EFFECT OF NON-LINEAR SOIL TYPES ON SEISMIC RESPONSE OF BRIDGE PIER SUPPORTED ON WELL FOUNDATION

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Abstract - *For both steel and RCC Bridges passing rivers or creeks, common practice in many countries is to provide concrete wells to support the bridge girders. For many bridges that are strategically important in terms of defense or trade, it is essential that they remain functional even after a strong earthquake hits the structure. The present state of the art for design of well foundation is still marred with a number of uncertainties where a simplistic pseudo static analysis of its response only prevails, though it is a well-known fact that load from super structure, character of soil and its stiffness plays an important role in defining its dynamic characteristics. The present paper is thus an attempt to present a dynamic analysis model trying to cater to a number of such deficiencies as cited above and also provide a practical model (amenable to design office application) that can be used to estimate the pier, well and soil's dynamic interaction*

Keywords *Well Foundation, Bridge Pier, Non Linear Soil , Seismic Anaysis , Earthquake "Effect Of Non-Linear Soil Types On Seismic Response Of Bridge Pier Supported On Well Foundation"*

1. INTRODUCTION

Earthquakes are one of the most destructive natural hazard and have been occurring continually all over the globe. A large magnitude earthquake may last for less than a minute, but can kill and injure a large number of persons and destroy huge number of buildings and other structures leaving behind the survivors reeling for a decade or so. It is neither possible to control or restrict an earthquake nor to predict as to where and when an earthquake would occur nor what would be its magnitude. Therefore, the only option left is to reduce or eliminate the consequences i.e. damages due to earthquakes. Bridge components are designed for more than a life time along with the expectation that the behaviour of all the members, structural or non-structural, shall remain intact [1]. But over the past century the study of behaviour of the structural components subjected to various hazards, such as earthquake, has revealed that components did not behave as expected or desired [2]. Many times the unexpected behaviour had been attributed to undesired behaviour of soil supporting the structure. For determining the seismic response of structures, a common practice is to assume the structure to be fixed at the base, implying free field motion at the base of bridge pier. But this is far from truth when structure is supported on other types of medium because in reality, soil is not always stiff. Studies done on the past earthquakes such as 1985 Mexico City, 1995 Kobe, and 2011 Christchurch earthquakes have shown the importance of accounting for the soil-structure interaction to estimate the seismic response of superstructures, where otherwise the loss of life and property is unavoidable. The conventional assumption of structures considering rigid foundation were abandoned gradually while soil flexibility was taken into consideration in the seismic analysis. Accordingly, various studies were done across the globe and various methods for considering flexibility of soil and inertial effects of structure were developed and was termed as soil-structure interaction[3] [4]. Majority of the developed methods were based on empirical derivations or had serious shortcomings that limited their ability to properly model the phenomena. The soil was modelled with distributed spring damper elements. The incorporation of soil flexibility was proven to affect the behaviour of various structural elements. To characterize dynamic stiffness model of embedded foundations dynamic stiffness constants and radiation damping coefficients were developed. Dynamic coefficients for translation and rotation of base of foundation were also developed [5]. The development of these models made it possible to predict the seismic behaviour for structures on foundations having elastic medium. NEHRP Recommended seismic Provisions provided guidance for consideration of SSI effects in forced-based procedures for several decades but these procedures were not found to be of significant use in practice. Practical application of SSI gained momentum after publication of FEMA 440 which provided practitioners with procedures to incorporate the effects of soil-structure interaction in pushover type analyses. The extensive parametric studies considering flexible foundation resulted in reduced structural stresses, larger total displacements and more flexible systems resulting in reduced structural cost and could be duly accounted for [5] [6]. In later studies foundation uplift was also found to affect the behaviour of structure and consequently, simple practical procedures to account for such effects were developed [7]. Bridge piers and abutments are the most critical elements for the integrity of superstructures during earthquakes. Studies were conducted and an easy to use approach was developed to analyse the longitudinal bridge pier response to seismic excitations in horizontal direction. SDOF models were developed having identical response amplitudes to that of MDOF systems [6]. The idealised design spectra with increased fundamental period and effective damping to account for SSI in codes lead invariable to reduced shear force but it was shown that an in certain seismic and soil condition an increase in fundamental natural time period due to SSI may actually have a detrimental effect on seismic demand. This contradiction put a question mark to the popular belief of beneficial effects of

SSI by various authors [8] while assessing the effects of SSI on inelastic bridge piers.

