Pile Geometry on Soil-Structure Interaction-An Analytical Survey

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ABSTRACT
In this paper, the concept of pile geometry on Soil-Structure Interaction is introduced, and the research methods on effect of pile shape are discussed. A systematic summary of the Soil-Structure Interaction research that takes into account adjacent structures is proposed. This study about the pile geometry on Soil-Structure Interaction reviews the growth of SSI and advantages, disadvantages, and uses of various methods are discussed.

Key-word: Soil-Structure Interaction; pile geometry; finite element analysis.

I. INTRODUCTION

The process in which the response of soil influences the motion of the structure and the motion of the structure influences the response of the soil is termed as "soil – structure interaction (SSI). Neglecting SSI is reasonable for light structures in relatively stiff soil such as low rise buildings and simple rigid retaining walls. The effect of SSI becomes prominent for heavy structures resting on relatively soft soils for example nuclear power plants, high-rise buildings and elevated highways on soft soil.

Damages caused by recent earthquakes have pointed out that the seismic behaviour of a structure is highly influenced not only by the response of the super structure but also by the response of the foundation and ground as well. Hence modern seismic design codes such as Standard specifications for Concrete structures: seismic performance verification JSCE 2005 mention that the response structural system including super structure, foundation and ground.

Soil-structure interaction one of the most major subject of earthquake engineering has been paid attention in recent decades. It concerns the wave propagation in a coupled system, buildings erected on soil surface. The development in this field has been expedited by the needs of nuclear power and offshore industries. It has been helped by powerful computers and simulation tools such as finite element and by the needs for improvement in seismic safety.

II. SSI & ITS DETRIMENTAL EFFECTS

(a) Effect Of Soil -Structure Interaction On Structural Response

It has been conventionally been considered that soil structure interaction has beneficial effect on the seismic response of a structure. Many design codes have indicated that the effect of SSI can be neglected for seismic analysis of structures. This myth about SSI stems from the false perception that SSI reduces the overall seismic response of a structure and hence leads to improved safety margins. Most of the design codes use oversimplified design spectrums which attain constant acceleration to a certain period and thereafter decreases monotonically with period. Considering SSI makes a structure more flexible and thus increasing the natural period of the structure compared to the corresponding rigidly supported structure. Moreover considering the SSI effect increases the effective damping ratio of the system. The smooth idealization of design spectrum suggests smaller seismic response with the increased natural periods and effective damping ratio due to SSI.

(b) Detrimental Effects of SSI.

Using rigorous numerical analysis Mylonakis and Gazetas have shown that increase in natural period of structure due to SSI is not always beneficial as suggested by the simplified design spectrum. Soft soil sediments can elongate the period of seismic waves and the increase in natural period of structure may lead to the resonance with the long period ground vibration. The study also indicated that ductility demand can significantly increase with the increase in the natural period of the structure due to SSI effect. The permanent deformation and failure of soil may further aggravate the seismic response of the structure.

When a structure is subjected to an earthquake excitation, it interacts with the foundation and the soil and thus changes the motion of the ground. Soil-structure interaction broadly can be divided into two phenomena a kinematic interaction and b inertial interaction.

Earthquake ground motion causes soil displacement known as free-field motion. However the foundation embedded in to the soil will not follow the free field motion. This inability of the foundation to match the free field motion causes the kinematic interaction. On the other hand, the mass of the super structure transmits the inertial force to the soil causing further deformation in the soil which is termed as inertial interaction.

Owing to rapid development of metro cities all over the world, the building structures are built close to each over the soft soil deposit.. Dynamic interaction among building structures will occur through the radiation energy emitted from a vibrating structure to other structures. Hence dynamical characteristics as well as the earthquake response characteristics of a structures are unable to be independent of those of the adjacent structures.

SSI investigations have indicated that dynamic response of a structure supported on flexible soil may differ significantly from the response of the same structure when supported on a rigid base. The reason for this difference is that part of the vibrational energy of the flexibly mounted structure is dissipated by radiation of stress waves in the supporting medium and by hysteretic action in the medium itself.

