Soil Structure Interaction of Chimney
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ABSTRACT

A soil-pile system and a soil-pile system accompanied with stack like structure (chimney) is analyzed. Linear analysis is carried out. For simulating radiation condition at infinity, Kelvin element was considered as boundary condition. Seismic excitations consisting of transient motion (El Centro earthquake time history) is used. Response (top nodes displacement) of a 2D soil-pile model system is compared with the response of 3D soil-pile model. The response (horizontal displacement) of top node of chimney without soil-pile (fixed base) is compared with chimney with soil-pile model.

Keywords: Soil- Structure interaction, soil dynamics.

1. Introduction

Most of the civil engineering structures involve some type of structural element with direct contact with ground. When the external forces, such as earthquakes, act on these systems, neither the structural displacements nor the ground displacements, are independent of each other. The process in which the response of the 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). Conventional structural design methods neglect the SSI effects. 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, however, becomes prominent for heavy structures resting on relatively soft soils for example nuclear power plants, high-rise buildings and elevated-highways on soft soil. Much of the reported research in the field of dynamic analysis of pile foundations assumes linear behavior of soil media. Substantial research has been carried out on the linear analysis of single piles and pile groups in frequency domain e.g., Kaynia and Kausel (1982), Gazetas (1984), Markis and Gazetas (1992), but only a few researchers e.g., B.K. Maheshwari, have performed time domain analyses.

In this paper dynamic analysis of high-rise chimney structure with soil-pile system and chimney with fixed base is done. To adequately represent the infinite soil media, Kelvin elements (spring and dashpot) are used at the boundary, simulating radiation conditions at infinity. Both the models are analyzed considering El Centro earthquake time history.
1.1 Modeling of System

Full three-dimensional geometric models were used to represent the soil-pile system. Taking advantage of symmetry and antisymmetry (Fig. 2), only one-fourth of the actual model was modeled. The pile is completely embedded in soil and it is assumed to be bearing on bedrock and hence all bearing nodes are taken as fixed. 8 noded element is used to model both, the soil structure and the pile.

To simulate an infinite soil medium, Kelvin elements (springs and dashpots) are attached on the side walls of the foundation which provide the proper boundary conditions (Fig. 1). These Kelvin elements are used in all three directions along the boundary. The coefficients of springs and dashpots are derived separately for horizontal and vertical directions. Fig. 3 shows the meshing of soil-pile model. Equal meshing is done in all the three directions. Size of mesh is kept as 1m X 1m. Numerical Data for the quarter model: Size in plan 10m X 4m (Fig. 3(a)) and height of 6m (Fig. 3(b))
2. Formulation

2.1 Boundary Conditions

Kelvin elements are used at the boundary (Figs. 3(a) and (b)). The presence of the springs provides stiffness, giving this boundary a distinct advantage over the standard viscous boundary (Novak and Mitwally 1988; Wolf 1985). Even though frequency independent viscous dampers can be used as a transmitting boundary as shown by Maheshwari et al. (2002), frequency dependent Kelvin elements proposed by Novak and Mitwally (1988) are used in this study as they perform better than viscous dampers when their constants are properly evaluated. The mesh size required with Kelvin elements is much smaller than that needed when using viscous dampers. To use Kelvin elements in the time domain analysis, a Fourier spectrum of the input time history is derived and the predominant frequency of loading is determined. The stiffness and damping constants of the Kelvin model are evaluated based on the predominant frequency of loading. The springs and dashpots constant (of the Kelvin
element) in the two horizontal directions were calculated using the solution developed by Novak and Mitwally (1988) and is given by:

**Stiffness Matrix Formulation**

Stiffness matrix is given by

\[ k_r^* = \frac{G}{r_0} \left[ S_1(a_r, \nu, D) + iS_2(a_r, \nu, D) \right] \]  --1.1

- \( k_r^* \) = complex stiffness
- \( G \) = shear modulus of soil
- \( S_1 \) and \( S_2 \) = dimensionless parameters from closed form solutions
- \( D \) = material damping ratio
- \( \nu \) = Poisson’s ratio
- \( r_0 \) = distance in plan from centre of pile to the node where Kelvin element is attached.

