Soil Saturation and Water Table Effects on Impedances at the APT Target Facility

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ABSTRACT

During the conceptual design phase of the Accelerator Production of Tritium (APT), seismic issues associated with the deeply embedded target facility of the accelerator were raised. These concerns stem primarily from the proximity of the deep structure to the water table, as well as from the quality of the layered soil surrounding the target facility. In an effort to obtain a better understanding of the seismic response of such heavy and deeply embedded structure, which houses the most critical systems of the accelerator facility, the particularities of the soil-structure interaction are studied. The key goal of this exercise is to estimate the role that the soil saturation plays and to quantify the way it alters the dynamic interaction of the structure with the soil. Specifically, dynamic impedances which account for the position of the water table relative to the structure are estimated. This is achieved by treating the saturated soil as a two-phase medium that follows Biot’s theory. While the adopted formulation is based on a 2-D SSI description, significant conclusions regarding the role of soil saturation and water table position relative to the structure are drawn.

INTRODUCTION

The Accelerator Production of Tritium (APT) facility includes the Target/Blanket building which houses the accelerator target and its heavy shield, the flood/storage pool and the tritium separation facility (TSF). It represents the most critical APT structure because of the elements it contains. The T/B building is embedded to a depth of approximately 60 ft and it potentially penetrates the water table. Because of the importance that surrounds the T/B, considerations of the dynamic interaction between the embedded part of the structure and the surrounding soil were made via a detailed analysis. In this study the influence of the water table relative to the embedded structure is assessed thru the evaluation of dynamic impedances.

Dynamic response of foundations interacting with saturated media has drawn some attention, primarily because of the role of the pore fluid on the response parameters. In actual design, however, an equivalent representation of the saturated soil is adopted. Specifically, a material with Poisson’s ratio near \( \nu = 0.5 \) replaces the saturated soil. This effort attempts to quantify the differences which result from the choice of soil
representation and identify dynamic frequency ranges over which the response (seen as impedances in this study) is mostly affected.

To address the SSI problem, dynamic finite element procedures were adopted. The governing equations are those of wave propagation in saturated media as developed by Biot [1]. The finite element discretization of the two-dimensional, plane strain governing equations was implemented into the specialized computer code POROSLAM [5] which has been designed to analyze problems involving saturated porous media.

Analytical solutions to the problem that can be used for comparative purposes before embarking into complicated cases are very limited. The dynamic response of a rigid strip footing that is bonded to the surface of an elastic half space has been studied in [1]. In this particular work, compliances for vertical, horizontal and rocking footing motions were computed in closed-form solutions. The work in the current study used the results in [1] to check the performance of the finite element formulation. While the available closed form solutions are representative only of a dry underlaying soil medium, the comparison is still useful in assessing both the impedances and the performance of the radiating boundaries. Shown in a later section are comparative results of the analytical and finite element solutions. Excellent agreement between the two solutions has been achieved. In order to assess how soil saturation impacts on the dynamic response of foundations, the case of saturated half space was studied and its results are presented in this paper.

To address the problem at hand that involves an embedded structure in proximity to the water table, various scenarios regarding the elevation of the water table with respect to the foundation were analyzed. The goal of the study is to see how the impedances vary as a result of the water table. In addition, the question regarding the validity of the practice in which the saturated soil is treated as an equivalent dry one with a Poisson’s ratio close to 0.5 has been addressed.

**PROBLEM FORMULATION**

The cross section of the T/B building and the supporting soil is shown in Figure 1. The embedded building is approximated by an infinite strip of width \(2b = 100 \text{ ft}\) which represents the shorter of its two dimensions. The embedment depth is \(D = 60 \text{ ft}\) while the embedded structure is considered to be massless and rigid. A perfect bond is assumed between the walls of the embedded structure and the surrounding soil. The water table assumes different elevations with respect to the structure while the soil portion under the horizon is considered to be fully saturated. The portion of the structure that penetrates the water table is assumed impervious. The soil consists of discrete layers with different dynamic properties. Radiating boundaries at the bottom and side boundaries allow for a finite domain to be analyzed. A rectangular Cartesian coordinate system in \(x\) and \(y\) is considered for the plane with origin at the bottom middle of the foundation.

