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STATIC- SOIL STRUCTURE INTERACTION ANALYSIS OF NUCLEAR BUILDING SUPPORTED ON COMBINED PILED RAFT FOUNDATION SYSTEM FOR A ALLUVIAL SITE

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ABSTRACT

One of the proposed soil site in the northern part of India, a twin unit of 700MWe Nuclear Power Plant (NPP) (based on Indian PHWR) are proposed. Nuclear safety related structures being heavy due to their functional, structural and shielding requirements are typically have raft foundation for distribution of load over a larger area and they are founded on rocky stratum. Controlling the overall and differential settlement is a challenging task for heavy structural system supported on a soil stratum. Combined piled-raft foundation (CPRF) system is considered as a suitable foundation system to control the overall and differential settlement structure supported on stiff soil site. In CPRF system, it is important that the computational model shall contain different interactions namely pile-soil, pile-pile, pile-raft and raft-soil interactions.

In this paper, detailed soil-structure-interaction study is presented for nuclear building supported on CPRF system using site-specific geotechnical parameters accounting the different interactions. In this study, behaviour of complete system is investigated under gravity and laterals load conditions. Elastic plastic behaviour of the pile-soil and raft-soil interface is simulated using three parameter model i.e. elastic slip, maximum shear strength and frictional coefficient. An approach to derive the input parameters to estimate the interface properties is developed and discussed. Mohr-coulomb plasticity model is used for continuum soil medium. Load sharing between pile and raft i.e. pile raft coefficient (α_{CPRF}) is estimated for both vertical and lateral load cases. It is found that the piles shares a major fraction of gravity load for a desired settlement level and contribution of raft resistance is significant under lateral loads. In addition to above, behaviour of the piles in terms of load transfer through skin friction and end bearing is studied and presented. Influence of different interactions namely pile-to-pile, pile-to-soil, raft-to-soil and raft-to-pile on load settlement behaviour of a pile in piled-raft foundation with respect to an isolated single pile is also presented.

INTRODUCTION

Twin unit 700MWe Nuclear Power Plant (NPP) based on Indian PHWR technology are being planned to be constructed at different sites located in various parts of the country. Two of the similar units are already under advanced stage of construction in Kakrapra (Gujarat) and Rawatbhata (Rajasthan) site. In both of these sites, rock is available at the shallow depth and hence, NPP safety related structures are founded on rocky stratum. One of the proposed site in northern part of India has alluvial soil site. Nuclear safety related structures being heavy (in general) due to functional, structural and shielding requirements are typically have raft foundation for distribution of load over a large area. Controlling the overall and differential settlement is a challenging task for such a heavy structural system founded on alluvial soil. Based on different parametric studies with site specific geotechnical parameters, it is found that a combined piled-raft foundation (CPRF) system is suitable for NPP safety related structures as founding medium consists of comparatively stiff soil, which ensures adequate bearing through raft elements.

Various researchers namely Katzenbach et al. (2006), Poulos et al. (2011) and Kumar et al.(2015) have recognized that CPRF has been widely accepted as optimised foundation for high rise buildings due to its effectiveness in load bearing by both raft and pile components. International guideline on combined pile raft foundation (Katzenbach, K. and Choudhury, D. (2013)) suggested that different interactions namely pile-soil, pile-pile, pile-raft and raft-soil shall be appropriately considered in the detailed soil-structure-interaction analysis. Based on the detailed finite element analysis, Clancy P. and Randolph M. F. (1993) has brought out a procedure to assess various interaction factors. Poulos et al. (2011) suggested that for control of settlement, a piled-raft foundation should be designed in such a manner that piles provides most of the stiffness at serviceability loads, and the raft element provides additional capacity at ultimate loading. Katzenbach, K. and Choudhury, D. (2013) suggested that resistance offered by raft and pile element depends on acceptable settlement level. It is found that as fraction of load shared by pile increases, settlement of foundation reduces. Poulos H. (2008) mentioned different design strategies of piled raft system. In first option, a piled-raft system is configured with the piles designed using conventional safety factor, where piles shared majority of loads. In second option, piles are designed with lower safety factor and in third option, piles are designed with their full capacities. Qualitative load settlement curve indicates that settlement level increases with progressively from first to third option.

