Analysis of Gas Turbine Foundation under Harmonic Loading with and Without Consideration of Soil –Structure Interaction Effect

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Abstract

Response of turbine-generator foundations under dynamic loads is considered as very important problem because of such foundations are very sensitive to the transformation of the loads from the machine itself to the foundation and the supporting soil medium. Using the finite element modeling, this paper investigates the dynamic response of turbine-generator foundation of Al-Mansurya power plant station in Iraq under the vertical harmonic excitation; layered-soil with linear elastic model considering and ignoring the soil-structure interaction effect are concerned in this study. The soil structure interaction has been analyzed with direct method (i.e. the soil and structure analyzed together in one step). Free vibration analysis is also performed in order to find the natural frequencies and the corresponding mode shapes in additional to force vibration analysis. The response was assessed at the soil and the foundation during the operational conditions using ABAQUS (v 6.13) program and results of the analysis showed that the natural frequency of the turbine foundation should be far different from machine operating frequency to avoid resonance, also the response of the system with and without the taking the SSI effect were compared for foundation under the vertical excitation and the results leading to conclude that the soil structure interaction must be considered when analyzing such sensitive structure due to its significant effect on the overall response.

Keywords: Turbine-generator foundation, Soil-structure interaction, harmonic excitation, FEM.

INTRODUCTION

Generally, the turbine-generator foundation (TGF) are required a special attention because they transmitting the dynamic loading to the soil underneath this foundation in additional to the static loads due to the foundation self-weight, the machine and its auxiliaries. There are many different types of the machine that produce the periodic forces as the rotary machine, the impact and the reciprocating machines. The suitable selection of the foundation is depending upon the type of the machine itself, the geometric size and capacity of the machine. The effect of soil on the structures response becomes of great interest especially for the power plant station and the offshore industries at which the dynamic soil properties such as the shear modulus and Poisson's ratio, playing a significant role in the performance of such foundations and. Solution techniques for the problem of the SSI are nowadays rapidly advanced due to the evolution of the computers with the capabilities to handle larger computations with small time.

Usually, the analysis of the turbine generator foundation is considered as very important problem due to the interaction between the machine, foundation and the supporting soil medium. For such machine foundations, the important parameters in designing and analysis are the natural frequency and the amplitudes at the natural operation, and also the safety and stability performance of the machines is depending largely depending on the manufacture, design, and the supporting medium. In common design problems of the loading, assuming the buildings to be as fixed at their basis, but in reality, the soil medium that supporting such buildings allow the movement for some extent due to the ability of the soil to deform; this may lead to change the stiffness for the whole structural system. The interdependent behavior of the structure and soil should be taken into account when design and analysis of the structures especially for heavier structures like turbine power plant station.

Many researches followed the numerical representation of the behavior and response of the physical problems of machine foundation under the effect of dynamic and static loads.

<table>
<thead>
<tr>
<th>Year</th>
<th>Reference</th>
</tr>
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<tbody>
<tr>
<td>2014</td>
<td>Presented detailed procedures to model the turbo-generator foundation by finite element method and performed the dynamic analysis to check...</td>
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<tr>
<td>2015</td>
<td>The interaction effect are concerned in this study. The soil structure interaction has been analyzed with direct method (i.e. the soil and structure analyzed together in one step)....</td>
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</tbody>
</table>
the resonance conditions and ensure that the amplitude is within the accepted limits. [16] have been described a new 3D finite element model using the linear-elastic single degree of freedom SDOF and non-linear elastic response of the foundation soil system under the seismic loading conditions. [18] presented dynamic response analysis of finite element model for turbo generator foundation taking into considering the Winkler spring soil model, solid finite elements and dynamic loading conditions using SAP:2000 17.1 software. [19] Were inspected a new approach to suggest the possible solutions of the soil-structure interaction effect.

Therefore, the objective of this paper is to investigate the dynamic response of local site condition in Iraq considering and ignoring the influence of soil-structure interaction on the response of gas turbine-generator foundation in additional to the foundation free vibration analysis for Al-Mansuriya station. Abaqus v.6.13 finite element software has been used for 3D simulations including the whole project (the foundation and local soil site).

