Ministry of Higher Education
and Scientific Research
University of Diyala
College of Engineering

# SIMULATION AND ANALYSIS OF SOIL-STRUCTURE INTERACTION FOR TURBINE FOUNDATION UNDER DYNAMIC LOAD

**A Thesis Submitted to Council of College of Engineering, University of Diyala in Partial Fulfillment of the Requirements for the Degree of Master of Science in Civil Engineering**

*By*

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بسم الله الرحمن الرحيم

**قَالُواْ سُبْحَانَكَ لاَ عِلْمَ لَنَا إِلاَّ مَا عَلَّمْتَنَا إِنَّكَ أَنتَ الْعَلِيمُ الْحَكِيمُ**

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*To:*

*My parents, without them none of this would be possible.*

*I am truly blessed.*

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*Saba Ismael Jawad*
*December 2017*

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## ABSTRACT

In fact, the turbine-generator foundations are considered as one of the most critical structures because they have very strict limits of vibration requirements specifically at the bearing locations. Finite element simulation and the dynamic analysis of the soil-structure interaction (SSI) phenomena for turbine-generator foundation have been considered in this study. Al-Mansuriya (728MW) Power Plant Station located in Diyala province/ Iraq has been taken as case study for this purpose. The foundation and the soil have been modeled by using Abaqus v.6.13 package.

This model has been used to carry out all the analysis steps with the consideration of all variables (i.e static,harmonic and seismic loading steps). Mohr-Coulomb elasto-plastic model has been implemented for soil in additional to linear-elastic model for concrete body. The type of applied loads and the influence of the interaction between the soil and the foundation systems are considered as important aspects which have been studied to check their effects on such sensitive and massive foundations.

This study tries to explore SSI on the performance (maximum displacements and stresses) of the foundation and the surrounding soil medium under various loading conditions.

In static analysis, it is noted that the results obtained when using the elasto-platic model for soil gives larger values of response other than when using the elastic soil model because the soil has been allowed to move in elasto-plastic

range. In addition, the results show that SSI effect produced significant increment for the displacements reach to 25.3%.

In free vibration analysis, it can be showed that the fundamental mode is the vertical bending mode, while the effect of the torsional appeared for the second and third mode, Therefore, in this case it is important to take this modes of deformation into account when design such foundations.

The soil-foundation system was analyzed under the operational case (i.e. the harmonic force excitation). The influence of the approaches between the `frequency of the foundation and the frequency of the machine has been observed. When the two frequencies coming near, the response also get increase. Additionally, when comparing the results obtained from analyzing the system with and without taking SSI effect under such loads, it showed that there is significant increase of the response when accounting SSI effect by 28.2%.

The system performance under the effect of seismic excitation has also been analyzed. Two different ground motions (i.e. El-Centro and Ali Al Gharbi earthquakes) have been applied in two different directions. The analysis was performed once with SSI consideration and another without taking the SSI effect.

The results showed that SSI effect should be taken into account, especially in the region with strong ground motions activities. For the strong ground motion, the displacement increased by 37% and the stress increased by 25%.

Finally, the soil-structure system analyzed under the effect of earthquake during the operational conditions (i.e. coupled loading: harmonic and earthquake). Pronounce increase in the maximum displacements and the stresses for the soil-foundation system for the strong ground motion reaching (38.8%) and (31%) respectively when taking soil structure interaction effect.

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# *NOTATIONS*

| | |
|---|---|
| $f(t)$ | External Dynamic Forces as A Functions of the Time |
| $p_i$ | Unbalance Force |
| $f$ | Operating Frequency |
| $t$ | Time |
| $m_i$ | Proportional Part of The Rotating Masses |
| $e$ | Eccentricity |
| $\omega$ | Circular Operating Frequency |
| $\omega_n$ | Natural Frequency |
| $\zeta$ | Damping Ratio |
| $E$ | Young's Modulus |
| $G$ | Shear Modulus |
| $v$ | Poisson's Ratio |
| $\varepsilon$ | Strain |
| $\sigma$ | Normal Stress |
| $\tau$ | Shear Stress |
| $\emptyset$ | Material Angle of Friction |
| $c$ | Cohesion of the Material |
| $s$ | Half of the Difference Between the Maximum and Minimum Principal Stresses |
| $r_o$ | Radius of the Circular Rigid Loading |
| $\rho$ | Mass Density |
| $u$ | Relative Displacement of the System |
| $m$ | Mass of Machine and Foundation |
| $g$ | Gravitational Acceleration |
| $f_{\grave{c}}$ | Compressive Strength of the Concrete At A 28 Days |

