PHYSICAL AND NUMERICAL MODELING OF TUNNELS UNDER IMPACT AND BLAST LOADS

SWAPNIL MISHRA

DEPARTMENT OF CIVIL ENGINEERING
INDIAN INSTITUTE OF TECHNOLOGY DELHI
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by

SWAPNIL MISHRA

Department of Civil Engineering

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in fullfllment of the requirements of the degree of Doctor of Philosophy

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Dedicated to

All the Mothers and Mother - in - laws for supporting their

Daughters and Daughter- in-laws to fly High with Pride

CERTIFICATE

This is to certify that the thesis entitled **"PHYSICAL AND NUMERICAL MODELING OF TUNNELS UNDER IMPACT AND BLAST LOADS"** being submitted by **Ms. Swapnil Mishra** to the Indian Institute of Technology Delhi, is a record of the Bonafide research work carried out by her under our supervision and guidance. This thesis work, in our opinion, has reached the requisite standard, fulfilling the requirements for **DOCTOR OF PHILOSOPHY** degree.

The thesis or any part thereof has not been presented or submitted, in part or full, to any other University or Institute, for any degree or diploma.

Prof. N. K. Gupta
Emeritus Professor
Department of Applied Mechanics
Indian Institute of Technology Delhi
New Delhi - 110016, India

Prof. K. S. Rao
Professor
Department of Civil Engineering
Indian Institute of Technology Delhi
New Delhi - 110016, India

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"When walking through, difficult paths, and undue pressure, I never believed I can achieve it;
But with the continuous support of Guide, Almighty, Family, and Friends I successfully managed to receive it."

Place: New Delhi **Swapnil Mishra**

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ABSTRACT

With the increase in population and the shortage of ground space, underground exploration has become an important part of modern infrastructure. Today's civil infrastructure depends largely on underground structures. Underground facilities are used for a wide range of civil and military applications such as subways and railways, highways, material storage, and water and sewage conveyance. The most important of these applications are the metro tunnels.

Numerical simulation is relatively affordable compared to experimental studies and is becoming more and more indispensable in engineering analysis and design. The use of it is essential in the understanding of the complex response seen in some experiments prior to the development of any design guidelines. It is costly and difficult to conduct field test of blasting every time for reasoning proper support system required to resist such loads. There must be a generalized simple, empirical equation or correlation relating heavy devastating blast load with simple and low profile impact testing or impact load. From the simple static loading or low strain rate dynamic/impact load coming to the structure, one can predict the high strain rate blast induced deformations without performing any real blast test. There is a great urge in the researchers and scientists all over the world to predict the behavior of tunnels under surface blast and impact loads.

The thesis provides a detailed parametric study of shallow tunnels subjected to impact and blast load. It comprises of seven chapters. The thesis basically divides into four different stages, which are covered in Chapter 3, 4, 5, and 6 respectively. The first part of the thesis deals with the characterization of some new laboratory modeled synthetic rockmasses like GM1, GM2, and GM3. These rockmasses are formulated by mixing available geomaterials like kaolinite clay, Badarpur sand, PoP, Mica etc in different proportions and water content. Basic idea is to replicate the weathered and weak rockmasses which is found at upper few metres in natural field conditions. In order to capture deformations to the rockmass and shallow tunnels with and without lining in field, it is important to create a scenario where laboratory modeled rock tunnel assembly is subjected to dynamic loading conditions in the laboratory.

For achieving that, a servo controlled large scale impact testing facility (ITF) of 40 kg capacity is designed and fabricated, having immense capability of conducting drop tests rigorously. Impact testing have been performed on physically modeled rock tunnel assembly with C/D ratio varying from 1.0 to 0.5.

The second part of the thesis comprises of extensively framed experimental programme on casted rock tunnel models both lined and unlined case. Parameters responsible for increase/decrease in longitudinal deformation along tunnel length are varied and physical modeling is carried out. Load- displacement and Energy-displacement curves for different C/D ratio is determined with the help of Impact Testing Facility (ITF) in the present study.

The third part presents a detailed numerical procedure using ABAQUS/CAE 6.13 FEM commercially available software. It also depicts about the validation part of the experimental studies carried out in small scale models. An exhaustive numerical simulation have been carried out featuring shallow tunnels subjected to different loading conditions like static and impact loading.