DESCRIPTION OF THE FINITE ELEMENT MODEL

Al Mansuriya (728MW) gas fired power plant is located in Al Mansuriya region in Diyala province, northeast of Baghdad in Iraq has been taken as a case study; this plant is based on the GT13E2 gas turbines. The turbine generator foundation with block type was simulated with dimensions of 24.4m in the longitudinal direction and 5.8m in the transverse direction with foundation thickness is about 1.5m. The layout of the foundation is shown in Fig.1.

In order to explore the effect of soil structure interaction on the response of the foundation, two cases were adopted. For the case of taking the SSI effect, the soil mass were selected to be 5B x 5L (L, B are the length and width of foundation respectively). The assembly of the soil layers with foundation is shown in Fig. 2. The simulation of the model was done in 3D system by Abaqus (v.6.13) while the case of ignoring the effect of soil structure interaction, RC turbine-generator foundation was modeled with all details using the quadratic elements and replacing the soil mass in the system by linear distributed springs in vertical and horizontal direction as shown in Fig.3. The springs were attached to the foundation at each node where the soil should be considered. The springs coefficients were calculated based on (Whitman and Richard 1967) as shown in Equations (1-2); the finite element mesh was generated with quadratic tetrahedral elements used for the foundation and soil body simulation as depicted in Fig.4.

\[ k_v = \frac{4G \mu}{1 - \nu} \]
\[ k_h = \frac{8G \mu}{2 - \nu} \]

... (1)

... (2)
Constitutive Models

The soil mass is considered as rectangular layers, with constant width and length (122m length, 29m width) while the depth and properties of each layer as listed in Table 1. The concrete body of the foundation is modeled using linear elastic model. The soil was considered as elastic-body by adopting the general Hook's law.

Table 1: Soil and reinforced concrete properties

<table>
<thead>
<tr>
<th>Soil layers</th>
<th>Depth (m)</th>
<th>Density (Kg/m³)</th>
<th>Elastic modulus (Pa)</th>
<th>Poisson's ratio</th>
<th>Cohesion (Pa)</th>
<th>Friction Angle</th>
</tr>
</thead>
<tbody>
<tr>
<td>Layer1</td>
<td>3</td>
<td>1711.5</td>
<td>2.17E+08</td>
<td>0.38</td>
<td>53000</td>
<td>11</td>
</tr>
<tr>
<td>Layer2</td>
<td>2.5</td>
<td>20068.7</td>
<td>5.32E+08</td>
<td>0.25</td>
<td>50000</td>
<td>12</td>
</tr>
<tr>
<td>Layer3</td>
<td>7</td>
<td>1761</td>
<td>6.00E+08</td>
<td>0.37</td>
<td>52000</td>
<td>11.3</td>
</tr>
<tr>
<td>Layer4</td>
<td>3.5</td>
<td>2481.7</td>
<td>8.50E+08</td>
<td>0.38</td>
<td>30000</td>
<td>20</td>
</tr>
<tr>
<td>Layer5</td>
<td>4</td>
<td>15618.8</td>
<td>7.00E+08</td>
<td>0.4</td>
<td>45000</td>
<td>18</td>
</tr>
<tr>
<td>Concrete</td>
<td></td>
<td>2400</td>
<td>2.50E+10</td>
<td>0.2</td>
<td>...</td>
<td>...</td>
</tr>
<tr>
<td>Steel</td>
<td></td>
<td>7800</td>
<td>2.00E+11</td>
<td>0.3</td>
<td>...</td>
<td>...</td>
</tr>
</tbody>
</table>

Contact Interactions

The interface can be defined as the connection between the subgrid that can slide or open (i.e. separate) during the calculation process. Generally, in case of taking the effect of SSI when simulating the overall system, for modeling the contact behavior between the soil and foundation surface material, it is essential to obtain the friction coefficient between the two materials which is again a function of the surface roughness, the adhesion, porosity and etc. The friction between the soil and foundation is defined by two components: the normal friction which is perpendicular to the interface between the two systems and the shear friction which is the tangential component. 'Coulomb' theory used for obtaining the friction coefficient in this study between two surfaces ($\mu = \delta \tan \theta \approx 0.6 \tan \theta$) The concept of the master-slave the master-slave concept is widely used recently due to its capabilities to simulate the large deformations within the area of contact including the geometrical formulation and the constitutive laws of interface [3].