NPP safety related structures are designed to perform their intended functions under different loading scenarios starting from normal operating, accidental conditions and extreme earthquake situations. Even their performance is assessed for beyond design basis earthquake events. Thus, a graded approach is adopted in the design of Indian PHWR NPP safety related structures founded on soil site. Under normal operating condition, piles in a CPRF system will be designed with a conventional safety factor and for extreme conditions, piles will be designed with reduced safety factor. For beyond design basis events, full capacities of the piles will be utilised.

Combined piled raft foundation system is in the process of finalisation for NPP safety related structures of Indian PHWR based plants for alluvial site. In this paper, detailed soil-structure-interaction study is presented for nuclear building using site-specific geotechnical parameters accounting the different interactions. A detailed finite element model of nuclear building along with CPRF and soil medium is developed in ABAQUS version 6.14.1. Different issues pertaining to modelling aspects has been discussed in detail. Static soil structure interaction analyses are performed for both gravity and laterals load (seismic loads with pseudo-static approach). Load sharing between pile and raft i.e. pile-raft coefficient (α_{CPRF}) has been estimated for both vertical and lateral loads. From this study, it is found that the piles shares a major fraction of gravity load for a desired settlement level. It is also found that contribution of raft resistance is significant under lateral loads. Group effects as well as other applicable interactions of CPRF on load displacement/settlement behaviour of a pile located in the central portion has been compared with that of isolated pile on same stratum.

FINITE ELEMNT MODEL OF NUCLEAR BUILDING AND SOIL MEDIUM

The nuclear building (NB) consists of different sub-structures viz., (i) reactor building (RB) containing inner containment (IC) structure, outer containment (OC) structure and reactor building internal structure (RBIS), (ii) reactor auxiliary building (RAB) consisting of spent fuel storage bay (SFSB) and remaining portion of framed structure connected to OC structure housing other reactor auxiliaries and various services. It is supported on a CPRF and size of the raft is around 100 m x 100 m. The geometric model of NB is shown in Figure 1 and Figure 2.

Soil stratification have been modelled as multiple horizontal layers. Different material properties for these layers have been estimated from various geotechnical parameters obtained from preliminary geotechnical investigations. Elasto-plastic behaviour of the pile-soil and raft-soil interface is simulated using three parameter model i.e. elastic slip, maximum shear strength and frictional coefficient. Mohr-coulomb plasticity model is used for continuum soil medium.

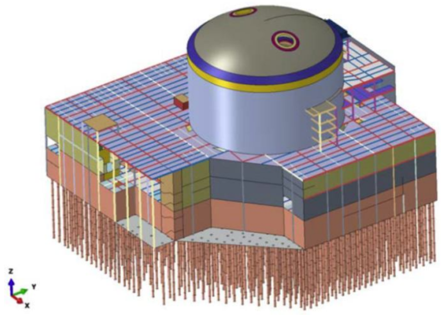

Figure 1. FE model of NB alongwith piled-raft

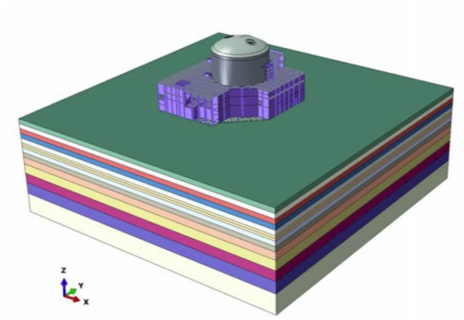

Figure 2. Soil layers modeled for NB

Finite element discretization

Different element types namely solid, shell, beam and springs and mass elements are used to model different structural elements along with major equipments of NB. Pile and some portion of raft (solid) is discretized using 8-noded hexahedral elements (C3D8R). Raft, wall, slabs were discretized using 4-noded general shell elements (S4R). The beams/columns have been modelled using 2-noded 3d-beam elements (B31). Some mechanical components are modelled as mass and 3D spring element.

