NUMERICAL ANALYSIS OF INTERACTION BETWEEN TWIN TUNNELS AND TUNNEL FOUNDATION SYSTEMS UNDER STATIC AND SEISMIC CONDITIONS

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by

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CERTIFICATE

This is to certify that the thesis entitled "**Numerical Analysis of Interaction between Twin Tunnels and Tunnel-Foundation Systems under Static and Seismic Conditions**" being submitted by **Mr. Jishnu R B** is worthy of consideration for the award of the degree of **Doctor of Philosophy**. This thesis has been prepared under my supervision and guidance in conformity with the rules and regulations of Indian Institute of Technology Delhi and is a record of the original bonafide research work. The results presented in this thesis have not been submitted in part or full to any other universities or institutes for the award of any other degree or diploma.

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ABSTRACT

Due to the increased transportation demands and less utilizable space on the ground, metro transportation by underground means has become the preferred alternative in many developing economies. The capital city of India, New Delhi is no exception. But in congested cities like New Delhi, it becomes important to quantify the construction stage interactions between infrastructure facilities and metros. Another issue at hand is the high seismicity of New Delhi. Thus it becomes imperative that seismic interactions also need to be incorporated. Finally as an engineer, it also becomes important to ensure the safety of tunnel liner against static and seismic loads irrespective of ground conditions (liquefiable or non-liquefiable).

In this study, an attempt was made to capture the aforementioned interactions for the geotechnical/site-specific seismic conditions in New Delhi. Hence studies were subdivided in to twin-tunnel interactions, tunnel-shallow foundation interactions, tunnel-pile foundation interactions and behaviour of tunnels in liquefiable soils. After extensive numerical studies performed for geotechnical conditions in New Delhi, a pillar width of '*2D*' between twin tunnels was deemed safe against static and seismic interactions (Here '*D*' represents tunnel diameter). However, it was clear that cumulative strains induced on the tunnel liner during seismic activity caused serviceability issues. A critical observation during the course of this study was the manifestation of earthquake energy as amplified spectral responses around the pillar, especially for shallow tunnels (cover depth<*2D*). Thus it could be safely concluded that, any ground response analysis should include the presence of underground cavities (if present) for a realistic surface response. After performing tunnel foundation interaction studies, it was clear that, tunnel liners should be designed for additional safety factors, by incorporating the presence of foundations, if foundations were allowed to undergo maximum permissible settlements. The trend of safety factors with cover depth revealed an evident decrease of the same, as improvement of

soil modulus happens with depth, especially for Gibson soil profiles. Load displacement curves of the footing under varying construction sequence of the tunnel were observed and trends were understood. Volume loss phenomenon during the course of tunnel construction evidently resulted in the bearing capacity loss, when the effects of tunnel construction on existing foundations were considered. The reverse problem revealed the stiffening of soil deposits due to un-load reload phenomena, that occurs during tunnel construction. It was observed that, foundations constructed around the pillar of the tunnel were subjected to amplified spectral responses, resulting in high zonal factors. Tunnel- pile-foundation interaction studies revealed an evident "zone of large pile displacements" where tunnels were constructed near pile foundations. These zones were observed at 45^{o} with respect to the tunnel springing line. Any pile constructed at an offset ratio of less than 1.0 was subjected to high pile displacements, where ground improvement was unavoidable. On the similar lines a safe offset ratio (beyond which more than 80% of load carrying capacity of piles are assured) of 2.5 have been identified. For any pile constructed at a safe clearance (i.e. pile tip to tunnel crown distance) of more than $0.5D$, tunnel liner was found to be safe against safety and serviceability issues. Like it was observed for shallow foundations, piles constructed around the pillar were found to be subjected to amplified seismic responses. For tunnels constructed in liquefiable soils, especially at shallow cover depths, thrust increments on the tunnel should be given importance in design. Uplift was also observed as a serious problem in these cases for tunnels. The thrust increments on tunnels in liquefiable soils were identified due to the load-transfer phenomena between liquefied soil pockets and tunnel liner. While increasing the tunnel cover depth was suggested to be an option, considering practicality, ground improvement by grouting was suggested as a method to encounter these problems. All the mentioned studies regarding interactions and the behaviour of tunnels in liquefiable soils finally resulted in simplified design suggestions which could be easily incorporated to the design of underground structures, especially in New Delhi and in other places with similar geotechnical profiles.

