Numerical Analysis of Unconnected Piled Raft Foundation System Under Dynamic Loading

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Abstract. Deep foundations i.e. piled raft foundations are commonly used to bear the heavy loads of buildings and structures, however, earthquake loading may cause enormous bending moments and shear stress in the piles due to which they may fail. Thus, this paper signifies a numerical analysis of non-connected piled raft by introducing a granular layer (cushion) between the piles and raft. For this study, models are simulated in Plaxis 3D under earthquake loading with staged construction. A series of models are analyzed to compare the impact of cushion properties and geometry of the foundation system. Validation of numerical model has also done in this paper. In the case of connected piled raft foundation, the piles are directly loaded by the raft through their heads but in unconnected case, the load is redistributed through the cushion. The mobilized capacity of pile depends on the pile-subsoil relative stiffness in connected case but on the compressibility of the interposed layer in a later case. The simulation results have shown that a well-designed combination of connected and non-connected piles can be used to reduce total settlement, shear stresses and bending moments simultaneously, which will be more efficient and economical when compared to the conventional method.

Keywords: Cushion, Numerical analysis, Unconnected piled raft.

1 Introduction

Unconnected piled raft sub-structures are categorized by having no structural connection to a raft. The granular cushion is used to fill the gap of raft-pile in which huge amount of uniform pressure is generated on the raft results in diminishes of differential settlement. Pile is separated from the raft and also consider these piles as reinforcement to subsoil rather than the conventional structural member. Unconnected pile raft foundation is also designed with the help of researched technique and it is found usually to be cost-effective than coupled pile raft foundation.

In earthquake prone areas or active zones, the dynamic or cyclic lateral loads results for high horizontal shear forces and overturning moments if piles are structurally connected with a raft.

For the unconnected pile system, plain concrete piles are suitable, without the necessity of reinforcement, where the reduction of maximum settlements and strengthen the top are the main basic functions.

Cushion, which contains a mixture of sand-gravel, in which gravels are compacted in the layers between raft and top of piles. The cushion makes a significant role in mobilizing the bearing capacity of the sub-soil and modify the load transfer process of piles. Satisfactory circumstances for unconnected pile raft are correlative to connected pile raft. But the unconnected pile raft foundation mechanism is comparatively less effective foundation system. To increase the efficiency the geotextiles are cased around the cushion. In an unconnected pile raft foundation, the location of maximum axial load is lifted downwards to a certain depth below the pile head. It also has a significant role in mobilizing the bearing pressure or capacity of the subsoil and modifying the load transfer mechanism of piles. By providing connected pile system at a critical location (critical location is to be identified through modeling or another appropriate method), the differential settlement can be reduced. To reduce overall settlement, a cushion of higher thickness with a relatively higher modulus of elasticity shall be provided. But if we opt for higher elastic modular cushion the section tends to be uneconomical. So, a combination of two or more different materials (thus different elastic modulus) shall be used. Geofoam instead of soil can be used and should be investigated for the economy. The following figure depicts a hypothetical general case of how the combination of CPRF and UCPRF.

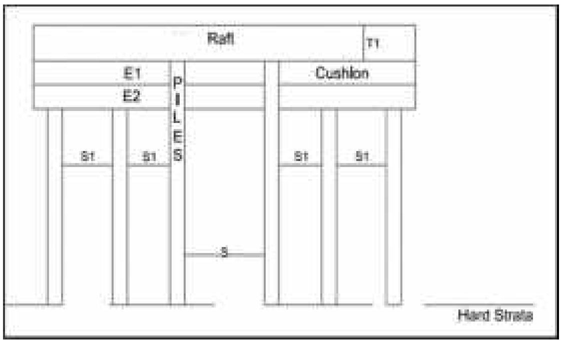


Fig. 1. Hypothetical combination

An extensive array of related computer software is currently available, thereby offering several alternative routes in solving a given problem. But engineers need carefully to check the basic assumptions implicit in such numerical analysis as well as the interpretation and coverage characteristics of computed results. Under reliance on unfamiliar packages or codes is best avoided, whilst uncritical acceptance of computer output can be a recipe of disaster. Numerical methods clearly have a central role in the evolution of subject, but it is their application to real projects which is of primary interest in the present context.

