CONSTRAINING THE FAR-FIELD MAXIMUM HORIZONTAL STRESS IN THE PLATE TECTONIC AREA

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ABSTRACT

In orogenic belts, the far-field horizontal stresses of tectonic origin often control the stress regime in the nearby regions. However, due to the non-uniform convergence of the tectonic plates, the far-field horizontal stresses show local variation. The syntaxial bends in the orogenic belts are areas where the orientation of far-field maximum horizontal stress shows marked deviation from the general trend of the plate movement. The Hazara Kashmir Syntaxis (HKS), located in the western Himalayas, is one such structure where the major crustal-scale faults are making a loop. This looping of the thrust faults makes it difficult to constrain the orientation of the far-field horizontal stresses in the core of the HKS. The Neelum Jhelum Hydropower Project's (NJHP) headrace tunnel traversing the core of the HKS revealed important information regarding the bedrock geology and in-situ stress state in the syntaxis. This information has not been previously used for constraining the far-field horizontal stresses in the area. The purpose of this study is to constrain the far-field horizontal stress in the HKS based on field observations and the geological and geotechnical data collected during the excavation of the headrace tunnel. The study utilised 3D finite element modelling approach to examine the complex interaction among the gravitational stresses due to current topography, exhumation-induced remnant stresses, excavation-induced perturbations, and far-field horizontal stresses. The simulated results were compared with the measured in-situ stresses for model validation. The simulation results demonstrated that the orientation and magnitude of gravitational principal and horizontal stresses at shallow depths are largely controlled by the current topography. The addition of the exhumation-induced gravitational remnant stresses caused changes in the orientation and magnitude of the principal stresses. However, the orientation of the maximum horizontal stress (S_H) was less affected. The S_H was also found to be less perturbed by the tunnel excavation. In the subsequent analysis, the models were compressed using horizontal straining from different directions to get S_H magnitude and orientation similar to the measured S_H. The results showed that the modelled S_H orientation at the different monitoring points could be achieved by applying different magnitudes of horizontal straining. These results suggested that the 0° Model with east-west directed maximum straining shows S_H trends consistent with the measured S_H trends. The east-west directed far-field horizontal stress derived during this study is consistent with the local movement direction of the Main Boundary Thrust (MBT) fault in the study area. The study revealed that the S_H orientation is a better candidate for constraining the far-field horizonal stresses. Moreover, the study revealed that the local variation in the strike of MBT causes local variations in the orientation of far-field horizontal stresses in the HKS.

ABSTRAK

Di dalam lingkaran orogenik, medan tegasan mendatar jauh pada tektonik asal sering mengawal rejim tegasan di kawasan berhampiran. Walau bagaimanapun, disebabkan penumpuan plat tektonik yang tidak seragam, medan tegasan melintang jauh menunjukkan variasi setempat. Lengkung sintaksis dalam lingkaran orogenik adalah kawasan di mana orientasi medan tegasan mendatar maksimum jauh menunjukkan sisihan yang ketara daripada arah aliran umum pergerakan plat. Sintaksis Hazara Kashmir (HKS), yang terletak di Himalaya barat, adalah salah satu struktur sedemikian, di mana, sesar skala-kerak utama membuat gelungan. Gelung sesar tujah ini menyukarkan untuk mengekang orientasi medan tegasan mendatar jauh dalam teras HKS. Terowong utama Projek Tenaga Hidro Neelum Jhelum (NJHP) yang merentasi teras HKS mendedahkan maklumat penting mengenai geologi batuan dasar dan keadaan tekanan di-situ dalam sintaksis. Maklumat ini tidak pernah digunakan sebelum ini untuk mengekang medan tegasan mendatar jauh di kawasan tersebut. Tujuan kajian ini adalah untuk mengekang medan tegasan melintang jauh di HKS berdasarkan pemerhatian lapangan dan juga data geologi serta geoteknik yang dikumpul semasa penggalian terowong *headrace*. Kajian ini menggunakan pendekatan pemodelan unsur terhingga 3D untuk mengkaji interaksi kompleks antara tegasan graviti akibat topografi semasa, tegasan sisa akibat penggalian, gangguan akibat penggalian dan medan tegasan mendatar jauh. Keputusan simulasi telah dibandingkan dengan tegasan di-situ yang diukur untuk pengesahan model. Keputusan simulasi menunjukkan bahawa, sebahagian besar topografi adalah mengawal orientasi dan magnitud prinsip graviti dan tegasan mendatar pada kedalaman cetek. Penambahan tegasan sisa graviti yang disebabkan oleh penggalian menyebabkan perubahan dalam orientasi dan seterusnya meningkatkan magnitud tegasan utama. Walau bagaimanapun, orientasi tegasan mendatar (S_H) kurang terjejas. S_H juga didapati kurang terganggu disebabkan oleh penggalian terowong. Di dalam analisis seterusnya, model telah dimampatkan dengan menggunakan terikan mendatar dari arah yang berbeza untuk mendapatkan magnitud dan orientasi S_H yang serupa dengan S_H yang diukur di tapak. Keputusan menunjukkan bahawa, orientasi S_H yang dimodelkan pada titik pemantauan yang berbeza boleh dicapai dengan menggunakan magnitud penegangan mendatar yang berbeza. Keputusan ini mencadangkan bahawa model bersudut 0° dengan penegangan maksimum terarah E-W menunjukkan aliran S_H selaras dengan aliran S_H yang diukur. Medan tegasan mendatar jauh terarah kepada E-W yang diperoleh semasa kajian ini adalah konsisten dengan arah pergerakan tempatan sesar Teras Sempadan Utama di kawasan kajian. Kajian itu mendedahkan bahawa orientasi SH adalah calon yang lebih baik untuk mengekang tegasan melintang medan jauh. Selain itu, kajian itu mendedahkan bahawa variasi tempatan dalam jurus MBT menyebabkan variasi tempatan dalam orientasi tegasan melintang medan jauh di HKS.

