SED

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Theme :

Tunnel / Under Ground Structures (Part-1)

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About IAStructE

Indian Association of Structural Engineers (IAStructE) is national apex body of structural engineers in India established with the objective to cater to the overall professional needs of structural engineers. The Association has become the source of expertise and information concerning all issues that involve structural engineering and public safety within the built environment. It has no commercial objective. IAStructE has signed an MoU with IStructE (Institution of Structural Engineers) of UK, JSSI (Japan Society of Seismic Isolation), SEAONC (Structural Engineers Association of Northern California), ICE (Institution of Civil Engineers, UK) and Structural Engineers Association of Nepal (SEANeP) for exchange of information and promotion of Structural Engineering profession

IAStructE is purely a professional learned society with the prime objective of supporting and protecting the profession of structural engineering by upholding professional standards and acting as a mouthpiece for structural engineers in India. It endeavors to ensure that its members develop the necessary skill in structural engineering and work to the highest standards by maintaining a commitment to professional ethics and standards within structural engineering. It strives for continued technical excellence; advancing safety and innovation across the built environment. It also strives to make available to the Government, Public Sector and Private Sector - a credible source of well qualified and experienced Structural Engineers. A nationwide database of Structural Engineers has been compiled and is being constantly updated.

The Association provides opportunity for all the members to develop skills in Structural Engineering and helps members to be at the forefront of Structural Engineering practice. Towards achievement of its aims and objectives, IAStructE is engaged in organizing the following:

- Continuing Professional Development (CPD) Courses for Professionals
- Refresher Courses for young & Practising engineers
- Student's orientation program
- Seminars/Workshops/Conferences
- Technical Lectures related to the latest technological advancements and Technical Discussions
- Publishing of Structural Engineering Digest (SED) Technical Journal of IAStructE

IAStructE is currently operating from four regional/state centres. These regional centres are located in the Eastern, Western, Northern and Southern parts of the country.

How to become a member ?

Membership form and details are available at http://www.iastructe.co.in/membership-form.html; For membership information and other details contact the Indian Association of Structural Engineers Secretariat.

From the Desk of President

Ramancharla Pradeep Kumar
President, IAStructE

Dear SED Readers,

Warm greetings on behalf of the IAStructE.

While we take a moment to reflect on how much we have accomplished in 2023, I am happy share with you yet another wonder edition of Structural Engineering Digest. I congratulate Publications Committee for bringing out his edition on a special topic "Tunnel/Underground Structures". The aim of this edition is to present state-of-the-art information on the tunnelling and underground structures which is of relevance to the construction industry.

A tunnel is an underground or undersea passageway. It is dug through surrounding soil, earth or rock, or laid under water, and is enclosed except for the entrance and exit, commonly at each end. Much of the early technology of tunneling evolved from mining and military engineering. It is used by transportation planners as a device to bypass obstacles that obstruct or otherwise make more costly the movement of freight and passengers. Justifying the use of this expensive technique to solve transportation problems involves consideration of the direct and indirect benefits and costs unique to the particular obstacle to be bypassed. Looking at the importance of the issue, the Bureau of Indian Standards (BIS) has released IS 5878 Code of practice for construction of tunnels and IS 15026 -Tunnelling methods in Rock masses, etc.

This special issue contains some of the extremely good papers from experienced and knowledgeable authors. They cover a wide spectrum of aspects like Harnessing the Power of Geophysics for Tunnel/ Underground Projects in Pre-Construction, opportunities and Challenges in underground Metro stations, Precast in Underground Station Construction, Settlement Analysis Due to EPB Tunneling: A Case Study from High Speed Underground Metro Project, A Case Study on Damage Assessment of Brick Sewer due to TBM Tunnelling, A design overview on Steel Fiber Reinforced Concrete (SFRC) in Tunnel segment linings, and Challenges of TBM Tunnelling in Delhi Metro Rail Project, Phase – III, CC-04. The readers are expected to find the articles useful in improving their understanding and continuing structural engineering practice.

Over past editions, IAStructE is receiving many encouraging comments from the readers for bringing out theme-based editions. I am happy to mention that our next edition is also dedicated to "Tunnel/ Underground Structures", for which articles, papers and case studies are invited. Your suggestions & feedback are important for its improvement.

I wish you all happy & prosperous New Year 2024.

With best regards,

(R. Pradeep Kumar)

From the Desk of the Chief Editor

Rajiv Ahuja
Chief Editor, SED

Dear SED Readers

Greetings on behalf of the Editorial Board.

This issue of SED is dedicated to the theme 'Tunnels and Underground Structures" and covers various aspects of their design, investigation, pre-casting in construction and a few case histories describing the challenges faced in construction. I sincerely thank all the authors who have contributed articles to this important issue. The paper by Dr. Sanjay Rana et al. highlights the crucial role of geophysical investigations starting from the initial planning and pre-construction through to construction and maintenance stages and describes various geophysical techniques adopted during various stages of planning & construction of tunnels and underground structures. There are a few very interesting case studies viz. the Challenges faced in underground metro stations in Bangalore Metro by Mr. Svaraj et el., Damage assessment of very old brick sewer due to TBM tunnelling in Kolkata by Mr. Neil Banerjee et el. and Challenges of TBM Tunnelling in Delhi Metro Project faced due to encountering of unforeseen geotechnical strata by Mr. Swarup Maiti. The paper by Dr. Laksman Rao et el., presents a case study of settlement analysis due to EPB tunnelling for a high-speed underground metro project on Delhi-Ghaziabad-Meerut corridor and compares the designed settlement with the actual settlement and volume loss observed. All these case studies present the unique challenges faced in design and during construction phase, the projects being located in busy urban habitats. The paper by Ms. Muthu Alias Vasukidevi P et el., describes the innovative use of precast elements in Bangalore Metro underground station construction to enhance the speed of construction while minimising the use of manpower & workspace and resulting in cost saving and better quality of construction. The paper by Mr. T. Cibin et el., presents an overview of the design considerations and methods for using Steel Fiber Reinforced Concrete (SFRC) in tunnel segment linings as an alternative to the conventional Reinforced Concrete segments.

There is an interesting article on life and achievements of Dr. E.Sreedharan who is an iconic civil engineer and administrator well known for his immense contribution to the construction of Metro Rail projects all over India written by Mr. Partha Pratim Banerjee, the guest editor of this issue. I am sure the readers will find all the articles quite interesting and informative and I welcome their suggestions and ideas for future issues of SED.

Happy Reading

With warm regards

Rajiv Ahuja

From the Desk of Guest Editor

Partha Pratim Banerjee
Guest-Editor

Tunnelling and Underground Space Engineering are indispensable in various sectors such as transportation, hydraulic power, urban infrastructures, subterranean city development, and utility projects. This field of Civil Engineering necessitates a harmonious interface of Knowledge between Geotechnical and Structural Engineering. The risk involved due to uncertainty in local geotechnical conditions, utilities have major impact in the risk profile of any underground projects. The recent tunnel accident near Barkot underscores the critical role of technical expertise and effective risk management in tunnelling and underground engineering. Safety is very important aspect to be taken care during design and construction of any underground projects. Recognizing the significance of underground and tunnel engineering, Indian Association of Structural Engineers decided to dedicate this issue to the theme "Tunnel/Under Ground Structures". This dedication spans two issues, with the current publication being the first part. Both editions feature a range of papers related to design & construction of Tunnel and Underground Structures. In this issue, we delve into the multifaceted aspects of underground construction, shedding light on the complexities faced by engineers and construction professionals. One of the primary challenges in underground and tunnel design is achieving a delicate balance between functionality, safety, and economy. There are articles that showcase innovative design approaches that not only meet the technical requirements but also integrate with functional requirement. One non-thematic paper has been incorporated into the SED editorial board's policy. It specifically delves into the achievements of Dr. E. Sreedharan, an eminent civil engineer and technocrat, showcasing his impactful contributions to the field of civil engineering. The younger generation is likely to find it exceptionally captivating.

I express my gratitude to all the authors and contributors for dedicating their time to compose papers and share their knowledge and experiences through this platform. My aspiration is that this compilation of articles serves as a source of inspiration, stimulates thought, and enhances your understanding and admiration for the remarkable accomplishments in the field of Underground Engineering.

Partha Pratim Banerjee

The Journey of Dr. E. Sreedharan: India's Iconic Technocrat and Metro Man

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Mr. Partha Pratim Banerjee, presently working as “Technical Director” in AYESA. Before joining AYESA, he worked in Egis and BSEC. He has rich experience in the field of Structural & Bridge Engineering in the areas of planning, design, detailing, cost optimization, tender documents for various major Bridges/Flyovers/Underpass/ Metro Viaduct/Stations/Tunnels, Multistorey Building Projects and other Structural Engineering works. He was closely associated with Dr. E. Sreedharan during his work as Technical Lead for Kochi Metro between 2012-2015. Mr. Banerjee had been impressed with his management brilliance, commitment, and innovative ideas during this association.

1. Prologue

Dr. Elattuvalapil Sreedharan, an eminent civil engineer and technocrat, has earned a plethora of accolades and recognition, both in India and abroad, for his exceptional contributions to landmark infrastructure projects. His unwavering commitment to taking on new challenges is exemplified by his decision to accept the post of Chairman and Managing Director of Konkan Railway even after his retirement. Dr. Sreedharan not only embraced this challenge but also successfully completed the formidable task of connecting northern Kerala to Mumbai through challenging forested and hilly terrain within a remarkable seven-year timeframe.

Sreedharan is celebrated as a trailblazer in India due to his unparalleled contributions as a technocrat who modernized and elevated the country's urban transportation systems to global standards. While his legacy includes monumental engineering and management achievements, it is his philosophy of unwavering commitment and ethical work that truly sets him apart. Dr. Sreedharan's steadfast dedication to his core values, both in his personal and professional life, laid the strong foundation for his unmatched success.

His unwavering commitment to these values propelled him to the pinnacle of achievement in the field of civil engineering. Dr. Sreedharan drew inspiration from the Bhagavad Gita, often sharing its messages with his colleagues. Beyond his professional accomplishments, he established a trust to assist financially disadvantaged students, enabling them to overcome obstacles and complete their education.

Dr. Sreedharan's life and work serve as a shining example of dedication, integrity, and excellence, leaving an indelible mark on India's infrastructure landscape and inspiring future generations to strive for greatness.

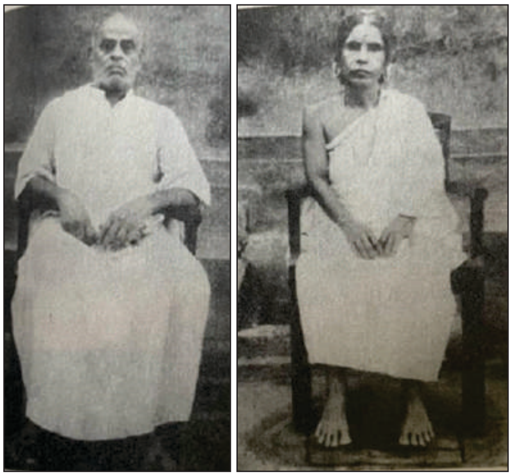
This paper represents the author's endeavor to provide a glimpse of the genius of a national icon, highlighting qualities such as integrity, hard work, sincerity, professional competence, and strong values that have not only influenced fellow civil engineers but also inspired the younger generation beyond his specific field of work.

2. Childhood, Early Life and Education

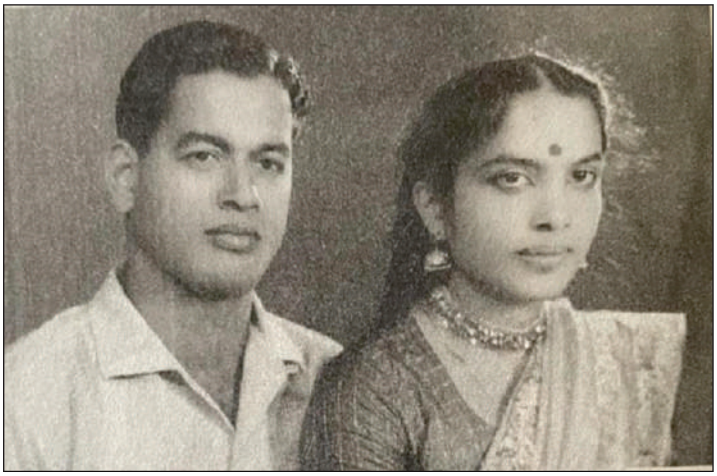
Sreedharan was born in Menon family on 12 June 1932 at Karukaputhur village, near Koottanad town, Kerala. He was the youngest child in the family after six brothers and two sisters. At that time, 'Marumakkathayam' was a system of matrilineal inheritance prevalent in Kerala.

Sreedharan's personal account sheds light on his family background and the values instilled in him by his parents. According to his version "Under the system, descent and the inheritance of property was traced through females. All of us children were staying with my mother at her house, which was run by her brothers. My father was quite well off, but as the tradition had it, he could not stay with my mother in the house. Mother's family was not doing so well. My mother told me that one day when my father visited her, he found her weeping as there was not as single morsel of food in the house for the children. My father could not stand this. He decided to take her and the siblings to his own house till he could arrange financial security for them. Later he moved to my mother's house and built a small abode for himself. He did not live with us as such but stayed on the same premises. It was from there that the family's real growth began.

My father was very particular about giving all his children a good education. People used to suggest that he buy another plot of land instead, but my father spent his savings to educate his children in the best possible way. It is from there that we got the real values of education and integrity."



Sreedharan's Father and Mother



Sreedharan with his Wife

Sreedharan's early fascination with trains is a captivating childhood memory (at the age of six) that he shared in an interview "I used to be fascinated by trains, and I remember my very first train journey from Pattambi to Payannur with my father. The rattling of the train's wheels and the fast-moving panorama outside the wood-framed windows of the coach they were in, mesmerized me throughout the five-hour-long journey. The electric surge of blood through the veins, the excitement and ecstasy as the steam engine blew its whistle and chugged ahead was an incomparable wonder to a child who had never seen a train before."

After finishing his primary schooling in Chathannoor, near his village, his father enrolled him in Quilandy Government school. This decision was influenced by the fact that Sreedharan's oldest sister had settled there. During his time at this school, he actively engaged in playing football and joined the school's scout group. Later on, he continued his education at Basel Evangelical High Mission School in Palakkad, where he completed his 10th grade. Subsequently, he pursued his intermediate education at Victoria College in Palakkad. After completing his intermediate studies, young Sreedharan followed the guidance of his elder brother, Krishna Menon, who played a significant role as a father figure and mentor in his life. Following his brother's advice, he secured admission at Kakinada Government Engineering College in Andhra Pradesh. His passion for football remained strong, and he even achieved the position of captain for the college's football team.

