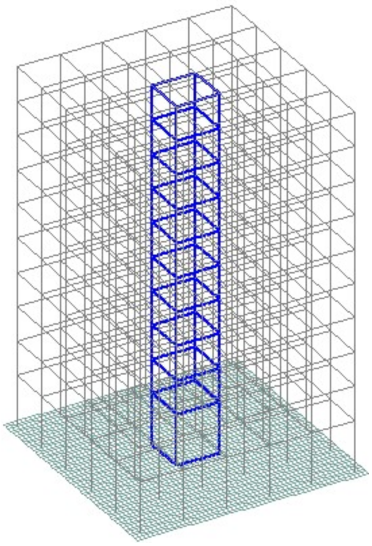
The first method is the seismic coefficient method, which is a linear static method of analysis. In this method, the seismic coefficient ($ZIS_a/2Rg$) was calculated as per guidelines provided in IS code [4] and multiplied by the vertical load to be considered in earthquake analysis to obtain the equivalent horizontal point load at each node of structure (beam-column junction) above ground level. Second method is the response spectrum method, which is a linear dynamic analysis method. A seismic load definition was generated for Bhuj city (high seismic prone area) and medium stiffness soil conditions. A load case was generated and response spectrum in X direction was generated considering damping value of 0.05 and a factor (ZI/2R) is calculated from the values given in IS code [4]. All other loads such as dead load and live load were defined in all three directions for earthquake analysis. Third method is the time history analysis, which is non linear dynamic analysis method. The time history definition (time versus acceleration), for the selected site (Bhuj), has been provided as input through an external text file [8]. Predefined time step value in STAAD Pro., has been utilized and the damping ratio of 0.05 and an arrival time were defined. A load case was generated and time history data in X-direction has been given as seismic load. All other loads such as dead load, member load and live load were given in all three directions in separate load cases.

2.3 Modeling of Shear walls

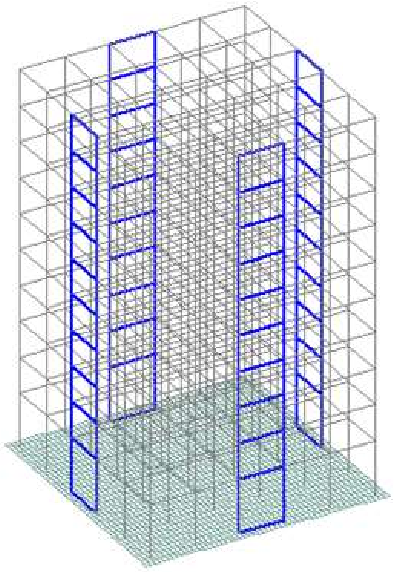
Shear walls in STAAD Pro. are modeled using the surface element command. Four noded surfaces were created and each surface panel was of size 5m x 4m. For the study, two arrangements of shear wall were created as shown in the Figure 2. Initial thickness considered for the shear wall is 300 mm.

3. Results and discussion

Considering three values of modulus of subgrade reaction, K_s (2000 kN/m^3 , 6000 kN/m^{3}and 12000 kN/m^3), two values of raft thickness (0.5 m and 0.9 m) and the three different approaches for analysis for earthquake loading (seismic coefficient designated as method-I, response spectrum designated as method-II and time history analysis designated as method-III), a total of 18 models were analyzed for the building with raft foundation, in absence of shear wall. Further, two shear wall arrangements have been studied (refer Figure 2) with K_s = 2000 kN/m^3 , 6000 kN/m^{3}and 12000 kN/m^3, and raft thickness as 0.5 m and 0.9 m. The analysis with shear wall was carried out by using time history analysis approach. Hence total of twelve models were created with shear walls. For each model, foundation base pressure, settlement, shear force and bending moment were obtained and the values are compared for different cases.