| | |
|---|---|
| $\tau$ | Shear Stress |
| $\mu$ | Friction Coefficient |
| $m_i$ | Proportional Part of the Rotating Masses |
| $k_v$ | Vertical Spring (Stiffness) Constant |
| $k_h$ | Horizontal Spring (Stiffness) Constant |
| $c_v$ | Vertical Dashpot (Damping) Constant |
| $c_h$ | Horizontal Dashpot (Damping) Constant |
| $M$ | Mass Matrix for the Soil and the Entire Structure–Foundation |
| $C$ | Material Damping Matrix of the Soil and the Structure |
| $K$ | Stiffness Matrix of Entire System |
| $Ms$ | Mass Matrix Having Non-Zero Masses for the Structural Degrees of Freedom |
| $\ddot{u}_g$ | Free Field Ground Acceleration |
| $u$ | Vector of Relative Displacement |
| $B^T$ | Strain Displacement Matrix |
| $B$ | Function of The Displacements |
| $\delta X$ | Displacement Increment |

# *ABBREVIATIONS*

| Symbol | Definition |
|---|---|
| *FEM* | Finite Element Method |
| *SSI* | Soil-Structure Interaction |
| *TGF* | Turbine-Generator Foundation |
| *LSST* | Large–Scale Seismic Test |
| *SDOF* | Single Degree of Freedom |
| *ELM* | Equivalent Linear Method |
| *NFM* | Near Field Method |
| *UCSD* | University of California San Diego |
| *UCD* | University of California Davis |
| *SPSI* | Soil-Pile-Structure Interaction |
| *ACI* | American Concrete Institute |
| CG | Center of Gravity |
| PGA | Peak Ground Acceleration |
| F.I.M | Free Input Motion |

# CAPTER ONE
# INTRODUCTION

## 1.1 General

Generally, most of civil engineering structures are in contact with the surrounded soil. Thus, when the structures which have a certain dynamic properties are attached to the underlying soil medium, which in turn has different dynamic properties, the response of the overall system will become dependent on the coupling between the soil and the structural system and the contact part between the soil and structure expected to effected directly in such types of problem.

This interdependent behavior of the soil and structure at which the two systems are influencing the motion of each other is named as soil-structure interaction (SSI) (Tuladhar et. al. 2006). Therefore; this issue needs to be investigated via different methods to assess the influence of SSI specifically on machine foundations.

## 1.2 Overview of Soil Structure Interaction (SSI)

Usually, the effects of soil-structure interaction are present whenever soil and structural responses are coupled, i.e. the motion of node in the soil may differ in case of absence or presence of the structure. Thus the soil behavior will be influenced by the structure deformations and in turn the structural response will be influenced by the soil deformations. This problem has become increasingly important especially in large scale structures which can be considered as an interdisciplinary field that gathering the geotechnical and structural engineering.

During the past few decades, the particular importance of SSI analysis was recognized and received a worthy of attention, therefore, when the structure interact with the surrounding soil; it is not permissible to analyze only the structure, because in many cases like earthquake excitation, the load is applied to the soil, and this means that the soil must be modeled anyway.

Mostly, in communal design practice of the dynamic loading, assuming buildings to be as fixed at their foundations, but in reality, soil medium that supporting allow movement to some extent due to the soil properties and its ability to deform, this may lead to change the stiffness for the whole geotechnical system. This interdependent behavior of the soil and the structure should be taken into consideration when analysis and design of structure especially for heavier and sensitive structures and weak soil conditions (Bhattacharya 2004).