It is observed that the designed numerical programme is capable of predicting deformation profile of tunnel but longitudinal displacements is over predicted for lined and unlined tunnels when compared with experimental results. Based on the tests conducted on rock tunnel model both experimentally/numerically with different cover depth to diameter of tunnel (*C/D)* ratio and varying surrounding rockmass, a new model based on Buchingham π theorem (Jones, 1989) for predicting deformation along the tunnel length is proposed. The general proposed equation based on numerical and experimental observation is given below.

$$\frac{Ymax}{D} = \frac{(E\prime/cD^3)}{35.6}\left(\frac{1}{C/D}\frac{E/c}{10407}\right) - 0.012$$

where Y_{max} is the maximum deformation obtained at the point of impact loading (mm), *D* is diameter of tunnel (mm), *C* is cover depth (mm), *E* is elastic modulus (MPa), *c* is cohesion of surrounding rock mass (MPa) and *E'* is incident energy (J) which is equal to kinetic energy of drop hammer and is function of mass of drop weight and velocity at time of incident.

The proposed equation is in good agreement with experimental investigations and numerical simulations. Due to difficulty in undergoing gigantic experimental and numerical programme very time when tunnels are subjected to impact loading for a given site condition, the proposed equation provides an insight about the crown deformation in the tunnel and deformation to the surrounding rockmass.

In the fourth and final part of the thesis, work is extended for incorporating deformations in the tunnels for real field conditions. Prototypes of rock tunnel assembly is created according to proper scaling laws and then subjected to both heavy impact loading and surface detonations. It is observed that the scaling of the velocity is very important to get the accurate results. It is found that the velocity of hammer in prototype is 2 times the velocity of hammer in the small scale model. It is also observed that the deformations of the tunnel crown in prototype are 100 times the deformations of the scaled model. The numerical investigation suggests that the deformation of the crown increases with increase in the blast loads. In the present study an exponential relation is developed to calculate the crown deformation under impact and blast loads. The proposed relation of U/C ratio with C/D ratio is expressed as:

$$\frac{U}{C} = Ae^{B\left(\frac{C}{D}\right)}$$

where U is crown deformation (mm), D is diameter of tunnel (mm), C is cover depth (mm), A and B are material parameters which depends on the type of loading. These parameters can be calculated by conducting the experimentation on the small scale models.

Several numerical analyses are illustrated in the thesis to demonstrate the efficacy of the developed methodologies. The results obtained from this study suggests that the proposed methodology in understanding the behavior of shallow tunnels in fragile ground conditions has the potential to provide useful information to the engineers before undergoing designing of blast resistant underground structures. The proposed equation and detailed study is capable of providing a basic understanding of the key parameters responsible for the failure and fracture of surrounding rockmass and tunnels under static and dynamic loading conditions.

सारांश

जनसंख्या में उत्तरोत्तर वृद्धि और जमीन की निरन्तर कमी के फलस्वरूप भूमिगत अन्वेषण आधुनिक आधारभूत संरचना का एक महत्वपूर्ण हिस्सा बन गया है। वर्तमान में नागरिक आधारभूत संरचना मुख्यरूप से भूमिगत संरचनाओं पर निर्भर करती है। आमतौर पर भूमिगत सुविधाओं का उपयोग विभिन्न नागरिक तथा सैन्य अनुप्रयोगों – जैसे कि भूमिगत मार्गों, रेलवे, राजमार्गों, भौतिक भंडारण एवं जल तथा मल पदार्थों आदि के परिवहन के लिए किया जाता है। नागरिक अनुप्रयोगों में सबसे महत्वपूर्ण अनुप्रयोग मेट्रो सुरंग हैं।

प्रयोगात्मक अध्ययन की तुलना में संख्यात्मक अनुकरण अपेक्षाकृत किफायती एवं सामर्थ्यवान होने के कारण अभियांत्रिकीय विश्लेषण और अभिकल्प में इसका अधिक से अधिक उपयोग प्रायः अपरिहार्य हो रहा है। किसी भी ढांचे के दिशानिर्देशों के विकास से पहले प्रयोगों में दृष्टिगोचर जटिल प्रतिक्रिया को समझने हेतु इसका उपयोग आवश्यक है। ऐसे भारों का प्रतिरोध करने के लिए आवश्यक उचित समर्थन प्रणाली को तर्कसंगत बनाने हेतु हर बार विस्फोट के क्षेत्र–परीक्षण का संचालन करना महंगा एवं कठिन होता है। भारी व विनाशकारी विस्फोट–भार एवं सरल और सामान्य पार्श्वचित्र या रूपरेखा पर प्रभाव–परीक्षण या प्रभाव–भार के मध्य सम्बन्ध दर्शाने हेतु एक सामान्यीकृत सरल एवं अनुभवजन्य समीकरण या सह–संबन्ध होना चाहिए। हम वास्तविक विस्फोट–परीक्षण किए बिना, सरल स्थैतिक–भारण या कम तनाव–दर संरचना से आने वाले गतिशील/प्रभाव भार से उच्चतनाव–दर विस्फोट प्रेरित विकृतियों की भविष्यवाणी कर सकते हैं। वर्तमान में वैश्विक स्तर पर शोधकर्ताओं और वैज्ञानिकों में सतह–विस्फोट और प्रभाव–भार के तहत सुरंगों के व्यवहार के बारे में पूर्वानुमान लगाने या भविष्यवाणी करने की बहुत उत्सकता है।