The problem is formulated based on Biot’s classical theory of elastodynamics in porous, saturated medium. The equations of motion in the saturated medium are expressed in terms of the soil matrix and pore fluid displacements,

\[
\frac{\partial \tau_{xx}}{\partial x} + \frac{\partial \tau_{xy}}{\partial y} = \rho \ddot{u}_x + \rho_f \ddot{w}_x ; \quad \frac{\partial \tau_{yx}}{\partial x} + \frac{\partial \tau_{yy}}{\partial y} = \rho \ddot{u}_y + \rho_f \ddot{w}_y
\]  

(1)

and

\[-\frac{\partial p_f}{\partial x} = \rho_f \ddot{w}_x + \frac{1}{f} \rho_f \ddot{w}_x + \frac{\eta}{k} \dddot{w}_x ; \quad -\frac{\partial p_f}{\partial y} = \rho_f \ddot{w}_y + \frac{1}{f} \rho_f \ddot{w}_y + \frac{\eta}{k} \dddot{w}_y\]

(2)

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where, \( u_i \) are the solid matrix displacements, \( \omega_i \) are the pore fluid displacements, \( \tau_{ij} \) are the total stresses, \( p_f \) is the pore pressure, \( \phi \) is the porosity, \( \varrho \) is the total mass density, \( \varrho_f \) is the fluid mass density, \( \alpha \) is the compressibility of the solid, \( M \) is the compressibility of the fluid, \( \eta \) is the fluid viscosity, and \( k \) is the soil permeability.

Constraint conditions associated with vanishing of stresses at the free surface, continuity of stresses and displacements along the far boundaries which allow for energy radiation and interface conditions between the footing and the surrounding soil are implemented into the well defined problem. Specifically, the intergranular stresses and pore pressures vanish at the free surface and outside the interface of the foundation and the substratum. For a saturated substratum, the foundation is assumed impermeable to the pore fluid which is allowed to move along the foundation-soil interface. In all cases the foundation is assumed massless and rigid. Radiating conditions that allow the simulation of a half space have been used quite extensively but not with a saturated medium. In previous works and by using this formulation the successfull implementation of such boundaries was achieved on the basis of one-dimensional wave propagation.

In order to evaluate the impedances, the foundation was subjected to harmonic vertical, horizontal and rocking motions of unit amplitude and varying frequency. Impedances are viewed as the total resisting force exerted by the soil on the harmonically vibrating foundation and is mathematically shown below,

\[
F_i = \int_C \tau_{ij} ds \quad ; \quad i, j = x, y
\]

where \( C \) is the structure/soil interface boundary and \( \tau_{ij} = \sigma_{ij} - \alpha p_f \) is the bulk stress. Impedances for vertical, horizontal and rocking motions respectively are expressed in the form,

\[
\begin{align*}
K_{yy} &= k_{yy} + i\alpha_\omega c_{yy} \\
K_{hh} &= k_{hh} + i\alpha_\omega c_{hh} \quad \text{(4)} \\
K_{rr} &= k_{rr} + i\alpha_\omega c_{rr}
\end{align*}
\]

where, \( k_{ii} = Re[F_i] \) and \( c_{ii} = Im[F_i] \), \( \alpha_\omega = \frac{\omega b}{V_f} \), is the dimensionless frequency of the analysis that relates the frequency of foundation vibration \( \omega \) with the half width \( b \) and
the shear velocity of the soil $V_s$. The surrounding soil was discretized in a way that allows the transmission of all the frequencies in the selected range.

