

**PREDICTION OF FREE FIELD GROUND
VIBRATION DUE TO UNDERGROUND
MOVING TRAINS: IN-SITU MEASUREMENTS
AND NUMERICAL MODELLING**

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**DEPARTMENT OF CIVIL ENGINEERING
INDIAN INSTITUTE OF TECHNOLOGY DELHI
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MOVING TRAINS: IN-SITU MEASUREMENTS
AND NUMERICAL MODELLING**

by

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DEPARTMENT OF CIVIL ENGINEERING

Submitted

in fulfilment of requirements for the degree of Doctor of Philosophy

to the



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DEDICATION

I would like to dedicate my thesis to my family, for their endless support and boundless love for making me the person I am today.

CERTIFICATE

This is to certify that the thesis titled “**Prediction of Free Field Ground Vibration Due to Underground Moving Trains: In-Situ Measurements and Numerical Modelling**” submitted by Mr. Arnab Sur, to the Indian Institute of Technology, Delhi, for the award of the degree of **Doctor of Philosophy**, is a bonafide record of the research work done by him under our supervision and guidance. The contents of this thesis, in full or in parts, have not been submitted to any other Institute or University for the award of any degree or diploma.

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ABSTRACT

In metropolitan cities underground railway lines of Mass Rapid Transit Systems (MRTS) are the lifeline to the daily commuters. When trains move along underground tunnels vibrations are generated at wheel-track interface. These generated vibrations then travel through the tunnel lining and surrounding soil to reach the ground surface and nearby structures. The major concern of this ground-borne vibration is annoyance of residents living nearby underground metro alignment. Moreover, although vibrations induced by railway traffic do not structurally damage modern buildings, there are incidences of structural damage or façade damage of heritage buildings and non-engineered masonry buildings. Therefore, detailed study of vibration characteristics of underground tunnels naturally becomes an important research subject. The objective is to develop an analysis method based on earlier research works on similar problems and validate the obtained results with the field measured results from operational metro line. Thereafter performing parametric study by varying parameters which influence the vibration characteristics of the problem. Using analysis results of parametric study perform regression analysis using ANN model to find relationship of individual parameter with the vibration response at the ground surface. Finally preparing design charts which may be used for accurately predicting peak vibration response at ground surface based on salient input parameters for any tunnelling project.

Numerical analysis model in 2D FE using coupled analysis of two sub-models is proposed. Another study in 3D FE is performed and the results are compared with in-situ measurements and 2D FE results. It is observed that 2D FE results are reliable and reasonably accurate. Therefore, parametric studies are performed in 2D FE analysis. The ground borne vibrations caused by underground train is influenced by several factors such as tunnel's shape, depth and distance of tunnel, the stiffness of the surrounding soil and the speed of the train. In some conditions of shallow depth tunnel and soft ground condition, the vibration levels at the surface can surpass the threshold that may cause damage to sensitive buildings. The vibration amplitude also exceeds the threshold limit of human perception for shallow depth tunnels. The produced design charts and ANN model can be useful for design engineers working in industry for assessment of ground vibration.

सार

महानगरीय शहरों में मास रैपिड ट्रांजिट सिस्टम (एमआरटीएस) की भूमिगत रेलवे लाइनें दैनिक यात्रियों के लिए जीवन रेखा हैं। जब रेलगाड़ियाँ भूमिगत सुरंगों से होकर चलती हैं तो व्हील-ट्रैक इंटरफ़ेस पर कंपन उत्पन्न होता है। ये उत्पन्न कंपन सुरंग की परत और आसपास की मिट्टी से होते हुए ज़मीन की सतह और आस-पास की संरचनाओं तक पहुंचते हैं। ज़मीन से होने वाले इस कंपन के कारण सबसे बड़ी समस्या भूमिगत मेट्रो लाइन के आसपास रहने वाले निवासियों की परेशानी है। इसके अतिरिक्त, हालांकि रेलवे यातायात से प्रेरित कंपन आधुनिक इमारतों को संरचनात्मक रूप से नुकसान नहीं पहुंचाते हैं, फिर भी विरासत भवनों और गैर-इंजीनियरिंग चिनाई वाली इमारतों के संरचनात्मक क्षति या इमारतों के अग्रभाग की क्षति की घटनाएं होती रहती हैं। इसलिए, भूमिगत सुरंगों की कंपन विशेषताओं का विस्तृत अध्ययन स्वाभाविक रूप से एक महत्वपूर्ण शोध विषय बन जाता है। इसका उद्देश्य समान समस्याओं पर पहले के शोध कार्यों के आधार पर एक विश्लेषण पद्धति विकसित करना और परिचालन मेट्रो लाइन से क्षेत्र-मापित परिणामों के साथ प्राप्त परिणामों का सत्यापन करना है। इसके बाद विभिन्न मापदंडों द्वारा प्राचलिक (पैरामीट्रिक) अध्ययन किया जाना है जो प्रस्तुत कंपन विशेषताओं की समस्या को प्रभावित करते हैं। प्राचलिक (पैरामीट्रिक) अध्ययन के विश्लेषण परिणामों का उपयोग करके ज़मीन की सतह पर कंपन प्रतिक्रिया के साथ व्यक्तिगत प्राचल (पैरामीटर) के संबंध को खोजने के लिए ANN मॉडल का उपयोग करके प्रतिगमन (रिग्रेशन) विश्लेषण किया जाना है। अंत में प्रारूप लेखाचित्र (डिज़ाइन चार्ट) तैयार किया जाना है, जिसका उपयोग किसी भी सुरंग परियोजना के लिए मुख्य आगत (इनपुट) मापदंडों के आधार पर ज़मीन की सतह पर चरम कंपन प्रतिक्रिया की सटीक भविष्यवाणी करने के लिए किया जा सकता है।