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LIST OF ABBREVIATIONS

BEM	-	Boundary Element Method
C	-	Cohesion
CGGC	-	China Gezhouba Group Company
Ch.	-	Chainage
DFN	-	Discrete Fracture Network
E_{rm}	-	Rock mass Deformation Modulus
FDM	-	Finite Difference Method
FEM	-	Finite Element Method
FMS	-	Focal Mechanism Solution
GB	-	Giga Bite
GHz	-	Gigahertz
GPa	-	Gigapascal
GSI	-	Geological Strength Index
HI	-	Hollow Inclusion
HKS	-	Hazara Kashmir Syntaxis
IKSZ	-	Indus Kohistan Seismic Zone
Ja	-	Joint Alteration
JCond89	-	Joint Condition based on Rock Mass Rating 1989 version
Jr	-	Joint Roughness
km	-	Kilometre
m	-	Meter
MBT	-	Main Boundary Thrust
MFT	-	Main Frontal Thrust
m*i*	-	Hoek-Brown constant for intact rock
MPa	-	Megapascal
NJC	-	Neelum Jhelum Consultant
NJHP	-	Neelum Jhelum Hydropower Project
RQD	-	Rock Quality Designation
S_1	-	Major Principal Stress
S_2	-	Intermediate Principal Stress

S_3	-	Minimum Principal Stress
Sd	-	Standard Deviation
SG	-	Specific Gravity
S_H	-	Maximum Horizontal Stress
S_h	-	Minimum Horizontal Stress
$S_{H, far\text{-}field}$	-	Far-field Maximum Horizontal Stress
$S_{h, far\text{-}field}$	-	Far-field Minimum Horizontal Stress
S_m	-	Octahedral Mean Stress
TBM	-	Tunnel Boring Machine
U/S	-	Upstream
UCS	-	Uniaxial Compressive Strength
UCS_{rm}	-	Uniaxial Compressive Strength of Rock mass
WSM	-	World Stress Map

LIST OF SYMBOLS

ϕ	-	The angle of Internal Friction
°	-	Degree
F	-	Force
ν	-	Poisson's Ratio
mε	-	Milli-strain
γ	-	Unit weight
Z	-	Depth below surface
β	-	Co-efficient of linear thermal expansion
G	-	Geothermal Gradient
E	-	Elastic Modulus
H	-	Overburden Height
τ	-	Shear Stress

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CHAPTER 1

INTRODUCTION

1.1 The Background of the Study

According to the plate tectonic theory, the earth's crust is divided into several large rocky slabs called "Plates", which move relative to each other. The places where these plates interact with each other are called plate boundaries. The plate boundaries are of three types, convergent, divergent, and transformed boundaries (Moernaut, 2020). Each of these boundaries initiates different features on the surface of the earth. The convergent boundary refers to the collision between plates. The Himalayan Mountain Range formed due to the collision between Indian and Eurasian tectonic plates during the mid-Eocene epoch. Due to the collision, the upper crust of the Indian plate sheard into a series of regional crustal thrust faults, namely, the Main Central Thrust (MCT), Main Boundary Thrust (MBT) and Main Frontal Thrust (MFT) (S. M. Ali et al., 2021).

