Soil structure interaction in framed structure on a hilly area: a case study

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Abstract. There are many problems in civil engineering which are involving some kind of structural element in straight connection with the land. When there is some forces are applied to the structural element, both component (structural element and soil/ground) must deform and move in compatible manner. These types of problems are referred as Soil-Structure Interaction (SSI) problem. In this project, an analysis of a building on the slope (10°) with 5 stories was carried out.

The soil under the building are make up by 8 layers consist different type of material. The study in this project is focusing on development of finite element model in order to analysis of a framed structure foundation comprised of a pile system and soil media resting on a hilly area. A beam bending element that calculate the outcome of transverse shear deformation and the axial interaction is then formulated. Based on the interaction behavior of the superstructure foundation soil system, bending moment in the superstructure is found to increase in the external beam and decrease in the inner beams.

The effect of hill slope influences the displacements, and subsequently, the forces in the superstructure. This study also compares the result from SSI program and conventional analysis to find out the weakness of the conventional analysis.

1.0 Introduction

Connection between the structure components such as column and combined footing, contact pressure, and bending moment in an elastic combined footing is various. Lots of researchers have been working on this issue, Grasshoff [1] and Sommer [2] in 1975 and 1957 worked on the analyzing the foundation beams and slab. Heil [3] studied on analyzing the settlement pattern by considering the time, concrete creep. Lee and Harrison [4] represented two methods, which can indicate that contact pressure is adapted inconstantly. Haddadin [5] found a 2D pattern to analysis the combined frams. Lee and Brown [6] found out a new analysis which was interaction and was for 7storey building by using the Winkler models.
King and Chandrasekaran [7] used a 2D rafted plane which the frame and combined footing are
distinct into beam bending elements. Viladkar et al. [8–13] and Noorzaei et al. [14–16] widely studied
about the soil structure complication in a framed structure by proposing different physical and
constitutive modeling approaches. These investigations mainly assumed the superstructure and
foundation as linear elastic, whereas soil media were considered as nonlinear. Badet et al. [17–19]
presented a mathematical model using a quadratic elastic foundation element for vertical subgrade
reactions, soil shear stiffness, and friction between the superstructure and the soil. Bhattacharaya et al.
[20, 21] presented a detailed literature review on soil structure interaction in frame structure. In the
present study, the authors discuss a different nonlinear soil model and ultimately recommend the
Winkler model in the idealization of the soil media. Yerli et al. [22] idealized the superstructure
foundation and soil system problem using coupled finite and infinite elements. F. Homaei et al. [24]
investigated about the probabilistic seismic performance of vertically irregular steel buildings,
considering soil–structure interaction effects and revealed that the main effect of stiffness and strength
irregularities was checked in reduction of the structural ductility factor and the mean yearly frequency
of exceeding limit states. M.P. Santisi d’Avila and F. Lopez-Caballero [25] also worked on 3D frame
structure and 1-Directional propagation of a 3-Component seismic wave and proposed a model which
allows the analysis of those structural dynamic features, seismic wave and local soil stratigraphy, that
produce changes in the ground motion at the surface. The model reproduces well expected
phenomena, in the case of layered soil with increasing nonlinearity and for different inertia
distribution in the frame structure.

2.0 Problem identification

The literature review indicates the existing interactive analyses did not attempt to cover soil structure
interaction analysis with respect to hilly areas. Moreover, most of the earlier studies deal with soil
structure interaction supported by combined mat foundation. Thus, such a gap presents the need for
interaction analysis of the framed structure supported by pile foundations. The present study conducts
soil structure interaction analysis of the framed structure supported by a pile foundation system built
on a hilly area.

3.0 Mathematical modeling

Discretization of the plane-frame pile footing oil system on a hilly area includes the following
elements:

(a) Eight nodded regular parabolic finite elements to indicate the soil mass [23];
(b) Three nodded isoparametric beam bending elements with three degrees of freedom per node
to be the frame members, foundation beam, and pile. A brief description of this element is
discussed as follows.