(a) Shear wall in the core region



(b) Shear wall in periphery of building

Figure 2 Shear wall arrangements

3.1 Comparison of methods of seismic analysis

Three methods of seismic analysis are compared for different values of modulus of subgrade reaction and foundaion thickness. Figure-3 shows the comparison of maximum and minimum base pressure for different cases. In the figure, bold plot corresponds to maximum base pressure and dotted plot corresponds to minimum base pressure. From the figure, it is observed that the Response spectrum method gives more conservative result for medium stiff soil (K_s = 6000 kN/m^3) and time history analysis method yields conservative result (higher values) for hard soil (K_s = 12000 kN/m^3). For the foundation in loose soil all three methods yields more or less same result for both maximum and minimum base pressure and there is not much influence of change in the thickness of raft in the value of maximum and minimum base pressure for loose soil whereas there is an increase in maximum base pressure and decrease in minimum base pressure value with decrease in raft thickness for medium stiff and hard soil.

Figure 4 shows the variation of maximum and minimum settlement for different cases. It can be observed that for the stiff soil, the values obtained for maximum and minimum settlement are comparable (viz., differential settlement is less), while there is no visible effect of thickness. Whereas for the medium stiff soil, all three approaches yields comparable results for maximum and minimum settlement but increase in thickness leads to reduction in the value of settlement. For the loose soil there is no significant effect of thickness for both the dynamic approaches on settlement values. However, maximum and minimum settlement increases with static analysis approach.