**EVALUATION OF IMPEDANCE FUNCTIONS**

The impedances of the surface strip foundation analytically computed in [1] were evaluated first. In [1] closed-form solutions of an elastic half space with Poisson's ratio $\nu = 0.5$ are available in the form of compliances. Results of approximate solutions of other values of $\nu$ are also available. Using the case of $\nu = 0.5$ as base of comparison, the finite element solution to the different modes of footing motion was obtained. Poisson’s ratios approaching 0.5 were used due to obvious limitations inherent in the finite element representations. For the cases of vertical and horizontal motions the solution exhibits a singularity in the real part (rigid displacement) as the frequency of vibration tends to zero. Such response is solely the result of the two dimensional formulation of the problem. While the agreement was very good, the finite element could not quite distinguish which part of the solution is unbounded. The comparison of the compliances for the vertical case are shown in Figure 2. The rocking case comparison, where no singularity is present, is shown in Figure 3 and it is apparent that the finite element solution closely follows what is predicted by the analytical formulation. Figure 4 depicts the affect the pore fluid has on the impedances (shown in the form of compliances) for a footing on the surface of a half space. The purpose of this comparison is to quantify the potential deviation if the saturation is ignored. The Poisson’s ratio for the soil matrix for the above case is $\nu = 0.25$.

In analyzing the embedded Target building of APT, a comparison between the actual saturated soil beneath the foundation and its equivalent material has been made for the vertical motion of the building and is shown in Figure 5. The equivalent material maintains the same shear velocity and shear modulus but its direct velocity incorporates the pore fluid. Subsequently, a new Poisson’s ratio is computed for the saturated material. The results of Figure 5 indicate that for up to approximately $a_o = 3$ in the dimensionless frequency of foundation vibration the equivalent material is a reasonable representation at least for the real part of the impedance. It is at very low frequencies the pore fluid impacts on the radiation part. The key finding in analyzing this case is that the stiffness part of the impedance solutions is significantly affected by the pore fluid in the higher frequency range.

Figures 6 and 7 depict the impedances for different positions of the water table underneath the building foundation. Specifically, the case of the water table level being at exactly the foundation bottom is compared, with the cases of the water table at two and five feet below. For the vertical case, shown in Figure 6, one observes changes for the entire frequency range and most profoundly for the radiation part. The radiation component appears insensitive to the position of the water table indicating that the energy loss is primarily the effect of the near field. The stiffness part, however, is affected by the table at the higher frequency zone. Less profound differences are observed for the horizontal vibration of the embedded structure. This is due to the fact that resistance to the foundation motion is in the form of shear in the solid matrix at the interface. As it is anticipated, the ability of the fluid part of the soil to radiate energy at low frequencies is affected as the table moves away from the interface.

**CONCLUSIVE REMARKS**

The effect of soil saturation and the water table position on the impedance functions for the embedded T/B facility at the APT site has been estimated. Based on this
Figure 2: Rocking compliances for saturated and dry half spaces ($\nu = 0.25$)

Figure 3: Vertical impedances of the embedded structure. Saturated vs equivalent substratum

Parametric study it appears that the presence of the pore fluid influences the dynamic interaction between the foundation and the soil. For vertical vibrations the pore fluid effects become apparent in higher frequencies where differences in wave speeds between the saturated and the corresponding dry media more profound. Similar conclusions were drawn for the dissipation part of the horizontal case where more dissipation is observed in the lower frequency range. Further, it is shown that for low frequencies equivalent dry soil can represent saturated soil. This, of course, has been the practice in the field. Differences, however, are seen in the ability of the soil to radiate energy at the lower end of the frequency range.
REFERENCES


Figure 4: Surface vertical compliances ($\nu = 0.5$). Analytic vs. FE solution

Figure 5: Surface rocking compliances ($\nu = 0.5$). Analytic vs. FE solution
Figure 6: Vertical impedances of the embedded structure. Water table effects

Figure 7: Horizontal impedances of the embedded structure. Water table effects