The element which is given is of the isoparametric family with three degrees of freedom per node,
as shown in Figure 1. The shape function could be seen as:

\[ N_1 = -\frac{1}{2}\xi(1-\xi); \]
\[ N_2 = (1-\xi^2); \]
\[ N_3 = \frac{1}{2}\xi(1+\xi); \]  

(1)
Figure 1. One dimensional beam bending element in natural co-ordinate system.

Displacements in nodes at any node \( i \) are taken as

\[
\{ \delta_i \} = \{ u_i, v_i, \theta_i \}^T ;
\]  

(2)

Displacements in the \( x \) and \( y \) directions are \( u_i \) and \( v_i \) are, respectively, and is the rotation in the \( z \) is shown by \( \theta_i \). This beam element is isoparametric, not similar to regular elements, allows deformation because of shearing. The total rotation at any section \( \theta \) is shown as

\[
\theta = \frac{\partial v}{\partial x} + \phi
\]  

(3)

\( \phi \) could have effect on rotation caused by transverse shear. Furthermore, at any point displacements and rotations would be represented by shape functions in the conventional function as

\[
\begin{align*}
  u &= \sum_{i=1}^3 N_i u_i; \\
  v &= \sum_{i=1}^3 N_i v_i; \\
  \theta &= \sum_{i=1}^3 N_i \theta_i; \\
  \phi &= -\sum_{i=1}^3 \frac{\partial N_i}{\partial x} + \sum_{i=1}^3 N_i \theta_i
\end{align*}
\]  

(4)

4.0 Strain displacement relation

Generally, the relationship between the strain components at any point and nodal displacements is represented by

\[
\begin{bmatrix}
  \varepsilon_x \\
  \phi \\
  \frac{\partial \theta}{\partial x}
\end{bmatrix} =
\begin{bmatrix}
  \frac{\partial N_i}{\partial x} & 0 & 0 \\
  0 & -\frac{\partial N_i}{\partial x} & N_i \\
  0 & 0 & \frac{\partial N_i}{\partial x}
\end{bmatrix}
\begin{bmatrix}
  U_i \\
  V_i \\
  \theta_i
\end{bmatrix}
\]  

(5)

Where \( \frac{\partial \theta}{\partial x} \) is a pseudo-curvature and the effective shear rotation is \( \phi \).

5.0 Stress–strain relation

Stress–strain relation for the element may be expressed as

\[
\begin{bmatrix}
  P_x \\
  P_y \\
  M_x
\end{bmatrix} =
\begin{bmatrix}
  AE & 0 & 0 \\
  0 & S & 0 \\
  0 & 0 & EI
\end{bmatrix}
\begin{bmatrix}
  \varepsilon_x \\
  \phi \\
  \frac{\partial \theta}{\partial x}
\end{bmatrix}
\]  

(6)

The cross-sectional area of the beam is shown by \( A \), the flexural rigidity is \( EI \), the shear rigidity (\( S = A.G/\alpha \)) is indicated by \( S \), and \( G \) is the shear modulus. \( P_x \) and \( P_y \) are the loading in the \( x \) and \( y \)
directions; bending moment is $M_z$; the warping the stiffness matrix factor is $\alpha$. The element stiffness matrix is generally conducted as

$$[K]_e = \int [B]^T [D] [B] \, dv \quad (7)$$

For on direction beam element, the stiffness matrix is written as

$$[K]_e = \int [B]^T [D] [B] \, |J| \, d\xi \quad (8)$$

if node number 2 (Figure 1) is used halfway through the element, the Jacobian determinant $|J|$ is about trivial and acts only as a constant, that is, $|J| = L/2$, $L$ shown as the length of the element. The $[K]$ matrix, which is the global stiffness matrix of any frame member, is shown as

$$[K]_e = \frac{L}{2} \int_{-1}^{1} [R]^T [B]^T [D] [B] [R] \, d\xi \quad (9)$$

The rotation matrix could be seen here as

$$[R] = \begin{bmatrix} \frac{1}{J} \frac{dx}{d\xi} & \frac{1}{J} \frac{dy}{d\xi} & 0 \\ \frac{1}{J} \frac{dy}{d\xi} & \frac{1}{J} \frac{dx}{d\xi} & 0 \\ -\frac{1}{J} \frac{dy}{d\xi} & -\frac{1}{J} \frac{dx}{d\xi} & 0 \end{bmatrix} \quad (10)$$