Different forms of modelling are used to present the ground strata and the foundation structure, and different calculation methods are used in the corresponding analyses.

2 Literature review

Different researches have been done in the past regarding the study of seismic loads and the development of designs and concepts to minimize the damage caused by them. This study fundamentally manages the investigation of the unconnected piled raft under dynamic loading conditions. Diverse methodologies were thought about amid the procedure which incorporates both experimental and numerical methodology. Exceptional accentuation is additionally laid on Plaxis 3D software as a numerical tool to evaluate the behavior of soil and foundation interaction.

In 2011 Eslami et al. [1]performed 2 & 3-dimensional finite element investigationon three contextual studies including a 12-storey residential building, a 39-storey tower, and the Messeturm tower. The analysis incorporates the investigation of the effect of piles spacing, embedment length, piling configuration and raft thickness to optimize the design. After seen the effect of pile length Sharma et al. [2] used a combination of long and short piles to reduce the construction cost. Further to reduce bending moments and shear forces generated at the top of short piles P. et al. [3] introduced a layer of compacted sand-gravel mix between the piles and the raft named as a cushion. The following figure depicts the combination used in that study.

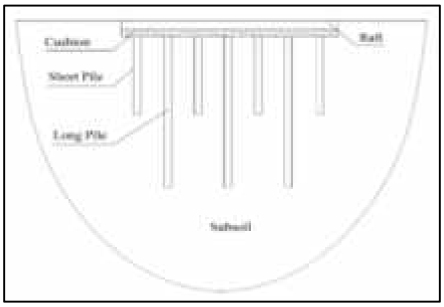


Fig. 2. Cross section of the foundation model used by P. et al. [3]

Saha et al. [4]examined the seismic response of soil-pile raft-structure system considering soil-structure interaction effect. However, soil flexibility could result in vital changes within the response of the soil-pile raft-structure system. The examination considers one storey framework comprising of a mass in the form of a rigid floor slab which is supported by four columns. The piles are demonstrated by beam-column component supported by horizontally conveyed and dampers.

Mattsson et al. [5] and Chen et al. [6] did an experimental study of non-connected piled raft under the action of vertical loading and found out the impact of cushion properties. They proposed a well-designed combination for a nuclear waste storage facility is being built near Lyon, France.

Despite the experimental study, a numerical study is more significant as mobilized damping properties of soil layers can't be depicted in laboratory tests. A 3D study in ABAQUS for different properties of piles and cushion was analyzed by Alaa et al. [7] in the case of vertical loads. A significant result was found for high values of young's modulus of elasticity. Further for seismic loads, Saadatinezhad et al. [8]conducted the same study for a seismic data of El- Centro and also compared the test results with experimental tests done by Giretti et al. [9]

3 Numerical study

It fundamentally includes the accumulation of primary experimental data to build up a relation between experimental and numerical results. The main purpose of this numerical study is to investigate the performance of the unconnected piled raft of various geometries and dimensions. The parameters studied in this paper are cushion thickness, pile diameter and pile length. As dimensions of structural components (pile and cushion) are mainly responsible for stiffness and overall stability of structure.

3.1 Research methodology

A three-dimensional finite element method software Plaxis 3D is used in this analysis. Bore hole data is taken from reference paper, where massive industrial and residential development has been recently planned and constructed. The following figure depicts the cross section of the foundation used in this study.

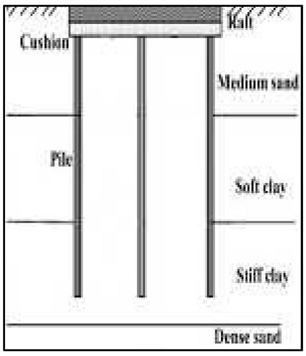


Fig. 3. Cross section of foundation adopted

In this analysis, raft and piles are modeled as elastic materials. The nonlinear behavior of soil is modeled with the elastic ideally plastic constituent model. The soft clay layer is modeled as an elastoplastic material with a non-associated flow rule and using the modified cam clay plasticity model. The other soil layers are modeled by elastic ideal plastic constitutive model following the Mohr–Coulomb yield criterion. Soil mass is described by an eight-node brick, tri-linear displacement, and tri-linear pore pressure element. Raft, pile, and cushion are modeled as elastic materials by an eight-node linear brick element with reduced integration and hourglass control.