Soil medium is modelled using 3D solid elements. Optimised element sizes has been adopted during mesh discretization considering both analytical accuracy and solution time. Soil have been discretized using quadratic wedge elements (C3D15R) in the region around piles and quadratic tetrahedral elements (C3D10R) in the regions away from the piles facilitating increasing the element size in horizontal as well as in vertical direction away from pile. Element size near to pile surface was kept quite fine due to requirement for convergence of contact algorithm and increased with distance from it. The FE model of NB is shown in Figure 3 and Figure 4.

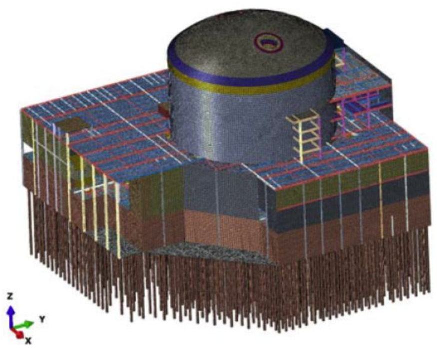

Figure 3. FE discretization NB alongwith CPRF.

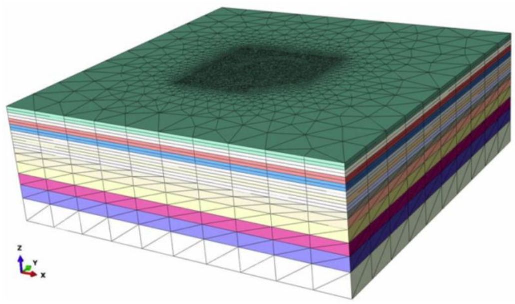

Figure 4. FE discretization of soil medium

Modelling of contact zone

The soil-structure interaction analysis requires considerations of the interaction or coupling between the structure and the founding media. Two contact zones are required to be modelled in piled raft foundation, i.e. the pile-soil and the raft-soil.

a) Pile-soil interaction:

The interface behavior of the pile and soil (frictional force vs. relative displacement) is pictorially shown in Figure 5. The interaction behavior is divided into two parts: a) sticking phase and b) slipping phase. Initially, during the sticking phase, pile-soil interface allows some relative movement (i.e. elastic slip) between the pile and the soil surface. Once the induced shear stress between the pile and soil reaches the critical shear stress, the interface enters in the slipping phase. The above sticking and slipping phase of the pile-soil interface is simulated using elastic coulomb friction model as shown in Figure 5. Normal behaviour at the pile-soil interface is modelled as a hard contact (Refer Figure 6).

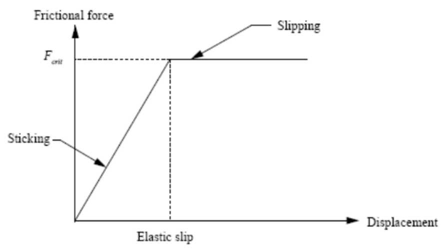

Figure 5. Pile-soil interface behaviour in tangential direction

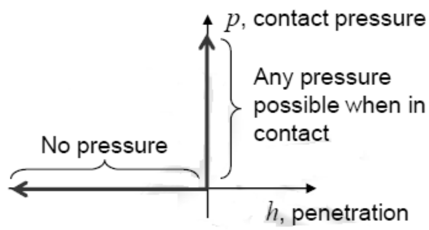

Figure 6. pile-soil interface behaviour in normal direction

<u>Calculation of contact parameters:</u>

Interface parameters are usually estimated from soil parameters (cohesion, angle of internal friction, elastic modulus). Considering the uncertainties regarding mobilisation of resistances at interface, it is recommended in (BS 8002 (1994)) that the design value of the friction or adhesion to be mobilized at an interface with the structure should be 75 % of the design shear strength to be mobilized in the soil itself, which is described as follows:

Coefficient of friction at the interface, $\mu = 0.75 * \tan(\phi)$
Interface shear strength, $\tau_{max} = 0.75 * (c + \sigma \tan(\phi))$

There is no specific guidelines for computing the elastic slip at the pile-soil interface. There are some literatures which gives relationship between shear stress and relative displacement at the interface (Kraft et al. (1981); Coyle and Reese (1966)). The approach suggested by Kraft et al. (1981) is adopted in the present study.

