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GROUND SUBSIDENCE DUE TO TUNNELING AND EFFECTS ON PILE FOUNDATIONS

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Abstract: Tunnels are essential components of infrastructure development projects. But, tunneling in urban areas essentially brings its interaction and hence conflict with existing deep foundations. The stage by stage construction of tunnel below the ground surface causes the settlement of the subsoil and ground surface and also induces axial stresses, moments, settlement etc. on the embedded foundation systems. The amount of settlement and stresses generated again may depend on a number of factors viz. the properties of soil considered, distance of pile foundation system to the tunnel, the tunnel construction phase (tunnel length) etc. The study aims at exploring the characteristics of subsoil profile under the influence of tunneling and feasibility of finite element analysis in studying the effects of variations of soil (sand; as considered here), proximity of tunnel to the pile and the tunnel staged construction. Results showed trends of sagging down subsurface settlement profile affecting the settlement behavior of pile. Also the phase by phase construction of the tunnel also influences the overall soil-pile behavior. Again as the friction angle increases, the deflection of the soil and hence the embedded pile foundations for all the considered cases were found to decrease.

Keywords: settlement; phases of construction; deflection; induced stress

1. Objectives and scope of the study:

The objectives of the present research study are to obtain realistic and reasonable predictions of ground subsidence and pile structural performance using the Finite Element (FE) method in 3D tunnel-soil-pile interaction studies.

The scope of the research encompasses two main parts. The first part involves studying the ground subsidence phenomenon caused by tunneling by revisiting the experimental and analytical work in that area and thereby developing a new FE model involving Non Linear Elasto-Plastic Isotropic analysis of the tunnel-soil-pile system. In the second part of this study, the model was tested for tunnel-soil-pile interaction analysis under the three excavation phases of the tunnel mentioned in the methodology to study the various factors influencing pile performance when subjected to tunneling induced ground movements. The tunnel pile system problem was analyzed while varying the soil properties; especially angle of friction and stiffness. Pile size and pile length were assumed constant for all analyses.

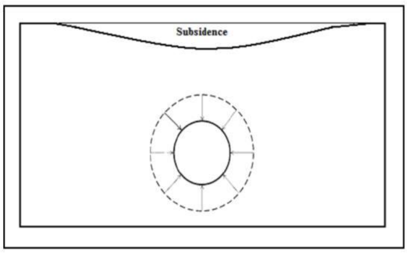

Figure 1: Tunneling activities represented by the circle will cause the surrounding soil to collapse as indicated by the arrows (Figure courtesy: [1]).

2. Study of ground subsidence and tunnel-soil-pile interaction: review of earlier work:

Various methods are available to the engineer to study and to some extent, predict soil deformation due to tunnel excavation.

(i) Analytical and Numerical methods

(ii) Experimental methods

Peck [2] established an empirical method of representing surface settlements due to tunneling. Based on data from a variety of sources, his results showed that the settlements above a tunnel are approximately symmetrical about the vertical axis of the tunnel. The equation states the vertical deflection can be expressed as
$S = S_{max} \exp(-x^2/2i^2)$, where S_{max} is the maximum settlement over the tunnel axis, x is the distance to the tunnel centerline and i is the inflection point in the normal distribution curve as shown in Figure 2. This curve is also commonly called as Gaussian settlement trough.

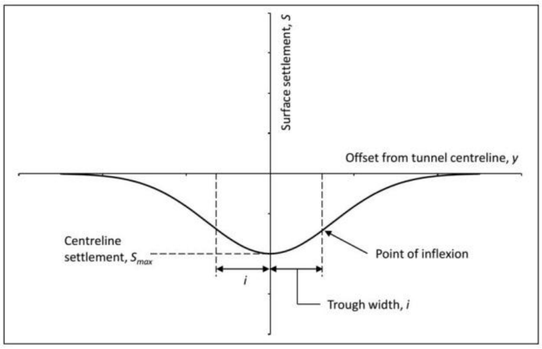

Figure 2: The reflected normal curve approximates the settlement trough due to tunneling according to [2] and [3] (Figure courtesy: ICE Research and Development Enabling Fund Grant 1021, Surface settlements due to deep tunnels in clay, Report no. 1021 03).