3.2 Properties of material

Table 1. Properties of soil layers

Properties	Medium sand	Soft clay	Stiff clay	Dense sand
MODEL	Mohr- coulomb	Modified cam-clay plasticity	Mohr- coulomb	Mohr- coulomb
λ-factor	-	0.170	-	-
k-factor	-	0.029	-	-
Voids ratio	0.60	1	0.65	0.50
Poisson ratio	0.32	0.48	0.35	0.25
γ (kN/m^3)	18	17	18	18
E (kN/m^2)	45,000	1,300	20,000	70,000
K (m/s)	0.0001	1×10^{-8}	1×10^{-7}	0.0001
K_0	-	1	1	-
Cu (kPa)	-	14	125	-
Φ°	32	-	3	35
Elevation (m)	0-3	3-8	8-12	12-20

Table 2. Properties of structural elements

Properties	**Raft**	**Cushion**	**Pile**
MODEL	Elastic	Elastic	Elastic
Poisson ratio	0.25	0.2	0.2
γ (kN/m^3)	24	19	25
E (kN/m^2)	3.38E+07	4.02E+04	2.05E+07

Table 3. Raft dimensions and pile geometry

Raft Dimensions		
Length (m)	**Breadth (m)**	**Thickness (m)**
10	10	0.6
Pile Group Geometry		
Number	9	
Pattern	Square matrix of 3 x 3	

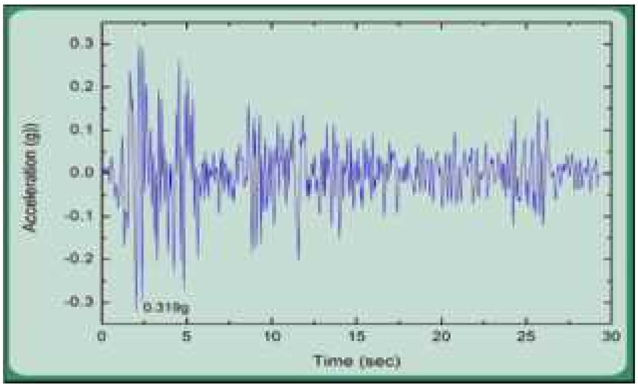


Fig. 4. Time acceleration of El-Centro earthquake

For this study acceleration data of El-Centro earthquake is used as this was more relevant to the experimental tests taken from literature. Also, the magnitude was in permissible limits of model.

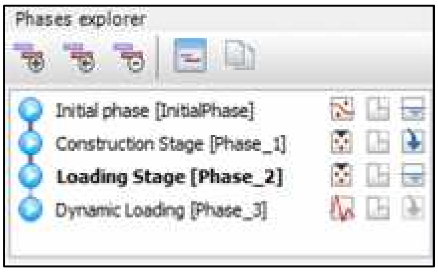
The response of the structure under seismic excitations is affected by interactions between three structural parts; the super structure, the foundation, and the soil underlying and surrounding the foundation. Seismic design of pile foundations is often based on pseudo static approaches which only consider the pile head inertial forces generated from the oscillations of the super structure.

3.3 Analysis in PLAXIS 3D

Finite element calculations can be divided into several sequential calculation phases. Each calculation phase corresponds to a particular loading or construction stage. Each calculation phase is generally divided into a number of calculation steps. This is necessary because the non-linear behavior of the soil requires loadings to be applied in small proportions.

In this study following phases are defined:

- **Initial phase** – gravity was applied to the whole model to generate in-situ stresses.
- **Construction phase** – piles and cushion were placed to be simulated as whished-in-place without causing initial stresses
- **Loading phase** – the vertical static load from the super structure was applied directly on the top surface of the raft.
- **Dynamic loading phase** – the dynamic load was applied at the bottom of the model.