Analytical methods to calculate the dynamic soil structure interaction effects are well established. When there is more than one structure in the medium, because of interferences of the structural responses through the soil, the soil structure problem evolves to a cross – interaction problems between multiple structures.

III. DEVELOPMENT OF SSI – A CHRONOLOGICAL REVIEW

The theory proposed by **Reissaner (1936)** about vibrational foundation marked the beginning of the SSI study whereas the study of Warburton el al between 1969 and 1972 initiated the start of SSSI study. Taking advantage of the soil structure model proposed by Parmelee the authors derived some equations for the response of two geometrically identical cylindrical bodies attached to the surface of an elastic half space. The result shows that when one of the bodies is excited by an external harmonic force, the presence of the second mass modified the vertical components of displacements of the excited mass by relatively small perturbations. The perturbations occur at resonant frequencies of the second mass and introduce relatively small rocking and horizontal translational displacements of the first mass. This is the first publication that expounded the significance of SSSI.

Whiteman (1969) first introduced the through-the soil coupling of foundations as an important problem that requires further study. The 1970s was the initial phase of SSSI study. The soil structure system model can be a multi mass or multi spring mass system in several system or several geometries on an elastic visco-elastic stratum over rigid bed rock. Structures-soil-structure interaction (SSSI) put forward in recent decades means the dynamic interaction problem among the multi structure system through soil ground. **Luco and Contese (1973)** came up with structure-soil-structure interaction designation for this area of study. SSSI also calls for foundation-soil-foundation interaction FSFI.

Soon after **MacCalden and mathhisen (1973)** extended the work of **Bycoft (1956)** which determined an analytical model for the motion of a single rigid circular foundation on an elastic half–space and developed a matrix formulation for the solution of the induced dynamic displacements of a foundation near a harmonically loaded foundation attached to an elastic half space.

An earthquake is a widely known stochastic process. In nature two completely identical earthquakes do not exist. Thus more and more scientists resort to the random method to study seismic motion. **Kobori el al (1973)** studies the cases of identical two and seen-mass system and those of identical and different two spring mass system which are along a line on the surface of Voigt type visco-elastic stratum over rigid bed rock.

Luco and Contese (1973) in 1973 followed by **Wong and Trifunac (1975)** and **Murakarmi and Luco (1977)** addressed the two dimensional anti-plane problem of the interaction between two or more infinite shear walls placed on rigid circular foundation and subjected to vertically adjacent harmonic SH waves. They actually solved a 2D wave diffraction problem and through parametric studies showed that groups of closely spaced buildings could result in interaction effects near the fundamental frequencies of the buildings and at very low frequencies.

Seed (1975) deemed it was not suitable for the analysis of dynamic interaction of structure with a deep foundation for the exclusion of material damping and radiation damping. Due to the difficulty of the solution for the analysis method and the excessive simplification of the model for soil and structure, it was far from the real solution for problem of SSSI. When super structure foundation, and topographic and geological conditions become complicated producing a mathematical solution can be difficult.

Kobori and Kusakabe (1980) investigated a cross interaction systems between two structures. Soil is a multi phase system with high variability and strong randomness of material properties and space distribution. The random heterogeneities in the soil medium seem to have a tremendous effect on the dynamic soil-structure interaction. This explains why deterministic parameters for the properties of soil is not reasonable. In this field **Hryniewica (1993)** considered the randomness in the soil medium for the first time. The authors investigated two 2D strip foundation based on a semi infinite medium.

The lumped parameter method is a common method used for the analysis of SSI and SSSI where soil is simulated by spring mass and damper or an equivalent impedance function.

Ervin Hegedus and Khosla Vijay K (1984) determined experimentally the pull out capacities of H piles under axial tension loads in stiff clay, dense sands, silts and stratified soils. The test results were interpreted by 3 different procedures. Measured pull out capacities were compared to predicted pull out capacities based on semi-empirical approaches. Predicted capacities vary greatly with subsurface condition at site, effective failure surfaces of piles, pile lengths and soil shear strength parameters. Earth pressure parameters and adhesion values obtained from the tension load tests are generally found to be consistent with the previously published data.