2 Objective

Complexity in the analysis considering soil-structure interaction and unavailability of validated standard techniques results in ignoring the influence of the foundation for the structural design. The main challenge for soil-structure interaction incorporation is that the two disciplines of geotechnical and structural engineering meet simultaneously. Design of structures including SSI needs no emphasis. Researchers have developed various models employing different techniques and tools to properly address the issues associated with the complexities while incorporating SSI [6] [9] [10] [11] [12]. For simplicity of analysis nonlinear soil foundation-structure interaction can be represented with simple non-linear springs where the nonlinear interaction between the substructure the superstructure can be artificially prevented.

The present study titled "Effect of non-linear soil types on seismic response of bridge pier supported on well foundation" was formulated with main objectives as

To study top displacement and base shear/moment demands of varied bridge piers height with total weight of embedded portion of well for different soil types and seismic zones.

To study the effects of soil-structure interaction on the design base shear/moment for bridge pier.

3 Scope of Study

The analytical work for the analysis of bridge pier on well foundation and to assess the effects of soil-structure interaction has been analysed by Force Based Method. The reinforced concrete bridge pier of varying heights (6m, 9m, 12m, 15m, 18m, 21m and 24m) and constant diameter of 2.5m was considered. The weight of super-structure transferred to the bridge pier top was taken as 7100 kN.

One case were considered for this study: With total weight of embedded portion of well. To assess the effects of SSI analysis was done for bridge pier with fixed base and then for well foundation for the case of weight of embedded portion of well foundation. Foundations are supported and surrounded by soils which influence the seismic response of the structure. The foundation soils were considered homogeneous and of three types: hard, medium and soft and their characteristics were used in the analysis. The site where the structure is located also influences the seismic response of the structure and this effect is dependent on the probability of expected seismic severity at the site. According to Indian codes to account for this effect, seismic zone factor of 0.16, 0.24 and 0.36 were considered for zone-III, IV and V respectively. Also the scope of study is described by Figure 1.1.

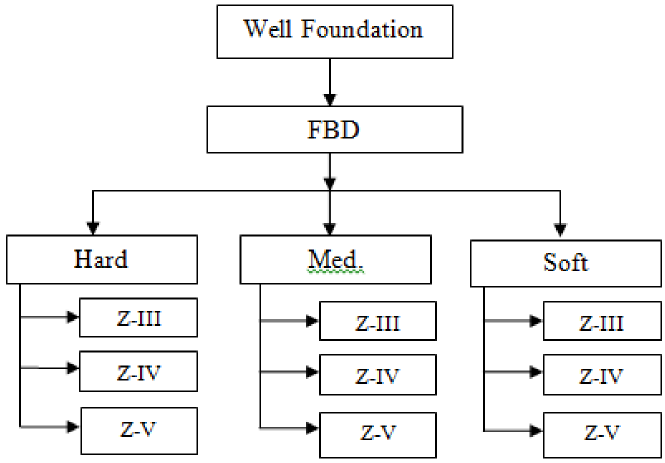

Figure 1.1 Scope of the study

4 Structure of thesis

The entire thesis has been organized into five chapters, which in turn, have been divided into sections and subsections.

Chapter one includes the theoretical background, objective and scope of the work to be carried out and structure of thesis.

Chapter two presents the review of previous work carried out on soil-structure interaction on deep foundations and development of Force Based Design method with previous work done on it.

Chapter three includes the procedure for computation of dynamic stiffness for considering well soil interaction and the explanation of Force Based Method for seismic analysis of structures. Force Based Method is currently used in Indian seismic design code.

Chapter four presents the results of the seismic analysis. The analysis has been carried out for the case: case-I considering total weight of well embedded portion of well. Comparison of base shear, base moment and top displacement has been done for varying pier height and their results along-with the observations have been presented. The assessment of soil-structure interaction and soil-structure index is also presented in this chapter.

