EXPERIMENTAL AND NUMERICAL STUDIES ON THE EFFECTS OF RAFT FOUNDATION ON UNDERGROUND TUNNELS IN COHESIONLESS MATERIAL

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by

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Dedicated to My Beloved Parents
Shri Narender Kumar Gupta and
Shrimati Sushma Devi

CERTIFICATE

This is to certify that the thesis entitled **"EXPERIMENTAL AND NUMERICAL STUDIES ON THE EFFECTS OF RAFT FOUNDATION ON UNDERGROUND TUNNELS IN COHESIONLESS MATERIAL"** submitted by **MR. SUMEET MAHAJAN** to the Indian Institute of Technology Delhi is a record of the bonafide research work carried out by him under our supervision and guidance. This thesis work, in our opinion, has reached the standard, fulfilling the requirements for **DOCTOR OF PHILOSOPHY** degree. The research report and the results presented in this thesis have not been submitted, in part or full, to any other university or institute, for the award of any degree or diploma.

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ABSTRACT

The present research aims at investigating the effect of basement raft foundation excavation and loading on the existing tunnels using a comprehensive experimental and numerical (Finite Element: FE analysis) studies. The study includes characterization of materials, 1-*g* model experiments and two-dimensional (2D) and three-dimensional (3D) FE analyses. The direct shear tests and triaxial tests were conducted to determine engineering properties of the soil and the interface properties between soil and steel. Model experiments were carried out considering Yamuna sand as soil, which is filled at medium dense condition (60% relative density) based on typical field SPT-N values of Delhi region. An experimental model setup including tunnel excavation system was designed and fabricated in the laboratory for conducting the model experiments as per the experimental program. The results obtained from model tests are analyzed and used to validate the FE (2D and 3D) models.

Two-dimensional (2D) and three-dimensional (3D) analyses were carried out in PLAXIS software. Soil, tunnel lining basement excavation, and raft foundation were modelled with optimum mesh density. To minimize the boundary effects, sensitivity analysis was carried out in both 2D and 3D, and the dimensions of the model were arrived at. The behavior of Delhi silt is analysed using the Hardening soil constitutive model and response of the tunnel lining is compared with the Mohr-Coulomb constitutive model, widely used in practice. After analyzing the various geotechnical profiles of the Delhi region, it is noticed that water table is very deep therefore water table level is considered at a depth of 50 m below the bottom of the model. Standard boundary/support conditions are used. Fine mesh density was used for the overall soil model, but closer to the tunnel, fineness of mesh was increased. The parametric studies were carried out by considering the various important parameters: cover depth (*C/D* ratio), clear distance between tunnel and raft (*X/D* ratio), number of basements, width of raft foundation, and length of raft foundation (in 3D). It is found from

the results that the construction of basement excavation and foundation loading have pronounced effect on the existing urban metro tunnels. The effects are significant on all response parameters of tunnel lining, especially total displacement and strain. 2D-FE analysis indicated that the total displacement and strain are higher when excavation is closer to tunnel location and tend to become negligible when excavation is carried out at a distance greater than 2.5 times the tunnel diameter, for the loading conditions considered. Similar observation is found in 3D-FE analysis as well. The width of raft foundation and number of basements are also found to have significant effect on the tunnel response. Additional bending moments, axial and shear forces are mobilized in the tunnel lining due to excavation and foundation loading, for which the reinforcement details and thickness of tunnel lining may have to be verified. 3D-FE analysis indicated that the foundation with larger dimension placed across the tunnel and smaller dimension placed along the tunnel direction results in less influence on the tunnel lining due to the raft excavation and loading.