Muliken and Karabalis (1994,1998) presented efficient discrete models with frequency-independent masses, springs and dampers. Each model has modes of vibration considered independent degree of freedom (DOF) for predicting the dynamic interaction .

Wave passage effect known as special variability of ground motion including deterministic and stochastic components, deterministic component is actually the solution of the wave equation in a medium consisting of homogenous layers.

Yenumula V. S. N. Prasad and S. Narasimha Rao(1996), examined the behavior of helical piles under lateral loads in clayey soils through an experimental investigation on model piles. Tests were conducted on rigid helical piles with different numbers of plates. Model anchors were made of 13.8 mm diameter mild steel shafts to which mild steel plates of 33 mm diameter were welded. For comparison, a single straight shaft with a diameter of 13.8 mm was also tested. Test results revealed that the lateral capacity of helical piles is greater than that of straight shaft piles. A simple theoretical model is suggested to estimate the lateral capacity of rigid helical piles. The theoretical model suggested incorporates lateral resistance of the soil on the shaft, bearing resistance on the bottom of the helical plate, uplift resistance on the top of the helical plate, and frictional resistance on the surface of the helical plate. The validity of this model is examined.

As per study done by Jiang and Yan (1998) those two buildings with distance less than 2.5 times of width of foundation are interacting with each other and when the distance was less than one time of width of foundation the response of the structure may increase or decrease tens of percent. Thus the interaction between neighbouring buildings have to be investigated.

Considering primarily the spatial variability of ground motion **Behnamfar and Sugimura (1999)** investigated an idealized 2D system made up of two structural systems each consisting of a rigid roof at the top held by mass-less and elastic columns. The column are connected to the rigid foundation which are bonded to the surface of a medium consisting of a homogenous visco-elastic layers resting over a half-space and considering PSV and Rayleigh waves through deterministic and random approaches.

All those discussions have laid a solid theoretical and practical foundation for the subsequent research on SSSI. However most of the those studies are based on the elastic half space theory which make analyzing the structure with a shallow foundation attached to a homogenous and thick soil layer simple and practicable for engineers.

Scott A Ashford and Teerawut Juirnarongrit(2003) presented the results of a study on the effect of pile diameter on the initial modulus of sub grade reaction. A series of ambient and impact vibrations tests were performed on four different diameters of cast-in-drilled-hole piles to determine the natural frequencies and damping of the soil-pile systems. The measured natural frequencies were then compared with those estimated from a numerical model. The soil springs in the numerical model were established by implementing two different concepts on initial modulus of sub-grade reaction. One is based on Terzaghi's concept in which the modulus of sub-grade reaction may be linearly proportional to pile diameter. It was found that the measured natural frequencies were in good agreement with the computed ones when the diameter-independent modulus of sub-grade reaction was employed. In additional, the test results show that the damping ratio of the system varied with pile diameter from 3% to 0.4 m pile to 25% for 1.2 m pile. Refer figure 1,2,3,4,5,6 in this regard.