Mair and Taylor (1993) amalgamated two different methods of simulating the tunneling process. They found that for predicting the behavior of clay around a tunnel heading, a spherical cavity can be assumed whilst for predicting the behavior above and on the sides of the tunnel; a cylindrical cavity can be approximated. For a cylindrical cavity(unloaded form), the closed form plasticity solution is

$$\frac{\delta_r}{a} = \frac{S_u}{2G}\left(\frac{a}{r}\right)\exp(N-1)$$

where, δ_r = radial movement at radius r a = inner radius of the tunnel, N = stability ratio = σ_0/S_u, ζ = initial total stress at the cavity boundary. For N = 1, the soil behaved elastically; for larger values of N, a plastic zone developed around the tunnel which strongly influences the magnitude of the deformations.

[5] on the other hand adopted a methodthat is so-called virtual image procedure and comprised of some features modeled from fluid mechanics but modified for use in geomechanics. This modification directly replaces the velocities as a quantity from fluid flow into displacements. The use of a virtual image in the full-space would eliminate the stress acting on the free ground surface.

In brief, the analysis considers that a stress applied below (sink) a plane of symmetry has a dual image across that plane, essentially doubling the stress amount which in turn allows displacements to be determined. Any influence of the free surface could then be incorporated at the end of the solution. The method also assumes the soil medium to be infinite, and be homogeneously isotropic. He showed that, where displacements are imposed at some points and only the resulting strain field was required, the incompressibility equation provided much of the information. Hence if the remaining boundary conditions could be reasonably simplified so that this equation could be integrated, the solution obtained would be close to the exact solution.
[6] combined the virtual image method of [5] and equations from the theory of elasticity. There are two equations to describe both lateral and vertical directions of displacements. In addition, two geotechnical coefficients were introduced which they called ε for the radial strain and δ for the distortion or ovalization of the tunnel thereby include field measurements in order to obtain more refined surface

settlement evaluation.VB equationcan better describe tunnels that are placed at farther depths below ground. The influencing variable in this case is the Poisson's ratio υ at 0.5. A heave should be experienced close to the tunnel centreline at the surface.

D. E. L. Ong (2008) of Swinburne University of Technology [7], Malaysia studied abou**t** pile behaviour subject to lateral soil movement involving benchmarking of FE analysis against centrifuge modeling to study pile behavior subject to lateral soil movement and the effect of smearing the properties of a 3-D pile in a 2-D FE environment.

J. Surjadinata, T. S. Hull, J. P. Carter and H. G. Poulos, in 2006 **[8],** described a practical method of analysis to predict the effects of tunneling on existing single pile foundations. The method involves a combination of the finite element and boundary element (FAB) methods, The method allows prediction of the full three dimensional 3D response of the pile as tunnel excavation proceeds towards the pile and away from it. They obtained good agreement between predictions of the pile response obtained by the FAB method and a 3D finite-element analysis which specifically includes the pile in the finite-element mesh.

Again in 2004, **C. Y. Cheng, G. R. Dasari, C. F. Leung, Y. K. Chow, H. B. Rosser [9]**, carried out a research in which a series of 3D finite element simulations were performed to investigate the influence of tunneling induced ground movements on existing piled foundations. Soil convergence around the tunnel excavation was modeled using a kinematic method. Results show that for the case of a single floating pile, induced bending moments are generally negligible beyond a pile horizontal offset from tunnel centre greater than 2 tunnel diameters.

The phased simulation of tunnel boring in soft soil carried out by **W. Broere, R.B.J. Brinkgreve [10]**, also includes an investigative study on the tunnel induced deformation of a row of houses founded on piles. They adopted a phased excavation scheme used in Plaxis 3D Tunnel (as presented by Vermeer, 2001; Brinkgreve, 2001) to simulate the deformations caused by tunneling. A comparison was made with field measurements obtained at the Second Heinenoord Tunnel.