Due to the continuous subduction of the Indian plate beneath the Eurasian plate, the regions lying on the Himalayan range are in a state of lateral compression. In general, the Indian plate is moving north to northeastward, which results in crustal shortening. This shortening accommodates along the crustal-scale faults (MCT, MBT, MFT etc.). However, the strike of these faults is irregular, due to which the crustal shortening direction in certain localities deviates from the general movement direction of the Indian plate. This deviation from the general trend is more pronounced in the north-western Himalayas. According to Treloar and Coward (1991), before the collision, the northernmost part of the Indian plate was diamond-shaped, with two oblique boundaries on its northern margin. The oblique convergence along these plate boundaries resulted in the post-collisional counterclockwise rotation of the Indian plate.

The Hazara Kashmir Syntaxis (HKS), located in the western Himalayas of Pakistan, is a structural feature that preserves records of the Indian plate rotation. The HKS is formed by a stack of thrust sheets along the major crustal faults namely the MCT locally named the Panjal thrust and the MBT, locally named the Murree thrust. Due to the tectonic-induced strains, the strata in the core of the HKS are folded (A. Ali et al., 2015). The overlapping and the continuous change in the dip direction of major thrust faults along the boundary of the HKS suggest complicated strain directions within the core of HKS. These strains can induce abnormal stresses, posing difficult ground conditions for the design and construction of underground engineering projects.

Higher crustal horizontal stress is a characteristic feature of the orogenic belts. However, constraining the magnitude and orientation of the far-field maximum horizontal stress ($S_{H,\ far\text{-}field}$) based on small-scale in-situ stress measurements is not straightforward. This is because the in-situ stress at a point below the ground surface generates as a result of the combined effect of the weight of overlying material, topographic undulations, rock mass strength and stiffness properties, lithology, exhumation-induced stresses due to erosion, residual tectonic forces, current tectonic forces, glaciation and deglaciation, the curvature of the earth and geological features and processes (Amadei & Stephansson, 1997). Therefore, before establishing the magnitude and orientation of the far-field horizontal stresses, we need to establish the contribution of all the other parameters to the total stress. In such circumstances, using a 3D numerical modelling approach can be helpful.

Several researchers used information from multiple sources in numerical models and presented it as a tool for inversion of regional in-situ stress. Ziegler et al. (2016) investigated near-surface stress tensors utilising three-dimensional elastic numerical models using morphological details, exfoliation fracture axis orientation, and limited in-situ stress measurement data from the Grimsel area (Switzerland). Figueiredo et al. (2014) characterised the in-situ stress field by integrating the measured in-situ stress results into a numerical model that considered the tectonics and topography effects. Similarly, C. Zhang, Feng, and Zhou (2012) determined the influence of topography on the distribution of in-situ stress within the Jinping II tunnel project site by using a 3D numerical modelling approach. Hence, this type of numerical treatment of in-situ stress data and information from other sources has great potential to be used in the geologically complex and tectonically active Himalayan range.