The present model being symmetrical in geometry and subjected to seismic loading, this distance approximately represents the corresponding radial distance for cylindrical model.

\[ \alpha_r = \text{dimensionless frequency} = \frac{\omega D}{V_s^2} \]

\( V_s \) = shear wave velocity of soil

\( S_1 \) and \( S_2 \) are the dimensionless parameters and are calculated by referring the Fig.4

Real and imaginary parts of equation 1.1 represent the stiffness and damping, respectively, i.e.

\[ k_r = \frac{G S_1}{r_0} \quad \text{and} \quad c_r = \frac{G S_2}{\omega r_0} \]  --1.2

Constants for vertical direction are given by (plane strain case)

![Figure 4: Dimensionless Parameters S1 and S2](image-url)
subscript $w$ is represent the vertical direction, stiffness and damping are

$$k_w = \frac{c_{s_w}^2}{\rho_0} [S_{w1}(\alpha, D) + iS_{w2}(\alpha, D)]$$

$$c_w = \frac{c_{s_w}}{\omega_{r_0}}$$

To determine the stiffness and damping of Kelvin elements, constants given by eqs. 1.2 and 1.4 are multiplied by the area of element face (normal to the direction of loading).

**Damping Matrix Formulation**

It consists of two parts, radiation damping $C_r$ and material damping $C_m$

$$C = C_r + C_m$$

Radiation damping $C_r$ is a diagonal matrix and has non-zero terms only at the nodes where viscous dampers are attached i.e. on the side walls of the model. At a particular node where dashpots are attached, damping coefficients for horizontal and vertical directions are found using eq. 1.2 and 1.4

$$C_m = \alpha K \text{ where } \alpha = \frac{2D}{\omega_0}$$

It is assumed that the pile is made of concrete and has a square cross section with each side $d$ equal to 1 m. The length of the pile is 6 m. Young’s modulus, mass density, and Poisson’s ratio for the pile and soil are, respectively:

- $E_{\text{soil}} = 20\text{MPa}$
- $E_{\text{pile}} = 20\text{GPa}$
- $\rho_{\text{soil}} = 12\text{kN/m}^3$
- $\rho_{\text{pile}} = 25\text{kN/m}^3$
- $\nu_{\text{soil}} = 0.45$
- $\nu_{\text{pile}} = 0.3$

**Dynamic Loading**

The seismic loading is applied as bedrock motion. For the transient motion, an acceleration time history for the El Centro Earthquake (Fig. 5. (a)) has been used. A smoothed Fourier spectrum of acceleration time history (Fig. 5. (b)) has been derived FORTRAN program was used to calculate the amplitude (ANNEXURE-I). It was found that the predominant frequency of excitation is approximately 2.14 Hz.
3. Validation of results

Based on the formulations (Eqs. 1.1 and 1.5), the stiffness and damping coefficients are calculated and are used as boundary conditions for 2D and 3D soil-pile models. These formulations are based on the symmetry of the structure. In case of 2D model, plain strain approach is followed and hence half model is considered for its analysis.

3.1 Analysis of 2D soil-pile model for Transient Motion

A 2D soil-pile model with fixed base and Kelvin elements along the boundary is analyzed considering uniform meshing. El Centro earthquake time history is used as a ground excitation. Uniform meshing is done throughout and hence the concrete pile is meshed in two halves vertically. Node no. 991 is the central node (Fig. 6). Horizontal and vertical displacements of the top nodes are noted.

Pile Size = 2m (Width) X 6m (Height), Total width = 20m

The calculated values for stiffness and damping are as follows

\[ K_{\text{hori}} = 1.71 \times 10^6 \text{kN/m} \]
\[ K_{\text{ver}} = 20 \text{kN/m} \]
\[ C_{\text{rh}} = 1267.2 \text{kN-s/m} \]
\[ C_{\text{rv}} = 20 \text{kN-s/m} \]
\[ C_{\text{mh}} = 12671.6 \text{kN-s/m} \]
\[ C_{\text{mv}} = 0.15 \text{kN-s/m} \]
The horizontal displacement of the node no. 991 was found out to be 0.22284mm.

3.2 Analysis of 3D soil-pile model for Transient Motion

A 3D soil-pile model with fixed base and Kelvin elements along the boundary in all three directions (X, Y and Z) is analyzed considering uniform meshing. El Centro earthquake time history is used as a ground excitation. Fig. 7 shows the top nodes of the 3D soil-pile model.