प्रस्तुत शोध–प्रबंध में प्रभाव और विस्फोट–भार के अधीन उथले सुरंगों पर सम्पादित एक आद्योपान्त प्राचालिक अध्ययन की विस्तीर्ण झाँकी प्रस्तुत की गई है। इसमें कुल सात अध्याय सम्मिलित किए गए हैं। शोध–प्रबंध मूल रूप से चार अलग–अलग चरणों में विभाजित है, जिनका वर्णन क्रमशः अध्याय 3, 4, 5 और 6 में किया गया है। शोध–लेख के पहले भाग में जीएम 1, जीएम 2 और जीएम 3 जैसे प्रयोगशाला में प्रतिरूपित कुछ नए संश्लेषित शिला–खण्डों अर्थात शैल–पिण्डों की विशिष्टता पर प्रकाश डाला गया है। इन संश्लेषित शैल–पिण्डों का निर्माण उपलब्ध भू–सामग्रियों– जैसे चीनी–मिट्टी, बदरपुर रेत, प्लास्टर–अॉफ–पेरिस एवं अभ्रक इत्यादि को अलग–अलग अनुपात में पानी में मिश्रित कर के किया गया है। इसकी मूलभूत कल्पना प्राकृतिक क्षेत्र की स्थितियों में ऊपरी सतह पर कुछ मीटर की गहराई तक पाए जानेवाले अपक्षीण और कमजोर शैल–पिण्ड की प्रतिकृति बनाना है। क्षेत्र में अस्तर के साथ व अस्तर के बिना शिला–खण्डों एवं उथली सुरंगों की विकृतियों को समझने के लिए एक ऐसा परिदृश्य बनाना महत्वपूर्ण है जहां प्रायोगिक रूप में प्रतिरूपित शैल–सुरंग समायोजन का प्रयोगशाला में गतिक उदभारण के आधीन परीक्षण किया गया हो।

इसे प्राप्त करने हेतु 40 किलोग्राम क्षमता की सर्वो–नियंत्रित, बड़े पैमाने पर समाघात परीक्षण–समर्थ नमूने की एक ऐसी संरचना का निर्माण किया गया जिसमें पतन–परीक्षणों को दृढ़ता से संचालित करने की अत्यधिक क्षमता विद्यमान है। प्रभाव परीक्षण को भौतिक रूप से निर्मित 1.0 से 0.5 की भिन्नता के C और D के बीच के अनुपात वाले शैल–सुरंग संयोजन पर संपादित किया गया है।

शोध-लेख के दूसरे भाग में विस्तृत रूप से तैयार किए गए प्रयोगात्मक अस्तरयुक्त और अस्तररहित शैल-सुरंग नमूनों पर कार्यक्रम सम्मिलित है। सुरंग की लंबाई के साथ अनुदैर्ध्य विरूपण में वृद्धि अथवा कमी के लिए जिम्मेदार भिन्न मापदंडों पर भौतिक प्रतिरूपण किया गया है। वर्तमान अध्ययन में प्रभाव-परीक्षण सामर्थ्य की मदद से C और D के बीच के विभिन्न अनुपातों के लिए भार-विस्थापन और ऊर्जा-विस्थापन वक्र रेखाओं का निर्धारण किया गया है।

शोध-प्रबंध के तीसरे भाग में वाणिज्यिक रूप से उपलब्ध अबैकस/सीएई 6.13 फेम साफ्टवेयर का उपयोग करके एक विस्तृत संख्यात्मक क्रियाविधि प्रस्तुत की गई है। इसमें छोटे पैमाने पर नमूनों में किए गए प्रयोगात्मक अध्ययनों के सत्यापन के अंश को भी प्रदर्शित किया गया है। इस भाग में स्थैतिक और प्रभाव-भारण जैसी विभिन्न भारण स्थितियों के अधीन उथले सुरंगों की विशेषता वाले एक विस्तृत संख्यात्मक अनुकरण का भी वर्णन किया गया है।