He finished civil engineering with first class honours, his elder brother and mentor Krishna Menon asked Sreedharan to attempt the Indian Railway Service of Engineers (IRSE) to get a job in Railways. As per his brother's advice, he took up an academic job as a lecturer in civil engineering at the Government Polytechnic in Kozhikode, during his preparation for IRSE. He used the library of colleges for the books to prepare for the railway examination. Despite receiving job offers from various institutions due to his outstanding academic performance, he made the bold decision to leave his academic position shortly after passing the IRSE exam. Instead, he chose to join the Mumbai Port Trust, eager to explore fieldwork and practical experiences in his career.

3. Professional Career

In an isolated and breezy island, Butcher's Island-at the coast of Mumbai (now Jawahar Dweep), Sreedharan started his career as an Engineer. Sreedharan reminisced about his early days in one of his interviews "I used to stay at Mahim with my elder brother. I would take the early morning harbour-line local train to Victoria Terminus (presently CST, Mumbai) and, from there board a city bus to reach the Gateway of India from where the company ferry would take us to the island. In the evening, the same journey would be taken in reverse. Starting at 5.30am, I used to get back home only by 9.00pm. So rigorous was the routine."

The IRSE exam results were declared within a year of working with Mumbai Post Trust. Sreedharan cracked the exam with seventh rank in the country and was among the 18 candidates selected for Indian Railways Services for Engineers. He became the first member of his family to join Railways. A little-known fact about Sreedharan is that he not only loves to travel by train but also loves to collect models of trains. Sreedharan's wife, Radha Sreedharan, shared a charming detail about her husband in an interview "Whenever he goes, he comes back with trains. He picks them up on all his trips abroad and in India, these toy train sets. He brings them home, arranges them, and plays with the grandchildren playing with them."

The fledgling years of his career began at Bangalore in Southern Railway zone, but he was transferred to Shornur in Kerala after six months. He got the news of his father's death when he was posted in Shornur. Despite this emotional setback in his early career, Sreedharan engaged himself candidly in his work. Sreedharan's first major assignment was at the ongoing construction of a metre gauge rail line between Ernakulam and Kollam as an Assistant Engineer. Govind Parameswara Warrier, the legendary railway civil engineer, was leading the project. Warrier who identified the spark in young Sreedharan, always supported him professionally throughout his professional life. The project was completed in the year 1957 and opened for rail traffic in January 1958. He was transferred to Bezawada (now Vijaywada) as Divisional Engineer at the age of 26. It was the first time in Railways that someone so young (3 years experience) became a divisional engineer. Sreedharan was soon sent off to Hubli as he offended a senior officer by refusing to favor certain contractors. But the same senior officer had been shifted to Hubli too, G.P. Warrier, then Chief Engineer in the construction department, sensed the problem and counselled him to join the construction department. In one of his interviews, Sreedharan reflected on the early years of his career in the Indian Railways, "In the first 15 years of service in Indian Railways, I got 25 transfers. Some of these were planned, as they wanted me to get exposed to various kinds of workings. The other reason was that initially, I was handily available as bachelor. All this helped me quite a lot-it helped me to evolve a philosophy that one should not take transfers as a punishment."

The first signature Project- Pamban:

The restoration and re-construction of India's first Sea Bridge, The Pamban Bridge- the rail link between Rameswaram to Dhanushkodi, had built Sreedharan's reputation by himself. The Pamban bridge was built by the British and opened to the public in 1914, with a 'Scherzer' span, comprised of two leaves/sections used for navigational purposes. The engineering marvel, Pamban Bridge's major portions had been washed away by the cyclone on 22nd December 1964. Six coaches of train no 653, a passenger train between Pamban & Dhanushkodi, had been also washed away along with the bridge with a death toll of between 115 to 200. The Railways Ministry gave the restoration/reconstruction work of the bridge to Southern Railway with a deadline of six months. The bridge has two branch arms at Pamban, one leading to Rameswaram and the other to Dhanushkodi. Railways decided to abandon the bridge towards Dhanushkodi, since the city had been destroyed by cyclone and later Government of Madras declared the town unfit for living.

At that time, Mr. G.P. Warrier was Chief Engineer with Southern Railways and Mr Bankim Chandra Ganguli was the General Manager. Warrier approached Ganguli with a request to include Sreedharan in the team responsible for the restoration of the bridge. Sreedharan had been called from his Christmas leave and B.C. Ganguli informed him that he had only three months to restore the railway link, not six. Sreedharan couldn't say a word and he went straight to the site to assess the damage of the bridge. Upon assuming control of the project, he quickly realized that the task of restoring the bridge within the given time frame was virtually impossible. The process of molding and fabricating the required steel girders alone would require several months. According to Sreeharan's own account "Of the 146 spans, 125 had been damaged or washed away. We urgently needed meter-gauge girders to build the bridge. We sourced them from states as far as Punjab, Assam and Rajasthan, but there was still a shortage. Thankfully, the fisherman in Pamban came to our rescue. They had spotted many girders that had been swept away in the cyclone and were lying 40 feet below, on the seabed." Sreedharan and his team, decided to salvage the girders, lying in the seabed and worked at breakneck speed for restoration. In those days, steam cranes were available, which could restore one girder in five days at normal speed, from salvaging to erecting at it's place. Sreedharan designed a special type of pontoon crane (crane floating on a flattish boat), which salvaged girders lying in the sea. Sreedharan experience at the Mumbai Port Trust, had greatly helped in this regard. He also designed a launching gantry for girders, which could launch girders simultaneously from both ends, one of pioneer design at that time. It had reduced the launching time of girders from five to three days, but soon after work gathered steam, launching time reduced to a day from three. On the last two days, construction team could launch eight girders i.e., 4 girders per day. Sreedharan engaged workers from the framed community of 'Mappila Khalasis', who were known for their traditional and highly effective methods of hauling massive objects, especially ships. They worked with perfection to complete the restoration in time. During the erection and restoration process of the girders, Sreedharan simultaneously organized a dedicated team to construct railway tracks. The objective was to ensure that once the bridge was ready, the pre-constructed tracks with sleepers could be seamlessly positioned onto the bridge and securely fastened. This strategy proved highly effective in expediting the completion of the railway tracks shortly after the bridge's construction was finished. Sreedharan and his dauntless team completed the restoration of the bridge just 46 days, much ahead of the targeted deadline given by GM, Ganguli. This achievement earned Sreedharan the Minister of Railways' Award in 1964, marking it as his very first official recognition and award in his career.

During the restoration of the bridge, his elder daughter was born but he couldn't see her due to his dedication to the restoration works. He went home to see his daughter only after the bridge was back in operation. This portrays his dedication and commitment towards works, a true 'Karmayogi'.

First Metro Projects of India-Kolkata Metro:

After successful completion of Pamban Bridge, Sreedharan was back in Bangalore (now Bengaluru), where soon he received a promotion to the post of Deputy Chief Engineer. Due to unavailability of any vacancies of Deputy Chief Engineer post in Southern Railway, he moved to Kolkata with his family to join Eastern Railways, where vacancy was available. After some time, he received another transfer letter to join Bilaspur. He joined Bilaspur leaving his family in Kolkata but got a call from G.P. Warrier, then GM of Eastern Railways, after two months. Warrier advised him to join the Metropolitan transport project, Kolkata popularly known as Kolkata Metro. Initially, he was reluctant but finally joined India's first Metro project as Deputy Chief Engineer (Planning & Design), Metropolitan transport project (MTP) in 1971.

The Pamban Bridge after the Cyclone in 1964

The Rebuilding of Pamban Bridge

By 1971, the MTP had come up with a master plan to construct five rapid transit lines (total length of 97.5km) for Kolkata, for which the highest priority was given to the busy north-south corridor between Dum Dum and Tollygunge. The project was sanctioned in June 1972 by Government of India.

An International tunneling seminar was scheduled to take place in Tokyo, Japan. The Indian Railway initially suggested that J.N. Roy, who was then serving as the Chief Administrative Officer in MTP, Kolkata, attend the seminar. However, Mr. Roy declined the opportunity, explaining that he was nearing retirement, with just two years left before his retirement date. Instead, he proposed that the Railways send a young and promising engineer who had many years of service ahead of them, ensuring they could absorb as much knowledge as possible from the seminar. Consequently, he recommended Mr. Sreedharan as the ideal candidate to attend the seminar. Sreedharan was surprised and his statement in one of his interviews, 'How could he refuse the offer of foreign tour and recommend someone else! It is rare to find such people today. I felt happy and responsible. I took full advantage of it and went for the three-day seminar.'

The seminar was an eye-opener for Sreedharan, he picked up a lot of knowledge about the technologies that are required to build a metro. He decided to visit the Tokyo Metro closely and had a discussion with technical expert of Tokyo Metro. He needed to stay four days more after seminar but rare possibility of getting any financial help from the Railways. He contacted a relative in the USA and requested for a loan, who promptly sent him enough money for his additional stay in Tokyo. By the help of Indian Embassy, he visited the Tokyo Metro and had meetings with senior engineers and operators of Tokyo Metro including intricacies of design. Sreedharan managed to take the engineering drawings of the Tokyo Metro and the network. Later, the Indian Railways had sent two teams (including Sreedharan) on foreign visits to study many other metro rail system abroad, which helped the team to complete the planning & design of India's first Metro system.

The foundation stone of Kolkata Metro was laid on December 1972 and construction began in 1973. However, the project faced various problems like non-availability of funds, shifting of underground utilities, court injunctions, irregular supply of vital materials etc., from the beginning of the project. After spending five years there, Sreedharan was demoralized since the work was not gathering any pace. Fortunately, he received his transfer order as Divisional Railway Superintendent to Mysuru. During one of his interviews, Sreedharan expressed the viewpoint that the project could have been approached in a different manner rather than as a departmental project. He emphasized that the experience served as a valuable learning opportunity for everyone involved. As a result, when they undertook the Delhi Metro project, they consciously opted for a significantly different approach to its construction.

The Shipyard Commander:

After spending two years working in Mysore, Sreedharan was reassigned to Kolkata as the Chief Engineer (Construction) for a six-month period. During this time, the Ministry of Shipping was actively seeking a suitable candidate to fill the position of Chairman and Managing Director (CMD) for Cochin Shipyard. Despite not applying for the role, Sreedharan's name was recommended by the Indian Railway. He was ultimately selected for the position and assumed office at the end of 1979, at a time when Cochin Shipyard was having its own teething troubles. Upon taking over from Vice Admiral Krishnan, Sreedharan faced the complex task of overseeing the construction of 'Rani Padmini,' the yard's first ship, which was the largest ever built in India, measuring 245 meters in length and weighing 17,260 tonnes. As CMD, he made it a priority to ensure the completion of the ship within a year, even in the face of challenges such as strikes, trade unions, and undisciplined workers. Sreedharan led by example, demonstrating determination and resolve to overcome these obstacles and successfully completed the project. An old employee recalled, 'The Shipyard had become a den of indiscipline and Sreedharan brought in discipline among the ranks by personally walking down the shipyard early every morning and catching those who took voluntary half days and issuing charge sheets.'

Sreedharan started one-to-one interaction with employees and workers mingling with them and started every Monday open house called 'Durbar', where employees could share their grievances with him directly. This led to a drastic change in the environment, the employees were happy to get a boss who heard their problems and fixed them. But this had created an imbalance as the powerful trade unions, traditional forum for worker's issues, were losing their platform. Former Cochin Shipyard employee and trade union leader, Vijayanathan Patil acknowledged Sreedharan's contribution, 'It was the arrival of E Sreedharan, who helped the shipyard turn-around and helped launch Rani Padmini under his leadership. But he had a bitter time at the shipyard as some vested interests wanted him out. When Sreedharan suspended a few employees who got into a fight, the trade unions jumped in and called a strike until the suspended employees were called back to duty, but Sreedharan refused to let them in. This led to a long stalemate, which was eventually resolved by the intervention of then Kerala Chief Minister.'

Sreedharan faced another challenge related to his compensation during his tenure as CMD, in addition to the issues at the Shipyard. The Ministry of Shipping proposed to pay him according to the salary scale applicable to Railway engineers rather than as the CMD, citing the level of his career. From the outset, Sreedharan disagreed with this arrangement and expressed his desire to return to his original organization, the Indian Railways. This disagreement led to an extended exchange of correspondence between him and the Ministry of Shipping on the matter. He continued to fight with trade union opposition, to make sure that work didn't suffer. Due to his consistent efforts, 'Rani Padmini' was ready by January 1980 and trial-sailed by October 1980. At that time, he had received tele-printer message from the Ministry of Shipping to hand over the charge of CMD to D. Jayachandran from Bharat Heavy Electricals. Employees were shocked that Sreedharan was removed unexpectedly just as the shipyard was about to deliver its first ship to the Shipping Corporation of India. The employees clearly stated that, under Sreedharan's leadership over the years, the shipyard's output had shown remarkable exponential growth. Sreedharan left the Cochin shipyard in November 1980 and there were a number of protests showcasing telegrams that began to reach the Ministry of Shipping from the staffs. It was only then the Chief Minister of Kerala requested the Ministry to reconsider the transfer decision. The Ministry tried to spread news that Sreedharan didn't want to serve due to a pay scale issue. Later, Sreedharan disclosed the true reason behind his abrupt transfer: a divergence of viewpoints with the Ministry concerning the selection of companies to supply the expensive engines for the ships intended to be constructed by the shipyard.

Last Decade of his carrier in Railways:

Sreedharan returned to the Railway Ministry and was subsequently promoted to the role of Chief Engineer (Construction) in Chennai. During this phase of his career, he was actively engaged in several projects. Notably, this was the period when the Chennai Mass Rapid Transit System (MTP) was being planned for construction, following the year 1985. Drawing from his earlier experience in the

Kolkata Mass Transit Project (MTP), Sreedharan was involved in the planning and execution of the Chennai MTP as well. But he had been again promoted and transferred to Central Railway (Mumbai) as Chief Administrative Officer (Construction). During a review meeting, he discovered that there was no progress on the construction of the Vashi Railway Bridge, a crucial part of the Mankhurd-Belapur Railway project. Even though CIDCO had already deposited the required funds with the Railways, the work on the project had not yet begun. This connectivity was of utmost importance as it was essential for Mumbai to have access to the newly planned township of Navi Mumbai. In response, Sreedharan took action by convening a meeting of all the project stakeholders, including officials from CIDCO, Central Railways, the construction company AFCONS, and the German consultants. During this meeting, the German consultants made a sarcastic comment, implying that only a wealthy country could afford to delay a project like this. This remark hit him hard, as the project had experienced delays despite having all the necessary approvals and funding in place. He rallied his team and worked tirelessly to kick-start the project. Although the project was later transferred to Western Railway, Sreedharan continued to oversee its progress, ensuring that it eventually became a reality. This is the story of how Navi Mumbai acquired its inaugural rail connection to Mumbai, transforming a vision on paper into a tangible reality. Even today, the rail bridge remains one of the most vital links for commuters traveling between Navi Mumbai and Mumbai.