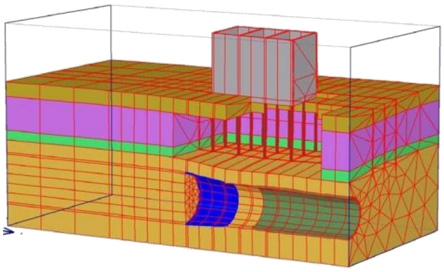

Figure 3: Partial view of the deformed mesh obtained in the analysis (Deformations enlarged 50 times).

3. Materials and methodology adopted:

The analysis considered here is elasto-plastic with the inclusion of five basic parameters of soil viz. modulus of elasticity, E, Poisson's ratio ν, (to account for elastic behaviour of soil), Angle of friction Φ, Cohesion C

(these two for soil plasticity), and angle of dilatancy Ψ (numerically 0°). The soil mass is considered as homogeneous and isotropic sandy soil. For sandy soil, essentially the drained condition is considered and the permeability is considered accordingly. The soil model adapted for analysis was the Mohr Coulomb model which known for its non-linearity in nature. The properties of the sand were varied throughout the study based on the angle of friction.

Table 1: Soil property variations throughout the study.

Soil Type	**Angle of Friction (ϕ)°**	**Cohesion (c) in kPa**	**Poisson's Ratio (ν)**	**Saturated Unit Weight (kN/m^3)**	**Unsaturated Unit Weight (kN/m^3)**	**Drainage Condition**

1	22	1	0.3	20	17	Drained
2	25	1	0.3	20	17	Drained
3	28	1	0.3	20	17	Drained
4	31	1	0.3	20	17	Drained
5	34	1	0.3	20	17	Drained
6	37	1	0.3	20	17	Drained

D modeling of the system

The finite element unit for generation of the model is a 15 noded wedge element, also called as volume element. The stress concentration, if any, is being taken care of by considering a finer mesh at the affected area.

Initial stress in soil prior to excavation

The initial horizontal stress is related to the vertical stress by the co-efficient of earth pressure, $K_{0.}$ ($\zeta_{h,0}$= $K_0\zeta_{v,0}$), where, $\zeta_{h,0}$ = Initial horizontal stress; $\zeta_{v,0}$ = Initial vertical stress

Tunnel staged excavation and volume loss

To carry out a staged construction, a cross section of the model (here, the tunnel-pile-soil system) is created in X-Y plane and in 3D extension of the model; the objects are extended along the Z plane perpendicular to the cross section. Objects are activated or deactivated trough different slices (portion between two consecutive Z planes) for simulating the tunnel pile system. Three stages of tunnel construction were considered. 10m, 25m, 50m (fully excavated).

Table 2: Specifications of the soil-tunnel–pile system used in the analysis.

Parameter	**Specification**
Soil-tunnel–pile Model	Model dimensions 200 x 50 x 50 m
Soil type	Homogeneos and isotropic sandy soil conforming to Mohr-Coulomb model
Pile	Concrete pile of size 0.5 x 0.5 m (square pile) and length 10 m, provided with a pile cap of size 1.5 x 1.5 x 0.5 m at the top Young's modulus, $E = 2.6 \times 10^6$ N/mm^2 Unit weight, $\gamma = 24$ kN/m^3 Model = Linear elastic
Tunnel	Circular tunnel of diameter 6m provided with spreyed concrete lining located at a depth of

	15m from pile tip. **Tunel lining:** EI = 2.2 x 10^7 kNm^2/m I = Moment of Inertia E = Young's modulus Poisson's ratio, ν = 0.15