1.2 Problems Statement

Establishing the trend of the $S_{H, \textit{far-field}}$ in the core of HKS is a potential problem for geoengineers and geoscientists. Numerous researchers studied the formation of Hazara Kashmir Syntaxis (P Bossart et al., 1988; Paul Bossart et al., 1990), its geology (A. Ali et al., 2015; Calkins et al., 1975; Mughal et al., 2018; Zaheer et al., 2017), geological structures (Meigs et al., 1995; Mugnier et al., 1994; Zubair et al., 2022), seismicity (Avouac et al., 2006; Hussain & Yeats, 2009; Khalid et al., 2016; Sana & Nath, 2016), stress field (Amici et al., 2018; Pecher et al., 2008) and underground construction challenges (Naji, Emad, et al., 2019; Rehman et al., 2021; Yang et al., 2017). The HKS in the western Himalayas is formed by a stack of thrust sheets along the major crustal faults, namely the MCT and the MBT. Being surrounded by active thrust faults, the HKS is under the direct influence of high horizontal stresses of tectonic origin. The present-day crustal stress field is a function of time and space (P. Li & Cai, 2022) and evolved due to multistage tectonism, including historic tectonism and neotectonics (P. Li & Cai, 2018). In orogenic belts, erosion is considered the primary exhumation process (Ring et al., 1999). It is reported that the Himalayan foreland preserves records of erosional exhumation (Cerveny et al., 1988; Copeland & Harrison, 1990). In the exhuming upper crustal rocks, the regional tectonic straining, erosional unloading, and temperature variation tend to generate or relieve the bedrock stresses (Leith et al., 2014). Due to these reasons often, abnormal stresses are encountered in the orogenic belts. On a global scale, the stress orientation data is being compiled in the World Stress Map (WSM) (Heidbach et al., 2018). Based on the WSP data, the orientation of the $S_{H, \textit{far-field}}$ is often linked to the tectonic plate motion (Baouche et al., 2020; Coblentz & Richardson, 1995; Reiter, 2021). However, the major crustal faults form a loop around the HKS, thereby making it more difficult to establish the direction of $S_{H, \textit{far-field}}$.

Despite all our previous knowledge related to the HKS, the trend of $S_{H,\ far\text{-}field}$ is apparently less discussed in the literature. The oblique convergence of the Indian plate in the northwestern Himalayas has deformed and thickened the crust (Treloar & Coward, 1991). Due to the intense and multistage deformation, the rock in the HKS is folded with fold axes oriented in both NW-SE and NE-SW directions (A. Ali et al., 2015; Zubair et al., 2022), making it more challenging to decide on the direction of crustal shortening in the syntaxis. Moreover, the faults in the HKS are active and have thrust and strike-slip components that make a complex energy release pattern (Verma & Sekhar, 1986). Also, due to the frequent earthquake in this region, the stress regime may be undergoing frequent stress changes (Khalid et al., 2016; Sakaguchi & Yokoyama, 2017; Wu et al., 2016). Similarly, the in-situ stress measurements and rockbursting events reported during the excavation of the Neelum Jhelum Hydropower Project (NJHP) headrace tunnel revealed high magnitudes of principal stresses in the core of HKS. However, earlier, the in-situ stress measurement data and knowledge of the bedrock geology have not been interpreted and correlated with the movement of surrounding major crustal faults and exhumation processes.

The contemporary tectonic stress directions are often very stable and closely associated with the movement direction along the geological structures (Heidbach et al., 2018). Thus, the in-situ stress measurement results can be used to explore the movement direction along the nearby major faults. Many researchers incorporated the borehole in-situ stress measurement data of HKS in their studies (P.-X. Li et al., 2019; Naji, Emad, et al., 2019; Yang et al., 2017). However, their interpretation was only limited to the local stress-induced failures in the NJHP headrace tunnel. The in-situ stress in the core of the HKS is the result of the combined effect of regional tectonic straining, erosional unloading, and complex bedrock geology. Therefore, the attributes of tectonics, exhumation and topographic history will be reflected in the distribution and magnitude of the in-situ stresses (Leith et al., 2014). Although the interaction between these attributes is complex, however, the effect of each of these can be estimated by using numerical techniques.

The major crustal scale thrust faults tend to compress the core of HKS from different directions. Thus, making a complex orientation of the far-field horizontal stresses in the region. In orogenic belts the far-field horizontal stress is a major contributor to the in-situ stress field. A review of the relevant literature shows that the far-field horizontal stresses in the HKS have gained little attention in the past and is a potential research gap. Therefore, this study intends to explore the effect of current topography, residual stresses due to erosion of paleo-topography, bedrock lithology, excavation-induced disturbances, and tectonic straining on the measured in-situ stresses in HKS using 3D finite element modelling. The study will interpret the local trends of local maximum horizonal stress (S_H) at the in-situ stress measurement locations (monitoring points) and correlate it with the movement direction of the surrounding thrust faults with a view to establish the direction of $S_{H,\ far\text{-}field}$ in the region.

1.3 Research Aim and Objectives

This study aims to determine the orientation of the $S_{H,\ far\text{-}field}$ in the core of the HKS. To achieve the aim, the following objectives were considered for this study.

I. To investigate the effect of topographic undulations on the subsurface gravitational stresses

II. To analyse the residual stresses induced by the erosion of paleo-topography during the exhumation of the present-day landscape in the HKS.

