RESPONSE OF METRO TUNNELS TO NEARBY BASEMENT EXCAVATION AND BUILDING CONSTRUCTION: INSIGHTS FROM PHYSICAL AND NUMERICAL MODELLING

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by

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Submitted

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Dedicated to My Grandparents

CERTIFICATE

This is to certify that the thesis entitled **"RESPONSE OF METRO TUNNELS TO NEARBY BASEMENT EXCAVATION AND BUILDING CONSTRUCTION: INSIGHTS FROM PHYSICAL AND NUMERICAL MODELLING"** submitted by **MR. VINAY KUMAR SINGH** to the Indian Institute of Technology Delhi, is a record of the bonafide research work carried out by him under my supervision and guidance. This thesis work, in our opinion, has reached the standard, fulfilling the requirements for a **DOCTOR OF PHILOSOPHY** degree. The research report and the results presented in this thesis have not been submitted, in part or in full, to any other university or institute, for the award of any degree or diploma.

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ABSTRACT

Over the past few years, urbanization has grown rapidly due to factors such as population increase, economic progress, and advancements in technology. This trend has led to a significant migration of people from rural regions to urban centers, seeking improved job opportunities, education, healthcare, and quality of life. For any city's growth, a good transportation system and better land use patterns play a vital role in sustainable development. 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.

सार

पिछले कुछ वर्षों में शहरीकरण जनसंख्या वृद्धि, आर्थिक प्रगति और प्रौद्योगिकी में उन्नति जैसे कारकों के कारण तीव्र गति से बढ़ा है। इस प्रवृत्ति के परिणामस्वरूप बेहतर रोजगार अवसरों, शिक्षा, स्वास्थ्य सेवाओं और जीवन गुणवत्ता की तलाश में ग्रामीण क्षेत्रों से शहरी केंद्रों की ओर बड़े पैमाने पर जनसंख्या का पलायन हुआ है। किसी भी शहर के विकास के लिए एक सुदृढ़ ट्रांसपोर्टेशन सिस्टम और बेहतर लैंड यूज़ पैटर्न्स सतत विकास में महत्वपूर्ण भूमिका निभाते हैं। शहरी क्षेत्रों में उपलब्ध विभिन्न सस्टेनेबल ट्रांसपोर्ट विकल्पों में अंडरग्राउंड मेट्रो सिस्टम्स को प्रभावी माना जाता है, क्योंकि ये सतह स्तर पर ट्रैफिक कंजेशन को कम करने में सहायता करते हैं और भूमि के ऊपर के मूल्यवान क्षेत्र को अन्य विकास कार्यों के लिए मुक्त करते हैं।

हालाँकि, अंडरग्राउंड टनल्स के निर्माण में आसपास की मौजूदा संरचनाओं की सुरक्षा पर विशेष ध्यान देना आवश्यक है। इस उद्देश्य से संभावित जोखिमों का आकलन और प्रबंधन करने के लिए अनेक एनालिटिकल, सेमी-एनालिटिकल तथा न्यूमेरिकल अप्रोचेज, के साथ-साथ फील्ड मॉनिटरिंग तकनीकों का उपयोग किया जाता है। जैसे-जैसे शहरी विकास मेट्रो कॉरिडोर्स के आसपास बढ़ता है, यह क्षेत्र नए निर्माण कार्यों के लिए प्रमुख स्थान बन जाता है। वर्तमान में मेट्रो लाइन्स के निकट कई भवनों का निर्माण किया जा रहा है, जैसे रेजिडेंशियल कॉम्प्लेक्सेस और कमर्शियल सेंटर्स, जिनमें बेसमेंट लेवल्स प्रायः पार्किंग फैसिलिटीज, कैंटीन्स और स्टोरेज फैसिलिटीज के लिए बनाए जाते हैं। अतः यह अत्यंत आवश्यक है कि इन नए निर्माण कार्यों का मौजूदा टनल्स पर प्रभाव का मूल्यांकन किया जाए। अतीत में ऐसे कई रिपोर्ट उपलब्ध हैं जिनमें बेसमेंट एक्सकेवेशन जैसे नए विकास कार्यों के कारण टनल्स को क्षति होने की घटनाएँ दर्ज की गई हैं।