सार

बढ़ती परिवहन मांगों और भूमिगत मेट्रो द्वारा भूमिगत परिवहन पर कम उपयोग करने के कारण कई विकासशील अर्थव्यवस्थाओं में पसंदीदा विकल्प बन गया है | इनमें भारत की राजधानी, नई दिल्ली कोई अपवाद नहीं है | लेकिन नई दिल्ली जैसे भीड़भाड़ वाले शहरों में बुनियादी सुविधाओं और महानगरों के बीच निर्माण चरण की बातचीत को निर्धारित करना महत्वपूर्ण हो जाता है | एक और मुद्दा नई दिल्ली की उच्च भूकंपी है | इस प्रकार यह अनिवार्य हो जाता है कि भूकंपीय बातचीत को भी शामिल करने की आवश्यकता है | अंत में एक इंजीनियर के रूप में यह महत्वपूर्ण हो जाता है कि ज़मीन की स्थिति के बावजूद स्थैतिक और भूकंपीय भार के खिलाफ सुरंग लाइनर की सुरक्षा सुनिश्चित की जाए (तरलीकृत या गैर द्रवीभूत)| इस अध्ययन में, नई दिल्ली में भू-तकनीकी / साइट-विशिष्ट स्थितियों के लिए पूर्वोक्त बातचीत को पकड़ने का प्रयास किया गया था। इसलिए अध्ययनों को जुड़वां सुरंगों की बातचीत, सुरंग उथले नींव की बातचीत, सुरंग ढेर नींव की बातचीत और सुरंगों के व्यवहार के द्रवीभूत जमाव में विभाजित किया गया था। नई दिल्ली में भू-तकनीकी स्थितियों के लिए व्यापक संख्यात्मक अध्ययन के बाद, जुड़वां सुरंगों के बीच '$2D$' की एक स्तंभ चौड़ाई को स्थैतिक और भूकंपीय बातचीत के खिलाफ सुरक्षित माना गया था (यहाँ (D) सुरंग व्यास का प्रतिनिधित्व करता है)| हालांकि, यह स्पष्ट था कि भूकंपीय गतिविधि के दौरान टनल लाइनर पर संचयी तनाव प्रेरित होता है, जो सेवाक्षमता के मुद्दों का कारण बनता है | इस अध्ययन के दौरान एक महत्वपूर्ण अवलोकन भूकंप ऊर्जा का प्रकटीकरण था, जो स्तंभ के चारों ओर प्रवर्धित वर्णक्रमीय प्रतिक्रियाओं के रूप में था, विशेष रूप से उथले सुरंगों के लिए (कवर गहराई $< 2D$) | इस प्रकार यह सुरक्षित रूप से निष्कर्ष निकाला जाएगा कि, किसी भी जमीनी प्रतिक्रिया विश्लेषण में यथार्थवादी वास्तविक प्रतिक्रिया के लिए भूमिगत गुहाओं की उपस्थिति (यदि मौजूद है) शामिल होनी चाहिए | सुरंग फाउंडेशन इंटरेक्शन अध्ययन करने के बाद, यह स्पष्ट था कि, नींव की उपस्थिति को शामिल करके अतिरिक्त सुरक्षा कारकों के लिए सुरंग लाइनरों को डिज़ाइन किया जाना चाहिए, यदि नींव को अधिकतम अनुमेय बस्तियों से गुजरने की अनुमति दी गई थी | सुरंग के अलग-अलग निर्माण अनुक्रम के तहत फुटिंग के लोड विस्थापन