सार

वर्तमान शोध का उद्देश्य एक व्यापक प्रयोगात्मक और संख्यात्मक (फिनिट एलिमेंटः FE विश्लेषण) अध्ययनों का उपयोग करके मौजूदा सुरंगों पर बेसमेंट बेड़ा नींव खुदाई और लोडिंग के प्रभाव की जांच करना है। अध्ययन में सामग्रियों का लक्षण वर्णन, 1-जी मॉडल प्रयोग और दो-आयामी (2D) और तीन-आयामी (3D) FE विश्लेषण शामिल हैं। मिट्टी के इंजीनियरिंग गुणों और मिट्टी और स्टील के बीच इंटरफ़ेस गुणों को निर्धारित करने के लिए डायरेक्ट शियर टेस्टस और त्रीआक्सीअल टेस्ट्स किए गए थे। यमुना की रेत को मिट्टी मानते हुए मॉडल प्रयोग किए गए, जो कि दिल्ली क्षेत्र के एसपीटी-एन मूल्यों के आधार पर मध्यम सघन स्थिति (60% सापेक्ष घनत्व) पर भरा गया है। प्रयोगात्मक कार्यक्रम के अनुसार मॉडल प्रयोगों के संचालन के लिए सुरंग खुदाई प्रणाली सहित एक प्रयोगात्मक मॉडल सेटअप को डिजाइन और प्रयोगशाला में तैयार किया गया था। मॉडल परीक्षणों से प्राप्त परिणामों का विश्लेषण और FE (2D और 3D) मॉडल को मान्य करने के लिए उपयोग किया जाता है।

PLAXIS सॉफ्टवेयर में दो-आयामी (2D) और तीन-आयामी (3D) विश्लेषण किए गए। मिट्टी, सुरंग अस्तर, तहखाने खुदाई, और बेड़ा नींव इष्टतम जाल घनत्व के साथ मॉडलिंग की गई थी। सीमा प्रभाव को कम करने के लिए, संवेदनशीलता विश्लेषण दोनों 2 डी और 3 डी में किया गया है, और मॉडल के आयामों पर पहुंचे थे। दिल्ली सिल्ट के व्यवहार का विश्लेषण हार्डनिंग साइल कोंस्टीटूटिव मॉडल का उपयोग करके किया जाता है और सुरंग अस्तर की प्रतिक्रिया की तुलना मोहर-कूलम्ब कोंस्टीटूटिव मॉडल के साथ की जाती है, जो व्यापक रूप से व्यवहार में उपयोग किया जाता है। दिल्ली क्षेत्र के विभिन्न भू-तकनीकी प्रोफाइल का विश्लेषण करने के बाद, यह देखा गया है कि जल तालिका बहुत गहरी है इसलिए जल तालिका स्तर को मॉडल के तल से 50 मीटर की गहराई पर माना गया। मानक सीमा/समर्थन शर्तों का उपयोग किया गया। समग्र मिट्टी के मॉडल के लिए महीन जाली घनत्व का उपयोग किया गया था, लेकिन सुरंग के करीब, जाल की उत्कृष्टता वृद्धि की गई थी। विभिन्न महत्वपूर्ण मापदंडों पर विचार करके पैरामीट्रिक अध्ययन किया गया: कवर गहराई (सी/डी अनुपात),

सुरंग और बेड़ा (एक्स/डी अनुपात) के बीच स्पष्ट दूरी, बेसमेंट की संख्या, बेड़ा नींव की चौड़ाई, और बेड़ा नींव की लंबाई (3डी में)। परिणामों से यह पता चलता है कि बेसमेंट की खुदाई और नींव लोडिंग के निर्माण ने मौजूदा शहरी मेट्रो सुरंगों पर स्पष्ट प्रभाव डाला है। प्रभाव सुरंग अस्तर के सभी प्रतिक्रिया मापदंडों पर महत्वपूर्ण हैं, विशेष रूप से कुल विस्थापन और तनाव। 2 डी-एफई विश्लेषण ने संकेत दिया कि कुल विस्थापन और तनाव अधिक है जब खुदाई सुरंग स्थान के करीब होती है और अगर सुरंग के व्यास से 2.5 गुना अधिक दूरी पर खुदाई की जाती है, जब लोडिंग का प्रभाव नगण्य हो जाता है। इसी तरह का अवलोकन 3D-FE विश्लेषण में भी पाया गया है। सुरंग की प्रतिक्रिया पर बेड़ा नींव और बेसमेंट की संख्या का भी महत्वपूर्ण प्रभाव पाया जाता है। खुदाई और नींव की लोडिंग के कारण टनल लाइनिंग में अतिरिक्त बेन्डिंग मोमेंट, एक्सियल एंड शियर फोर्सेज मोबिलीज़ेड हो जाते हैं, जिसके लिए सुरंग के अस्तर के रएंफोर्समेंट विवरण और मोटाई को सत्यापित करना पड़ सकता है। 3 डी-एफई विश्लेषण ने संकेत दिया कि सुरंग के अक्रॉस रखा गया बड़ा आयाम और सुरंग दिशा के साथ रखे गए छोटे आयाम से खुदाई और लोडिंग के कारण सुरंग के अस्तर पर कम प्रभाव पड़ता है।