Shear stresses decay radially in the soil according to: $\tau = f\left(\frac{R_p}{r}\right)^n$ ....(1)
(Refer Figure 7)

Where,
- τ = shear stress in the soil
- f = side friction at pile soil interface
- r = radial distance from the pile centerline
- G = soil shear modulus of elasticity.
- R_P = radius of the pile

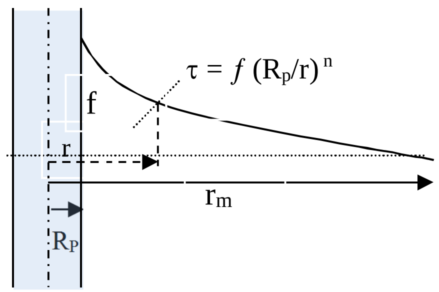

Figure 7. Radial decay of shear stress

The computed shear deformation (Kraft et al. (1981)) is;

$$\gamma = \frac{f}{G}\int_{R_P}^{r_m}\left(\frac{R}{r}\right)^n dr \quad ....(2)$$

where, $r_m = 2L(1-\rho)$ is the limiting radial distance beyond which deformations of the soil mass are negligible; L is length of pile and ρ is called as soil non-homogeneity factor.

Based on field test data, Broms B. (1979) suggested that the pile displacement required to mobilize the skin friction in the range of 1.0 to 8 mm. It is found that elastic slip computed considering cubic variation of shear stress matches with these suggested values. Thus, computed elastic slip is determined using followings equation:

$$\gamma_{crit} = \frac{\tau_{max}}{G} R_p{}^3 \frac{1}{2}\left(\frac{1}{R_p{}^2} - \frac{1}{r_m{}^2}\right) \quad .... (3)$$

b) Raft-soil interaction:

Raft interacts with the soil, in the same way as discussed in the preceding section. Hence, for simulating normal and tangential behaviour of the interface between raft and soil, same model as used for pile-soil interaction has been used.

Material properties:

Soil parameters:

Soil parameters considered for this study are based on preliminary soil investigation data. However, final soil investigation is under progress. Soil parameters upto a depth of 100m has been considered. The soil is mainly granular type having angle of internal friction (ϕ) in the range of 34o to 39o. Typical value of poisons ratio is 0.31.

Concrete:

Following material properties of both reinforced concrete and pre-stressed concrete element considered for analysis which are in line with safety standard AERB/SS/CSE-1 (AERB (2001)).

Modulus for concrete: $E_c = 5000 \sqrt{f_{ck}}$(MPa)

Poisson's ratio = 0.2

Density: Normal concrete (2.5 t/cum), Heavy concrete (3.75 t/cum), Special heavy (4.2 t/cum).

Structural Steel:

Following material properties of structural steel elements considered for analysis which are in line with safety standard AERB/SS/CSE-2.

Modulus of elasticity = 2.0×10^{05} MPa

Poisson's ratio = 0.3; Density =7.85 t/m^3

Different Loads:

Different loading situation considered for this study are described below:

Dead Load (DL)

Self-weight of different structural elements are computed by the software based on the unit weight of material and section properties data. Dead weight of non-structural elements are computed and applied on supporting structural elements.

Equipment Load (EQL)

Major equipment are already included in the finite element using equivalent beams with appropriate stiffness and lumped masses at respective location. Other equipment supported at different floors of reactor building and reactor auxiliary buildings are represented with equivalent nodal/area loads at respective locations.