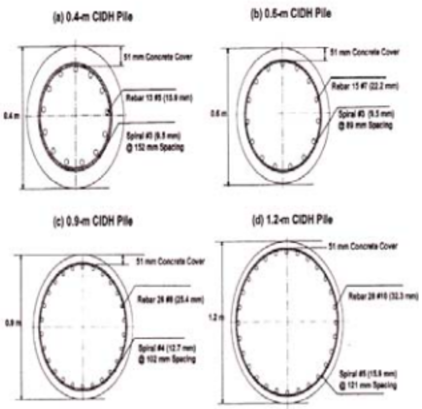

Fig. 1 Pile cross sections

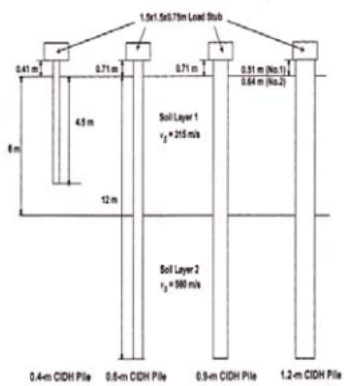

Fig. 2 Pile geometry

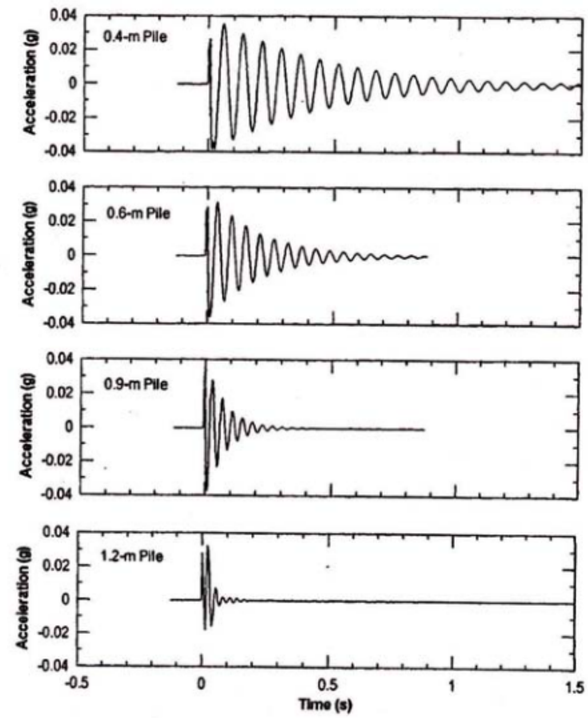

Fig. 3 Acceleration versus time for each CIDH pile in E-W direction from impact vibration tests