Being the last chapter, presents the conclusions formulated from the analytical work. Future research works that could be carried out have also been recommended.

5 Literature Review

5.1 Soil-Structure Interaction

Priestley et al. (1979) studied the dynamic response of bridge piers modelled as single-stem and double stem subjected to natural and synthetic records of earthquake ground motions considering foundation flexibility. The extended leg of the pier under the ground was modelled replacing the soil by an equivalent spring system. The plastic hinge behavior of the pier was modeled by a bilinear moment curvature loop. The ductility demands were calculated considering different foundation flexibility and compared with the rigid foundation case. The study concluded that curvature ductility factor demand is increased while displacement ductility demand is reduced due to foundation flexibility. The results of single stem bridge pier showed that additional damping due to soil yielding had no significant effect on reducing dynamic response [13].

Chopra et al. (1983) developed simplified analysis procedures to consider the beneficial effects of foundation-mat uplift for computation of seismic response of structures, which respond essentially as SDOF systems in their fixed condition. The analysis procedures were presented for structures attached to rigid foundation supported on rigid soil or flexible foundation soil being modelled as two spring-damper elements. Winkler model had been used with distributed spring-damper elements on viscoelastic half space to model the foundation. Base shear and displacement for an uplifting structure were computed directly from the response spectrum using acceleration. In practical structural design for estimating base shear and displacement this simplified analysis procedure could be made use of to a certain degree of accuracy. Structural response analysis is repeated for a range of parameters to establish design values for foundation design. The procedure presented could be used for such repetitive analysis. It was found that the base shear values decreased due to foundation mat uplift for a wide range of time period. However, it was found that for short period structures base shear demand increased due to foundation mat uplift, especially on stiff soils [7].

Spyrakos (1990) attempted to estimate the effect of soil-structure interaction on the seismic response of bridges and its significance for design of bridge pier placed on homogeneous deep soil strata or on shallow soil strata over a rigid bedrock against horizontal earthquake excitations. The bridge was modeled as three-degree-of-freedom system with mass concentrated at deck level. The deck was considered to be rigid and the equivalent stiffness as springs and equivalent damping as dampers were used to model impedances of foundation soil (horizontal and rotational spring with associated dampers) to account for soil-structure-interaction effects. The analysis was carried out for the longitudinal response of the bridge in horizontal direction. The results of analysis showed reduction in base shear values due to soil-structure-interaction effects. The reduction in structural stresses led to the conclusion that SSI effects should be accounted for in the seismic design for reduction in design costs [6].

Spyrakos (1991) has studied the effects of soil-structure-interaction on the response of bridge piers with circular foundation placed on homogeneous deep or shallow soil stratum overlying rigid bedrock subjected to horizontal seismic excitations. The soil supported bridge pier with circular foundation was modeled as spring and damper elements in the horizontal and rotational directions. The material, hysteretic and radiation damping ratios were also considered. The study revealed that the consideration of soil-structure-interaction caused significant reduction of base shear and consequent decrease in structural stresses effecting economy in structural cost [14].

Gazetas (1992) presented a set of dimensionless chart and algebraic formulas for readily estimating the dynamic impedances (dynamic stiffness (K) and damping (C) coefficients) for foundations oscillating harmonically in homogeneous half-space. All modes of vibration (significant translational and rotational modes) possible, a range of Poisson's ratio and a range of frequencies were considered. Two numerical examples were used to illustrate the use of these formulas and charts and to explain clearly the role of foundation shape and its embedded depth on radiation damping for various modes of vibration. However, the formulas and charts valid for a constant depth of embedment and for a solid base of foundation. These formulas can be used as a reference in practice and for interpreting the results considering multi-layered and nonlinear analyses. During initial calculations for preliminary design these formulas and charts could be made use of [15].