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NOTATAIONS

Units

^{0}	Degree
c	Centi
ft	Feet
g	Gram
g	Acceleration due to gravity
G	Giga
k	Kilo
M	Mega
m	meter
mm	millimetre
μ	Micron
N	Newton
Pa	Pascal
rpm	Rotations per minute
s	Seconds

Nomenclature

A_{sup},	Average area of Support (tunnel lining) cross-section per unit length
AF	axial force
B	Width of raft
B_{bsmt}	Basements
BM	Bending moment
C	Cover depth
$c = c_{ref}$	Cohesion
c'	Effective cohesion
ϕ	Angle of friction
ϕ'	Effective friction angle
ψ	Dilatancy angle

C_u	Coefficient of Uniformity
c_u	Undrained cohesion
C_c	Coefficient of Curvature
C^*	Compressibility Ratio
CD	Consolidated Drained Test
D	Diameter of prototype tunnel
D_e	Depth of embedment
D_m	Diameter of Model tunnel
D_r	Relative Density
DCM	Displacement Control Model
DMRC	Delhi Metro Rail Corporation
2D	Two-Dimensional
3D	Three-Dimensional
EPBM	Earth Pressure Balancing Machine
E	Young's Modulus of elasticity
E_u	Undrained modulus of soil
E_0	Initial tangent modulus of the soil
E_s	Deformation modulus of soil
E_{sup}	Young's Modulus of elasticity of support/tunnel lining
E_{st}	Young's Modulus of elasticity of steel
E_c	Young's Modulus of elasticity of concrete
E_{50}	Secant modulus at 50% strength
E_{50}^{ref}	Reference secant modulus
E_{oed}	Stress-dependent oedometer modulus
E_{oed}^{ref},	Reference Oedometer modulus
E_u	Undrained Young's modulus
E_{ur}	Unloading - reloading modulus
E_{ur}^{ref}	Reference unloading-reloading modulus
E_{HDPE}	Young's Modulus of elasticity of HDPE material
EI	Bending stiffness

$(EI)_P$	Bending stiffness of prototype
$(EI)_P$	Bending stiffness of model
EA	Axial stiffness
Exp	Experiment
f_c	Strength of concrete
f_y	Yield strength of steel
F^*	Flexibility ratio
$F_{max,Comp}$	Maximum axial compressive force
$F_{max,tens}$	Maximum axial tensile force
FE	Finite element
FAB	Finite and Boundary Element Model
FEM	Finite Element Method
G	Shear Modulus
G_s	Specific gravity
GM	Gravels with sand
h	Depth of tunnel horizontal axis level;
H	Depth of excavated soil
H_e	Depth of excavation
HDPE	High-Density Polyethylene
HS	Hardening soil constitutive model
$I_3 = I_2$	Moment of the Inertia
I_{sup}	Moment of the Inertia of Support (Tunnel Lining) Cross-section per Unit Length
K_0	Jaky's coefficient for in-situ stress.
L	Length
L_{de}	Length of the Unlined Zone
L_s	Out of plane spacing
m	Power of stress-level dependency of stiffness
M	Grade Mix
MC	Mohr-Coulomb
MCC	Modified Cam Clay