Phases explorer

Initial phase [InitialPhase]

Construction Stage [Phase_1]

Loading Stage [Phase_2]

Dynamic Loading [Phase_3]

Fig. 5. Staged Construction phases

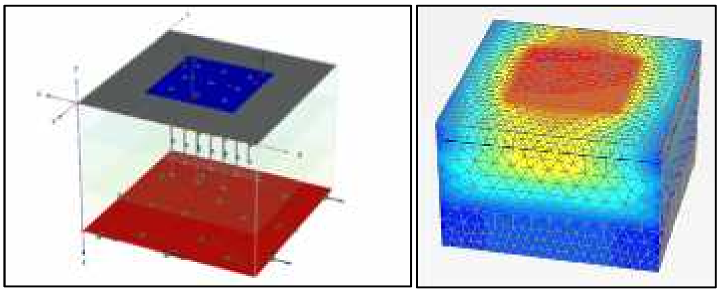


Fig. 6. a) A Model showing structural elements, b) 3D view of the model showing displacement variation

3.4 Validation

For validation of this proposed model, a 3D FEM analysis was done on the test obtained from 65g centrifuge tests conducted in reference paper [9].

In this model, piles were made from an aluminum alloy pipe. The miniaturized load cells, made from stainless steel, had a 4mm square cross section; two active strain gauges were attached to each of the flat surfaces, one to measure pile longitudinal strain, the other the pile-transversal strains.

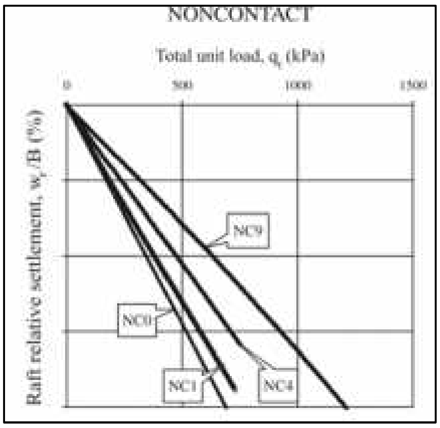


Fig. 7. The result has taken from literature

4 Results and discussions

4.1 Validation of model

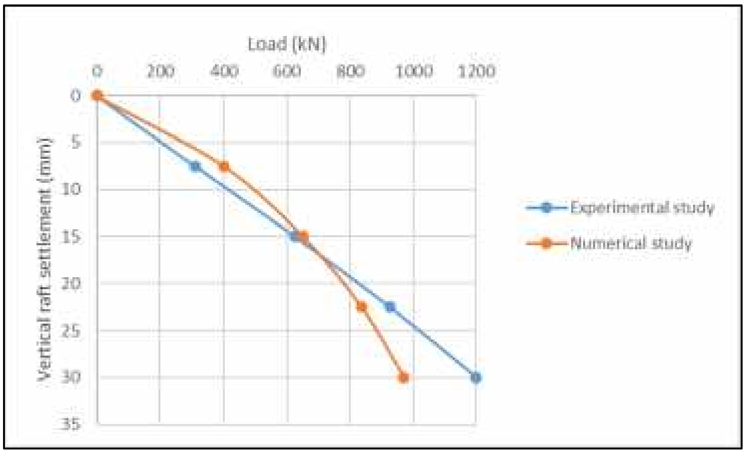


Fig. 8. Comparison of the results from 3D FE and numerical analysis

Table 4. Correlation data analysis

	Experimental data	Numerical analysis
Experimental data	1	
Numerical analysis	0.978989901	1

We usually use correlation coefficient (a value between -1 and 1) to display how strongly two variables are related to each other. Data analysis add ins were used to found coefficients.

For validation of this proposed model, a 3D FEM analysis was done on the test obtained from 65g centrifuge tests conducted in reference paper [9].

4.2 Comparison of connected and non-connected piled raft

The vertical settlement is more in UCPR due to the generation of negative skin friction. Bending moment is reduced to zero due to a disconnection between piles and raft. Shear stress is reduced due to the distribution area of load increases.