Ciampoli and pinto (1995) investigated effects of soil-structure interaction on dynamic response of bridge piers responding in inelastic range and considering the maximum required ductilities in the critical ranges of superstructure. The study was conducted on single cantilever bridge column with inertial mass at the top representing realistic case of bridge pier of various shapes and height on spread foundations. A large number of parameters were considered and in total 240 cases were examined with ductility demands ranging between 1.5 and 7. Due to wide band frequency and high intensity of seismic motion the response of bridge piers were found to be well within inelastic range and maximum curvature ductility was found to be in the order of 7. It was found that displacement ductility demand for piers decreased by SSI effects. This effect was defined in terms of the difference between total displacements and displacement with fixed base. The results were proved to be valid for cases in which soil compliance took lowest values but compatible with the response spectrum. The results were also valid for spectral acceleration being close to the upper bound of response spectrum in areas of high seismicity [16].

Carlo et al. (2000) have studied the effect of soil-structure-interaction effects on the seismic response of bridge pier with circular shallow foundation. The pier was modeled as linear beam elements, distributed masses and mass proportional viscous damping. The material nonlinearity was considered in a rigid-plastic hinge with hardening at the base of pier. The soil was idealized as a linear elastic half space, modeled as lumped parameter. The study showed that the soil structure interaction effect increases the period of vibrating structures, decreases the base shear values and increase the displacements at the pier top. The decrease in base shear indicates conservative design while increased displacement at the pier top emphasizes careful design of connections and bearings [17].

Thakkar et al. (2002) have studied the effect of the inertia forces associated with the embedded portion of the well foundation on the seismic response of structures with well foundation. Three scenarios (with full mass, half mass and without mass of embedded portion of well) were considered for the analysis of 7 bridges and parameters, such as base shear, base moment and top displacement of the bridge piers were compared. Important conclusions arrived at are: consideration of full mass may lead to 4% to 15% larger response compared to 50% mass and the foundation mass has larger effect on seismic response in soft soil than rock type strata and also for flexible substructure [18].

Sextos et al. (2003) have developed a general purpose computer model which uses comprehensive methodology for the seismic analysis of reinforced concrete bridges considering soil-structure-interaction. The model is capable of modifying time histories, spring-dashpot coefficients at each support accounting spatial variability, local site conditions and nonlinear behaviour of soil and structural component. This model can be used in any standard Finite Element software without any special dynamic SSI or inelastic features of soil, foundation and superstructure. All stages of the developed model have been validated with available models/procedure and test results establishing confidence in its application as well as results. The dynamic response of 20 different bridges were examined by the authors for various cases and for complexities involved in the analysis and were presented in a companion paper [19].

Jeremic et al. (2004) have presented the effect of soil-structure interaction on the seismic response of highway bridges. The analysis also included the inelastic behaviour of soil as well as the structure components. The study has shown that the displacement demand increased as a result of additional soil-foundation flexibility while the effect on superstructure could be beneficial or detrimental would depend on the characteristic of motion. However, in most of the cases it was found that soil-foundation-structure interaction had beneficial effects on seismic response of structure. It was shown that it is almost impossible to arrive at general conclusions about the behaviour of soil-foundation structure interaction during seismic motions. An approach to simulate soil-foundation-structure interaction using domain reduction method was presented as an alternative to non-linear analysis incorporating soil-foundation-structure interaction [20].

Mergos and Kawashima (2005) have studied the influence of foundation uplift on the seismic response of bridge pier with special attention to the modifications of rocking response under biaxial and tri-axial excitation with respect to uni-axial excitation. The results have shown that inelastic rocking of footing gives isolation effect on the bridge response while the beneficial effect of biaxial excitation on isolation effect depends on the characteristic of ground motion. The vertical component of earthquake has negligible effect on isolation. The isolation effect of foundation rocking increases as the size of footing and yield strength of the underlying soil decreases [21]

Gerolymos and Gazetas (2006) investigated static, dynamic and cyclic response of Caisson foundation embedded in non-linear inhomogeneous soil with loading applied at the top. Caisson was modelled on a generalised Winkler model by four types of inelastic springs and dashpots: horizontal springs along the circumference, rotational springs along the circumference, vertical spring at the base and rotational spring at the base. The static and dynamic response of Caisson foundation was studied using soil nonlinearity and interface nonlinearity. Two cases were studied: one considering soil non-linearity and other considering soil and interface nonlinearities. The test revealed that interface nonlinearity significantly affects the inertial response of caisson. The results of the model were satisfactorily compared with the results from 3D FE analysis [10].