From there, Sreedharan moved on to Western Railway as General Manager. During his tenure, he prioritized train punctuality and spearheaded several electrification projects. According to Railway Archives, his leadership also marked significant advancements, including the introduction of fiber-optic cables between Churchgate and Virar and the implementation of the first-of-its-kind Auxiliary Warning System (AWS) in Indian Railways, which helps suburban train to automatically stop in case it crosses a red signal, enhancing safety and operational efficiency.

In July 1989, Sreedharan was elevated to the post of Member Engineering, Railway Board and Ex-officio Secretary to the Government of India during the tenure of Railway Minister Madhavrao Scindia. The Railway Board is the highest decision-making body for approval of all the policies and project planning for Indian Railways. As a Member Engineering, Sreedharan decided to discontinue the use of CST-9 i.e. cast-iron sleepers on Indian Railway tracks, as cast-iron sleepers were technically proven unfit. The Railway Board decided to upgrade the CST-9 to concrete sleepers, to improve the overall quality and life of the rails including riding quality of trains. Sreedharan's statement in one of the interviews, "After I took the decision, all hell broke loose. There were many attempts to convince me to undo it. Many of my deputies, and officers tried to tell me that there were tenders in waiting. They tried to convince me CST-9 was a big industry in West Bengal and that there would be immense losses due to which I should reverse my decision. But I stood firm. The matter went up to Railway Minister Geoge Fernandes and he called me to ask what the matter was. He too said that it was wrong, and I was depriving the livelihood of so many people. I explained to him that the decision was purely based on merit and explained the technical reasons behind it. He heard me out patiently and said technically if I felt what was being done was correct, I should go ahead. He was such a gentleman that he refused to interfere further". That's how the replacement of cast-iron sleepers had been started by concrete sleepers in Indian Railways.

Sreedharan had officially retired from the Indian Railway in June 1990 after thirty-six years of service. Immediately upon retirement, he was put in charge of planning and implementation of Konkan Railway by Railway Minister, Geoge Fernandes himself.

Influencer in Sreedharan's Life:

There are two senior Railway officers, whom Sreedharan had worked with during his services in Railways and considered them as icons - Govind Parameswara Warrier (G.P. Warrier) and Bankim Chandra Ganguli (B.C. Ganguli). When Sreedharan joined as probationary Assistant Engineer in southern Railway, Warrier was the Deputy Chief Engineer (construction), Southern Railway and Ganguli was General Manager of Southern Railway. Later, both of them became Chairman of the Railway Board in the seventies: Ganguli (1970-1971) and Warrier (1975-1977). Warrier is known for his pioneer roles in the construction of the Kollam-Ernakulam Metre gauge railway link in 1958, where he constructed metre gauge which made fit for even broad gauge trains to pass over. Later, when this link upgraded to broad gauge, everybody lauded the foresight of Warrier. He also played a key role in bridging the Ashtamudi and Paravoor Kayal lakes along the stretch. Ganguli is well known as the brainchild behind the high-speed Rajdhani trains in India and the laying of tracks in eastern and north-eastern India during the Second World war.

Both officers were known for their engineering and management abilities, professionalism, unmatched intelligence, diligence, and knowledge, also for their pioneering roles - the qualities picked up by Sreedharan. Warrier acknowledges Sreedharan's role in the restoration of Pamban Bridge in his autobiography, 'Time, Tide and My Railway Days': "On the railway bridge all the 144 steel girders were washed off……Sreedharan, one of our outstanding engineers, was in charge of the (restoration) work and it goes to his credit that he completed this very difficult task in just a short period."

4. Life after Retirement from Railways

After retiring from the Railways, E. Sreedharan was entrusted with larger and more challenging responsibilities. The then Railway Minister, George Fernandes, assigned him the monumental task of constructing the Konkan Railways. This project represented a significant and audacious leap in infrastructure development, blending technical expertise with a bold vision, and it was poised to become a remarkable achievement for post-independent India.

The Konkan Railway-Toughest Railway Project of Twentieth Century:

During Sreedharan's tenure as Member Engineering, he was closely associated with Railway Minister, Geoge Fernandes, for two projects one was the Chithoni-Bogha link in Bihar crossing the formidable Gandak River and another one was the West Coast Railway line (Konkan Railway). After successful kickstart of the first project, Fernandes called Sreedharan to discuss the implementation of the West Coast Railway link project. Sreedharan explained him that West Coast project will take at least 25-30 years for completion if executed as normal Railway projects. Normally, the planning commission sanctioned Rs 250-300crores (those days) per year for new-line railway projects and there were already about 20-25 new railway line projects sanctioned already, due to which each project would get hardly 5-10 crore, which was not enough to build the Konkan Railway projects. He suggested following an entirely different approach to complete the projects in a time-bound manner, by setting up a special body or a special corporation or a special authority to raise funds for execution of the project.

Sreedharan explained that it was a highly viable project, being financially very attractive, because it reduced the distance between Mumbai and Mangalore by 1127Km, saving 26 hours of journey time. He pointed out - "Because of this tremendous advantage, it should not be difficult to raise money from the market. The special body should be a joint sector company, with a majority share with the Railway Ministry of 51percent and the remaining 49 percent share to be taken by the four beneficiary states of Maharashtra, Goa, Karnataka, and Kerala and Money could be raised from the market." The concept appealed to Fernandes so much that he immediately took the matter to the Prime Minister, the Planning commission, and the Finance Minister. Within 48 hours, Railway Minister confirmed that the Government had in principle agreed to take up the Konkan Railway project the way Sreedharan suggested. This was how the Konkan Railway Corporation Ltd. (KRCL) was formed and registered as a company on 19 July 1990, 19 days of the retirement of Sreedharan. He was appointed as CMD of the corporation in October 1990.

The project was scheduled to be completed in seven years but subsequently it had been reduced to five years, which was very tight considering the fact that 80km of tunnels had to be dug and 20km of bridges had to be built at various points. The project had been launched in phases from either end progressively. The task was formidable with 1880 bridges and 91 tunnels to be built through forested hilly terrain containing many rivers and the project was perhaps one of the most difficult railway projects in twentieth century.

Firstly, Sreedharan had built an organization that was different from than existing Railway set-up: "We brought in an almost paperless type of functioning. The whole work of the administration was on the basis of trust. Powers were delegated on the basis of trust, and mutual trust. I made it sure that the background of anyone who joined the organization, would be analyzed thoroughly and only persons with impeccable integrity were brought in. If there is any doubt about a person's character, they would not be part of our organisation. They were all hand-picked and brought in. That is how it was a very small team, but it functioned extremely well". Sreedharan implemented the following in the organization and work cultures within KRCL:

- Officers had been selected from Sreedharan's network of trusted team members.
- The project was strategically divided into seven zones, aligning with seven revenue districts. Each zone was overseen by a Chief Engineer responsible for approximately 100-120 kilometers of the project corridor. Sreedharan's vision was to achieve the completion of each zone within a five-year timeframe under the leadership of a Chief Engineer, ultimately accomplishing the entire project within five years.

  To facilitate efficient progress, the Chief Engineers collaborated closely with the respective district collectors and superintendents of police to address project-related issues, and this approach proved highly successful. Additionally, they were granted the authority to make decisions at their level and below, reducing the need for constant involvement from the corporate office and expediting day-to-day operations.
- At KRCL, for the first time, the Railways successfully integrated its bureaucratic framework with that of the state government. This alignment was aimed at expediting decision-making processes in the project's best interest.
- The terrain was very difficult, and the establishment of communication was next to impossible at that time. Sreedharan focused on establishing a communication network by

hiring DOT lines, which established an excellent communication network between the offices of the Chief Engineers with Headquarters at Navi Mumbai. All the Chief engineer's office had been equipped with computers and fax machines. This helped to ensure that everybody could access any information from anywhere and communicate to others without any delay. This was also a visionary decision taken by Dr Sreedharan which sorted out communication problems at the beginning of the project resulting into quick decision-making and preventing stalling of work.

- A significant transformation within KRCL was the revision of the billing and payment process for contractors. Under this new system, contractors received 75% of their payment within 48 hours of submitting their invoices, with the remaining amount disbursed within one week after a thorough bill review. This approach deviated from the conventional Railway payment system.

  To further streamline operations, KRCL took on the responsibility of supplying critical materials such as cement, steel, various types of explosives (due to stringent regulations on their transportation and use), and even petrol. KRCL established its own petrol pumps along the project corridor, and the cost of these materials was deducted from the contractor's upcoming bill.

  In essence, KRCL viewed contractors as partners, recognizing that the success of the project relied on their contributions and collaboration.

- The project's execution introduced the innovative concept of a "reverse clock." These clocks were strategically placed at all project offices and sites to serve as a constant reminder of the value of each passing hour. This approach aimed to emphasize the importance of time management and efficiency in the project's execution, fostering a heightened sense of urgency and responsibility among the team members.

- Monday Meeting: Sreedharan started meeting with all Head of Departments on every Monday to discuss the problems and remedial measures. He elaborated, "We analysed the slippage in the previous week and then decided what was required to be done in the week ahead. On the first Monday of the month, field engineers were also brought in. I insisted that no minutes be recorded as I believe it is a waste of time and paper. We knew what was happening every day and everybody was involved. This sort of very transparent and dynamic approach to problems helped considerably in completing the project on time." He established a very dynamic and transparent style of project management, which was necessary to complete the projects within time, and laid down three corporate missions and ten corporate cultures needed to achieve the goal so that everyone in the corporation had to work with the same ethos, same approach same mission.

The Konkan Railways, one of the pioneer government organizations, adopted several cutting-edge technologies in construction and railway system operations, many of which were introduced for the first time in India. These technologies, which are now commonly used, helped the organization overcome the challenges posed by difficult terrains and improve railway operations.

- Introduction of incremental launching for the bridges
- The welded steel triangular girders for bridges over water: the Welded Steel

triangulars Girders had been designed and installed for the first time in India. The Neoprene bearings had been used also for first time in India to support these steel girders.

- Ventilation in tunnels: KRCL sent their engineers abroad to learn tunnel ventilation system, since it was an entirely new technology in the country. They successfully installed the ventilation system which had been used by other organizations later.
- Tracks to fit 160kmph train run, and Ballast-less tracks in tunnels - use of ballast-less tracks eliminated the maintenance, which is difficult in tunnels- one of the foresight decisions taken at that time. The Konkan Railway adopted new technology of pressure gas welding of rails, which could be executed at the site itself, by an imported machine from Japan to avoid welding of rails in advance in such difficult terrains.
- Ballasted deck -The KRCL decided to use ballasted deck and all the bridges had been designed with concrete decks, except three river spans in Goa - two across Zuari River and one across Mandavi River for permission of Navigational ship, where steel girders had been used.
- Another innovative adoption in telecommunication networks, was adoption of fibre-optic, a common technique nowadays, but was entirely new technology in Indian Railways at that time. After lots of opposition, KRCL persisted and was able to adopt the technology which proved out to be a great success in the future.
- In the Konkan Railway project, construction of tunnels within short time, was critical path, which required advanced, high-speed tunnelling equipment. The KRCL imported required equipment and provided to contractor in free of cost.

When Konkan Railway was sanctioned, Sreedharan's commitment was a period of 7 years for completion. However, Shri George Fernandes compressed it to 5 years, and Sreedharan was able to complete the projects in seven years as committed in spite of numerous hurdles faced as below:

1. Difficulty in Raising Funds: During the first two years of the project, there were challenges in raising funds through tax-free bonds, partly due to the stock market scam that occurred during that period. This financial setback hindered the project's progress.
2. Agitations in Goa: There were multiple agitations and protests in Goa, primarily related to the realignment of approximately 50 kilometers of the railway project. These protests and demands for changes in the alignment disrupted the project timeline.
3. Unexpected Tunnel Issues: The project encountered unexpected setbacks related to the construction of tunnels, particularly in areas with poor soil conditions. Tunnelling through such terrain proved to be more complex and time-consuming than initially anticipated.

The KRCL couldn't undertake the detailed geotechnical investigation since project had taken off very fast in between difficult terrains and encountered totally unexpected geology in some of the tunnels in Goa area. The soil in Sreedharan's word, "became like toothpaste, required innovative solutions. Due to frequent changes of strata, the construction strategy had to be altered every time soft soil or hard rock was met. The tunnel delayed the commissioning of the Konkan Railway project by five months".

Sreedharan inspecting a track switch at Konkan Railway
Courtesy : KR Archives

Sreedharan inspecting a Tunner during
Konkan Railway Construction
Courtesy : KR Archives

These factors, among others, contributed to the delay in the completion of the Konkan Railway project. Despite these challenges, the successful completion of the project remains a significant achievement in India's infrastructure development.

After the inauguration of the Konkan Railway project in May 1998, George Fernandes, who was the Defence Minister at the time, made a statement acknowledging the project's success. He said, "When the question of who should take credit for this achievement is discussed, I am of the firm opinion that if there is one person whose knowledge and dedication was responsible for the project, it is E. Sreedharan, the former Chairman and Managing Director of Konkan Railway." It's noteworthy that Sreedharan had overseen the completion of the project before transitioning to his new role as the Managing Director of the Delhi Metro in December 1997.

Controversy on Remuneration:

Sreedharan's appointment letter as CMD of Konkan Railway was issued two years after he assumed the role. In this letter, it was specified that his basic pay would be reduced by Rs 4,000 per month due to the pension he received from the Railways. Consequently, his net take-home salary was reduced to Rs 1,080 per month, without considering the contribution towards VPF (Voluntary Provident Fund). In contrast, Directors and Chief Engineers within the same organization had significantly higher take-home salaries of Rs 7,300 and Rs 4,000 respectively.

Feeling discontented with this situation, Sreedharan expressed his concerns through numerous letters to the Secretary of the Railway Board. However, he received no response from them. As a result, in April 2002, he took the matter to the Delhi High Court and filed a petition.