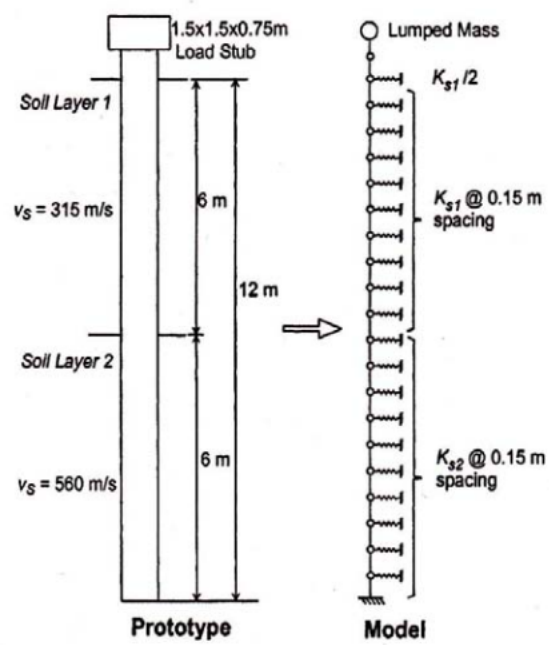

Fig. 4 Numerical soil-pile system model

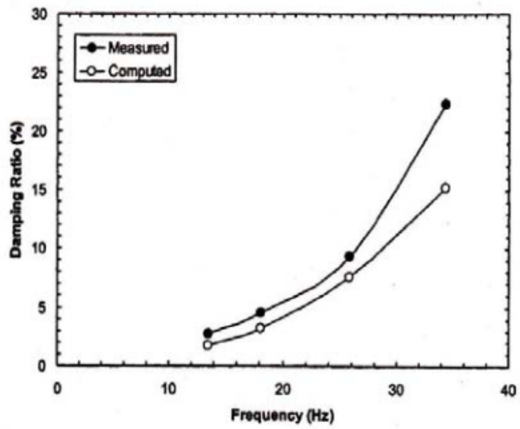

Fig. 5 Damping ratio versus frequency

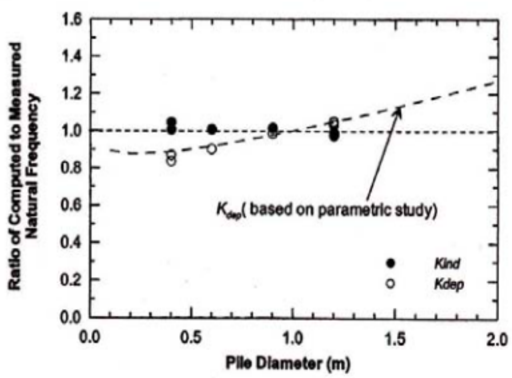

Fig. 6 Ratio of computed to measured natural frequency versus pile diameter

Harry G . Poulos (2006) examines some of the characteristics of behaviour of pile groups containing raked piles via a simplified and hypothetical example. Three cases are examined(1) a group subjected to vertical and lateral loadings with no ground movement(2) a group subjected to vertical and lateral loadings but with vertical ground movement acting on the group.(3) a group subjected to vertical and horizontal loadings but with horizontal ground movements acting on the group. In each case, the effect of pile rake on typical behavioural characteristics are examined. It is found that while the presence of raked piles can provide some advantages when the group is subjected to applied vertical and lateral loadings especially in relation to a reduction in lateral deflection, some aspects of group behaviour may be adversely affected when either vertical or horizontal ground movements act on the group. Thus caution may be exercised in employing raked pile when such ground movements are expected to occur.

D. Basu, M. Prezzi, R. Salgado, T Chakraborty(2007) presented a method of settlement analysis for axially loaded piles with rectangular cross section embedded in a multi-layered soil medium. The differential equation governing the displacements of the pile-soil system are obtained using variational principles. Closed –form solutions for pile deflection and axial force along the pile shaft are then produced by using the method of initial parameters. Suggest that rectangular piles deflect less than circular piles with the same cross-sectional area. See figure 07 and 08 in this regard.

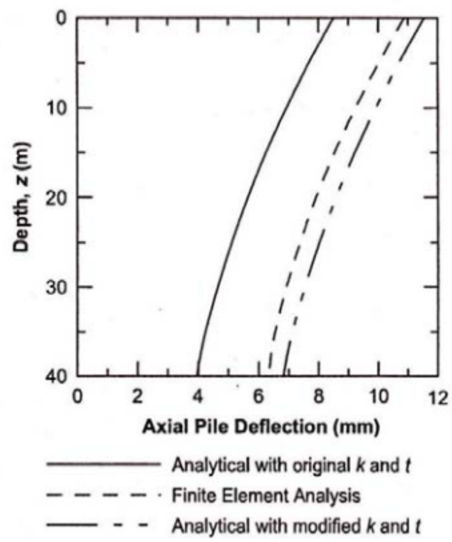

Fig. 7 A comparison between deflections obtained using the analytical method and 3D FEA for a 40-m long barrette.

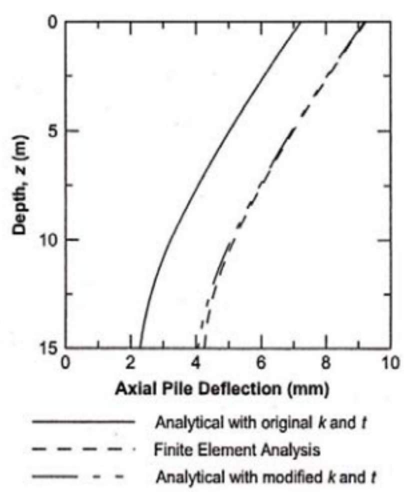

Fig. 8 A comparison between deflections obtained using the analytical method and 3D FEA for a 15-m long square pile.

Denton A Kart P. E. (2007) used sonar callipering technology to reveal the shape of the bored pile excavation in wet conditions. Case studies and numerical analyses using the software program FLAC illustrate the role of the sonar calliper in evaluating capacity of pies with anomalous shapes.

Jasin M. Abbas, Shafiqu, Mohd. R. Taha (2008) subjected piles to lateral loading, the failure mechanism of short pile under lateral loads are different from that of long pile. They presented 3D finite element analysis for the problem of a single pile under lateral loadings. The effect of pile shape for both circular and square cross-section on pile response was investigated. Also the influence of slenderness ratio L/B on the pile deformation was discussed. It was found that pile response is affected by the amount of loading, the pile cross-sectional shape and pile slenderness ratio. The lateral resisting of pile increase in proportional to the square shape of the pile. In both pile shape a short pile (L/B)=8.3 gave a small amount of lateral tip deflection than the long pile with a slenderness ratio more than 8.3 for the same amount of loading. Also the negative base deflection is high for short pile and reduces to zero for long pile.