वर्तमान अनुसंधान अध्ययन का उद्देश्य बेसमेंट एक्सकेवेशन और स्ट्रक्चरल लोडिंग के मौजूदा टनल्स पर प्रभाव की जांच एक व्यापक एक्सपेरिमेंटल और न्यूमेरिकल पद्धति के माध्यम से करना है। इस अध्ययन में सॉइल कैरेक्टराइजेशन, मॉडल एक्सपेरिमेंट्स और थ्री-डायमेंशनल फाइनाइट एलीमेंट

एनालिसिस सम्मिलित हैं। विभिन्न लेबोरेटरी टेस्ट्स द्वारा सॉइल के मटेरियल प्रॉपर्टीज निर्धारित किए गए, जिनमें इंजीनियरिंग प्रॉपर्टीज प्राप्त करने हेतु ट्राइएक्सियल टेस्ट्स शामिल हैं। कुल 20 मॉडल टेस्ट्स संचालित किए गए, जिनमें 12 मॉडल टेस्ट्स कोहेशनलेस सॉइल (यमुना सैंड) में और 8 मॉडल टेस्ट्स कोहेसिव सॉइल (काओलिनाइट क्ले) में किए गए। इन परीक्षणों में नंबर ऑफ बेसमेंट्स, कोहेसिव सॉइल की शियर स्ट्रेंथ, ग्राउंडवॉटर टेबल लेवल, नंबर ऑफ फ्लोर्स तथा टनल से हॉरिजॉन्टल ऑफसेट डिस्टेंस जैसे पैरामेट्रिक वेरिएशन्स पर विचार किया गया।

मॉडल टेस्ट्स के लिए एक एक्सपेरिमेंटल मॉडल सेटअप तैयार किया गया, जिसमें टेस्ट टैंक, हाइड्रॉलिकली कंट्रोल्ड टनल एक्सकेवेशन सिस्टम, शीट पाइल वॉल तथा राफ्ट-इंटीग्रेटेड रिटेनिंग वॉल शामिल थे। टनल लाइनिंग का प्रतिनिधित्व करने के लिए एचडीपीई पाइप का चयन किया गया। मॉडल एक्सपेरिमेंट्स में नए निर्माण के प्रभाव का आकलन करने के लिए स्ट्रेन गेजेस का उपयोग किया गया। स्ट्रेन गेजेस को टनल लाइनिंग के क्राउन, इनवर्ट और स्प्रिंग लेवल्स पर लॉन्गिट्यूडिनल तथा लेटरल दिशाओं में स्थापित किया गया ताकि परिवर्तनों को मापा जा सके।

मॉडल टेस्ट्स से प्राप्त परिणामों का उपयोग न्यूमेरिकल मॉडलिंग को वैलिडेट करने के लिए किया गया। न्यूमेरिकल एनालिसिस को साहित्य में उपलब्ध फील्ड तथा लेबोरेटरी डेटा के माध्यम से भी वैलिडेट किया गया, और पाया गया कि न्यूमेरिकल रिजल्ट्स अच्छे सामंजस्य में हैं। प्लैक्सिस में न्यूमेरिकल मॉडल के वैलिडेशन के पश्चात, दोनों प्रकार की सॉइल के लिए एक विस्तृत पैरामेट्रिक स्टडी की गई। सॉइल, टनल लाइनिंग, बेसमेंट एक्सकेवेशन और फाउंडेशन को ऑप्टिमाइज्ड मेश डेंसिटी के साथ मॉडल किया गया। बाउंडरी इफेक्ट्स को कम करने हेतु सेंसिटिविटी एनालिसिस किया गया, जिससे अंतिम मॉडल डायमेंशन्स निर्धारित किए गए। सॉइल को हार्डनिंग सॉइल मॉडल के रूप में मॉडल किया गया।

पैरामेट्रिक स्टडीज़ में कवर, टनल और फाउंडेशन के बीच हॉरिजॉन्टल डिस्टेंस, फाउंडेशन का साइज, नंबर ऑफ बेसमेंट्स, ग्राउंडवॉटर टेबल की स्थिति तथा क्ले के मामले में विभिन्न स्ट्रेंथ वैल्यूज़

जैसे प्रमुख कारकों का अध्ययन किया गया। सभी पैरामेट्रिक वेरिएशन्स को सम्मिलित करते हुए कुल 288 फाइनाइट एलीमेंट एनालिसिस किए गए।