Pile size = 1m x 1m
Pile Length = 6m
Width X-direction = 10m and width Y-direction = 4m. The calculated values for stiffness and damping are as follows
X- direction | Y- direction
---|---
$K_{\text{hori}} = 1.54 \times 10^6 \text{kN/m}$ | $K_{\text{hori}} = 3.85 \times 10^6 \text{kN/m}$
$K_{\text{ver}} = 20 \text{kN/m}$ | $K_{\text{ver}} = 20 \text{kN/m}$
$C_{\text{rh}} = 1140.4 \text{kN-s/m}$ | $C_{\text{rh}} = 2851.1 \text{kN-s/m}$
$C_{\text{rv}} = 20 \text{kN-s/m}$ | $C_{\text{rv}} = 20 \text{kN-s/m}$
$C_{\text{inh}} = 11404.5 \text{kN-s/m}$ | $C_{\text{inh}} = 28511.1 \text{kN-s/m}$
$C_{\text{mv}} = 0.15 \text{kN-s/m}$ | $C_{\text{mv}} = 0.15 \text{kN-s/m}$

The horizontal displacement of the node no. 26 was found out to be 0.22021mm ($X$-direction) and 0.216998mm ($Y$-direction). Considering the validation of 2D and 3D results, a 3D chimney with and without soil-pile system was modeled and analyzed using same earthquake time history and Kelvin elements at the boundary and the top node (of chimney) displacements were found out.

Dimensions of chimney considered are
Height = 60m
Internal Diameter = 4m

![Figure 8: Arrangement of Pile-cap and piles](image)

Thickness = 300mm
Other parameters considered are

\begin{align*}
E_{\text{soil}} &= 20\text{MPa} & E_{\text{con}} &= 20\text{GPa} \\
\rho_{\text{soil}} &= 12\text{kN/m}^3 & \rho_{\text{con}} &= 23\text{kN/m}^3 \\
\nu_{\text{soil}} &= 0.45 & \nu_{\text{con}} &= 0.3
\end{align*}

**Table 1:** Top Nodal Displacements of Chimney

<table>
<thead>
<tr>
<th>Remarks</th>
<th>Horizontal displacement (m)</th>
<th>Without soil (fixed base)</th>
<th>With soil (soil-pile system)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Top of Chimney</td>
<td></td>
<td>0.02336</td>
<td>0.02836</td>
</tr>
</tbody>
</table>

4. Conclusions

SAP can be used for analyzing axisymmetric structures. From Table 1, it can be observed that there is an additional top displacement of chimney which may be due to soil-pile system. Hence the soil-structure interaction cannot be ignored during analysis.

**Annexure I**

```
C PROGRAM FOR FOURIER SPECTRUM
dimension x(2000),x1(2000),a(60),b(60)
real k,del_t,j,loop
open(unit=1,file='input.txt',status='unknown')
open(unit=2,file='out.xls',status='unknown')
p=22.0/7.0
del_t=0.02
print*,'Number of terms in time history='
read*,n
print*,'no. of terms required in series & time increment'
read*,loop,del_t
do 10 i=1,n
read(1,*),t1,x(i)
10 continue
T=0.02*n
omega=2*pi/T
c to find a0
sum=0.0
do 20 i=1,n
sum=sum+x(i)
20 continue
sum=sum+0.5*(x(1)+x(n))
a0=sum*(0.02/T)
print*,'a(0)=' ,a0
WRITE(2,*),"a0=",a0
j=T/(20*del_t)
```
do 30 k=1,j
sum1=0.0
sum2=0.0
t1=0.0
do 40 l=2,n-1
  t1=t1+del_t
  sum1=sum1+x(i)*cos(k*omega*t1)
  sum2=sum2+x(i)*sin(k*omega*t1)
40 continue
sum1=sum1+0.5*(x(i)*cos(k*omega*0.0)+x(n)*cos(k*omega*T))
a(k)=sum1*0.02*2/T
print*,omega*k
WRITE(2,*),"a(",k,")=",a(k)
print*,"a(",k,")=",a(k)
sum2=sum2+0.5*(x(1)*sin(k*omega*0.0)+x(n)*sin(k*omega*T))
b(k)=sum2*0.02*2/T
WRITE(2,*),"b(",k,")=",b(k)
print*,"b(",k,")=",b(k)
WRITE(2,*),"omega*k,a(",k,"),b(",k,")=",b(k)
30 continue
stop
end

5. References