Kenneth Bell (2009) has published the use of H piles selected for New Power Plant based on Pre-award testing program and cost comparison. Here during the installation all piles were reviewed tested using dynamic testing which was then followed by static load testing. The results of the testing were then compared to August Cast piles that would be drilled to the top of rock. Based on evaluation of various H sections and ACP the project selected to go with driven H piles. Design proceeded with two pile loading capacities 1070 KN using an HP 10 x 42 and 1780 KN capacity pile using an HP 12 x 74. The project is now completed.

Wang X, Li H.L. and Chen YH (2009) studied Y shape cross section configuration on flexural behaviour of piles. Here they considered flexural factor of section and area ratio according to actual load on Y shaped vibro-pile under three conditions i.e. sharp angled location of cross section, concave arc position and typical tension point. Flexural behaviour under above three conditions is quite different and it changes with variation law of four independent variables of the cross section. The same template radian exists while the other three independent variables are defined so that flexural behaviour under conditions sharp-angled position and typical tension point reaches the minimum value. Solution of corresponding template radian of the minimum value of flexural behaviour has been introduced by utilizing the mathematical analysis software Mathematica.

H. Seo, D. Basu, M. Prezzi, and R Salgado (2009) studied the load-settlement response of rectangular and circular piles in multi-layered soil. The authors presented a settlement analysis that applies to piles with either rectangular or circular cross section installed in multilayered soil deposits. A user-friendly spreadsheet program(ALPAXL) was developed to facilitate the use of analysis. Refer figure 9,,10,11 and 12 .

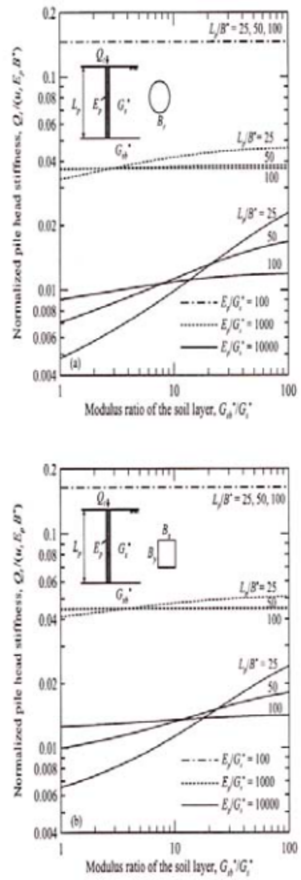

Fig. 9 Normalized pile head stiffness versus modulus ratio of base soil to shaft soil G^*_{sb}/G^*_s for: (a) circular pile; (b) square pile

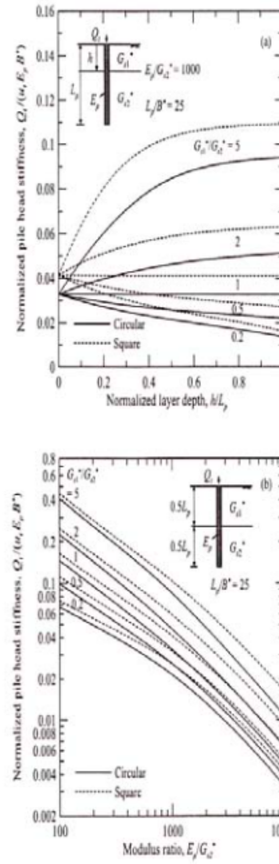

Fig. 10 Normalized pile head stiffness in two-layer soil versus: (a) h/L_p; (b) E_p/G^*_{s2} with $h=0.5L_p$

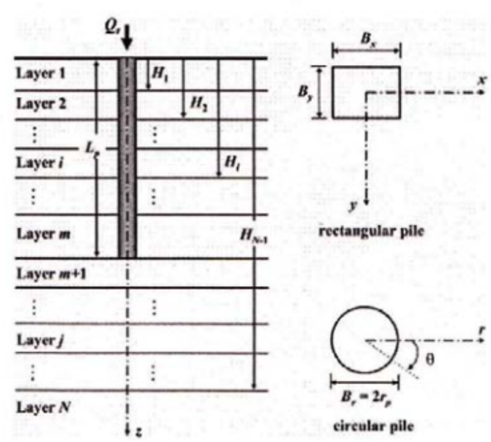

Fig. 11 Axially loaded pile with rectangular or circular cross section in multilayered soil

Christoph Knellwort, Herve Peton and Lyesse Laloui (2011) discusses several issues pertaining to heat exchanger piles. This paper presents a geotechnical numerical analysis method based on the load-transfer approach that assesses the main effects of temperature change on pile behaviour.