यह देखा गया है कि अभिकल्पित संख्यात्मक कार्यक्रम में सुरंग के विरूपण पार्श्वचित्र की सटीक भविष्यवाणी करने की क्षमता विद्यमान है, परन्तु प्रायोगिक परिणामों की तुलना में अस्तरयुक्त एवं अस्तररहित सुरंगों के अनुदैर्ध्य विस्थापनों के बारे में पूर्वानुमान अथवा पूर्वकथन उतना सटीक नहीं बल्कि आधिक्यपूर्ण होता है। शैल-सुरंग के नमूनों पर किए गए परीक्षणों के आधार पर C और D के बीच के भिन्न अनुपातों और शैल-संहति के घेरों की विभिन्न परिस्थितियों के साथ प्रयोगात्मक/संख्यात्मक रूप से किए गए दोनों परीक्षणों के आधार पर सुरंग की लंबाई के साथ विरूपण की भविष्यवाणी करने के लिए बकिंघम π प्रमेय पर आधारित एक नया प्रतिरूप प्रस्तावित किया गया है। संख्यात्मक और प्रयोगात्मक अवलोकन के आधार पर निम्न सामान्य समीकरण प्रस्तावित किया गया है:

$$\frac{\mathrm{Ymax}}{\mathrm{D}}=\frac{\left(E'/cD^{3}\right)}{35.6}\left(\frac{1}{C/D}\frac{E/c}{10407}\right)-0.012$$

उपरोक्त समीकरण में D सुरंग का व्यास है, C आवरण की गहराई है, E लोच का मापांक है, c चट्टान के आसपास के द्रव्यमान की सम्बद्धता का एक संयोजन है और E' आपतित ऊर्जा है जो हथौड़े की गतिशील ऊर्जा के बराबर है तथा आपतन के समय गिराए गए वजन के द्रव्यमान और उसके वेग के कार्य को दर्शाती है।

प्रस्तावित समीकरण प्रयोगात्मक जांच और संख्यात्मक अनुकरण के साथ अच्छे सामंजस्य की पुष्टि करता है। सुरंगों को किसी निर्दिष्ट कार्यस्थल की स्थिति के लिए भारण-प्रभाव के अधीन करने पर विशाल प्रयोगात्मक और संख्यात्मक कार्यक्रम को बारम्बार संपादित करने में उत्पन्न कठिनाई के दृष्टिकोण से प्रस्तावित समीकरण सुरंग में शिखर-विरूपण और आसपास की चट्टानों के विरूपण के बारे में अंतर्दृष्टि प्रदान करता है।

शोध-प्रबंध के चौथे और अंतिम भाग में क्षेत्र की वास्तविक स्थितियों के लिए सुरंगों में विकृतियों को समावेशित करने के कार्य का विस्तार किया गया है। सुरंग में चट्टानों के संयोजन के आदिप्ररूपों का उचित सोपान नियमों के अनुसार निर्माण करने के पश्चात उन्हें भारी भारण-प्रभाव और सतह-विस्फोट दोनों के अधीन किया गया है। इस कार्य के दौरान यह प्रेक्षित किया गया कि सटीक परिणाम प्राप्त करने के लिए वेग का अनुमाप बहुत महत्वपूर्ण है। यह देखा गया है कि

छोटे पैमाने के नमूने के वेग की तुलना में आदर्श नमूने में हथौड़े का वेग दो गुना होता है। अध्ययन के दौरान यह भी पाया गया है कि आदर्श नमूने में सुरंग के शिखर का विरूपण परिमापित नमूने में विकृतियों की अपेक्षा सौ गुना अधिक है। संख्यात्मक जांच से ऐसा विदित हुआ है कि विस्फोट–भार में वृद्धि करने से सुरंग के शिखर–विरूपण में भी बढ़ोत्तरी होती है। वर्तमान अध्ययन में प्रभाव और विस्फोट–भार के तहत शिखर में विरूपण की गणना के लिए एक घातीय संबंध विकसित किया गया है। C और D के अनुपात के साथ U और C के बीच के अनुपात का प्रस्तावित घातीय संबंध निम्न प्रकार से व्यक्त किया गया है:

$$\frac{U}{C} = Ae^{B\left(\frac{C}{D}\right)}$$

जहां U ताज विरूपण है, D सुरंग का व्या स है, C आवरण की गहराई है तथा A और B द्रव्यात्मक मानक हैं जो भारण के प्रकार पर निर्भर करते हैं। छोटे पैमाने पर नमूनों में प्रयोगात्मक विधि से इन मानकों की गणना की जा सकती है।