परिणामों से पाया गया कि बेसमेंट एक्सकेवेशन और स्ट्रक्चरल लोडिंग का मौजूदा अर्बन मेट्रो टनल्स पर महत्वपूर्ण प्रभाव पड़ता है। वॉटर टेबल की उपस्थिति से टनल डिस्प्लेसमेंट में 10 से 20% तक वृद्धि पाई गई जब यह इनवर्ट लेवल की तुलना में सरफेस पर स्थित था। ग्राउंड सरफेस और टनल के बीच कवर डेप्थ डिफॉर्मेशन को महत्वपूर्ण रूप से प्रभावित करता है, और डिफॉर्मेशन में 20% से अधिक वृद्धि देखी गई। नंबर ऑफ बेसमेंट लेवल्स का भी महत्वपूर्ण प्रभाव पाया गया, विशेष रूप से जब यह टनल के निकट (X/D = 0.5) स्थित था।

क्लेयी सॉइल्स में शियर स्ट्रेंथ को 20 kPa से 30 kPa तक बढ़ाने पर डिस्प्लेसमेंट में 30% से अधिक की कमी पाई गई, हालांकि डिस्प्लेसमेंट स्वीकार्य सीमाओं से अधिक ही रहा। फाउंडेशन को टनल से अधिक दूरी (X/D = 3.0) पर रखने से डिस्प्लेसमेंट में उल्लेखनीय कमी देखी गई। एक्सकेवेशन तथा लोडिंग स्टेज के दौरान टनल लाइनिंग में उत्पन्न स्ट्रेन कई मामलों में 150 माइक्रोस्ट्रेन्स (ACI, 2001) से अधिक पाया गया, जिससे अंततः टनल लाइनिंग में क्रैकिंग की संभावना उत्पन्न हो सकती है। डिस्प्लेसमेंट वैल्यूज़ विभिन्न रेगुलेटिंग एजेंसीज़ द्वारा निर्दिष्ट सीमा (15 तथा 20 mm) से अधिक पाए गए। यह रिलेटिव डिस्प्लेसमेंट टनल सेगमेंट्स के जॉइंट्स में स्पॉलिंग का कारण बन सकता है।

यह प्रभाव टनल की लंबाई तथा पार्श्व दिशा में टनल डायमीटर के 12 गुना से अधिक दूरी पर पूर्णतः समाप्त होता पाया गया, और टनल डायमीटर के 2.5 गुना से अधिक दूरी को सुरक्षित माना गया। अंततः यह निष्कर्ष निकाला गया कि सभी पैरामेट्रिक वेरिएशन्स निकटवर्ती नए निर्माण कार्यों के कारण मौजूदा टनल्स पर महत्वपूर्ण प्रभाव डालते हैं।

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LIST OF NOTATIONS

UN	United Nations
TBM	Tunnel boring machines
NATM	New Austrian Tunnelling Method
FE	Finite Element
E	Young's modulus
μ	Poisson’s ratio
IS	Indian Standards
C_u	Coefficient of uniformity
Cc	coefficient of curvature
G_s	Specific Gravity
γ	Unit weight
γ_{dmax}	Maximum dry density
γ_{dmi}	Minimum dry density
PI	Plastic index
CD	Consolidated drained
HDPE	High-density polyethylene
D_{ex}	Depth of excavation
D	Depth of penetration
RSL	Right Spring Level
LSL	Left Spring Level
D_w	Depth of the water table
GL	Ground level
IL	Invert Level
N_b	Number of basements
X	Horizontal offset distance between the edge of the raft and the center of the tunnel
D	Diameter of the tunnel
Su	Undrained Cohession

ACI	American Concrete Institute
ε	Strain
MC	Mohr Coulomb
HS	Hardening Soil
Ø°	Friction angle
p^{ref}	Reference pressure
E_{50}^{ref}	Plastic straining due to primary deviatoric loading
E_{oed}^{ref}	Plastic straining due to primary compression
E_{ur}^{ref}	Elastic unloading/reloading modulus
E_{oed}	Oedometer modulus
E_{oed}^{ref}	Reference Oedometer modulus
E_0	Initial tangent modulus
E_{50}	Secent Modulus at 50% strength
E_{ur}	Unload-reload modulus
c_u	Undrained Cohession
M	Bending Moment
I	Moment of Inertia
Q	Shear force
Ψ°	Dilatancy angle
m	Power for stress level dependency on stiffness
R_{inter}	Interface reduction factor
R-kn	Right Knee
R-sh	Right Shoulder
L-sh	Left Shoulder
L-kn	Left knee