It took nearly a decade, with the final verdict arriving in 2008, for Sreedharan to receive a sum of more than 9 lakhs from the Railways as a resolution to this issue. Notably, he chose to donate 50% of this sum to a charity fund.

Delhi Metro - Indian's First Successful Metro:

To overcome the severe transport crisis of Delhi, Delhi Metro Railway Corporation Limited (DMRC) had been registered in 1995 to build MRTS projects in Delhi. Sreedharan was never a competitor for the post of MD but was a member of the committee responsible for recommending a suitable MD. A board comprising the Lieutenant Governor, Chief Minister, Transport Minister, and Chief Secretary, Government of India approached him with the offer of the Managing Director position. Initially, Sreedharan was hesitant to accept the role due to ongoing responsibilities at Konkan Railways and concerns about his age, as government employees typically weren't hired beyond the age of 65. Despite these reservations, Sreedharan was appointed as the Managing Director in August 1997. He assumed dual responsibilities, overseeing both DMRC and Konkan Railway Corporation Limited (KRCL), until December 1997 to ensure the completion and successful handover of the Konkan Railway Projects.

Once again, Sreedharan was entrusted with a significant undertaking, and the government granted him full authority to execute the project and appoint senior management according to his discretion. In this capacity, he began by selecting key colleagues from his previous experience at Konkan Railways. Subsequently, he concentrated on creating a work environment that fostered a strong sense of mission and purpose, similar to the culture he had successfully cultivated at KRCL. This emphasis on a shared sense of purpose and commitment was instrumental in driving the Delhi Metro Railway Corporation Limited (DMRC) toward its successful completion and operation. To maintain a high standard of competence and eliminate the entry of candidates through pulls and pressures, Sreedharan recommended the implementation of a recruitment pattern similar to the Union Public Service Commission (UPSC) model for initial-level hires at DMRC. This pattern typically includes a written test, an interview, and a medical examination, ensuring that candidates selected are not only academically qualified but also capable and fit for their roles. This approach aimed to uphold meritocracy and transparency in the hiring process, helping to secure a qualified and dedicated workforce for DMRC.

At the initial period, Sreedharan faced 'hardest knock' for selection of gauge. He recommended standard gauge based on international practices and future growth. Sreedharan explained in one of his interviews, "The hardest knock which I received in my 50 years of professional life was the decision of the Government of India to choose the broad gauge for the Delhi Metro instead of the internationally favored standard gauge." After many years, all the state governments including Delhi Metro were convinced to opt for standard gauges with the help of then Chairman of the Group of the Minster, Sharad Pawar - who was fully convinced with the view of Sreedharan. The Green line of the Delhi Metro had been built with standard gauge and consequently, all the lines post green line, were also built with standard gauge. However, the interchangeability of train within two sets of gauges, remains a problem in Delhi Metro.

In his commitment to the benefit of Delhi and the timely completion of the Metro project, Sreedharan made the decision to redesign the entire system, changing it from standard gauge to broad gauge. To expedite this process, he sent DMRC engineers to Changwon, South Korea, where metro coaches were manufactured. These engineers were stationed there for approximately four months to ensure that all designs and approvals were promptly completed, without any delays. This effort was instrumental in meeting the deadline for the delivery of the coaches to Delhi. Despite some initial challenges, the first stretch of the Delhi Metro, from Shahdara to Tis Hazari, was inaugurated by Prime Minister Atal Bihari Vajpayee on December 24, 2002. Sreedharan's metro rail model, influenced by his earlier experience with the Kolkata Metro, rejuvenated the city's transportation system, positioning the metro as a modern and efficient mode of transport.

In recognition of the success of the Delhi Metro and the need for proper regulation, the Metro (Operation & Maintenance) Act was enacted in 2002. Initially, it applied only to Delhi, but it was later amended in 2009 to enable the Government of

India to extend the act to any city in consultation with the respective State Government. This legislation helped ensure the efficient operation and maintenance of metro systems across the country.

Phase I of Delhi Metro was dedicated to people in April 2006, completed within seven and half years within budget as against the schedule completion of 10 years targeted by Government, almost three years ahead of schedule. In one of the Interviews, Anuj Dayal mentioned about the foresight of Sreedharan - in forming two departments public relations and legal branch - "Court cases were carefully monitored, fought, and information supplied to the judiciary in detail, which helped in deciding cases. The MD himself took a lot of interest in all court cases too." Contractors had been considered partners and ensured timely payment, like Konkan Railway. Having all executive powers, Sreedharan didn't delay any decisions that might derail the progress of the project. He propelled the same culture within his officers so that they could take a swift decision. Even, though some decisions had been taken in haste for deadline pressures, Sreedharan did not believe in witch-hunting, if the intention of the person was not wrong. Dayal mentioned one bold decision, "during one of Sreedharan's initial site inspections deciding to place the metro line on an embankment rather than having it elevated between Shahdara and Seelampur-hundreds of crores were saved by this single on-the-spot decision". Sreedharan made a significant decision to merge the eligibility criteria for train operators and station controllers, which proved to be a practical choice. This allowed station managers to operate trains in case of emergencies, as they had received the same training as train operators. This decision enhanced the overall safety and flexibility of the system.

While Sreedharan's working style faced criticism from various quarters, his ability to successfully deliver massive projects on time and within budget was undeniable. He achieved remarkable results by challenging conventional norms and breaking established rules when necessary to achieve project goals.

Sreedharan initially intended to step back after completing the first phase of the Delhi Metro project. However, the government requested him to continue his leadership role until the completion of Phase-II, especially with the upcoming Commonwealth Games in Delhi on the horizon. During the execution of Phase-II, DMRC encountered numerous challenges and crises between 2008 and 2009. These were exceptionally tough times for Sreedharan, as he worked diligently to overcome the obstacles and ensure the timely and successful completion of Phase-II.

In October 2008, a launching girder, along with a few erected segments, fell onto a vehicle beneath the road at Lakshmi Nagar location during the Blue Line extension project. Subsequently, in July 2009, a section of a bridge, along with the launching girder, collapsed at Zamrudpur on the Central Secretariat-Badarpur line. Tragically, this incident resulted in the loss of seven lives and injuries to fifteen others. In response to this accident, Sreedharan visited the site and later announced his resignation during a press conference at Metro Bhawan. However, Sheila Dikshit, the then Chief Minister of Delhi, requested him to reconsider his decision, citing the significant amount of work that needed to be completed before the upcoming Commonwealth Games in 2010. Sreedharan decided to stay back to ensure the timely completion of these projects. However, the very next day, three cranes involved in the debris removal process at Zamrudpur collided with each other, injuring six people. This incident was broadcast live on television and drew heavy criticism regarding the safety measures adopted by DMRC, leading to discussions and scrutiny in the media and even in Parliament. During the month, Metro Bhawan was flooded due to excessive rains and logged it for a week without any electricity, Sreedharan (78 years old) used to climb eight floors daily to reach his office. The stress of managing these crises, combined with the pressure of meeting the Commonwealth Games deadline, took a toll on his health. In April 2010, while boarding for a flight to Kolkata, Sreedharan experienced discomfort in his chest and was promptly rushed to the hospital. He was diagnosed with 100% blockage of an artery and underwent bypass surgery at the Indraprastha Apollo Hospital. Thanks to his overall physical fitness, he made a relatively swift recovery and was able to resume his duties within just 40 days of the surgery. This incident underscored his determination and dedication to his work, even in the face of significant health challenges.

In 2012, Harvard Business School introduced a case study titled 'DMRC and Sreedharan' as part of its Advanced Management Programme. This case study served as an exploration of leadership and project management, particularly in the context of the 2009 accident when a construction span collapsed, resulting in the tragic loss of seven lives. The case study delved into the challenges that E. Sreedharan and his team faced as the crisis unfolded. It also highlighted the unique structure and management ethos of DMRC, which had, until that point, enabled the organization to consistently meet its timelines and budgetary constraints in executing projects.

By studying this case, students and business professionals could gain valuable insights into leadership, crisis management, and the principles that contributed to DMRC's successful track record in the field of urban transportation infrastructure.

After successfully completing Phase-II of the Delhi Metro project, which encompassed approximately 125 kilometers of routes and 85 stations, E. Sreedharan decided to retire from his position on December 31, 2011. His tenure at DMRC spanned an impressive 14 years.

Under his leadership, DMRC not only transformed Delhi's transportation but also played a pivotal role in spreading the Metro culture throughout India. Many cities across the country initiated the planning and construction of their own Metro Railways with the guidance and influence of DMRC and Dr. Sreedharan. This metro construction revolution, initiated and driven by him, earned him the well-deserved moniker of the 'Metro Man.' His visionary approach and dedication left an enduring legacy in the realm of mass transportation in India.

Following his retirement from DMRC, E. Sreedharan took on the role of Principal Advisor with full delegation of power to oversee the Kochi Metro project. Despite facing various challenges, bureaucratic hurdles, and political complexities, the first phase of the Kochi Metro rail project was successfully completed in about four years, from June 2013 to June 2017, under Sreedharan's guidance. Sreedharan was actively involved in every aspect of the project, from planning and design to execution, and he provided strong leadership to the entire team. The author vividly remembers the discussions held with Sreedharan, along author's team, regarding various aspects of the project, including architectural planning, structural arrangements, construction feasibility, and cost considerations for civil tenders.

One notable achievement was a significant cost saving of approximately Rs 500 crore in the construction of the 18-kilometer first phase of the Kochi Metro. This saving was attributed to innovative design approaches, which led to contractors quoting lower prices for rolling stock, civil works, electrical systems, and signalling works. Sreedharan's commitment to efficient project management and innovative solutions continued to make a significant impact on urban transportation infrastructure in India.

E. Sreedharan's expertise and leadership were recognized through his appointments to several significant committees and advisory roles. Some of the notable appointments and roles he held include:

- Kakodar Safety Committee: Sreedharan served on the Kakodar Safety Committee established by the Indian Railways, focusing on safety-related issues.
- Jammu and Kashmir Railway Committee: He was appointed to the J&K Railway Committee, which likely focused on railway-related matters in the region.
- United Nations Advisory Group: Sreedharan was part of a United Nations Advisory Group, on Sustainable Transport (HLAG-ST) showcasing his international involvement and contributions.
- One-Man Committee for Commercial Decisions: Railway Minister Suresh Prabhu appointed Sreedharan to lead a one-man committee tasked with suggesting a proper system and procedure to ensure accountability and transparency in making commercial decisions.
- Chief Advisor for Metro Projects: Sreedharan also served as Chief Advisor for various metro projects, including the Lucknow Metro, Jaipur Metro, and proposed metro rail systems in Visakhapatnam and Vijayawada (VGTM) in Andhra Pradesh. These roles highlighted his continued influence and guidance in the development of metro systems across India.

Sreedharan in a Metro Tunnel

Site Visit in Kochi Metro Project

Receiving Padma-Vibhushan

At Camp Office

5. Beyond the Engineering World

Spirituality

E. Sreedharan's belief in the importance of a spiritual attitude in balancing stress control within project management was a significant aspect of his life and leadership philosophy. He often turned to spiritual wisdom for guidance and inspiration, drawing on his favourite shloka (verse) from the Bhagavad Gita:

"*Mukta sango nahamvadi dhrty-utsaha-samanvitah, Siddhy-asidhyor nirvikarah karta sattvika uchyate*"

His explanation of this shloka emphasizes that to be a virtuous doer, one must not become overly attached to the work they are engaged in. Instead, they should approach their tasks with efficiency, boldness, energy, and enthusiasm while remaining unattached to the outcomes, whether success or failure. According to Sreedharan, adopting this mindset while executing a project can lead to success, and he considers the Bhagavad Gita a valuable guide for administration and business execution.

Sreedharan dedicated time to learning Sanskrit after retiring from the Railways, nurturing his personal interests in spirituality and ancient texts. His daily routine included starting the day with yoga, and he firmly believed in the power of discipline and focus in leading to success.

His introduction to Swami Bhoomananda Tirtha during a lecture at FICCI marked the beginning of his spiritual journey. Swamiji's teachings on the practical application of Vedanta, the Bhagavad Gita, and the Upanishads in everyday life resonated with Sreedharan. He became a devotee of Swamiji, and this spiritual perspective influenced the work culture of the organizations he led.

Sreedharan's inclination toward spiritual reading and his generous distribution of copies of the Bhagavad Gita, written by Swami Vidyaprakashananda, particularly one with explanations for the lay reader, reflected his commitment to infusing spiritual wisdom into the lives of those around him. His leadership style and personal philosophy were deeply intertwined with his spiritual beliefs, and this holistic approach had a profound impact on both his professional and personal life.

Charity

E. Sreedharan's commitment to philanthropy and social welfare is exemplified by his establishment of the 'Elattuvalapil Ammalu Amma Memorial Charity Trust,' named in honour of his mother. He involved all his family members as trustees and contributed a portion of his earnings from awards into this trust.

Furthermore, he contributed his entire award income to the trust, in addition to 50% of his income after leaving Konkan Railway. This generous act aimed to make a positive impact on society by supporting students facing financial constraints, enabling them to continue their education.

Through the trust, Sreedharan's legacy of giving back to the community and assisting deserving students in pursuing their education continues to uplift and empower those in need. His philanthropic efforts reflect his belief in contributing to the welfare of society beyond his professional achievements.

Politics

In February 2021, E. Sreedharan joined the Bharatiya Janata Party (BJP), marking his entry into active politics. He contested in the 2021 Kerala Legislative Assembly elections from the Palakkad assembly constituency as the BJP's Chief Ministerial candidate. While he put up a strong fight, he narrowly lost the election to his opponent by a slim margin. However, Sreedharan made the decision to quit active politics in December 2021,

With Wife and Children

Family Photo

signalling a shift in his focus away from the political arena. Despite his relatively brief foray into politics, he remains a respected and influential figure in India, known primarily for his remarkable contributions to infrastructure development and public transportation.

6. Family

Following retirement from Delhi Metro, Sreedharan chose to reside in Ponnani, Kerala, with his wife, Radha. The couple is blessed with three sons and a daughter, all of whom are happily married and leading successful lives.

The eldest son, Ramesh, an alumnus of IIT Chennai and former Vice President of Tata Consultancy Services, is currently engaged in freelancing as a life coach along with his wife, Priya. Another son, Achyuth Menon, is a doctor and practices in the UK, with his wife, also a surgeon.