दो उप-मॉडलों के युग्मित विश्लेषण का उपयोग करके 2D FE में संख्यात्मक विश्लेषण मॉडल प्रस्तावित है। 3D FE में एक और अध्ययन किया गया है और परिणामों की तुलना यथास्थान (इन-सीटू) मापनों और 2D FE परिणामों से की गई है। यह देखा गया है कि 2D FE परिणाम विश्वसनीय और यथोचित सटीक हैं। इसलिए, प्राचलिक (पैरामीट्रिक) अध्ययन 2डी एफई विश्लेषण में किए गए हैं। भूमिगत ट्रेनों के कारण होने वाला ज़मीनी कंपन कई कारकों से प्रभावित होता है जैसे सुरंग का आकार, सुरंग की गहराई और दूरी, आसपास की मिट्टी की कठोरता और ट्रेन की गति। उथली-गहराई वाली सुरंगों और ज़मीनी सतह के नरम होने की कुछ परिस्थितियों में, सतह पर कंपन का स्तर, सीमा से अधिक जा सकता है जो संवेदनशील इमारतों को नुकसान पहुंचा सकता है। कंपन का आयाम उथली-गहराई वाली सुरंगों के लिए मानवीय अभिज्ञता की सीमा से भी अधिक हो जाता है। उत्पादित प्रारूप लेखाचित्र (डिज़ाइन चार्ट) और एएनएन मॉडल ज़मीन की सतह के कम्पनों के मूल्यांकन के लिए उद्योगों में कार्यरत रूपांकन अभियंताओं (डिज़ाइन इंजीनियरों) के लिए उपयोगी हो सकते हैं।

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LIST OF SYMBOLS

- C_g = vibration attenuation due to propagation through the ground
 C_{gb} = vibration attenuation (coupling loss) between the ground and the building
 C_b = vibration attenuation due to propagation in the building
 $[C]$ = viscous damping matrix comprising viscous damping terms arising from the structure and vertical and horizontal boundaries of the model
 δ = Dirac's delta function
 E = Young's modulus of the beam material
 E_s = dynamic modulus of soil
 E_r = modulus of elasticity of rail
 f = octave-band centre frequency
 G = dynamic shear modulus
 I_r = Second moment of area of rail cross section
 I = second moment area of the beam cross section about its neutral axis
 k = spring constant per unit beam length
 K_r' = foundation stiffness defined as the force required to displace unit length of the foundation through unit distance
 $[K]$ = stiffness matrix
 $[K']$ = hysteretic damping matrix of the soil
 L_r = rail velocity level
 $L_a(\text{tunnel})$ = Octave band acceleration on the wall of a subway tunnel during a train pass
 μ = Poisson's ratio of soil
 $[M]$ = mass matrix
 N = Uncorrected SPT Values
 ν = Effective internal viscous damping per unit length of foundation
 P = applied concentrated load
 R_{tr} = track transmission loss
 R_{tu} = tunnel transmission loss
 R_g = ground transmission loss

R_b = building transmission loss

$\{R\}$ = nodal load vector

$\{r\}, \{\dot{r}\}, \{\ddot{r}\}$ = nodal displacement, velocity and acceleration vectors respectively

ρ = Effective vibrating mass per unit length of rail / mass per unit length of beam

ρ_s = density of soil

t = time

v = Velocity of train

V_s = Shear wave velocity in m/sec

W = strain energy at maximum shear stress

ΔW = amount of energy dissipated per cycle of loading at maximum shear strain

w = deflection of the beam

x = space co-ordinate measure along the length of the beam