The dynamic effect of SSI depends on the stiffness properties of the soil, the stiffness and mass of structure and the damping properties of both soil and structure (Datta, 2010). The soil structure interaction problem can be dominant by two mechanisms:

i. Kinematic interaction: the inability of the stiff foundations to move with same way with the displacement of the soil which is caused by the earthquake ground motion (i.e. the free field motion).

ii. Inertial interaction: this type is also affecting the vibration of the structures. The inertial forces of the vibration will produce base shear and moments at the level of foundation which in turn produces a relative displacements between the soil and foundation. It is important to know that these interactions will result in change of the structure vibration, the frequency and the damping characteristics.

## 1.3 SSI effects on turbine generator foundation (TGF)

It has been recognized that soil-structure interaction have signification impact especially in case of sensitive and vital structures like tall building, bridges and power plant stations (e.g. turbine generator machineries). These machines are used in power plant stations which are considered as the most expensive, important and vital equipment for the country that is often placed on sensitive foundation structures which they are flexible over running range of the machine and can contribute to its dynamic. Therefore, it is very important to know the sensitive behavior of such foundations to provide the normal operation condition during its life cycle (P. Jayarajan et. al. 2014). The turbine foundation can be classified into two types: block and frame foundation as shown in Figure 1.1.

Generally, the type of foundation can vary based on the type of the machine. These foundations must be able to withstand all types of loads that may impose during the operations like the vibrations and other environmental loads (e.g. earthquakes).