III. To examine the vulnerability of the in-situ test locations to excavation-induced stress perturbations.

IV. To establish the orientation of Far-field maximum horizontal stress in the study area

1.4 Scope of the Study

This study estimates the orientation of far-field horizontal stresses in the core of HKS. For this purpose, the NJHP site was selected as the study area. The already available in-situ stress measurement data was collected and reanalysed to get the orientation of the principal and horizontal stresses at six different locations in the study area. The 3D finite element modelling approach using the RS3 software was selected for subsequent analysis. The 30m resolution SRTM (Shuttle Radar Topography Mission) data was used to generate the surface topography of the study area. That topography was then used to generate the 3D model geometry of the study area. The daily excavation reports of the NJHP headrace tunnel showed that the bedrock comprises folded layers of siltstone and sandstone. The folded rock layers were incorporated into the model based on the location and layer thickness as encountered during the excavation of the headrace tunnel. The intact rock material properties determined during different laboratory testing campaigns were assigned to the different rock layers in the model.

Two types of model geometries were generated, i.e., one for simulating the present-day topography and the other for simulating the exhumation-induced remnant stresses due to the erosion of the paleo-topography. To simulate the erosion process, the present-day topography was smoothened and raised to the highest elevation in the model. The erosion process was then simulated in five stages thereby bringing it back to the present-day topography. In the first phase of our modelling, only the gravity loading was considered. In the second phase, the models were compressed horizontally using displacement boundary conditions to simulate the far-field horizontal stresses. The displacement or strain magnitudes were set based on the length or width of the models. The stresses were constantly monitored at the six in-situ stress measurement locations. The modelled stress tensors were solved to get the magnitude and orientation of the principal and horizontal stresses. The vulnerability of the in-situ stresses to excavation-induced perturbations was also simulated. The simulated stresses were compared with the measured stresses for model validation purposes.

According to P Bossart et al. (1988), the HKS formed in three phases. This involves rotation of the mass transport direction from southwestward to southeastward. Studying the tectonic fabric based on surface exposures showed that the NNE-SSW trending folds axes and stretching lineation dominate in the KHS (A. Ali et al., 2015). However, the bedrock exposed during the excavation of the NJHP headrace tunnel revealed folded rock strata with an NW-SE trending fold axis consistent with the initial southwestward mass movement direction. Therefore, based on these observations, we consider the NW-SE trending fold axis in the numerical modelling. In the numerical analysis, the rock material stiffness properties were assumed as linear isotropic whereas the rock mass strength was defined using the Generalized Hoek-Brown failure criterion with elastic material type. Only dry conditions were considered in the analysis. Moreover, the study area is seismically active and frequent earthquakes may change the stress state in the region. This study only relies on the in-situ stress measurement data and does not consider the changes in stress state due to the seismic activities.

1.5 Significance of the Study

This study provides new insight into the complex in-situ stress situation in the core of the HKS by highlighting the bedrock geology and linking it to the historical changes in the mass transport direction, topography, exhumation, and regional horizontal shortening directions. The findings of this study will be helpful to engineers and geologists in in-situ stress characterisation and the design of underground structures in HKS and syntaxial bends elsewhere in general.

1.6 Thesis Structure and Organization

This thesis is divided into six chapters, each describing a particular section of this study. Chapter 1 describes the background of conducting this study, the problem statement that explains the need for this study, objectives, scope, and significance of the research. Chapter 2 reviews the existing literature on a brief history of the

Himalayan range, regional geology and tectonics of the northwestern Himalaya, exhumation and brief history of landscape changes in the Pleistocene to Holocene epoch. This chapter also describes the development of the Hazara Kashmir Syntaxial bend during the Miocene age, regional thrust faults, and regional shortening. The trends of horizontal tectonic stress in the region inferred from recent and past earthquake focal mechanism solutions are also discussed. Tunnelling challenges experienced during tunnelling in the Himalayan mountains. The application of numerical modelling for stability analysis of tunnels in area having complex geology and active tectonic stresses. Likewise, current issues and numerical approaches employed for stability analysis of underground structures, their merits and demerits, challenges, and suggestions for improving the existing practice were also presented.

Chapter 3 presents in detail the methodology adopted to carry out this research. Chapter 4 describes the details of the data collection and subsequent analysis. Chapter 5 shows the results obtained from the numerical models and interpretation of the results. Finally, Chapter 6 outlines the conclusions derived from this study and suggestions for further research.

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LIST OF PUBLICATIONS

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