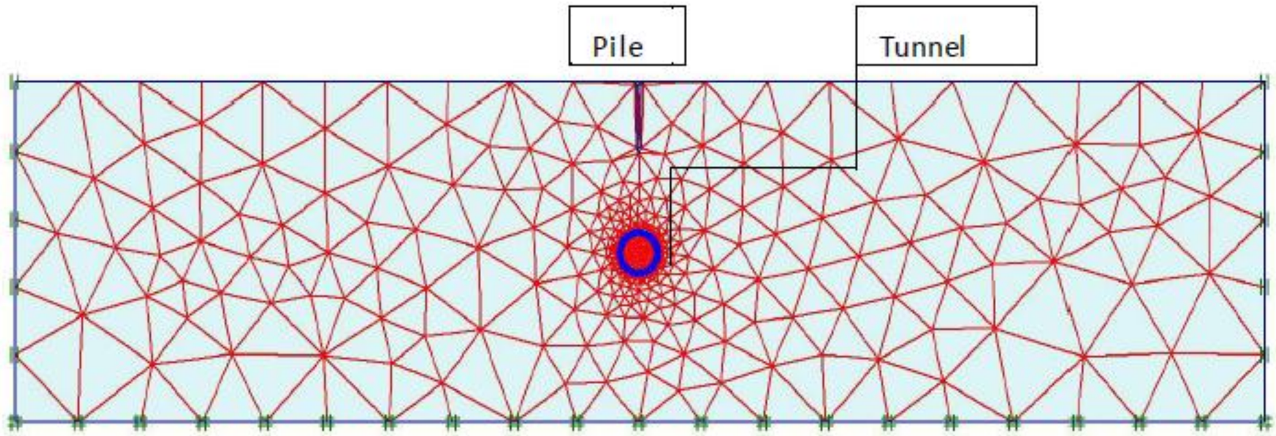

Figure 4: 2D finite element mesh of the system.

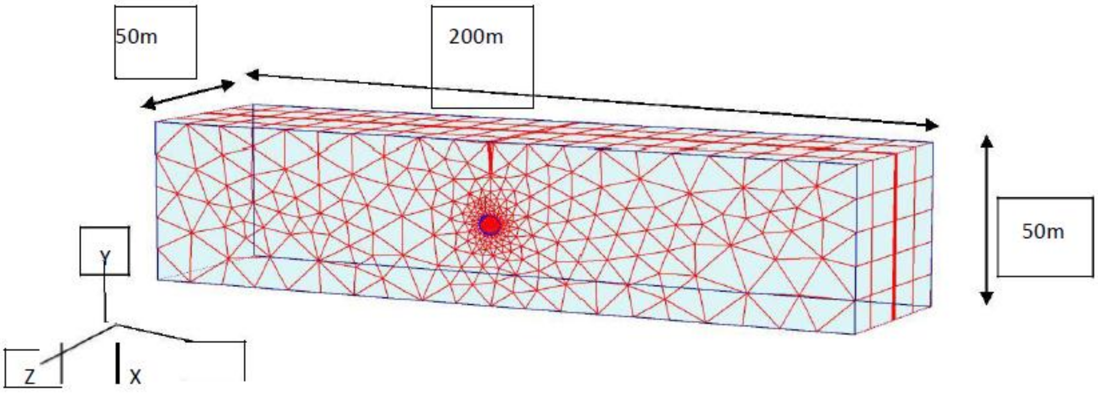

Figure 5: 3D extension of the mesh.

Again the amount of volume loss can be interpreted either from instrumentation and field monitoring or from empirical correlations or by the gap parameter value, which is optimized at 2% in the present study.

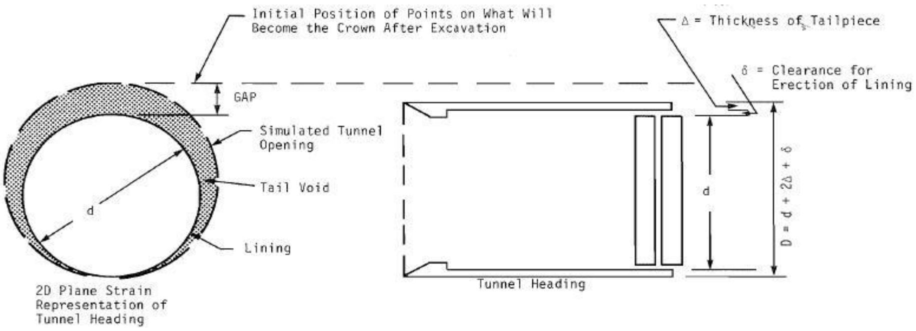

Figure 6: Definition of gap parameter (after Lo et al.1984).