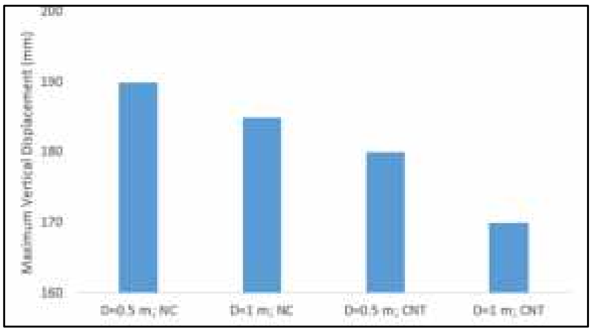


Fig. 9. Comparison of connected and non-connected piled raft

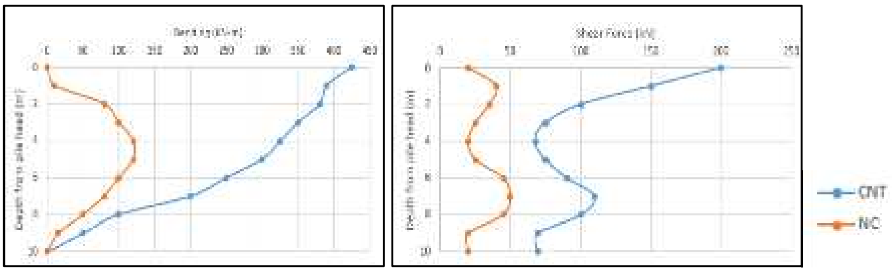


Fig. 10. Comparison of bending moment and shear force for connected and non-connected corner pile

4.3 Parametric study

Increase in pile dimensions increases the stiffness, so settlement, shear force and bending moment decrease.

4.3.1 Impact of pile length

As long piles go more deeper, the vertical settlement reduces and bearing capacity of raft increases.

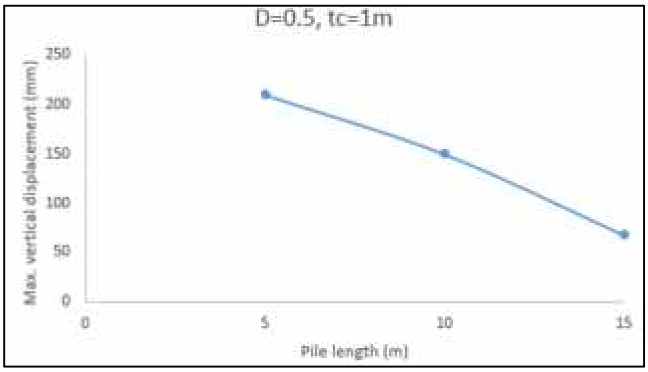


Fig. 11. Variation of maximum vertical displacement with a pile length

4.3.2 Impact of Cushion thickness and pile diameter

Stiffness of pile increases with increase in area of base leads to decrease in settlement. Further, cushion thickness increases the damping of material and increases the load capacity.

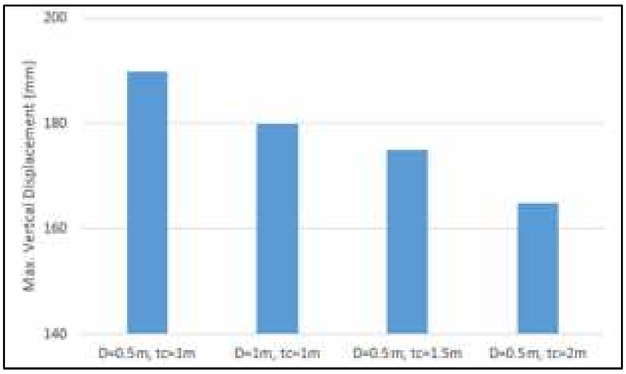


Fig. 12. Vertical settlement for different diameter of piles and thickness of the cushion

5 Conclusions

This study represents the results of a series of 3D FEM analysis on connected and non-connected piled rafts subjected to seismic loading. Many positive outcomes have been seen from this study; the following conclusions can be used to optimize the design of a foundation system according to field conditions.

1. Correlation factor between centrifuge test and numerical analysis is 0.97898, which shows a strong relationship between them.
2. When compared to the connected piled rafts, unconnected piles show higher displacements. Vertical displacement in the unconnected piled raft is 10-15% more than the connected case. The influence of higher horizontal and vertical displacements can be minimized by using appropriate cushion material.
3. Non connected piled raft shows considerably small shear force and bending moment. Bending moment reduces to zero for the non-connected case.
4. Pile length and pile diameter significantly influence the seismic response. For pile length, there is a reduction of 30% for every increase in 5m and 5% reduction in settlement for change in pile diameter with 0.5m.
5. 30 % reduction in stress is noted for every 0.5m increase in cushion thickness.

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