MRTS	Mass Rapid Transport System
MTS	Metro Jet System
ML-CL	Clayey sandy silt
ML-CL	Silty sand
N	Standard penetration value
n	Scale Factor
NATM	New Austrian Tunnelling Methods
NP	Non Plastic
N_c, N_q, N_r	Bearing Capacity Factors
N_b	Number of Basements
p	uniform pressure applied at the tunnel face
p^{ref}	Reference confining pressure
PIV	Particle Image Velocimetry Technique
PI	Plastic Index
ν	Poisson's Ratio
ν_{sup}	Poisson's Ratio for Support/Tunnel lining
ν_{ur}	Unloading-reloading Poisson's ratio
PVC	Polyvinyl Chloride
RCC	Reinforcement Cement Concrete
P	Primary
PGA	Peak Ground Acceleration
q_u	Ultimate Bearing Capacity
R	Tunnel Radius
RCC	Reinforced Cement Concrete
R_{int}	Strength factor/ Interface properties
R	Tunnel radius
RT	Right tunnel
RE	Basement raft excavation stage
RL	Final Raft Loading Stage
S	Number of Storeys
$s_{u,ref}$	Reference undrained shear strength of soil

SM-ML	Sandy silt with gravels
SF	Shear Force
SP	
T	Time
TBM	Tunnel Boring Machine
USCS	Unified Soil Classification System
X	Clear Distance from the Edge of Raft and tunnel Surface
x	lateral distance from tunnel centerline
X/D_m	Normalised Distance perpendicular to the model tunnel axis
X/D_m	Normalised Distance perpendicular to the prototype tunnel axis
Y	Distance Measured along the Length of Tunnel From Cross Section of The Tunnel Passing through the Center Line of Raft
Y/D_m	Normalised Distance along the model tunnel axis
Y/D	Normalised Distance along the prototype tunnel axis
z	Depth below ground surface
ZT1 (Crown-D)	Circumferential Strain at Crown,
ZT2(Crown-L)	Longitudinal Strain at Crown,
ZR1 (Right SL-D)	Circumferential Strain at Right Spring Level
ZR2 (Right SL-L)	Longitudinal Strain at Right Spring Level
ZB1 (Invert-D)	Circumferential Strain at Invert Level
ZB2 (Invert-L)	Longitudinal Strain at Invert Level
ZL1 (Left RL-D)	Circumferential Strain at Left Spring Level
ZL2 (Left RL-L)	Longitudinal Strain at Left Spring Level
Δ_{tp}	Distance Between the Centre of the Tunnel and the Pile Axis
i_{tp}	The Distance Between the Pile Tip and the Tunnel Spring-Line
Δ_{fp}	Distance Between the Tunnel Face and the Pile Axis
α_{dec}	Ratio of Stress Release
ρ_{st}	Density of steel
γ	Unit Weight of Soil
γ_{unsat}	Unsaturated Unit Weight of Soil

γ_{sat}	Saturated Unit Weight of Soil
γ_{xy}	Shear strain
σ_1	Major principal stress
σ_3	Minor principal stress
$\sigma_1 - \sigma_3$	Deviatoric stress
σ_3'	Average effective minor principal stress
σ_{xx}	Stress in *X*-Direction
σ_{yy}	Stress in *Y*-Direction
σ_{zz}	Stress in *Z*-Direction
$\sigma_{xy} = \sigma_{yx}$	Stress in *XY*-Plane
$\sigma_{yz} = \sigma_{zy}$	Stress in Z*Y*-Plane
$\sigma_{zx} = \sigma_{zx}$	Stress in *XZ*-Plane
$\varepsilon = \varepsilon_1$	Strain
ε	Ground loss ratio
ε^e	Elastic Strain
ε^p	Plastic Strain
L_{lin}	Distance Advanced by Tunnel Face in Each Step
L_{dec}	Length of the Unlined Zone
α_{dec}	Ratio of stress release
p	Uniform Pressure Applied at Tunnel Face
0.5Dm-EXP, 0.75Dm-EXP, 1.0Dm-EXP	Experimental Values when X/D_m = 0.5, 0.75 and 1.0
X/Dm = 0.5-Exp, *X/Dm* = 0.75-Exp, *X/Dm* = 1.0-Exp	Experimental values when X/D_m = 0.5, 0.75 and 1.0
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X/Dm = 0.5-3D

X/Dm = 0.75-3D PLAXIS 3D values when X/D_m = 0.5, 0.75 and 1.0

X/Dm = 1.0-3D

0.5Dm-P3D

0.75Dm-P3D PLAXIS 3D values when X/D_m = 0.5, 0.75 and 1.0

1.0Dm-P3D