Mohmoud Ghazavi, Omid Tavasoli (2012) presented numerical analysis of pile driving for tapered piles. A three-dimensional finite difference analysis for tapered angle and geometry effects has been used on pile driving response of tapered piles. Generally speaking tapered and partially tapered piles offer better drivability performance than cylindrical piles of the same volume and length. A soil-pile system has been simulated for pile driving phenomenon using a three-dimensional model for non-uniform cross section piles using FLAC3D.

Y. Xiao, L Chen(2012) discussed steel H shaped piles which are widely used in bridge foundation. The paper reports experimental results from monotonically loaded static tests on

on model steel H pile to pile-cap connections, in which the piles were subjected to tensile loading or horizontal loading with the bending in the strong or weak bending directions of the H pile. The tests indicate that H pile footing connections were effective in transferring vertical and lateral loads. The study also show that FEM analyses can capture the load and deformation relationship and load carrying capacity of the steel H pile to pile-cap connections satisfactorily.

Yaru Lv, Hanlong Liu, Xuanming Ding and Ganpolang Kong F(2012) investigated the behaviour of X-section cast-in-situ concrete piles. A series of static load tests for piles foundations are conducted on the basis of a soft soil reinforcement engineering for a sewage treatment plant in the north of Nanjing. China. Comparative analysis between an XCC pile and a circular section concrete pile with the same cross sectional area indicates that XCC pile shows increasing pile-soil stress ratio and reduce settlement. It has been found that pile spacing is an important factor in XCC piles and the XCC pile should be considered as special friction file owing to high skin friction sharing. Above all, XCC can significantly increase ground-bearing capacity.

IV. NUMERICAL METHODS FOR EFFICIENT COMPUTATION

(a) **Finite Element Method-**FEM is an efficient common computing method widely used in civil engineering, discretizes a continuum into a series of elements with limited sizes to compute for the mechanics of continuum. FEM can simulate the mechanics of soil and structure better than other methods, deal with complicated geometry and applied loaded and determine non-linear phenomena. FEM is used frequently in the study of SSI and has produced some notable achievements in the field of SSSI.
The development level of hardware and software has restricted the application of FEM in SSSI.

(b) **Boundary Element Method**
A new numerical method developed after FEM only discretizes the boundary of the definition domain. It is different from the discretization of total continuum and uses functions satisfying the governing equation to approximate boundary conditions. The BEM is more advantageous compared to FEM because it requires only a surface discretization and satisfies automatically the radiation condition without any need for using special complicated non-reflecting boundaries as required by FEM by **Wang S (1992).**

One disadvantage of BEM is its difficulty of application in the case of a heterogeneous medium.
(c) **Finite Element Method Boundary Element Method**
Owing to respective disadvantages of FEM and BEM the coupling method of FEM and BEM was developed in the field of SSSI in 1990s. this method shows the advantages of both FEM and BEM. FEM is used for simulation of super-structures, foundations and near field soils whereas BEM is used for far field soil.
(d) **General Finite Element Program**
At present there are a large number of available commercial finite element programs which have friendly interface and powerful nonlinear solver. They process well and are easy to master for users with great generality and therefore are very popular among SSI studies. When we are applying them to study SSSI, the biggest problem lies in how to solve huge calculations among brought by the large range of soil. Some common programs are ANSYS, ABAQUES, MSCMARC.

V. CONCLUSION

In this paper concept of pile geometry on Soil-Structure Interaction is presented which is significant. This leads to significant conceptual changes, especially concerning dynamic studies, structural analysis and land-use planning. The development of pile geometry on Soil-Structure Interaction is based upon the research results of SSI and the progress of the analysis of soil and structure.

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