The displacements of different nodes along all the 3 axes were determined during the analysis. The ground subsidence and the pile settlement are to be interpreted from these deformations.

4. Results and discussions:

For each tunnel construction phase, the pattern of the subsidence of the overlaying soil was noted;which were found to be alike for all the stages. The variations of the vertical deformation of the pile tip with respect to the angles of frictions were also recorded from the observations. The following plots showcase the data.

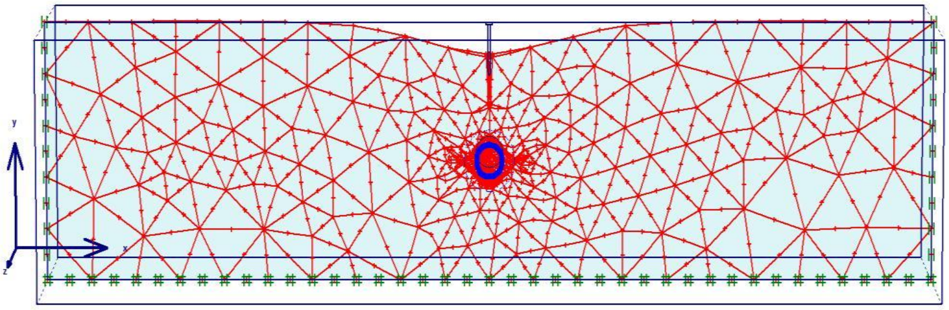

Figure 7: Deflected mesh around the tunnel

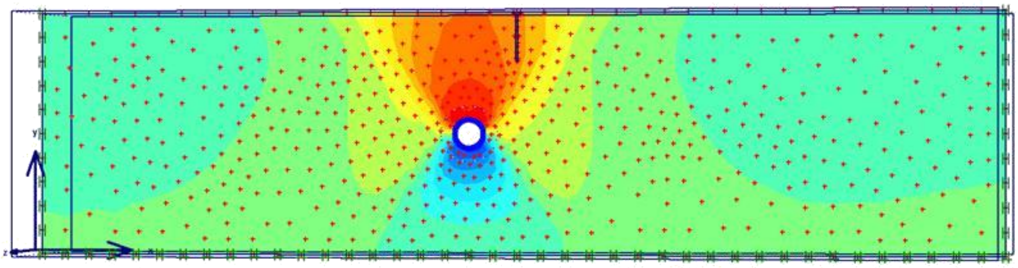

Figure 8: Vertical deflection of soil after tunneling. The deep red colour signifies heavysubsidence directly above tunnel, which is expected. Deflection towards tunnel cavity from all directions (blue indicates upward soil movement)is observable.