Live Load (LL)

Different parts of nuclear building are subjected to imposed/live loads depending on their intended use. Equivalent loads are appropriately distributed in respective areas.

Earthquake Loads

Seismic analysis of NB has been performed for the three orthogonal (two horizontal and one vertical) components of earthquake motion by response spectrum analysis method. The seismic forces safe shutdown earthquake (SSE) for horizontal directions (that is SSE-X, SSE-Y) and vertical directions (that is SSE-Z) thus obtained have been applied as equivalent static load on the top NB raft.

Analysis steps and modeling parameters:

One of the important aspect for geotechnical modelling soil medium is the state of stress due to self-weight of existing soil layers are to be captured at the first step. This phenomenon is known as geostatic condition, which is appropriately simulated in Abaqus. Since, pile-soil interaction problem involves modelling nonlinear interaction between soil-pile, initiation of contact is usually accompanied by non-convergence issues. Hence, these two steps should not be modelled simultaneously (to avoid the convergence issues); instead it should be carried out one by one: Geostatic analysis is carried out without soil-pile interaction and then interactions are initiated at the interface with small displacement at on the top of the pile to establish the contact and then regular force-based analysis is carried out.

SSI ANALYSIS FOR VERTICAL LOADS

The soil-structure analysis has been carried out for vertical load as mentioned in the previous section. Vertical displacement of soil-pile system is presented in Figure 8 and the same at raft level is shown in Figure 9. It is observed that for the present piled raft configuration α_{CPRF} value is around 0.8 under vertical loads. Estimated differential settlement at foundation raft level is around 40mm and overall settlement is around 80mm.

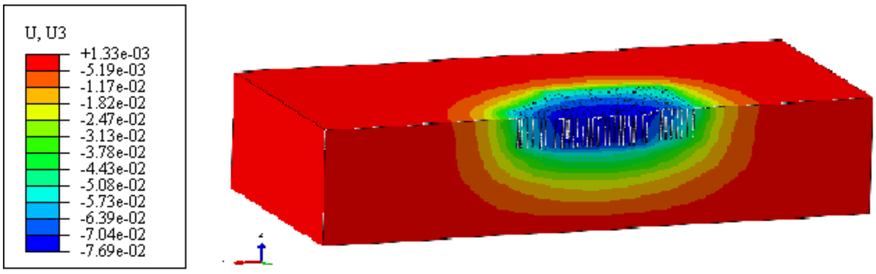

Figure 1. Displacement contour for soil-pile system under vertical static loading (Unit in meter)

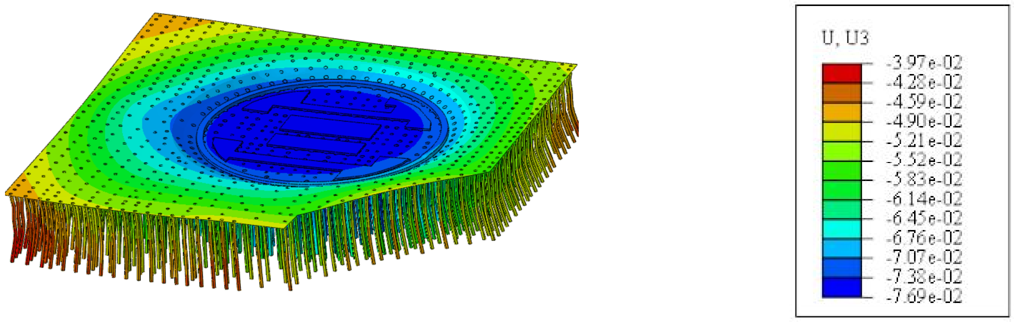

Figure 9. Vertical displacement contour at raft level under static loading (Unit in meter)

SSI ANALYSIS UNDER LATERAL PSEUDO-STATIC LOADING

The seismic reaction at the raft level are obtained from the response spectrum analysis and applied as equivalent static load on the NB raft at appropriate locations with a control mode sign. Non-linearity of the soil under dynamic loading condition is considered in the analysis by modifying the soil properties depending upon the induced strain in the soil during an earthquake.