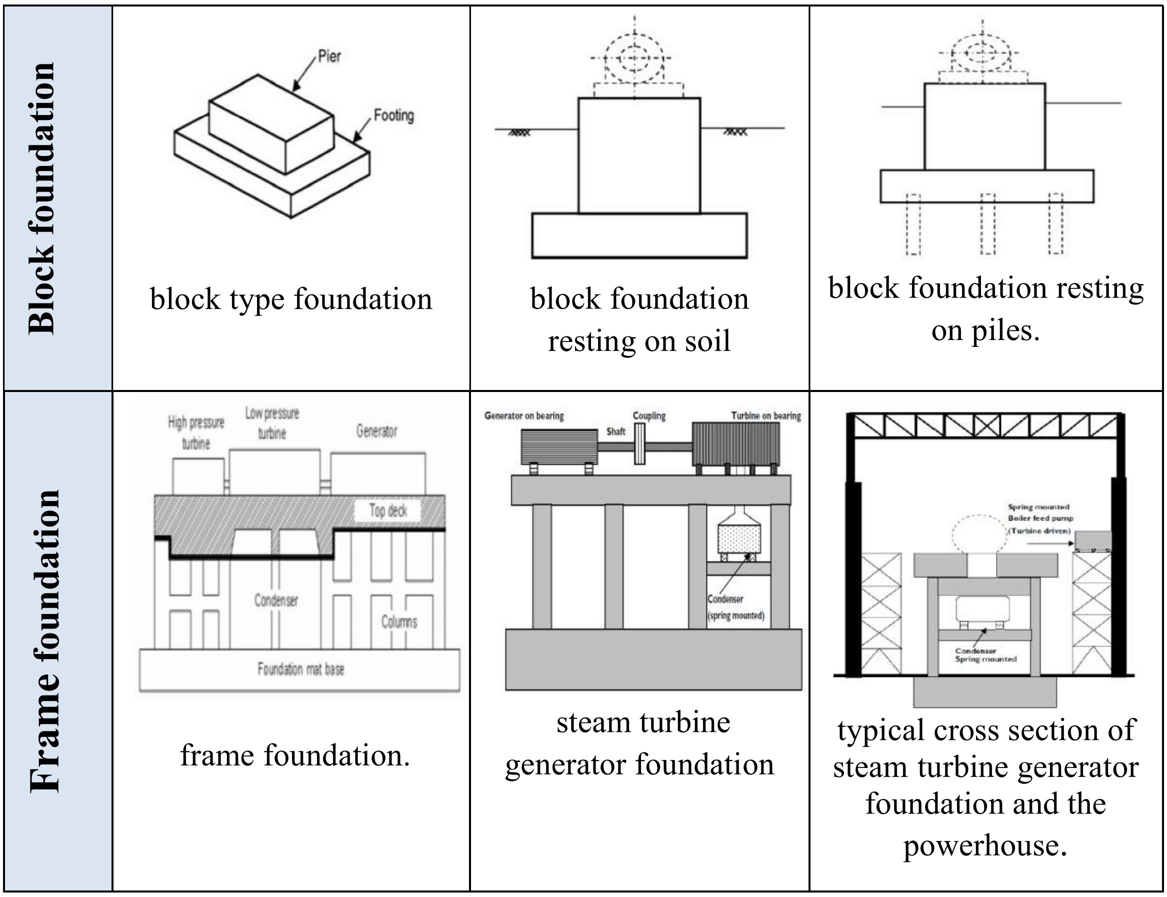


Figure (1.1): Types of Turbine Generator Foundations (after Abou Elsaoud, A. M. (2012)

The type of the turbine-generator foundation used in the in present study is block (raft) type, which is selected to be as a case study for Almansuriya Station located in Iraq/ Diyala province as shown in plate (1.1). The turbine generator foundation station of Al- Mansuriya district /Diyala province is selected, as shown in plate (1.2).

Plate (1.1): Al-Mansuryia power plant station-Diyala/Iraq


Plate (1.2): Turbine-generator foundation of Al-Mansuriya Station-Diyala/Iraq

## 1.4 Importance of the current study

Certainly, for large capacity turbo-generator foundation consideration may be taken for dynamic SSI so as to avoid any risk to the foundation during earthquake / machine induced load. Especially, in Iraq ignoring the soil stiffness in the overall response and treating it as a fixed base problem, the dynamic response of structure may not be the solution to the actual behavior of the foundation system . Therefore, the importance of this study is to provide some guidelines to assess more accurately the sensitivity of these huge structures for different loading condition by including the SSI effect in the analysis, and this may be helpful for seismic design for future.

## 1.5 Problem statement

Absolutely, sensitive structures like the turbine foundations play a very important role for the successful operation of the whole power plant station. This sensitivity usually comes from the complexity of designing and analysis of such foundations and also the strict limitations to work in good manner. Therefore; it is of important to represent this foundation in such accurate way and check all the factors that can affect it's behavior.

The silence effect of the soil structure interaction (SSI) problem for such foundations may be of a great interest to be studied in the analysis and design process in Iraq due to its possibility to affect the performance of such foundations in different conditions.

From the literatures, many researches focus on the analysis of turbine-generator foundation in different conditions. In these studies, ignoring the influence of the SSI made some confusion for whether these turbines will sustain the seismic load in case of normally operation condition or not. In additional to that, in Iraq ,there are a few studies concerned with this problem and especially when considering different loading conditions including the seismic effect after becoming as one of the seismically active regions in additional to other loading cases.

Therefore, the analysis of the turbine generator foundation with consideration of SSI and also the type of loading are not covered sufficiently for such foundations. This issue needs more studies to obtain better insight to the soil and foundation performance expectation.

**1.6 Objectives of the study**

The main objectives of the existing study are as follows:

1. To simulate the whole geotechnical system (soil and foundation) for turbine-generator with all environments.
2. To assess the influence of soil-structure interaction on turbine-generator foundations.
3. To compare the displacement and the stresses developed in the soil and foundation under different loading cases.

**1.7 Organization and outlines**

The present study consists of five chapters including the current one. Chapter one, contains general introduction about the soil-structure interaction phenomena, turbine generator foundation. In addition to the description analysis of the model by finite element method, and the objective of current study. Chapter two, demonstrate the historical background and brief discussion of the machine foundations analysis, the numerical analysis of the effect of SSI and finally, a brief review on the previous researches on the related mentioned topics.

Chapter three discusses methodology and detailed process to develop the numerical formulation, the geometry of soil-structure system and the material properties for the finite element modeling. Also chapter four contains numerical applications on existing turbine-generator foundation in a power plant station located in Iraq. And finally, Chapter five as last chapter, in which the conclusions and recommendations are given for future researches.