विकसित पद्धतियों की प्रभावकारिता को दर्शाने के लिए शोध–प्रबन्ध में कई संख्यात्मक विश्लेषणों का सचित्र वर्णन किया गया है। इस अध्ययन से प्राप्त परिणामों से यह पता चलता है कि कोमल एवं भंगुर–भूमि की परिस्थितियों में उथले सुरंगों के व्यवहार को समझने हेतु प्रस्तावित पद्धति में विस्फोट प्रतिरोधी भूमिगत संरचनाओं की रूपरेखा या ढांचा तैयार करने से पूर्व अभियंताओं को उपयोगी जानकारी प्रदान करने की क्षमता विद्यमान है। शोध–लेख में प्रस्तावित समीकरण और विस्तृत अध्ययन स्थिर और गतिशील भारण परिस्थितियों में चट्टानों के आस–पास के घेरों और सुरंगों की विफलता और विदारण के लिए जवाबदेह प्रमुख मानकों की बुनियादी समझ प्रदान करने में पूर्णतया सक्षम हैं।

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LIST OF NOTATIONS

F	normal and shear force
θ	stress component
H	overburden depth in mt
P_0	vertical stress just below the ground surface in MPa
K	insitu stress ratio
σ_θ	tangential stress in MPa
σ_r	radial stress in MPa
$\tau_{r\theta}$	polar coordinates of shear stress
a	radius of tunnel in mt.
r	overburden depth in radial component in mt.
z	overburden depth in Cartesian coordinates
υ	poission's ratio
σ_v and σ_z	vertical stress in MPa
σ_h	horizontal stress in MPa
σ_{tec}	tectonic stress due to plate tectonic stress in MPa
E_h	average deformation modulus in horizontal direction
γ	specific weight of rockmass in MN/m^3
DIF	dynamic increase factor
CRH	caliber radius head
a	shank radius
L	shank length

ρ	projectile material density
k	material constant
X	penetration (in inch)
d	diameter of projectile
Y	UCS of intact rock (psi)
W_T	projectile weight (lbs)
V_s	striking velocity (fps)
ρ	target bulk density (pcf)
RQD	rock quality index
L	length of the penetrator (mt.)
D	diameter of the penetrator (mt.)
n	nose length/round diameter
N	projectile nose performance constant
S	soil constant in scandian equation
M	penetrator mass
A	cross sectional area of penetrator (m^2)
V_o	impact velocity (m/s)
L/D	slenderness ratio
A,B, C	constants representing soil types
R/d	radius of ogive/projectile diameter
R^2	coefficient of determination
SEM	scanning electron microscope
UCS	unconfined compressive strength in MPa

V_p	sonic wave velocity in m/s
XRD	X-ray diffraction
X	material constant
$\Delta\sigma$	change in effective stress
σ_o	initial stress state
Ψ	dilation angle
Ξ	meridional eccentricity
e	deviatoric eccentricity
φ	angle of internal friction
S	deviatoric stress
r	third invariant of deviatoric stress
ϕ	deviatoric polar angle
p	equivalent pressure stress
q	mises stress
G	flow potential for Mohr Coulomb yield surface
σ_c	uniaxial compressive strength
σ_{cmax}	maximum uniaxial compressive strength
σ_t	Brazilian tensile strength
σ_1	maximum failure stress (major principal stress)
σ_3	confinment stress (minor principal stress)
τ	shear stress
σ_n	normal stress
ε_a	axial strain

ε_d	diametrical strain
ρ	density
υ	Poisson’s ratio
GM1	geomaterial 1
GM2	geomaterial 2
GM3	geomaterial 3
C	cover depth of tunnel (in cm and m.)
D	diameter of tunnel (in cm and m)
C/D	cover depth to diameter ratio
ITF	Impact testing facility
g	acceleration due to gravity (in cm/s^2)
LVDT	linear variable displacement transducer
EH	rockmass with low strength and high modular rario
L_1, L_1’, L_2….L_4	lvdt locations in rock tunnel model
SW	slightly weathered basalt
MW	moderately weathered basalt
HW	highly weathered basalt
PoP	plaster of Paris
TNT	tri nitro toulene used as explosive