Load condition

Foundation of machine should withstand all the forces that may imposed on the foundation during the service life, it is subjected to normal design loads of gravity in addition to the wind, earthquake and other loads during the operation (e.g. vibrations). For the purpose of checking the performance of the foundation during operation and ensuring that the natural frequency is at a good margin from the machine operating frequency, dead loads and live loads as static loads are applied on the foundation at specific locations as shown in Fig (5), for turbine machines the main dynamic forces which developed from eccentricities is coming from the unbalance of rotating component, these unbalanced masses produces centrifugal forces causes vibrations acting on the turbine machine foundation represented by harmonic forces at each bearing of the foundation (turbine and generator side) in any direction are given by the equation (3-4). Table 2 showed the value of the loads acting on turbine including dead and live component from the manufacturer.

$$f(t) = p_i \sin(\omega t) \quad \ldots (3)$$

$$p_i = m_i \omega^2 \quad \ldots (4)$$

Where:

$m_i$ : is the proportional part of the rotating masses.
$\epsilon$ : is the eccentricity.
$(\omega = 2\pi f) :$ is the circular operating frequency of the turbine generator;
$f :$ is the operating frequency (At nominal speed of the turbine $f = 50\text{Hz}$).
RESULT AND DISCUSSION

The dynamic analysis of the turbine-generator foundation (TGF) is done in two stages. The first stage includes the free vibration analysis in order to get the natural frequency of the foundation and the second stage named force vibration analysis due to vertical excitation to obtain the peak response for the foundation and the soil mass. Two nodes in soil mass and other two nodes the same location at the bottom surface of foundation under the turbine location where selected to determine the displacement and stresses due to the harmonic excitation as shown in Fig (6).

Free vibration analysis

The free vibration analysis is taking place in the absence of the external forces and any other motions. This study is performed in order to get the natural frequencies of the system and describing the principle behavior of the system. The figures below summarize the structure frequency corresponding to each mode shape. The first mode shapes showed the foundation with vertical bending along Y-axis at frequency 26.065 Hz, while the second and third mode shape showed the torsion around the Z-direction at frequency equal to 32.625 Hz and 36.228 Hz respectively. The forth mode shape showed the vertical movement of the foundation along Y- direction while the last two mode-shapes have a bending and torsional behavior as shown in Fig (7) and Table 3.
### Table 3: Free vibration analysis results

<table>
<thead>
<tr>
<th>Mode No.</th>
<th>Frequency (cycle/sec)</th>
<th>Frequency (rad/sec)</th>
<th>Period (sec)</th>
<th>Symmetrical/Unsymmetrical</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>26.065</td>
<td>163.77</td>
<td>0.0384</td>
<td>Sym. z-axis</td>
<td>Vertical bending</td>
</tr>
<tr>
<td>2</td>
<td>32.625</td>
<td>204.99</td>
<td>0.0306</td>
<td>Sym. z-axis</td>
<td>Bending +torsion</td>
</tr>
<tr>
<td>3</td>
<td>38.228</td>
<td>277.65</td>
<td>0.0278</td>
<td>unsym.</td>
<td>Bending +torsion</td>
</tr>
<tr>
<td>4</td>
<td>36.551</td>
<td>299.66</td>
<td>0.0274</td>
<td>sym. z-axis</td>
<td>Vertical bending 2 waves</td>
</tr>
<tr>
<td>5</td>
<td>42.054</td>
<td>264.23</td>
<td>0.0237</td>
<td>unsym.</td>
<td>Bending +torsion</td>
</tr>
<tr>
<td>6</td>
<td>44.985</td>
<td>282.62</td>
<td>0.0222</td>
<td>sym. z-axis</td>
<td>Bending +torsion</td>
</tr>
</tbody>
</table>

Soil and structural response under harmonic excitation

The responses of the soil mass with and without the consideration of soil structure interaction effect have been investigated and are of interest through this work.

Displacement responses

Fig (8) presents the displacement analysis of soil with time for various frequencies through time history analysis considering the effect of soil structure interaction.

It is observed that for the soil medium, the behavior started with large magnitude of amplitude occurs at frequency (50 Hz) with value of (0.62x10^-2 m) at the initial stage of the load application and then gradually decreases reaching the relatively constant value of (0.38x10^-2 m) for all of steps of frequency. Moreover, it can be seen that the central deformation (i.e. point A) is relatively produce large deformation comparing to that occur at the edge point of soil (i.e. point B), In the other hand, the foundation response seems to be as the same of soil as the deformation but with little variances in the magnitude due to the high stiffness of the reinforced concrete foundation as shown in Fig (9).