Their only daughter, Shanthi Menon, holds a master's degree and serves as the principal of a school in Bangaluru. The youngest son, Krishnadas, following in his brother's footsteps as an IIT Chennai alumnus, is employed at a multinational corporation.

According to Sreedharan's daughter, her father, often referred to as the "man of steel," is paradoxically one of the gentlest individuals she knows. She fondly recalls how, in the face of typical sibling mischief, he would tactfully guide them with a gentle touch. Reflecting on this, she recognizes the rarity of such an approach to parenting. Throughout her life, she has never witnessed her father's voice rise in agitation; instead, he believes in fostering dialogue and conversation.

The family's dining table remains a lively hub of discussion, covering a broad spectrum of topics, from personal choices and parenting to politics and philosophy. Sreedharan's commitment to engaging with each family member is unwavering, serving as the supportive force behind each of his children. Whether in the roles of father, son-in-law, husband, father-in-law, or grandfather, he approaches each with passion and dedication.

His influence extends to the nine grandchildren, as he actively contributes to shaping their perspectives. Evenings with his grandchildren are characterized by vibrant discussions around the dining table, accompanied by animated stories that captivate their attention.

Sreedharan's daughter emphasizes that the thoroughness and passion witnessed in his professional life are merely an extension of his deeply ingrained personal ethos.

7. Recognitions and Awards

Dr. E. Sreedharan's illustrious career has been marked by numerous awards, recognitions, and accolades, both nationally and internationally. Here are some of the major awards and honours he received:

1. Railway Minister's Award (1964)
2. SB Joshi Memorial Award (1995)
3. Padma Shri by the Government of India (2001) - The fourth highest civilian award in India
4. Man of the Year by The Times of India (2002)
5. Om Prakash Bhasin Award for professional excellence in engineering (2002)
6. CII (Confederation of Indian Industry) Juror's Award for leadership in infrastructure development (2002-03)
7. Featured in Asian Heroes by Time Magazine (2003)
8. AIMA (All India Management Association) award for Public Service Excellence (2003)
9. Knight of the Legion of Honour by the Government of France (2005)
10. Degree of Doctor of Science (Honoris causa) from IIT Delhi (2005)
11. Bharat Shiromani award from the Shiromani Institute, Chandigarh (2005)
12. Qimpro Platinum Standard (Business) National Statesman for Quality in India (2007)
13. CNN-IBN Indian of the Year 2007: Public Service (2008)
14. Padma Vibhushan by the Government of India (2008)
15. D.Litt by Rajasthan Technical University, Kota, Rajasthan, in 2009
16. Degree of Doctor of Philosophy (Honoris causa) from IIT Roorkee, 2009
17. Honorary doctorate by Cochin University of Science and Technology in 2010
18. D.Litt (Honoris Causa) by Jadavpur University, Kolkata, in 2012
19. Lifetime Achievement Governance Award by Grifles, 2013
20. Order of the Rising Sun, Gold and Silver star by the Government of Japan (2013)
21. Lifetime Achievement Awards for his lifelong contribution in the area of public transport, PHD Chamber of Commerce and Industry, in 2015
22. KPP Nambiar Award by IEEE Kerala Section (2017)
23. Lifetime achievement award by Project Management Associates (PMA) India (2019)

These awards and recognitions reflect Dr. E. Sreedharan's exceptional contributions to the fields of engineering, transportation, and public service, making him a celebrated figure both in India and abroad.

Two biographies have been written about E. Sreedharan's life: "Karmayogi: E. Sreedharante Jeevitha Katha" (translated as "Karmayogi: The Story of E. Sreedharan's Life") by M. S. Asokan, and "India's Railway Man: A Biography of Dr. E. Sreedharan" by Rajendra B. Aklekar.

The author drew facts from both these books along with additional references and discussions with his colleagues.

8. Views from Co-Workers

P. Sriram, an Indian Railway Service of Engineering (IRSE) member who had the privilege of working closely with Dr. Sreedharan since 1970, expresses his deep appreciation and respect for

Dr. Sreedharan in his words "After successfully completing a two-year probationary period, I commenced my role as an Assistant Engineer in Mysore Division in 1975. Notably, Dr. E. Sreedharan served as the Divisional Superintendent during that period. During our initial meeting in his office, he imparted invaluable advice that has since guided my professional journey:

- Prioritize both diligence and safety in railway operations.
- Make decisions promptly, avoiding unnecessary delays.
- Ensure that decisions made are in the best interest of the railways, rather than for personal gain.
- Uphold high standards of quality in all undertaken projects.
- Commit to continuous learning, striving to update your knowledge daily.
- Maintain a professional appearance by dressing neatly.
- Prioritize your well-being by consuming nutritious food.

These principles, shared by Dr. E. Sreedharan, have been fundamental in shaping my approach to work and have served as a compass for maintaining professionalism and excellence throughout my career. Under the exemplary guidance of Dr. E. Sreedharan, we successfully executed a range of significant projects for the Indian Railway/Konkan Railways/Metro, showcasing our commitment to excellence and innovation. These projects included:

- Doubling of track in Kerala of Tamil Nadu
- Important Bridge works in Kerala and Tamil Nadu.
- New line construction in Kerala and Tamil Nadu.
- Road over and Road under bridge works.
- Konkan Railway: Mangalore to Udupi - 67 km.
- Konkan Railway: New line construction in Goa state - 105 km.
- Konkan Railway: Important Bridge works across Zuari and Mandovi rivers.
- Konkan Railway: Tunneling works in soft soil.
- Konkan Railway: Ballast less track in Barcem tunnel - 3.5 km.
- Kochi Metro Project between Aluva to Peta.

He has been a mentor to me in both my professional and personal life. He is a very simple person and blended into our midst, assuming the role of an elder brother and, I pray for his good health."

9. Epilogue

The epilogue reflects the profound admiration and respect that Dr. E. Sreedharan earned during his remarkable career. Dr. A.P.J. Abdul Kalam, the former President of India, lauded Sreedharan's leadership and integrity, emphasizing his exceptional ability to work with integrity and achieve success.

Completing massive projects within specified deadlines and budgets is a formidable undertaking that involves navigating a myriad of complex factors in project management. Sreedharan's achievements were not only a testament to his technical prowess but also his ability to provide practical solutions swiftly, motivate his team consistently, manage personnel effectively, and navigate the intricate landscape of politics and other pressures.

His successful completion of high-profile projects like the Konkan Railway and Delhi Metro, all within budget and deadlines while operating within a government framework, showcases his extraordinary leadership and management skills. Key principles such as punctuality, integrity, professional competence, social responsibility, and goal orientation were embedded in his team and colleagues, contributing to the enduring legacy of his work. E. Sreedharan's contributions to infrastructure development and public transportation in India remain a source of inspiration and serve as a shining example of leadership and dedication.

To conclude my tribute, I'd like to share a quote from Dr. Mangu Singh, the President of the Indian Tunnel Association and a distinguished figure in the realm of Tunnel and Underground construction. Dr. Singh had the honor of working alongside Dr. E. Sreedharan in the Delhi Metro and later assumed the role of Managing Director at DMRC. According to Dr. Singh, "Sreedharan consistently encouraged and inspired his team to make decisions without the fear of failure or making mistakes. In times of urgency, he believed in swiftly identifying and implementing effective solutions rather than getting lost in endless fault-finding. He extended the opportunity for even the most junior engineers at a worksite to engage in technical discussions and welcomed their suggestions. Dr. Sreedharan's success stories were undoubtedly shaped by his patience and unwavering perseverance."

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Harnessing the Power of Geophysics for Tunnel/ Underground Projects in Pre-Construction, Construction, and Maintenance Stages

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Abstract

The need for comprehensive, high-quality subsurface information is pivotal in the design and execution of construction projects, particularly for underground structures like tunnels and caverns. Traditional exploratory work often falls short, leaving decision-makers grappling with incomplete and imperfect data. Geophysical techniques offer a solution, providing an efficient means of subsurface investigation that significantly augments the understanding of underground conditions. These techniques afford a low-cost, rapidly deployable solution, capable of generating comprehensive subsurface knowledge over large areas, thereby enriching geotechnical evaluation studies.

Recent technological advancements and the development of portable digital data acquisition systems have enhanced the versatility of geophysical techniques in site characterization and evaluating underground conditions. These state-of-the-art subsurface geophysical investigations aid in minimizing and optimizing conventional direct exploration methods, facilitating an accelerated and cost-effective development of underground construction projects. Moreover, geophysical investigations play an instrumental role in maintaining the quality of construction and performing non-destructive health checks throughout the lifecycle of underground structures.

This paper presents a range of applications for geophysical techniques at different stages of underground projects: from planning and pre-construction to construction and maintenance. It further delves into recent advancements in geophysical investigations, underscoring the significant potential for harnessing geophysics in transforming the approach to tunnel projects, ultimately boosting economic efficiency and structural reliability.

Keywords: Geophysical Techniques; Subsurface Investigation; Underground Construction Projects: Non-Destructive Health Checks; Technological Advancements in Geophysics.

1. Introduction

Geophysics is a branch of science that deals with the physical properties and processes of the Earth and its surrounding space environment. In the context of tunnel and underground projects, geophysical methods provide comprehensive, high-quality subsurface information, significantly augmenting the understanding of underground conditions. These techniques afford a low-cost, rapidly deployable solution, capable of generating a large amount of data that enriches geotechnical evaluation studies [1].

1.1 The Role of Geophysics in Tunnel/ Underground Projects

Geophysical techniques are key tools in the field of tunnel and underground construction. They provide essential data for assessing the subsurface conditions, including soil and rock properties, groundwater conditions, and potential geohazards. These techniques can be used to create detailed geologic profiles and maps that can guide the design, construction, and maintenance of tunnels. The data gathered can identify potential challenges such as zones of weak or fractured rock, fault lines, water-bearing strata, or anomalous geological structures. Such insights are invaluable for designing safe and effective tunnelling strategies, thereby reducing project risks and costs [2].

1.2 Relevance of Geophysical Investigation in the Construction Industry

The construction industry has increasingly recognized the value of geophysical investigations. These techniques offer the advantage of being non-destructive and provide a cost-effective means to rapidly assess large areas. In contrast to traditional exploratory techniques, geophysics can provide a comprehensive view of the subsurface conditions, offering the potential for early detection of issues that could impact the project schedule or budget [3]. Furthermore, by providing a more complete picture of the ground conditions, geophysical methods contribute to the optimization of design solutions, thus promoting the overall success of construction projects.

1.3 Significance of Subsurface Information for Decision Making

Subsurface information is pivotal to decision-making processes in tunnel and underground projects. Detailed understanding of subsurface conditions allows for better prediction of potential challenges, which can significantly influence the construction strategy and risk management plans. By providing early warning of potential problematic ground conditions or geohazards, geophysical techniques enable project teams to adapt their strategies proactively, enhancing construction safety, efficiency, and the project's economic viability.

1.4 Challenges with Traditional Exploratory Work

Traditional methods of subsurface exploration, such as drilling and excavation, are invasive, costly, time-consuming, and provide localized data. Additionally, these techniques often have a limited ability to detect certain types of subsurface features or conditions. In contrast, geophysical techniques offer a non-invasive approach that can cover large areas and provide continuous data, thus significantly improving the characterization of the subsurface and reducing uncertainties. Geophysical results can help optimise the traditional exploratory work and provide suitable locations for drilling to gather relevant data.

1.5 Technological Advancements and Digitization in Geophysics

Recent technological advancements, including the development of portable digital data acquisition systems, have significantly enhanced the versatility and efficiency of geophysical methods. Modern systems offer improved resolution, accuracy, and depth penetration, providing more detailed and reliable subsurface images. The shift towards digital data acquisition and analysis facilitates the integration of geophysical data with other datasets, improving the understanding of the subsurface and aiding in the visualization and communication of complex geological conditions. The increased digitization also supports machine learning and artificial intelligence applications [4], opening new possibilities for data interpretation and prediction.

2. Benefits and Limitations of Geophysics

In this section, we explore the advantages and potential drawbacks of using geophysics in tunnel and underground projects, offering a balanced view of these methodologies.

2.1 Advantages of Geophysical Techniques

Geophysical methods offer numerous benefits in the context of tunnel and underground projects. Here, we delve into some of the most significant ones.

2.1.1 Comprehensive Subsurface Information

Geophysical techniques provide a broad, detailed view of the subsurface, offering critical insights into the geological and geotechnical conditions. These insights can inform decision-making and risk management processes, contributing to the successful planning, construction, and maintenance of tunnel projects.

2.1.2 Non-invasive Exploration

Unlike traditional exploratory methods like drilling and excavation, geophysical techniques are non-invasive, which means they cause minimal disruption to the environment and the project site.

2.1.3 Cost and Time Efficiency

Geophysical techniques are typically faster and less costly than traditional exploratory methods. They can rapidly assess large areas and generate a wealth of data, which can lead to substantial savings in time and resources.

2.1.4 Data Integration

The data gathered through geophysical techniques can be integrated with other geospatial and geotechnical data, enabling a comprehensive understanding of the subsurface conditions. This data integration can enhance the accuracy of geotechnical models, aiding in the design and implementation of construction strategies.

2.2 *Limitations and Challenges of Geophysical Techniques*

Despite their many benefits, geophysical methods also have their limitations and can present certain challenges in the context of tunnel and underground projects.

2.2.1 Interpretation Challenges

Geophysical data can be complex and require skilled interpretation. Misinterpretations can lead to inaccuracies in the characterization of subsurface conditions, potentially affecting the project outcomes.

2.2.2 Dependence on Site Conditions

The effectiveness of geophysical techniques can depend on the specific geologic and environmental conditions at the site. Certain methods might not be suitable or effective for all types of ground conditions.

2.2.3 Need for Ground-Truthing

Despite their detail and breadth, geophysical surveys often need to be supplemented with direct methods such as drilling or excavation to confirm the findings - a process known as ground-truthing.

In summary, while geophysical techniques offer valuable benefits, it is essential to understand and address their limitations to ensure the effective harnessing of these methods in tunnel and underground projects. By recognizing these challenges, strategies can be developed to mitigate potential issues, ensuring that geophysics is applied in the most advantageous way.

3. Planning and Pre-construction Stage

3.1 *Heliborne Time Domain Electro-Magnetic Method (TDEM)*

The Heliborne Time Domain Electro-Magnetic method (TDEM) is a versatile geophysical technique that can cover vast areas quickly, providing an efficient means of collecting subsurface data. TDEM uses electromagnetic fields to induce currents in the ground. These induced currents generate secondary magnetic fields that are detected and measured by the system's receiver, providing information about the subsurface's electrical conductivity [5].