The analysis of NB CPRF system along with the soil has been carried out for pseudo-static loading corresponding two horizontal components (that is SSE-X and SSE-Y) and one vertical components (that is SSE-Z) due SSE condition. Horizontal displacement of soil-pile system due to SSE-X and SSE-Y components are presented in Figure 10 and Figure 11 respectively. Vertical displacement due to SSE-Z component is presented in Figure 12. It is observed that for the present piled-raft configuration with the assumed pile layout, α_{CPRF} value is around 0.3 and 0.5 for horizontal and vertical components of seismic loads. Thus significant portion of lateral load is shared by raft itself and estimated lateral displacement is around 18mm for the assumed pile layout and the preliminary soil data.

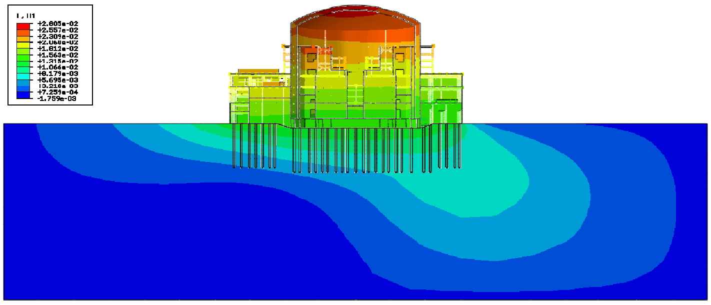

Figure 2. Horizontal displacement contour for SSE-X (Unit in meter)

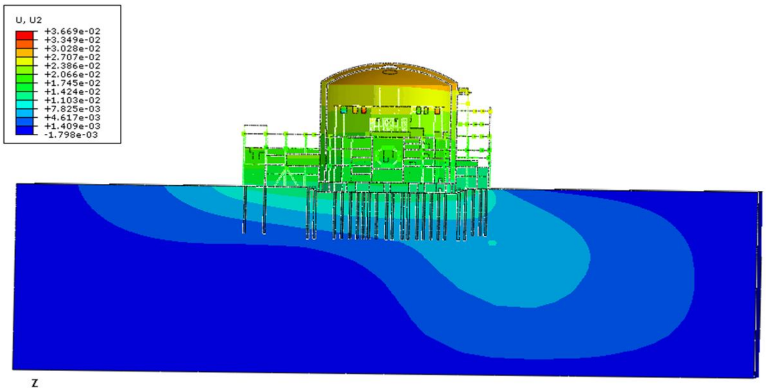

Figure 3. Horizontal displacement contour for SSE-Y (Unit in meter)

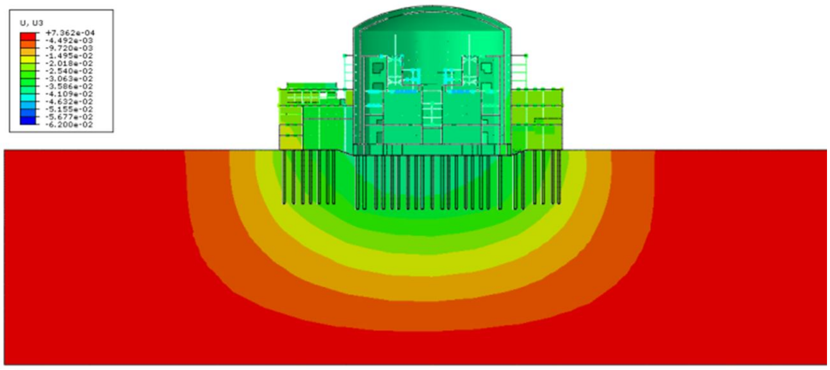

Figure 4. Vertical displacement contour for SSE-Z (Unit in meter)