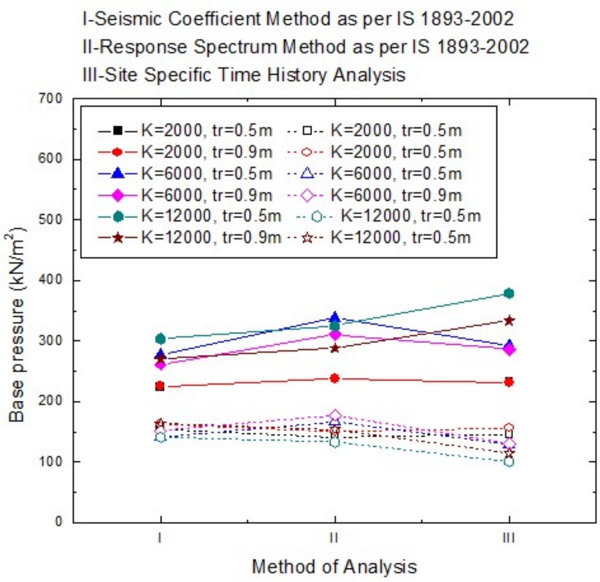


Figure 3 Variation of base pressure value with seismic analysis approach

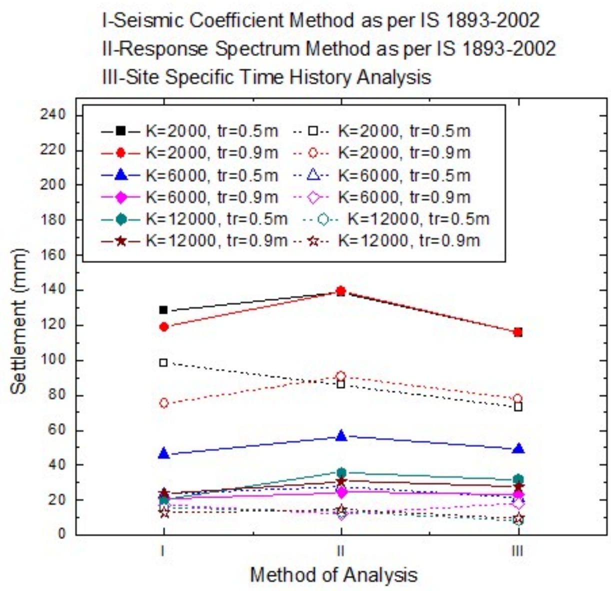


Figure 4 Variation of settlement value with seismic analysis approach

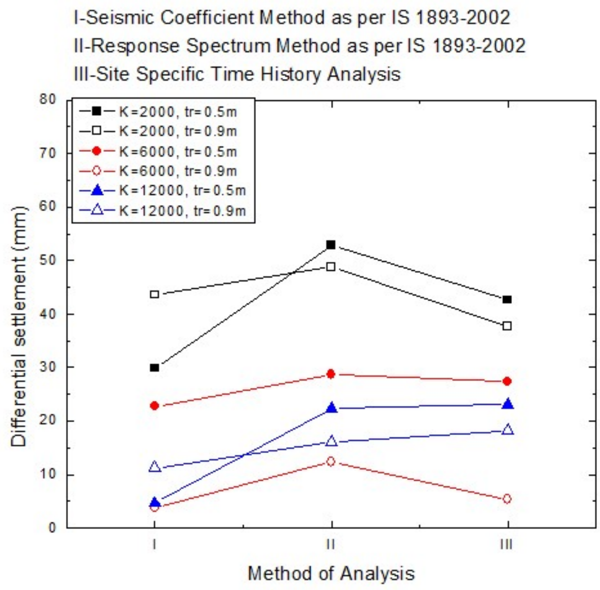


Figure 6 Variation of differential settlement

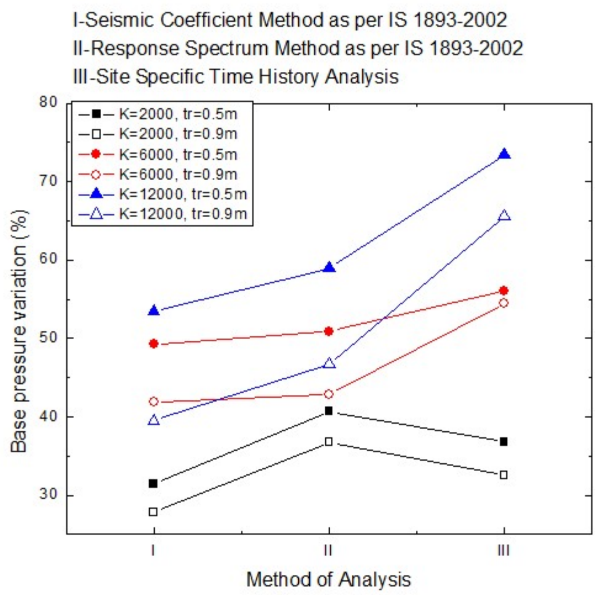


Figure 5 Variation of percentage variation in base ppressure value with seismic analysis approach

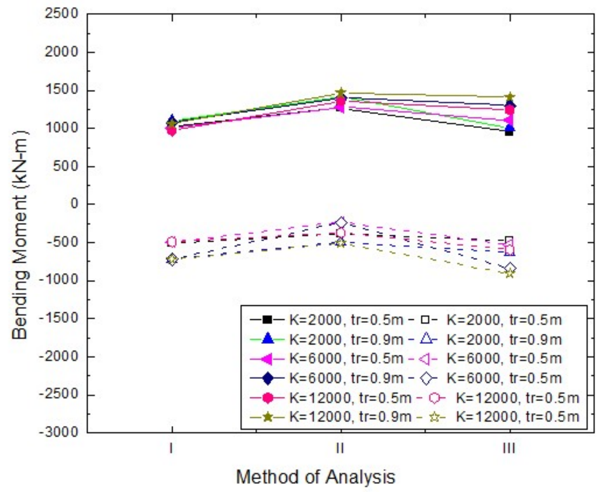


Figure 7 Variation of maximum foundation bending moment

From figure 5, it is can be observed that the static analysis approach (viz., seismic coefficient method) distributes pressure more uniformly for each case, hence the variation between maximum and minimum base pressure is lower. For medium stiff and hard soil, the base pressure variation is highest for the time history analysis whereas for the soft soil, response spectrum analysis yields higher base pressure variation. Further, base pressure variation increases with decrease in the raft thickness and increase in the modulus of subgrade reaction.

Figure 6 presents the differential settlement for different cases. As shown in the figure, response spectrum analysis yields maximum differential settlement for soft soil. For medium stiff and hard soil, the differential settlement is lower for the static analysis approach. For each case, static analysis approach yields minimum differential settlement value. When employing the dynamic analysis approaches, differential settlement increases with reduction in raft thickness; whereas, for the static analysis approach differential settlement increases with increase in raft thickness for soft and hard soil.