In a tunnel project, TDEM can detect variations in subsurface conductivity that could indicate the presence of different geological formations, such as water-bearing zones or areas with weak rock layers. These insights are crucial for understanding the challenges that might be encountered during tunnelling and can inform the development of mitigation strategies.

3.2 Deep Seismic Reflection Surveying

Deep seismic reflection surveying is a powerful technique used to image the subsurface. It involves the generation of seismic waves, which travel through the ground and are reflected back to the surface at the interfaces between different geological layers. The travel time and strength of the reflected waves are recorded and used to construct detailed images of the subsurface.

In tunnel construction projects, deep seismic reflection surveying can reveal key geological features, such as fault lines, folds, and variations in rock types. This information is vital for designing the tunnel route and construction method, helping to avoid potential geohazards and optimize construction efficiency.

3.3 Electrical Resistivity Imaging (ERI)

Electrical Resistivity Imaging (ERI) is a geophysical method that uses the principle of electrical resistivity to investigate subsurface conditions. By injecting an electrical current into the ground and measuring the resulting potential difference, ERI can estimate the resistivity of the subsurface materials. Different materials, such as rock, clay, or water, have different resistivity values, which can be used to identify these materials in the subsurface [6].

In the context of tunnel projects, ERI can help identify potential problem areas, such as clay zones that could cause instability or water-bearing strata that could lead to water inflow during tunnelling. By detecting these features in the pre-construction

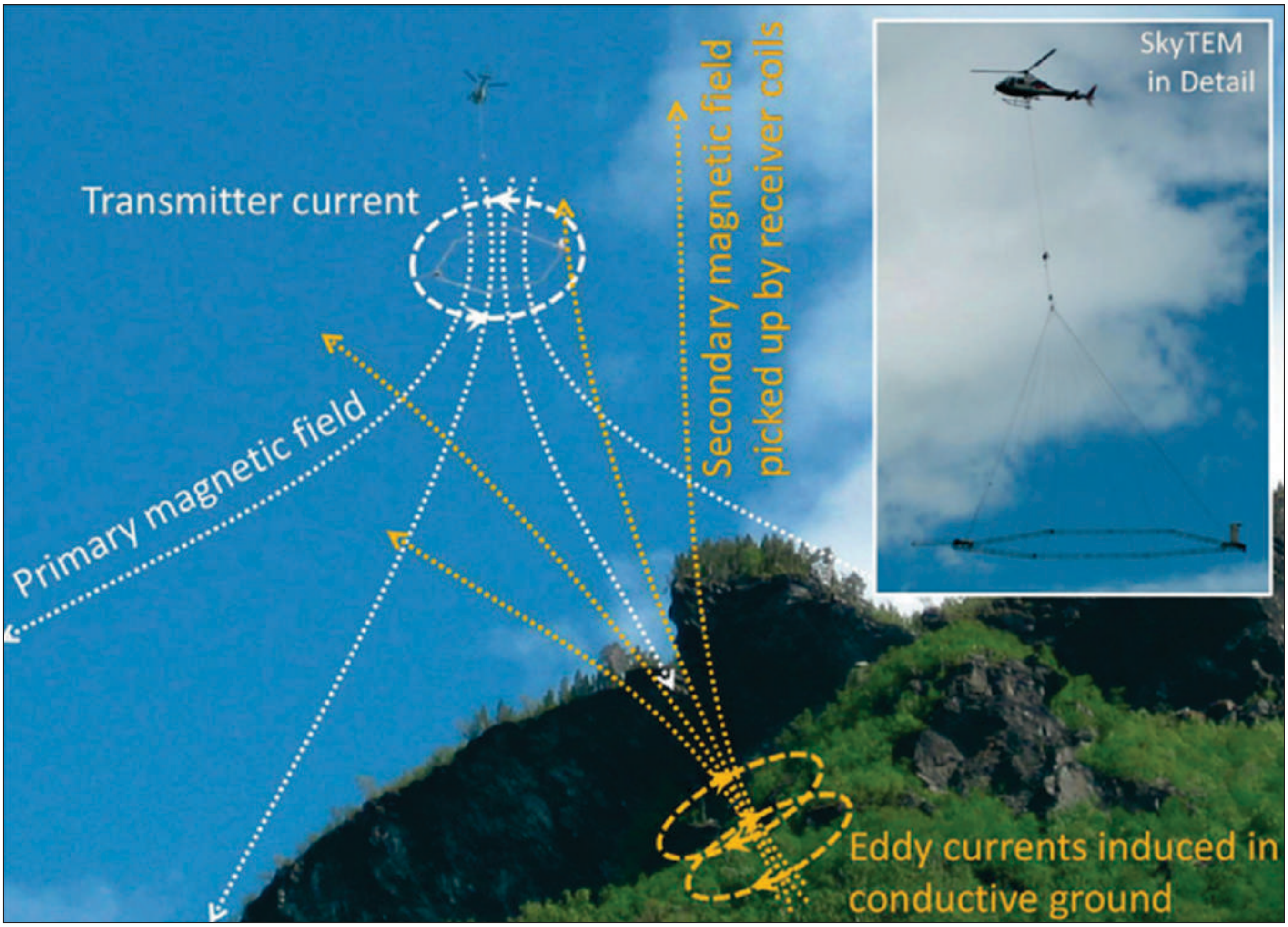

Figure-1: Working Principle of Heliborne TDEM [5]

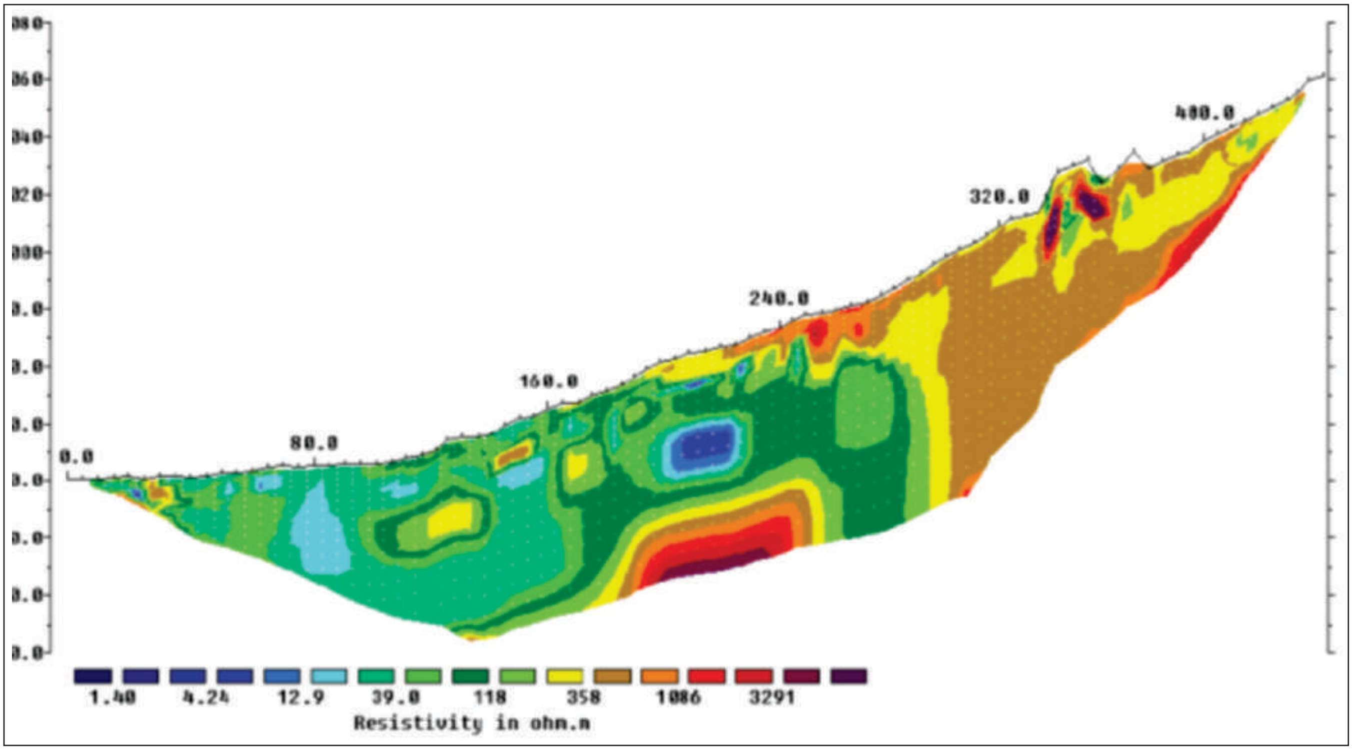

Figure-2: Shear Zone Detection Using ERI in a Tunnel Project [6]

phase, ERI can inform risk assessment and mitigation planning.

3.4 Seismic Refraction Tomography

Seismic Refraction Tomography (SRT) is a powerful geophysical method for investigating subsurface structures and conditions. SRT involves generating seismic waves, typically by striking the ground surface with a hammer or using a controlled explosive source. These waves travel through the subsurface, refract off interfaces between different layers, and are detected by geophones at the surface. The travel times of these waves are then used to construct a velocity model of the subsurface, revealing variations in the geologic structure and material properties [7].

In tunnel and underground projects, SRT provides a detailed view of the subsurface, delivering critical insights for project planning and risk management. For instance, velocity variations can highlight the presence of different geological formations, layers, and anomalies, such as faults or fractures, voids, and zones of weathered or weak rock.

By identifying these features in the pre-construction phase, SRT aids in assessing the feasibility of a tunnel route and optimizing construction strategies. It helps engineers to prepare for challenges that may arise during tunnelling, like encountering hard rock or water-bearing zones, contributing significantly to the planning of resource allocation, timeline, and risk mitigation measures. Furthermore, SRT complements other geophysical methods, providing comprehensive and reliable subsurface information necessary for the successful execution of tunnel projects. Subsequent drilling confirmed the geophysical investigation results.

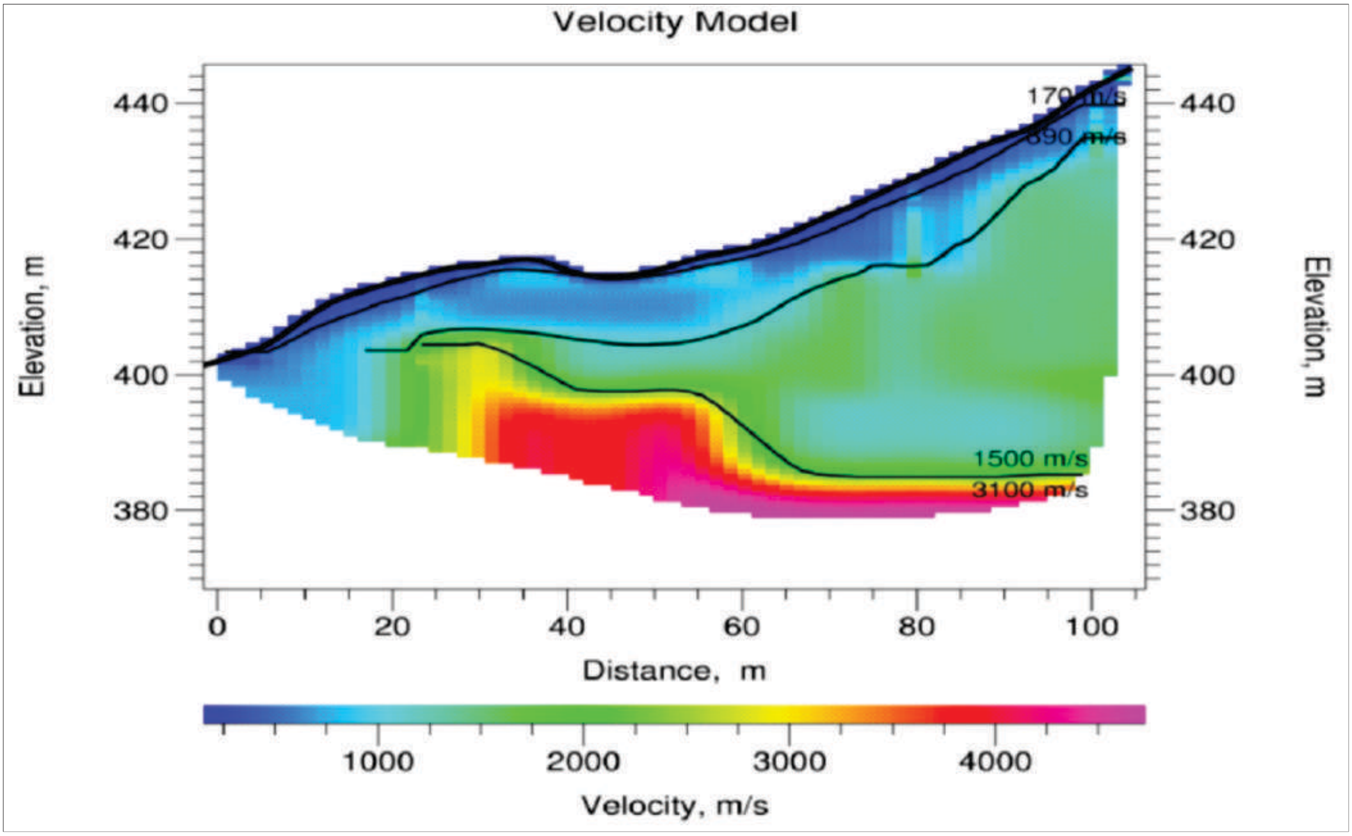

Figure-3: SRT Profile Revealing Highly Undulating Topography of Rock, and Abrupt Thickening of Overburden/Weathered Zone [8]

3.5 Refraction Microtremor (ReMi) and Multichannel Analysis of Surface Waves (MASW)

Refraction Microtremor (ReMi) and Multichannel Analysis of Surface Waves (MASW) are geophysical methods used to determine the shear-wave velocity structure of the ground. These techniques involve the recording of ambient seismic noise (ReMi) or artificially generated seismic waves (MASW), and the analysis of the waveforms to derive the velocity structure of the ground.

In tunnel projects, knowledge of the ground's velocity structure is important for assessing the ground's response to dynamic loads, such as those induced by tunnelling activities or potential seismic events. This information can guide the design of the tunnel support system and contribute to the overall safety and performance of the tunnel.