As compared the results with the case of ignoring the effect off SSI, note that the high values of the foundation response were observed when taking SSI effect due to real representation of soil layers (i.e. effect of site condition). Moreover, it’s clear that the foundation response and number of cycle peak amplitudes become less in case of without SSI effect due to lumping the stiffness of overall soil mass at the nodes as springs which in turn lead to more rigidity. Deformation shape and the displacements plots with time for mid and edge nodes on the foundation can be shown in Fig: (10) and Fig: (11) respectively.

The relation which obtained from different frequencies and amplitudes shown in Fig (12), depict the relation between the frequency ration \( \omega / \omega_n \) and the maximum vertical displacement for five amplitudes of harmonic load for machine foundation. It can be notice that the maximum amplitudes were found to be at frequency 50 Hz, and it can be noted that when increasing the amplitude of the harmonic loading over 50 Hz, the flatness of the curve increase downward and the peak amplitude becomes little. Also the amplitude of the mid-point is greater than that of edge pot but with same behavior.

Figure 7: Mode shapes of the turbine-generator foundation

Figure 8: Maximum displacement of the soil (i) node A (ii) node B

Figure 9: Maximum displacement of foundation (i) node C, (ii) node D
The stress analysis of the foundation and soil system showed that the stress in the midst node at the soil get increase to reach maximum value of (214273 Pa) at frequency 50 Hz for point A, and decrease to somewhat constant value for all frequencies with magnitude of (171111 Pa). Same behavior observed for node (B) but with magnitude larger than node (A) as shown in Fig (13). It can be seen that a short transient stage of stresses preceding the steady state stage of the analysis that become more notable and dominant for soil behavior. While it's clear that the stresses in the mid of foundation (i.e., node C) get larger value of (199825 Pa) at frequency 50 Hz and decrease to constant value of (32726 Pa) at the end of the loading time at same frequency and same behavior with the edge point of the foundation (i.e., node D) as shown in Fig (14) with variance in magnitudes, and it can observed that the response of the foundation shows little differences in the amplitude pattern. The difference between the values of the soil and foundation stresses can be attributing to large foundation stiffness comparing to soil medium.

In case of ignoring the effect of SSI, the overall response of the foundation was less than that obtained at the previous case as shown in Fig (15). Obviously, interaction phenomena should be taken into account when analysis the behavior of such turbine foundation due to the significant influence on the amplification of the system response and can give the actual behavior for the overall system.
CONCLUSION
In this paper, three-dimensional-finite element analysis of gas turbine foundation with and without considering the effect of soil structure interaction under harmonic excitation have been carried out with different operating frequencies. Furthermore, the free vibration analysis was performed to determine the fundamental natural frequency and the mode shapes of the foundation. Important conclusions drawn from this study as following:

1- The free vibration analysis showed symmetric mode shape about the Z-axis for the first frequency while the coupled bending – torsion mode shapes for the second and third frequencies, therefore the torsion design should be taken into account at the design of such turbine foundation in order to prevent the differential settlement of the foundation.

2- Force vibration analysis was performed to investigate the response of turbine generator foundation to the dynamic unbalanced force comes from machine to the foundation during the operation.

3- The response of the foundation and the soil due to the harmonic excitation showed larger magnitude at the initial time due to coupled effect of transit and the steady state of the harmonic excitation then the response decrease with time due to vanish of the transited component reaching a constant and this response may be de-amplified when ignoring the effect of SSI

4- Considerable change in the amplitudes of the structural response was indicated through the comparison between the case of with and without considering SSI effect.

5- The change in the maximum response to the vertical harmonic excitation reflect the change in the applying frequency so that at middle node on the soil and also in the foundation the results showed different peak values and it has maximum values at earlier applied frequencies due to a state of coupling steady state and transit state response.

6- For the turbine machine foundations, it worthy to take the full site effect (i.e. complete model of soil and foundation) in the dynamic analysis to get the better insight for the behavior of both soil and foundation through the investigation of soil-foundation interface.

REFERENCES