Figure 7 presents the maximum bending moment for different cases. The maximum positive bending moment values (viz., sagging moment) are comparable for the Response spectrum method and time history method for higher value of K_s. For the lower K_s values, the maximum positive moment values are comparable for seismic coefficient approach and time history analysis. Overall, bending moment values are less affected by the modulus of subgrade reaction and raft thickness values.

Figure 8 shows the comparison of maximum foundation shear stress for different cases. As shown in the figure, for more rigid raft (t= 0.9 m), the values for maximum positive shear stress in foundation is higher with response spectrum

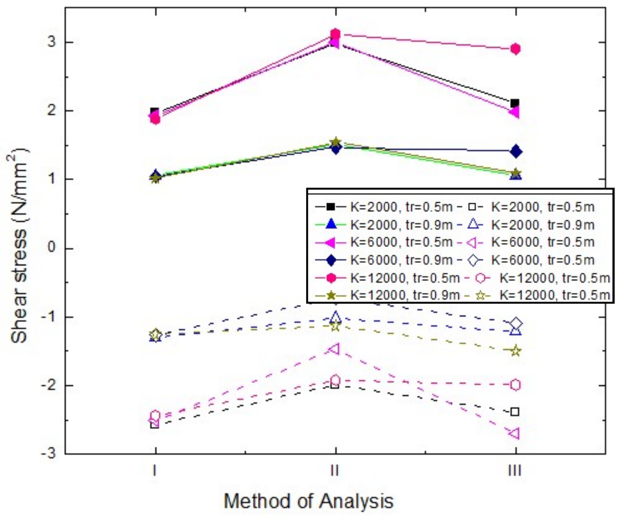


Figure 8 Variation of maximum foundation shear stress

analysis as compared to other methods. For t=0.5 m and higher value of K_s, response spectrum analysis and time history method gives similar values. For maximum negative shear stress, similar behavior is obtained. Increase in raft thickness decreases the value of shear stress and increase in modulus of subgrade reaction has negligible effect on shear stress.

3.2 Effect of Shear wall

Two different positions of shear wall have been studied and the results are compared with model without shear wall. The comparison plots are presented in the following figures.

As shown in the figures 9 to 12, all the geotechnical design parameters for the raft foundation i.e. base pressure, settlement, base pressure variation and differential settlements are not much influenced by introducing shear wall in inner region or peripheral location. Shear wall is the structural element and adds to the stiffness of the superstructure, however, the geotechnical paremeters for foundation design are not much influenced by introduction of shear wall in this study.