3.6 Cross Hole & Cross Face Seismic Tomography

Cross hole Seismic Tomography is a technique that involves generating and recording seismic waves between a series of boreholes. By analysing the travel times of the waves, it is possible to construct a detailed image of the subsurface between the boreholes. This method is particularly useful for characterizing the properties of the ground in the proposed tunnel alignment [9].

In tunnel projects, Cross hole Seismic Tomography can provide valuable insights into the variability of the subsurface conditions, which can affect the behaviour of the ground during tunnelling. These insights can inform the selection of the appropriate tunnelling method and the design of the tunnel support system, contributing to the overall success of the project.

Cross face seismic tomography can also be used to study and analyse cross-passage section after construction of twin tunnels and using their faces to shots and receivers. Results presented in Fig 4 were subsequently confirmed and validated by borehole laser mapping system.

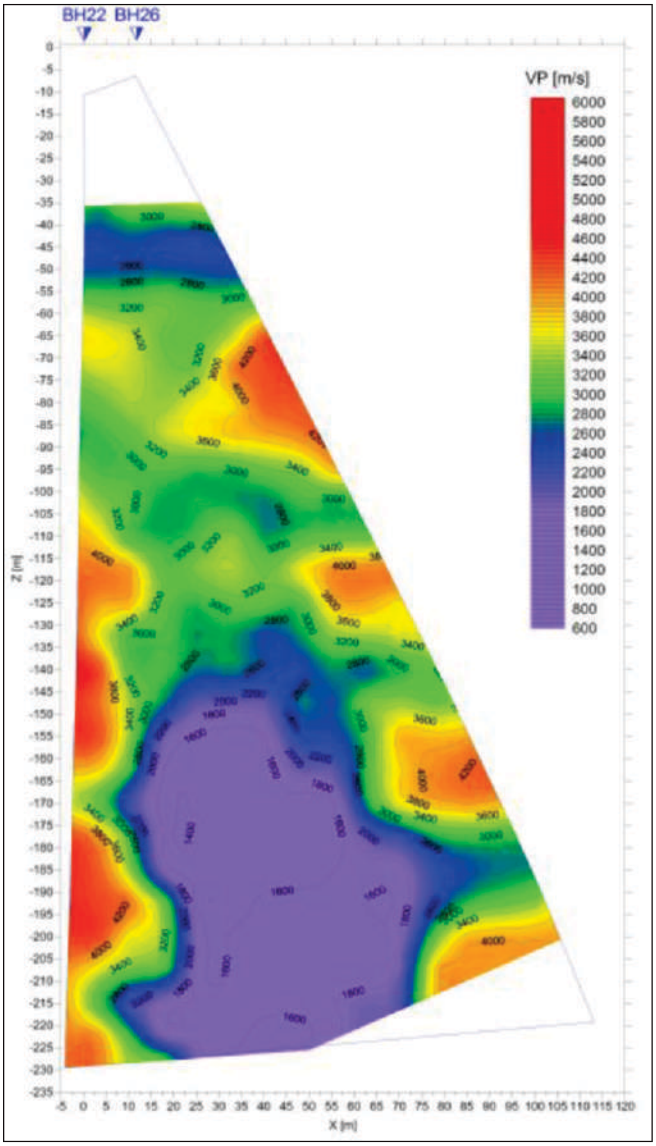

Figure-4: Cross hole seismic tomography delineating a large cavity in a tunnel project [10]

4. Construction Stage

Geophysical investigations also play a crucial role during the actual construction phase of tunnel and underground projects. They provide real-time, continuous monitoring of subsurface conditions, enabling timely decision-making and effective management of potential risks. The key geophysical techniques applied during the construction stage include Tunnel Seismic Prediction (TSP), Bore Tunneling Electrical Ahead Monitoring (BEAM), and Ground Penetrating Radar (GPR) [2].

4.1 *Tunnel Seismic Prediction (TSP)*

Tunnel Seismic Prediction (TSP) is a proactive geophysical technique used during tunnel construction for the detection of geological and hydrogeological hazards ahead of the tunnel face. TSP involves generating seismic waves from within the tunnel, which are then recorded by an array of sensors [11]. The analysis of these waves can provide information about the geological conditions up to 50 to 200 meters ahead of the tunnel face (depending on geology of the area).

This advanced warning system allows engineers to identify potential hazards, such as water-filled fractures or weak rock layers before they are encountered during excavation. This information enables the modification of the construction strategy in a timely manner, mitigating risks and preventing delays or accidents.

4.2 *Bore Tunneling Electrical Ahead Monitoring (BEAM)*

Bore Tunneling Electrical Ahead Monitoring (BEAM) is another powerful technique used to investigate the geological conditions ahead of the tunnel face during tunnel construction. BEAM uses the principle of electrical resistivity and induced polarization to detect changes in the subsurface. By introducing an electrical current into the ground and measuring the resulting potential difference, BEAM can identify anomalies that may indicate potential hazards, such as water-bearing zones or weak formations [12].

BEAM's ability to anticipate these challenges allows construction crews to take preventative measures, modify the tunnel design if necessary, and manage construction activities more efficiently, minimizing potential delays or safety risks. Results presented in Fig 5 were validated during actual TBM operation.

4.3 Ground Penetrating Radar (GPR)

Ground Penetrating Radar (GPR) is a versatile geophysical technique used during the construction phase of tunnel projects. GPR emits high-frequency radio waves into the ground, and the reflected signals are used to create images of the subsurface. This can be used to detect changes in material properties, such as the transition from hard rock to a soft soil zone.

In tunnel projects, GPR is commonly used to check the quality of the tunnel lining and to detect any irregularities in the subsurface, such as voids or fractures, during the construction process. This information can guide immediate remedial actions, ensuring the structural stability of the tunnel and the safety of the construction process.

In summary, the use of these geophysical techniques during the construction phase of tunnel and underground projects enhances the understanding of ongoing subsurface conditions, promotes safer and more efficient construction practices, and optimizes decision-making processes. This translates into a more controlled project execution, reducing both the likelihood of unexpected problems and the associated costs and delays.

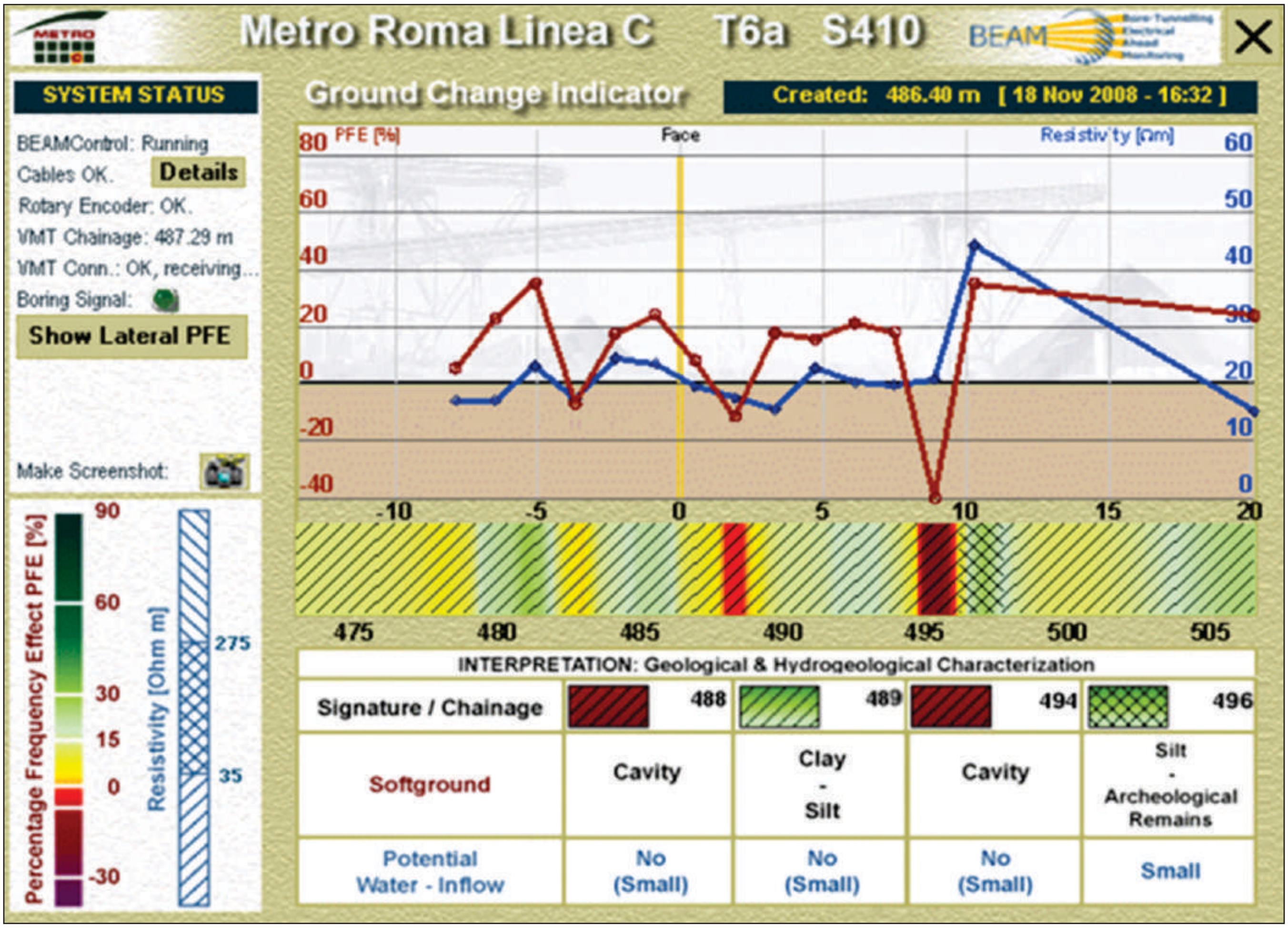

Figure-5: BEAM results in real time in terms of Resistivity and PFE (percentage Frequency Effect) and resultant formation classification

5. Maintenance Stage

After the construction phase, geophysical investigations continue to serve a vital function in the maintenance and inspection of the completed tunnel or underground structure. They offer non-destructive methods for ongoing health checks and early detection of potential structural issues, such as deterioration or damage to the tunnel lining. Ground Penetrating Radar (GPR) is a prominent technique used during this stage.

5.1 Ground Penetrating Radar (GPR) for Tunnel Lining and Defects

Ground Penetrating Radar (GPR) is a non-destructive geophysical method that can be effectively used for the maintenance and inspection of tunnel and underground structures. GPR operates by transmitting high-frequency radio waves into the ground and detecting the reflected signals from subsurface structures. The signal strength and travel time of these reflected waves provide information about the location, depth, and characteristics of these structures [2].

During the maintenance phase of a tunnel project, GPR is often used to assess the condition of the tunnel lining. It can detect variations in the thickness of the lining, which may indicate areas of deterioration or damage. GPR can also identify voids or defects behind the tunnel lining, which could signify issues such as water infiltration or material loss due to erosion.

The ability to perform these inspections without causing damage or disruption to the tunnel structure makes GPR a highly valuable tool for tunnel maintenance. Regular GPR inspections can facilitate proactive maintenance strategies, enabling early detection and repair of issues before they evolve into more serious problems.

5.2 Electrical Resistivity Imaging-Case Study of Existing Tunnel

The case study in question illustrates an application of geophysical techniques to identify areas of concern within a tunnel system, specifically focusing on saturated zones that were the source of seepage. This application highlights how these techniques can be used to address real-world issues in the operation and maintenance of tunnel systems.

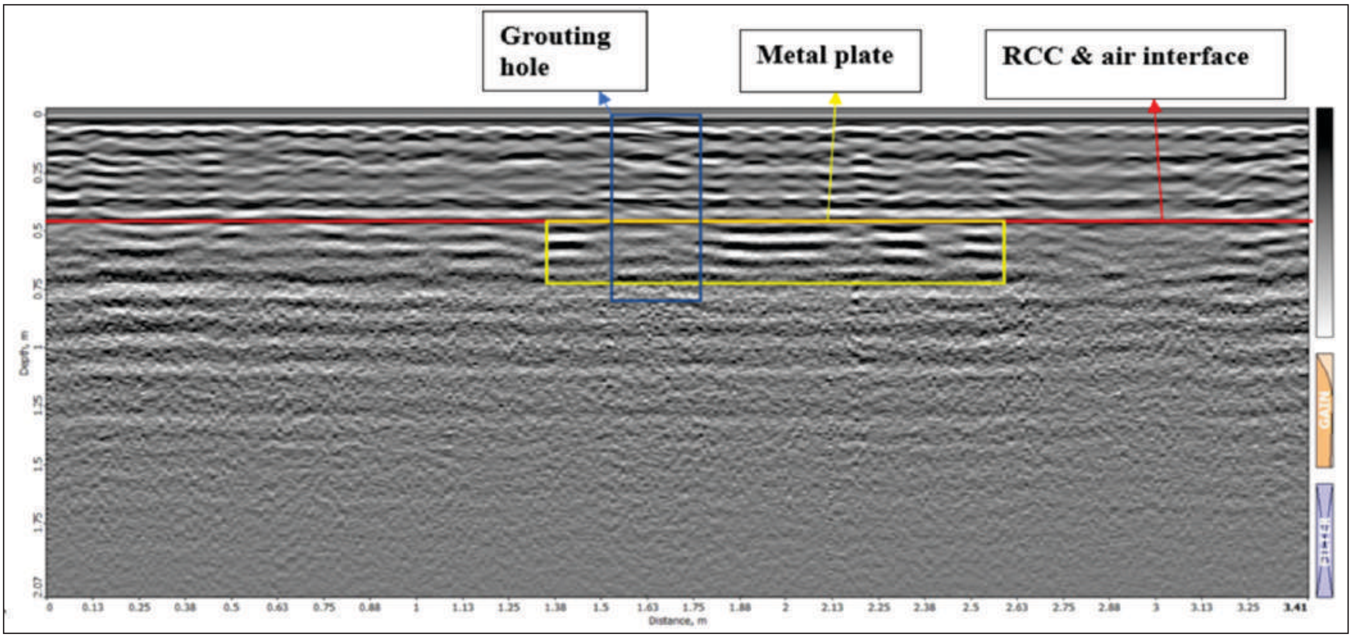

Figure-6: GPR results showing RCC-Air interface, grouting hole and metal plate (test)

In this particular study, an array of electrodes was strategically installed along the length of the tunnel. These electrodes were placed in a pattern that included several co-parallel lines, ensuring comprehensive coverage of the tunnel's interior. This arrangement allowed for the detection and monitoring of anomalies in the subsurface structures and materials, including zones of saturation that could potentially result in seepage.