Mylonakis et al. (2006) investigated the collapse of a segment of the elevated Hansin Expressway during 1995 Kobe earthquake. The issues examined were: seismological and geotechnical information at the site; free-field soil response; response of foundation-superstructure system with soil-structure interaction and its comparison with earlier studies without soil-structure interaction. Results of studies showed multiple role of soil that consequent the collapse. These were: soil deposit modified the bed rock motion to the extent that the resulting motion of the surface became detrimental to the structure, the vibration characteristic of the bridge was changed by the soil and foundation reach in the region of stronger response and the fundamental mode was altered by the compliant foundation so as to induce larger response. All these effects put together might have caused inelastic seismic demand more than double of that for the fixed base piers [22]

Gerolymos and Gazetas (2006) have presented a nonlinear Winkler model for the analysis of static, cyclic and dynamic response of bridge piers supported on caisson foundations. To account for the nonlinear soil reaction along the circumference and on the base of caisson, four types of springs and dashpots have been made use of : nonlinear lateral translational springs and dashpots to consider horizontal soil reaction; nonlinear rotational springs and dashpots to consider moment produced by the vertical shear on the perimeter of the caisson-soil interface; nonlinear base shear translational spring and dashpot to consider horizontal shearing force at the base of caisson and a nonlinear base rotational spring to consider horizontal shearing force at the base of caisson and moment produced by normal pressures on the base of the caisson. The springs and dash pots models also are used to consider the effects of soil failure, separation and gapping of caisson and soil, radiation damping and loss of strength and stiffness due material softening and pore-water pressure generation [9].The model was validated using 3-D finite element analysis as well as experimental study carried out by EPRI. The numerical analyses using developed model showed that the interface nonlinearities has significant effect on inertial response of a caisson [10].

Gerolymos and Gazetas (2006) have developed a general purpose multi-spring Winkler model for static and dynamic analysis of lateral response of bridge piers supported on rigid caisson foundation of circular, square or rectangular cross-section in homogeneous elastic soil. To incorporate the effect of soil-structure-interaction, four types of springs were considered. The spring and dashpot modulus were calibrated using elastic theory of embedded rigid foundation and the developed model was validated using 3-D finite element analysis and the seismic restudy using the model showed that it could capture the important phenomena related to soil-structure-interaction and wave flittering effect for frequencies larger than the first natural frequency of the soil deposit [23].

Mondal and Jain (2008) have carried out seismic response of bridge piers supported on well foundation using 2D finite element method considering nonlinearity in piers and well as well as soil-well-interaction effects. Three cases of embedment length were considered for analysis with two earthquake motions in longitudinal direction considering structure and interface nonlinearity. The separation between soil and well was modelled by compression only gap elements. The analysis was carried out in two steps: first, given time history was analysed to obtain the motion at the base of finite element model and use this motion in finite element model of soil-well-pier system. Linear and nonlinear analyses were carried out for different scour depth using two time histories. Linear analysis showed considerably higher bending moment demands exceeding the capacities by 20% to 70% in piers and 30% to 75% in well. The nonlinear pier with linear well did not show considerable reduction in force response of well. The nonlinearity of pier and well showed significant reduction of 15% to 50% rotational ductility demand in pier demanding adequate rotational ductility for well emphasizing the need to increase the capacity of well. [24].

Tsigginos et al. (2008) have developed an analytical method for the seismic analysis for bridge piers supported on rigid caisson foundation embedded in homogenous soil. Translational and rotational distributed springs and dashpots to simulate soil-caisson interaction have been introduced. Closed-form solution for vertical s-wave excitations were given in the frequency domain. Results of the proposed methods were compared with finite element analysis as well as other available methods and found to be in good agreement showing its reliability [11].