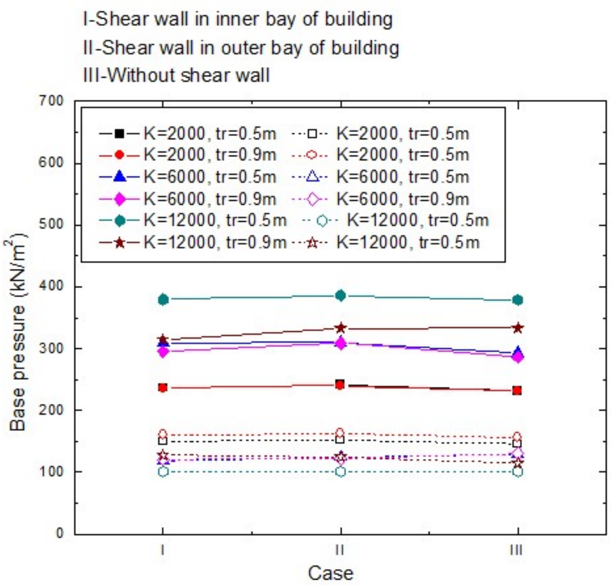


Figure 9 Variation in base pressure value with positioning of shear walls

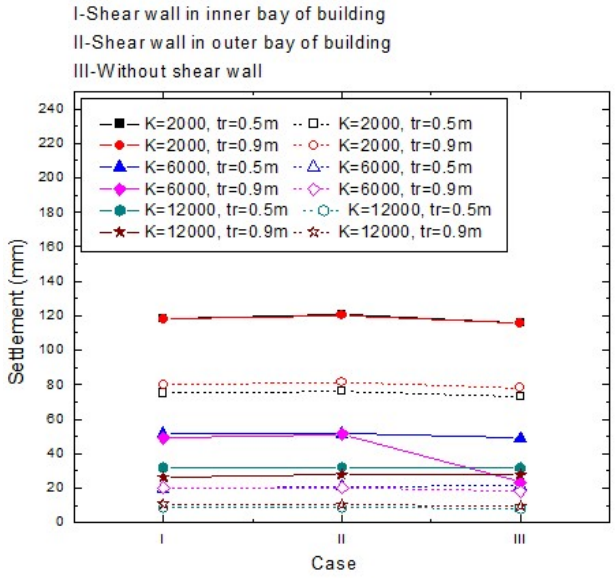


Figure 10 Variation in settlement value with positioning of shear walls

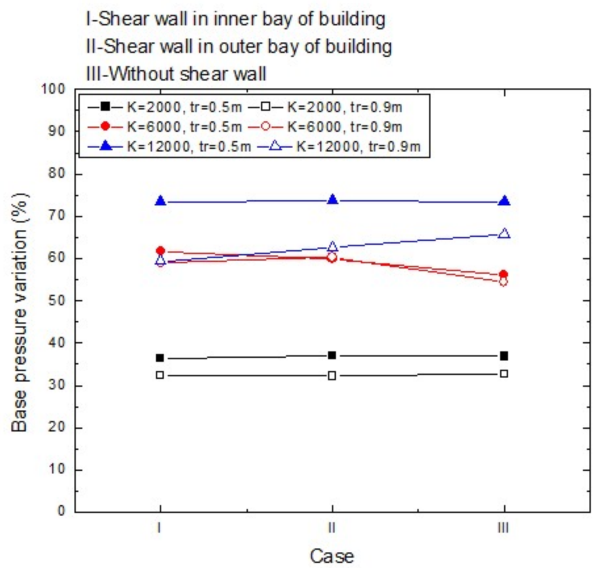


Figure 11 Variation in percentage base pressure variation with positioning of shear walls

The variation in the foundation bending moment and shear stress is somewhat affected by the provision and position of shear walls. As shown in figure 13, maximum positive bending moment (sagging moment) in foundation increases as shear wall moves toward the core, whereas negative maximum bending moment is not much influenced by the introduction of shear wall except for the case with K_s = 12000 kN/m³ and t = 0.9 m (rigid raft on hard/stiff soil). and K_s = 6000 kN/m³ and t = 0.9 m(rigid raft on medium stiff soil), but for these two cases maximum negative bending moment values for both shear wall position is comparable but the value is higher as compared to the case without shear wall.

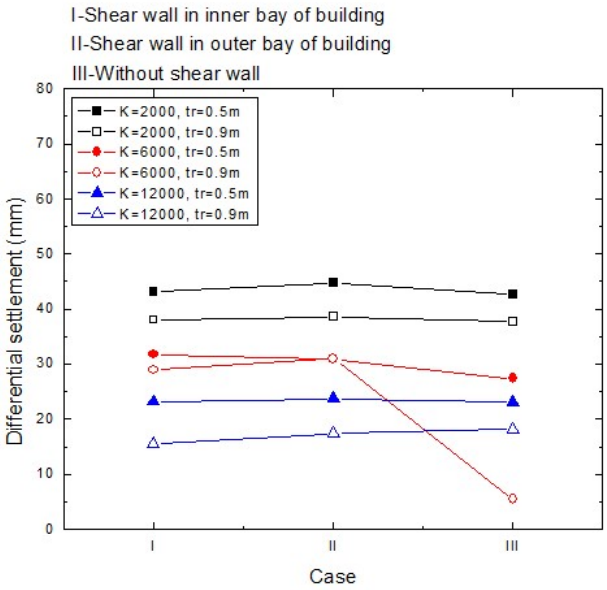


Figure 12 Variation in differential settlement value with positioning of shear walls

