PhD Thesis, titled

Response of metro tunnels to nearby basement excavation and building construction: Insights from physical and numerical modelling

Submitted by

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ABSTRACT

Among the various sustainable transport options in cities, underground metro systems are considered effective, as they help reduce surface-level traffic congestion and free up valuable land above ground for other developments. However, constructing underground tunnels requires careful attention to the safety of nearby existing structures. To address this, many analytical, semi-analytical, and numerical approaches, along with field monitoring, to assess and manage potential risks are available. As urban development increases the space around metro corridors, it becomes a prime area for new developments. Currently, many buildings are being constructed near metro lines, such as residential complexes and commercial centers, which include basement levels, primarily intended for parking facilities, canteens, and storage facilities. Therefore, it is critical to evaluate how these new constructions impact the existing tunnels. In the past, reports have also been available where tunnel damage is reported due to these types of new developments (mainly basement excavation) in the surrounding area of the tunnel. The aim of the present research study is to investigate the effect of basement excavation and structural loading on the existing tunnels using a comprehensive experimental and numerical method.

The study includes characterization of soils, model experiments, and three-dimensional finite element analysis. The different lab tests are conducted to find the material properties of the soil, which include triaxial tests for finding the engineering properties. A total of 20 model tests, which include 12 model tests in cohesionless soil (Yamuna sand) and 8 model tests in cohesive soil (Kaolinite clay) were conducted considering parametric variations of the number of basements, shear strength of the cohesive soil, groundwater table level, number of floors, and the horizontal offset distance from the tunnel. An experimental model setup, which includes a test tank and a hydraulically controlled tunnel excavation system, sheet pile wall, and a raft-integrated retaining wall, was fabricated for the model tests. HDPE pipe was selected to represent the tunnel lining. Strain gauges were used to assess the impact of the new construction on the existing tunnel in the model experiments. Strain gauges were fixed in both the longitudinal

and lateral direction at the Crown, Invert, and Spring Levels on the tunnel lining to measure the changes. The results obtained from model tests were used to validate the numerical modelling. Numerical analysis was also validated through existing field and lab test data available in the literature, and it was found that the numerical results are in good agreement. After the validation of the numerical model in PLAXIS, an extensive parametric study was carried out for both types of soil. The soil, tunnel lining, basement excavation, and foundation were modeled using an optimized mesh density. To reduce boundary effects, a sensitivity analysis was conducted, which helped in the determination of the final model dimensions. Soil was modelled as the hardening soil model. Parametric studies were performed by examining several key factors, including the cover, the horizontal distance between the tunnel, the size of the foundation, the number of basements, the location of the groundwater table, and the different strength values in the case of clay. A total of 288 finite element analyses were carried out, including all the parametric variations.

It is found from the results that the construction of basement excavation and structural loading has a significant effect on the existing urban metro tunnels. The impact of the presence of the water table was found to increase tunnel displacement by 10 to 20% when located at the surface compared to the invert level. Cover depth between the ground surface and the tunnel significantly affects deformation, as the effective distance between the tunnel and the foundation area is affected by the cover, and the deformation is found to increase by over 20%. The number of basement levels also had a significant impact, particularly when located closer to the tunnel ($X/D = 0.5$). In clayey soils, increasing shear strength from 20 to 30 kPa reduced displacement by more than 30%, though displacements still exceeded acceptable limits. Displacement was reduced significantly when the foundation was placed farther away ($X/D = 3.0$). The induced strain in the tunnel lining, both during excavation and the loading stage, is found to exceed 150 micro-strains (ACI, 2001) in many cases, which may eventually lead to the cracking of the tunnel lining. The displacement values exceed the limit specified by different regulating agencies (15 and 20 mm). This relative displacement may lead to spalling of the joints of the tunnel segments. The effect is observed to completely diminish beyond 12 times the dimension of the tunnel (Diameter) along the length of the tunnel and laterally, and was identified as safe for distances greater than 2.5 times the tunnel diameter. At last, it was observed that all the parametric variations have a significant impact on the existing tunnel due to the nearby new construction activities.