Varun et al. (2009) have developed a simple analytical model for lateral seismic response of large diameter caisson foundations. Winkler model was employed to represent the soil resistance mechanism at the circumference and the base of the caisson. Basically, four types of springs: translational and rotational at the circumference and similar at the base have been used. The effect of rotational spring at the base was found to be negligible and hence three spring model was considered and expressions were developed for them in terms of the ratio of the embedded depth of the caisson to its diameter and the loading frequency. The results of static analysis of the caisson embedded into multi-layered soil by the developed model were compared to the finite element 3D model and they matched quite well. For the prediction of forced vibration and transient seismic response, expressions were developed for foundation stiffness matrix and kinematic effects. The free field pier response transfer functions for translation and rocking motion induced by seismic excitations were computed by the developed method as well as 3D finite element model. The comparison of results showed that the simplified three spring model could be applied to capture the important response parameters like frequency content and evaluation of time history variation. The Winkler spring functions used in the developed model are applicable for linear elastic medium without material damping [12].

Kausel (2010) demonstrated the history of soil-structure interaction. Analysis considering soil-structure interaction started early in 19th century and progressed rapidly during second half of the century and with the advent of various computer analytical methods, simulation tools and Finite Element procedures there is a rapid increase in use of soil flexibility in seismic analysis, especially for nuclear power plant and offshore structure design. Various programs developed that have been used widely were SHAKE, SASSI, LUSH and CLASSI became means for solving any practical SSI problem. Later SSI problem was being solved considering linear elastic springs using soil stiffness to model Inertial and kinematic interactions. Over the years various static procedures considering linear behaviour of soil and the progress over the years has been presented [25].

Mondal et al. (2012) have studied soil-well interface nonlinear behaviour under earthquake motion and its effect on the seismic response of soil-well-pier system. Analyses were carried out using 2-D finite element model for full and partial embedment conditions of well. The well was assumed to be embedded in cohesion-less soil. The analysis considered the soil in dry and submerged states. The results of analyses were compared with those obtained for perfectly-bonded interface. It was found that the interface nonlinearity caused marginal reduction in displacement and force resultants and its non-consideration gives conservative values [26].

Chowdhury et al. (2012) have presented an analytical model for the seismic analysis of a bridge pier supported on well foundation considering soil-well-pier interaction. The model has been illustrated with an example of bridge supported on well foundation. The results show that soil-well interaction amplifies the response of fixed base pier and this effect increases with decreasing soil stiffness. The fundamental mode associated amplification are most critical [27].

Mondal et al. (2012) presented the seismic analyses of a bridge pier with well foundation by three approaches: 2D nonlinear, 2D equivalent linear and one dimensional spring dashpots. The nonlinear model deals with nonlinear behaviour more rigorously than the other two. The comparative studies showed that equivalent model is simpler and efficient than nonlinear but my cause an error up to 30% in design displacement and force resultants. One dimensional spring-dashpot model generally used in design offices must consider radiation damping otherwise displacement and force responses could be overestimated. For the bridges having fundamental periods more than that of fundamental period of soil, consideration of radiation damping causes underestimation of responses [28].

Drosos et al. (2012) have carried out experimental investigation of the effectiveness of foundation rocking on the seismic response of the slender bridge pier. To this end, three alternative designed foundations considered were: large, medium and small having seismic factor of safety as 1.07, 0.55 and 0.43 respectively. Performance studies were conducted through monotonic and slow cyclic pushover loading. The test results showed that rocking foundation could provide protection to structure during earthquake shaking [29].

Zafeirakos et al. (2013) have compared the response of over and under designed caisson foundations and also investigated the effect of nonlinearity developed into the caisson on the seismic demand of the superstructure. The caisson is embedded into two layer soil stratum and 3D finite element incremental dynamic analyses were conducted using 10 earthquake motions considering soil and structural nonlinearities. The study showed that drift and ductility demands were less in case of under designed caisson than that of over designed one; the maximum transmitted acceleration to superstructure formed a plateau and settlement and rotation were more in case of under designed foundation compared to that of over designed. Overall, the under designed caisson foundation showed high static factor of safety [30].

Liu et al. (2013) have carried out experimental studies to evaluate the effects of foundation rocking and yielding of columns on the seismic response of the structures. Four types model tests subjected to a suit of earthquakes were carried out. The studies portrayed that balanced design (when foundation rocking and structural yielding occur simultaneously) controls seismic response and greatly reduce the structural ductility demand while footings with restrained rocking demand more ductility on structure. The rocking dominated foundations significantly reduce the seismic demand on superstructures leading to greater protection. But the rocking capacity of foundation more than twice the structural fuse reduces the foundation rotation and thereby increased demand on the structure [31].