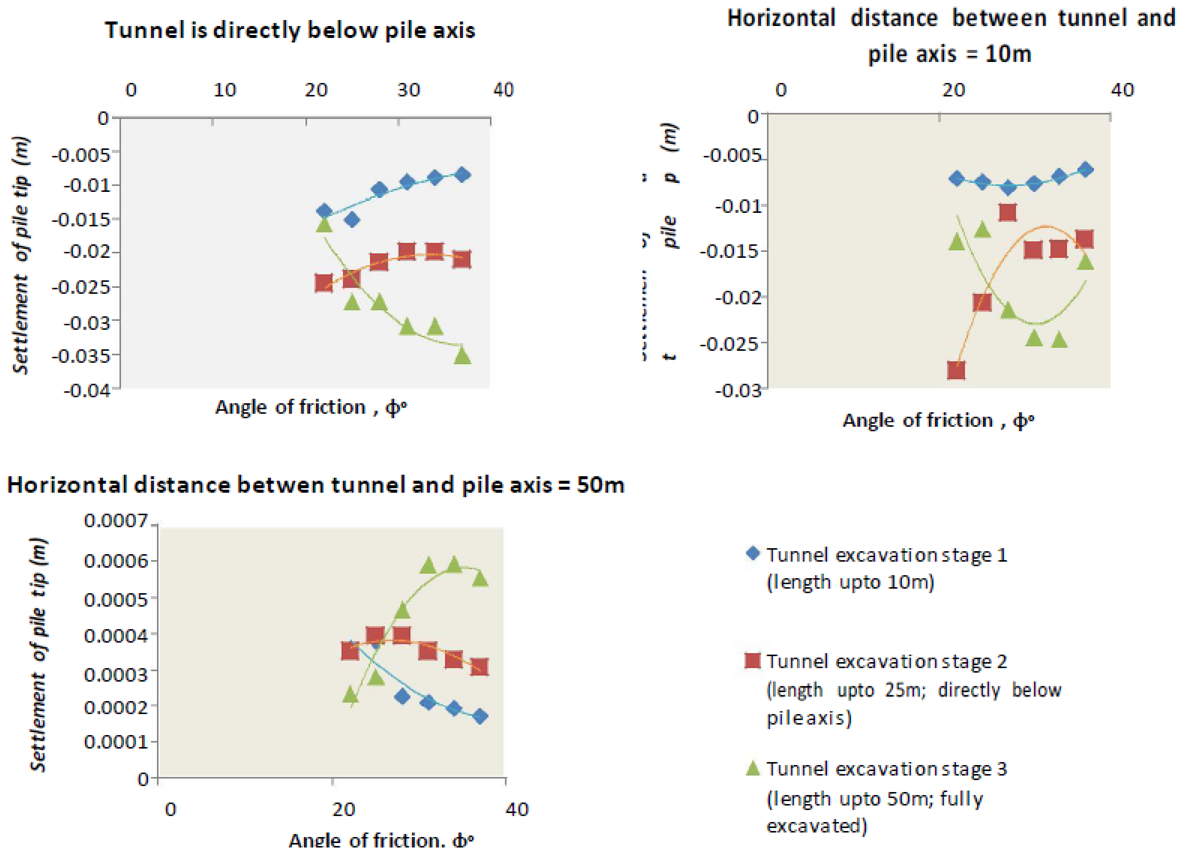

Figure 9: Variations of pile settlement with respect to angle of friction for 3 different proximities of the tunnel to the pile (0m, 10m, 25m).

Some general interpretations

- The subsurface subsidence profile was found to follow the Gaussian settlement trough given by [2] in almost all the cases.
- The settlement of pile in proximity of the tunnel is found to decrease with the increase in angle of friction of soil for a completed tunnel; but during the construction of tunnel, sometimes, the settlement is found to be more in sands having higher angle of friction.
- The horizontal proximity of the tunnel excavation to the pile is also noticed to influence the pile settlement (generally higher values in close proximity for settlement).

5. Conclusion:

Modeling of the soil pile tunnel system forms the backbone of any tunneling induced numerical analysis for tunneling excavation simulation. The soil model was carefully chosen so as encounter almost all the major parameters that may involve can be encountered.

Briefly the scope for further study on this topic will incorporate the following points:

- Variation in the soil mass (specially clayey and C-Φ) soil to be considered in the analysis.
- Anisotropicity, non-homogeneity and non-linearity of soil model in more realistic manner to be included in the behavior of soil to be considered in analysis.
- Pile group effect.
- Variation in shape and size of both tunnel and pile along with the distance between them are

important for a complete pile-soil-tunnel interaction analysis.

- Contact analysis of tunnel lining.
- Calculating the forces and bending moments acting upon the pile thus enabling modification or rectification of the structural designing of the piles.

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