COMPARITIVE LOAD SETTLEMENT BEHAVIOUR OF A PILE

Behaviour of a pile located in the central portion of the pile raft under vertical and lateral load is compared with that of an isolated pile. Comparative load deformation plots under vertical (static) and lateral (equivalent static) are presented in Figure 13 and Figure 14 respectively. It is observed that for isolated pile, the skin friction resistance is mobilized at displacement below 10mm and the end bearing resistance gradually mobilises at higher displacement values. The non-linearity of interfaces (skin friction and end bearing) is appropriately simulated in the present analysis. Though in case of an isolated pile, pile-soil interaction is very important, behavior of the pile in a CPRF, however, is significantly affected by group action and other interactions. Different non-linearities viz. contact nonlinearities at soil-pile and raft-soil interfaces and material non-linearity of soil medium are appropriately considered in the analysis process. It is, however, observed from the load-deformation characteristics that overall behavior of soil-pile-raft system is linear under design loads.

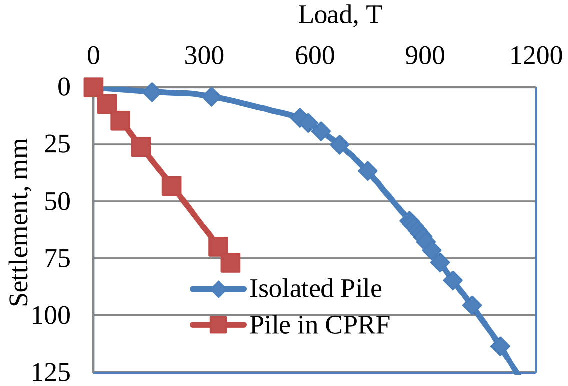

Figure 5. Load settlement behaviour under vertical load

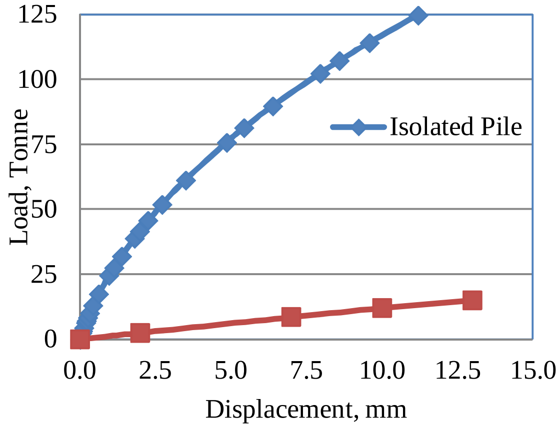

Figure 6. Load settlement behaviour under lateral load

CONCLUSIONS

The following conclusions are drawn from the preliminary static soil-structure-interaction analysis of nuclear building for a typical soil site:

(i) The vertical load sharing between pile and soil for static loading case is quite substantial (in the range of 0.8 for the assumed pile layout) and the same for pseudo-dynamic loading case is relatively less (in the range of 0.5 for the pile layout considered in the study). The load sharing of the soil is increased for pseudo-dynamic analysis case on account of dynamic soil parameters and thus, shows the effectiveness of combined piled-raft foundation (CPRF).

(ii) The horizontal displacement under equivalent static loading is around 18mm and for the present piled-raft configuration α_{CPRF} value is around 0.3 for horizontal components of seismic loads. Thus, significant portion of lateral load is shared by raft itself as compared to vertical static loads.

(iii) Elastic plastic behaviour of the pile-soil and raft-soil interface can be best simulated using three parameter model i.e. elastic slip, maximum shear strength and frictional coefficient. An approach to derive the input parameters to estimate the interface properties is developed and presented.

(iv) Though, in case of an isolated pile, pile-soil interaction is very important, but behavior of the pile in a CPRF is significantly affected by group action and other interactions. Different nonlinearities namely contact nonlinearities at soil-pile & raft-soil interfaces and material non-linearity of soil medium are appropriately considered in the analysis and it is found that the overall behavior of soil-pile-raft system is linear under design loads.

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