Gazetas et al. (2013) have studied the response of rigid footings (circular, square, strip and rectangular with different aspect ratios) under undrained conditions. Three stages of foundation states: initial elastic-fully bonded to nonlinear with partially uplifting and ultimate stage of soil bearing failure. The soil was modelled as an inelastic homogenous deposit. Based on the studies, simple formulas and charts have been developed for all stages of response in terms of non-dimensional parameters [32].

6. CONCLUSION

6.1 General

Earlier chapter were introduction, in which general introduction of soil-structure interaction, objective and scope of work. In the second chapter what was the earlier work which was carried out related to the topic is presented. In the third chapter calculation of spring constant and force based procedure is also discussed in this chapter. In the fourth chapter result is discussed. Conclusion being the last chapter conclusion of the work is discussed.

6.2 Base Shear

The base shear values of well foundation increase for the maximum cases in all the zones for hard, medium and soft soil.

While replacing linear soil spring to non-linear soil spring base shear values decreases. But decrease in base shear is at a slow rate upto fifteen number of replaced springs in most of the cases and after that base shear starts decreasing rapidly.

The decrease in base shear is due to flexibility because while using non-linear soil springs it provides more flexibility to the soil.

For the greater pier heights i.e. for 21m abd24m base shear values are increasing after certain number of nom-linear soil springs are replaced.

The increase in base shear is due to time period, when time period lies between 2 to 5 seconds base shear increases. with increasing pier height.

It is also observed that base shear also increase with increase in zone factor for all type of soil i.e. hard, medium and soft.

6.3 Base Moment

Base moments of well foundation increase sharply from 6m to 18m pier height and for greater heights it becomes constant in most of the cases for all the zones considered i.e. Z-III, Z-IV and Z-V.

After replacing linear soil spring to non-linear soil springs base moment for the pier heights of 6m and 9m is almost constant upto ten number of springs are replaced for all types of soil i.e. hard, medium and soft then it starts decreasing at a slow rate upto fifteen number of springs are replaced and if more springs are added then base moments decreases rapidly for above mentioned height for all the zones considered. For all type of soil i.e. hard, medium and soft for the pier heights of 12m, 15, and 18m is almost constant upto sixteen number of springs are replaced and above that base moment base moments starts decreasing rapidly for above mentioned height for all considered zones.

For the pier heights of 21m initially base moment is almost constant when ten number of springs are replaced, after replacing more springs base moment starts decreasing slowly upto the sixteen number of springs are replaced and then it starts decreasing rapidly after replacement of more springs for all considered zone.

For the pier height of 24m initially base moment is almost constant when ten number of springs are replaced, after replacement of more springs base moment starts decreasing slowly upto the sixteen number of springs are replaced and then it starts increasing rapidly after replacement of more springs for Z-III, Z-IV and Z-V.

The variation of base moment almost similar to the base shear because it is obtained by multiplying base shear values to the height gives the moment.

6.4 Top Displacement

Top displacements increase with increasing pier height in all seismic zones and for all types of soil i.e. hard, medium and soft soil.

It also increases from hard to soft soil and with increasing zone factor.

Top Displacements are goes on increasing when linear soil springs are replaced by non-linear soil springs but when upto the sixteen number of springs are replaced top displacement increases slowly after that if more springs are replaced then top displacement increasing rapidly for all the pier heights and for all the types of soil and for all considered seismic zones.

7 Suggestions for Future Research

This work was carried out considering non-linear soil properties. But, in reality soil as well as surface both does not behave linearly. The work can be carried out considering surface non linearity.

Only case were considered for the analysis considering total mass of embedded portion of well. Analysis can also be performed considering half mass of embedded portion of well and also by neglecting total mass of embedded portion of well. The mass of embedded portion of well can also be varied with respect to height and for this code provisions could be made use of.

Single bridge pier was considered in the analysis which is not practically applicable, to get more realistic result span of bridge pier could also be considered along with well foundation and considering soil structure interaction.

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