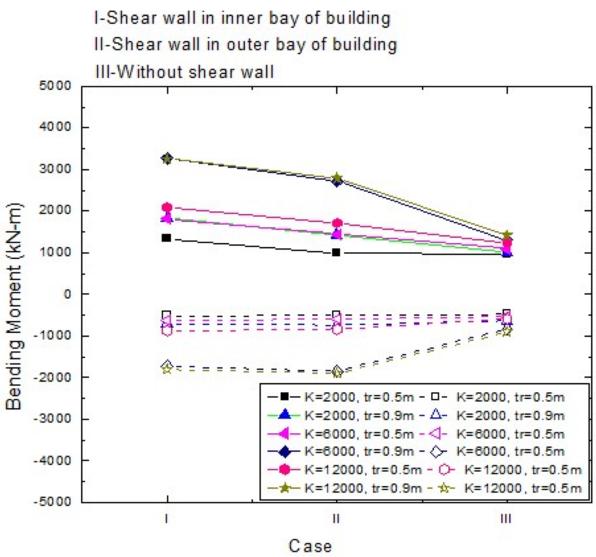


Figure 13 Variation in foundation bending moment with positioning of shear walls

As shown in figure14 maximum shear stress remains nearly unaffected for soft soil with introduction of shear walls, whereas for rigid raft (0.9m thick) on hard/stiff soil, the maximum shear stress increases as shear wall position moves toward core, whereas for less rigid raft (0.5m thick) on hard/stiff soil, the maximum positive shear stress increases as the position of shear wall moves away from core. For medium stiff soil, the maximum shear increases as shear wall moves towards the core. This could be attributed to higher concentration of stress in central portion of the raft due to provision of shear wall in inner core, making this region much stiffer than surrounding part of structure.

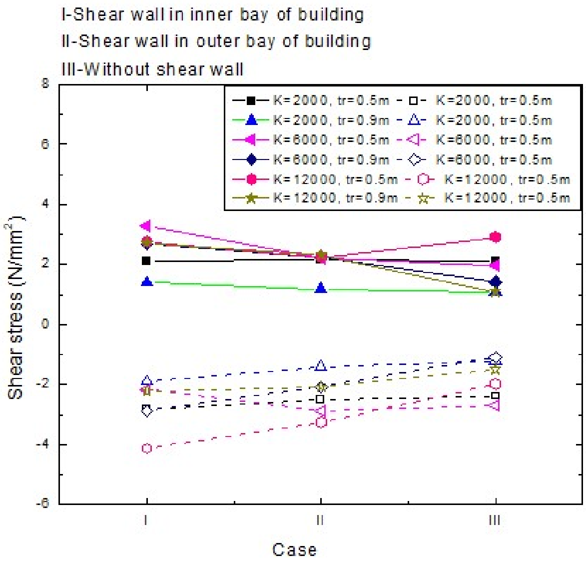


Figure 14 Variation in foundation shear stress with positioning of shear walls

4. Conclusions

Based on the study, the following conclusions are obtained:

1. For each foundation design parameter, in general, static analysis method (viz., seismic coefficient method) gives lower values as compared to dynamic analysis approaches. Further, in the static analysis, foundation base pressure distribution is more uniform and yields lower value of differential settlement for foundation raft as compared to the dynamic analysis.
2. For stiff soil (k_s = 12000 kN/m^3) as well as medium stiff soil (k_s = 6000 kN/m^3), response spectra method and time history analysis yield similar values for the maximum base pressure, settlement and bending moment; whereas in soft soil, seismic coefficient and time history analysis yields comparable values of maximum base pressure, settlement and bending moment values.
3. In case of shear stress for the rigid foundation on medium stiff soil (ks = 6000 kN/m^3), both dynamic analysis methods (response spectrum and time history analysis) yield comparable results and for rigid footing on soft (ks = 2000 kN/m^3) and stiff soil (ks = 12000 kN/m^3), seismic coefficient method and time history analysis yield comparable results.
4. Geotechnical parameters for design of raft (base pressure and settlement) are not much influenced by introduction of shear wall in the model. Values of structural design parameters (foundation shear stress and bending moment) for raft foundation increases due to introduction of shear wall and may require special foundation design for shear wall in some cases.

Disclosures

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