घटता देखा गया था और रुझानों को समझा गया था | सुरंग निर्माण के दौरान आयतन हानि की घटना के परिणामस्वरूप क्षमता में कमी आई, जहाँ मौजूदा नींवों पर सुरंग निर्माण के प्रभावों पर विचार किया गया। सुरंग निर्माण के दौरान होने वाली अनलोड-पुनः लोड होने वाली घटनाओं के कारण उल्टी समस्या ने मिट्टी के जमाव को सख्त कर दिया | यह देखा गया कि सुरंग के स्तंभ के चारों ओर निर्मित नींव प्रवर्धित वर्णक्रमीय प्रतिक्रियाओं के अधीन थे, जिसके परिणामस्वरूप उच्च आंचलिक कारक थे | टनल-पाइल फाउंडेशन इंटरेक्शन अध्ययनों से एक स्पष्ट "बड़े ढेर विस्थापन के क्षेत्र" का पता चला जहां ढेर नींव के पास सुरंगों का निर्माण किया गया था | ये जोन 45° में सुरंग वसंत लाइन के संबंध में देखे गए थे | 1.0 से कम के ऑफसेट अनुपात में निर्मित किसी भी ढेर को उच्च ढेर विस्थापन के अधीन किया गया था, जहां जमीनी सुधार अपरिहार्य था | इसी तरह की तर्ज पर 2.5 की एक सुरक्षित ऑफसेट अनुपात (जिसके अलावा 80% से अधिक भार वहन करने वाले बवासीर की क्षमता का आश्वासन दिया गया है) की पहचान की गई है | *0.5D* से अधिक सुरक्षित क्लीयरेंस (पाइल टिप से टनल क्राउन) पर निर्मित किसी भी ढेर के लिए, टनल लाइनर को सुरक्षा और सेवाक्षमता के मुद्दों के खिलाफ सुरक्षित पाया गया था | जैसे कि यह उथले नींव के लिए देखा गया था, स्तंभ के चारों ओर निर्मित ढेरों को भूकंपीय प्रतिक्रियाओं के अधीन पाया गया था | तरलीकृत मृदा में निर्मित सुरंगों के लिए, विशेष रूप से उथले आवरण की गहराई पर, सुरंग पर जोर वृद्धि को डिजाइन में महत्व दिया जाना चाहिए | सुरंगों के लिए इन मामलों में उत्थान को एक गंभीर समस्या के रूप में भी देखा गया | तरलीकृत मिट्टी में सुरंगों पर जोर वृद्धि की पहचान तरलीकृत मिट्टी की जेब और सुरंग लाइनर के बीच लोड ट्रांसफर घटना के कारण की गई थी | टनल कवर की गहराई को बढ़ाने के लिए एक विकल्प होने का सुझाव दिया गया था, व्यावहारिकता पर विचार करते हुए, इन समस्याओं का सामना करने के लिए ग्राउटिंग द्वारा ग्राउंड सुधार का सुझाव दिया गया था | तरलीकृत मृदा में सुरंगों के आदान-प्रदान और व्यवहार के संबंध में सभी उल्लिखित अध्ययनों के परिणामस्वरूप अंत में सरलीकृत डिजाइन सुझाव प्राप्त होते हैं जिन्हें आसानी से भूमिगत संरचनाओं के डिजाइन में शामिल किया जा सकता है, विशेष रूप से नई दिल्ली और अन्य जगहों पर समान भू-तकनीकी प्रोफाइल के साथ |

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ABBREVIATIONS

A_{exc}	Extra Excavated Area
A_{tunnel}	Tunnel Area
B	Shallow Foundation/Pile Cap Width
BR	Bed Rock Depth
C	Cover Depth
C_u	Undrained Cohesion of the Soil
C/D_{min}	Minimum Cover Depth Ratio
CL	Critical Influence Line
Cro	At Tunnel Crown Location
D	Diameter/Dimension of Tunnel
D_f	Depth of Footing
DBE	Design Basis Earthquake
DMRC	Delhi Metro Rail Corporation
EPB	Earth Pressure Balancing
EQ	Equivalent Joint System ($\eta = 0.65$)
FD	Tunnel Face Displacement
FF	Free Field Case
F.E.M	Finite Element Method
FOS	Factor of Safety for Tunnel Liner
FP	Face Pressure of the Tunnel
FSL	Factor of Safety Against Liquefaction
GOI	Government of India
GNCTD	Government of National Capital Territory of Delhi
H	Depth up to the Tunnel Springing Line
Inv	At Tunnel Invert Location
L	Foundation Placed Over Left Tunnel
L_p	Length of the Pile
LT	Left tunnel

M	Tunnel Liner Moment
M2D	Tunnel Liner Moment (from Two-Dimensional Analyses)
MC	Mohr-Coulomb
MCC	Modified Cam Clay
MCE	Maximum Credible Earthquake
MRTS	Mass Rapid Transport System
N	Tunnel Liner Thrust
Nicr	Increment of Tunnel Liner Thrust in Percentage
NATM	New Austrian Tunnelling Methods
NBC	Bearing Capacity Under Normal Condition
NMT	Norwegian Method of Tunnelling
NJ	No Joints Considered (η = 1.0)
NL	Normal Influence Line
N2D	Tunnel Liner Normal Thrust (from Two Dimensional Analysis)
P	Foundation Placed Over Twin Tunnel Pillar
PR	Concrete Poisson's Ratio
P1, P2, P3	Profile -1, 2, 3
PEBC	Bearing Capacity Under Seismic Condition
PGA	Peak Ground Acceleration
PW	Pillar Width
PSHA	Probabilistic Seismic Hazard Analysis
R	Foundation Placed Over Right Tunnel
RT	Right tunnel
S	Foundation Settlement
S_{lat}	Lateral Settlement for Pile
S_{per}	Permissible Vertical/ Lateral Displacement for Pile
Spr	At Tunnel Springing Liner Location
SF	Safety Factor
T	Time in Seconds
T1, T2	Type-1, Type-2
TBM	Tunnel Boring Machine

V_l	Volume Loss in Percentage
UHRS	Uniform Hazard Response Spectra
X	Offset Distance of Pile from Tunnel
Z	Zonal factor
ZPA	Zero Period Acceleration