6.0 Numerical example

The model has been subjected to analyze a five-story three-bay plane frame combined footing pile foundation soil media. The height of each story is 3 m and the width of each bay is 4 m. The material properties of the soil mass at different depths based on the experimental studies are presented in Table 1.

| layer | Soil types   | $E$ Kpa | $v$ |
|-------|--------------|---------|-----|
| 1     | Clayey sand  | 6400    | 0.25|
| 2     | Clayey sand  | 9280    | 0.25|
| 3     | Clayey sand  | 7680    | 0.25|
| 4     | Clayey sand  | 8320    | 0.25|
| 5     | Clayey sand  | 8640    | 0.25|
| 6     | Silty sand   | 7800    | 0.40|
| 7     | gravelly sand| 57600   | 0.40|
| 8     | gravelly sand| 67200   | 0.40|

Based on the BS6399 and BS648 code of practice, which is commonly used in Malaysia, the structure is subjected to both vertical and lateral loads. Thus, because of the unsymmetrical nature of the loading, a full finite element mesh has been considered, as shown in Figure 2.
7.0 Results and discussion

Figure 3 illustrates the horizontal deformation profile of the building along the height of the structure for columns C1 to C4. From this plot, the lateral displacement of the building is expected to increase along the height of the structure. The effects of the hill and of soil interaction are obvious at the first story and foundation level. Furthermore, the deflected profile of the columns follows the applicant direction of the wind load, which is from left to right.

Figure 3. Variation of Lateral Displacement along the Column Height.
The settlement profiles of the beams at each floor level are shown in Figure 4. The plots illustrate that the right side of the beam is displaced more than the left side. The settlement profile of the beams clearly follows the loading pattern and geometry of the structure. Moreover, relative displacement is developed between the left and right sides of the beam at each story.

![Vertical Displacement at Each Floor](image)

**Figure 4. Vertical Displacement at Each Floor.**

Figure 5 shows the bending moment diagram of each beam at a different story level. Moreover, the maximum bending moments are seen to drop to the minimum at the exterior beams. The plot demonstrates that the interactive nature of the framed structure foundation reduces the bending moment in the inner columns and increases it in the outer beams.

![Variation of Moment for the beam at each Floor](image)
Figure 5. Variation of Moment for the Beam Member at Each Floor.

Figure 6 illustrates lateral displacement of the 12 piles along the depth of the foundation and shows that at the bottom of the piles, the displacements fall to zero. Furthermore, the structural response of the piles as they attempt to build the superstructure is an equilibrated position with respect to the direction of external loads.

Figure 6. Variation of Lateral Displacement Along the soil Depth.

Figure 7 shows the displacement of the soil along six layers under the building. This plot displays a reduction in the variation of the displacement along the depth of the soil media, with the displacement of each layer decreasing along the soil profile.

Figure 7. Variation of Displacement of Soil along the building.
Figures 8 and 9 show the contact pressure distribution below the building foundation at various elevations. These figures demonstrate the pressure distribution effect by the piles.

**Figure 7.** Variation of Vertical Displacement at Difference Level.

**Figure 8.** Stress $\sigma_y$ at each layer.
Figure 9. Stress $\sigma_y$ at Each Layer.

8.0 Conclusion

The purpose of this study involves the finite element method to model the structure and soil to indicate the effect of the foundation flexibility. The program was written by using “FORTRAN” language. This research provided the formulation of a beam bending element that evaluate the effects of transverse shear deformation and the axial interaction. A computer program was written to analyze the framed structure foundation pile soil mass on a hilly area.

The analysed model was a structure built on the hilly area with the slope angle 10°. The obtained results were displacement of the node, Moment, axial force and stresses. The graph of vertical displacement and lateral displacement of the beam, column and soil was plotted based on the result obtained by using the SSI program.

Based on interactive behavior, the bending moment in the superstructure was found to increase in the external beam and decrease in the internal force. The effect of the hill slope influenced the displacements and, subsequently, the forces in the superstructure. The difference between conventional analysis and interactive analysis are very significant. As a conclusion, Soil-Structure Interaction should be considered in the analysis of the structure and the soil.

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