Through a meticulous analysis of the data collected from these electrodes, the team was able to pinpoint the areas within the tunnel where seepage was originating. These areas were represented in a visual format for easy interpretation. Notably, the region identified as the source of the seepage was color-coded blue for immediate recognition.

The presented case study provides a clear demonstration of the efficacy of geophysical techniques in diagnosing problems within constructed tunnel systems. It shows that with appropriate instrumentation and data analysis methods, it is possible to identify areas of seepage within a tunnel and take targeted action to address these issues. This practical application of geophysical investigations offers potential for improved maintenance and longer operational lifetimes for such underground structures [2].

6. Conclusions

This paper has highlighted the crucial role that geophysical investigations play at every stage of tunnel and underground projects. From initial planning and pre-construction through to construction and maintenance, geophysical techniques provide valuable subsurface information that can significantly enhance the success of these projects.

During the planning and pre-construction stage, geophysical methods such as Heliborne Time Domain Electro-Magnetic Method (TDEM), Deep Seismic Reflection Surveying, Electrical Resistivity Imaging (ERI), Refraction Microtremor (ReMi), Multichannel Analysis of Surface Waves (MASW), Seismic Refraction Tomography (SRT), and Cross hole Seismic Tomography provide comprehensive subsurface knowledge. This knowledge is critical for risk assessment, route selection, and the design of construction strategies, helping to optimize project timelines, resources, and risk mitigation measures.

During the construction stage, techniques such as Tunnel Seismic Prediction (TSP), Bore Tunneling Electrical Ahead Monitoring (BEAM), and Ground Penetrating Radar (GPR) provide real-time monitoring of subsurface conditions. This enables

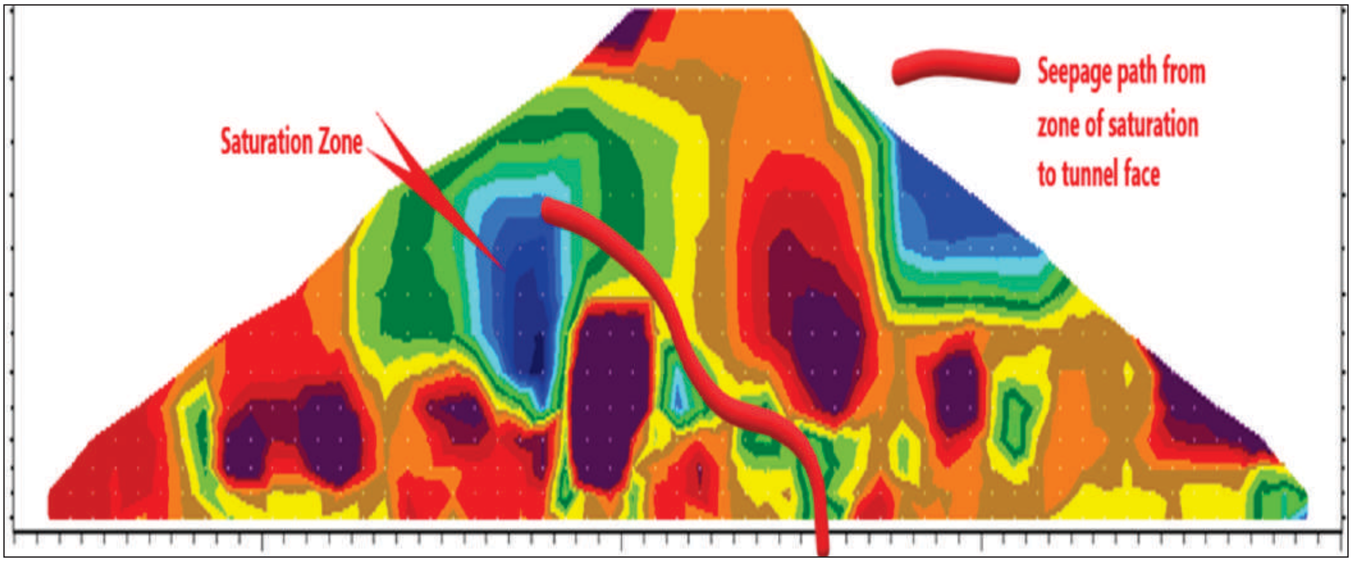

Figure-7: ERI results showing zone of water accumulation behind tunnel lining and seepage path timely decision-making, effective management of potential risks, and optimization of construction activities, contributing to a safer and more efficient construction process.

In the maintenance stage, GPR is used for ongoing health checks and the early detection of potential structural issues. Its non-destructive nature makes it an ideal tool for routine inspections, facilitating proactive maintenance strategies and promoting the longevity and reliability of the tunnel structure. ERI can be used to detect saturated zone behind the tunnel.

In conclusion, the adoption and integration of geophysical techniques in tunnel and underground projects represent a transformative approach. It enables the generation of detailed, accurate, and extensive subsurface data, optimizing every aspect of the project life cycle. This not only contributes to economic efficiency but also enhances the structural reliability of these essential infrastructures, ultimately promoting their sustainability and resilience in the face of evolving geotechnical challenges.

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A Case Study of Opportunities and Challenges in Underground Metro Stations

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Abstract

The paper delves into an analysis of the opportunities and hurdles faced during the development of Bangalore's underground Pottery Town Metro Station within the RT-03 Package. Initially, the station's design included a crossover and an additional stabling yard alongside 100 meters of NATM tunnel in both directions. However, operational challenges emerged due to unfavourable soil conditions in the NATM tunnel, leading to the shift of the crossover and stabling yard. This posed a unique challenge, as the creation of new crossing and stabling facilities within the project's constraints was difficult.

The strategic positioning of NATM tunnels became paramount since the stabling yard is located at the tunnel's end within a densely constructed underground area. To address this, a proposed integrating the crossover and stabling yard within the station was provided, leveraging existing site conditions, and collaborating closely with architectural and alignment experts.

The station's original design aimed for three tracks but had to be adapted to include a fourth track and stable yards due to limitations. Throughout the project, careful consideration was given to minimize the disruptions when introducing changes as per the client's request.

A significant challenge emerged in aligning the station for Tunnel Boring Machine (TBM) operation, involving the passage of the TBM through the station and its relaunch from a different end. The design of column arrangements to accommodate both the four-track provision and the TBM operation proved to be exceptionally demanding, by requiring the need to balance permanent and temporary configurations while meeting architect specifications.

In this paper, the project's potential and constraints will be, evaluating how well it aligned with the client's requirements and needs.

Keywords: Underground stations, NATM, Cut and cover tunnel, TBM operations, Construction methodology, TBM Drag through, Bottom-Up construction.

1. Introduction

Underground metro rail systems are indispensable in a densely populated metropolitan region due to its capacity to alleviate traffic congestion, minimize environmental harm, enhance transit efficiency, boost reliability and safety, and stimulate urban development. They serve as a critical component of sustainable urban transportation networks and play a pivotal role in modern urban planning. The development of metro rail systems has significantly improved urban transportation and connectivity in several Indian cities, offering a more efficient and sustainable mode of transit for commuters. The Kolkata Metro, also known as the Calcutta Metro, began its operations in 1984. It was the first metro system in India and played a pioneering role in urban transportation. The Delhi Metro, one of the most extensive metro systems in India, started its operations on 2002, with the inauguration of the Red Line. Delhi Metro has since expanded significantly, covering various parts of the National Capital Region (NCR). In this paper the opportunities and challenges faced in Bangalore metro project during the design and construction phase. Bangalore metro (BMRCL) Phase 2 line 4 (Pink Line) planned with 21.386km, in that 7.051km as elevated system and 13.885km as underground system. In pink line tender invited for 4 packages. Package RT-03 of Phase II encompasses two underground stations, namely Cantonment and Pottery Town Station, along with the corresponding tunnel infrastructure. This package commences at approximately Ch. 13938.328 meters, initiates at Shivaji Nagar Station, and concludes at Ch. 16822.521 meters, where it terminates at the retrieval shaft following Pottery Town Station.

2. Tender Conditions

As per the Tender document shown in Fig 2.1, pottery town station is located at chainage of

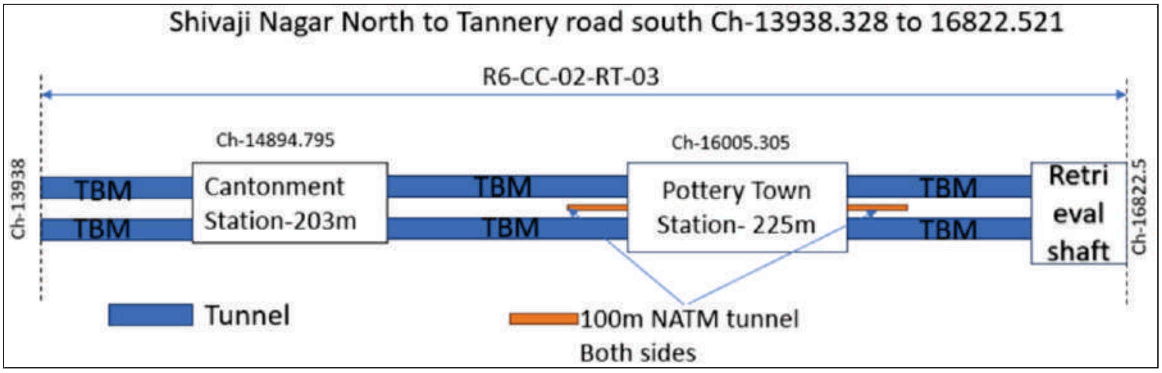

Fig 2.1 : Brief of tender Package RT-03

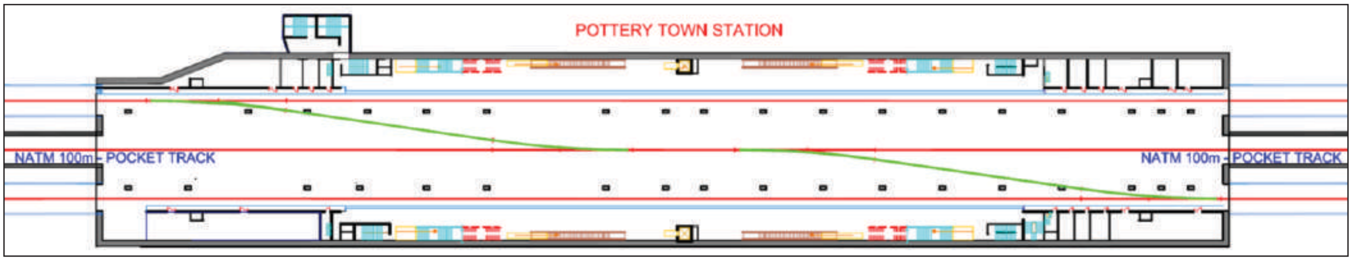

Fig 2.2 : Pottery Town Station Layout- Tender Stage

+16005.305m with the length of 225.3m and width of 36m. Pottery town station has two Public Entry/exit, one at north side another at south side. It is also considered as cross over point and pocket track location. The length of pocket track considered as 100m on both the south and north end. Due to the cross over condition, the station consist of two side platforms with staircase, escalator, and lifts as per the NBC requirements as shown in fig 2.2. As per the tender bore log details, station has encountered rock strata at the 13m from ground level. We (L&T) secured the contract in the month of March 2019 commenced the works.

3. Design and Construction Phase

The design and construction of an underground metro system involves a collaborative effort that integrates inputs from various teams and disciplines. This process encompasses architectural requirements, construction methodologies, coordination with the MEP (Mechanical, Electrical, Plumbing) team, environmental control systems team, track planning team, and the S&T (Signalling and Telecommunications) team. Delays in receiving input from any team or encountering constraints during construction can have a cascading effect, ultimately leading to project-wide delays. These changes can also influence project schedule and discrepancies in the quantity. Major issue in any underground metro station is geotechnical conditions, which plays a major role in selection of construction methods. Changes made before the project commencement are manageable with minimal impact on the overall project timeline. However, changes made mid-project can significantly disrupt both the schedule and the budget. The significant challenge for the engineers is to mitigate the impact of changes in a project effectively.

3.1 NATM Pocket Track construction.

In Bangalore, geological profile often comprises a mix of rock and soil strata. During the planning phase for Pottery Town Station, it was discovered that rock is encountered at a depth of 13 meters. Consequently, the decision was made to adopt the bottom-up construction method. In pottery town station all the expected changes were identified and get concurrence regarding the same from each team was received for General arrangement drawings. Station General arrangement is planned based on the architectural, track level, cross over condition and work has commenced with secant pile wall and excavation has initiated. TBM operation is considered as drag through method in station location. Columns are positioned based on the drag through condition. Due to the operation of the TBM certain columns have been affected and encroached upon. As a result, the execution team has been advised to prioritise work in Grid 3-17 of station location until the TBM work is completed. This clearance allows the site to proceed with construction activities at mid of the station (Grid 3-17). During excavation, it has been revealed that the southern end of the station site is characterized by highly unfavourable soil conditions. The soil in this area exhibits poor properties, being very loose and filled with materials. Fortunately, since the station is being constructed from the bottom up, it doesn't significantly affect the station's construction progress. However, the real challenge arises in the construction of the NATM tunnel in the pocket track area. In NATM tunnel Shaping a crown for the track location under these circumstances proves to be an intricate task, Geotechnical experts suggest that stabilizing soils through treatment is not effective, necessitating frequent testing and monitoring. This significantly impacts the project budget due to the extensive construction activities involved associated with it. This situation has prompted a need for critical thinking and the exploration of solutions to minimize these adverse effects.

3.1.1 Alignment modification

The primary solution for the problem is the modification of alignment. hence, four options were planned to address the same.

Option-1- Island platform in station

In this option, the pocket track is envisioned as a stabling yard, and the station layout remains unchanged. Initially, the station location was designed with a stabling yard and without crossover point in Pottery Town station. Therefore, it was proposed to relocate the crossover point closer to Cantonment station as shown in Fig 3.2. Cantonment station's location is characterized by hard rock strata, making it well-suited for NATM construction for the crossover. Considering this adjustment, Pottery Town station has been redesigned to feature an island platform arrangement instead of a side platform layout as shown in Fig 3.1. This modification involves shifting the positions of columns to accommodate the track switching requirements.

In this option, there are broader repercussions affecting various aspects were presented. Specifically, the TBM drag-through operation presents a critical challenge, but it can be effectively addressed using the side-shifting method. The impact is primarily confined to grid sections 1-5 and 15-19, and it is manageable within these limits. However, there is a secondary impact on the

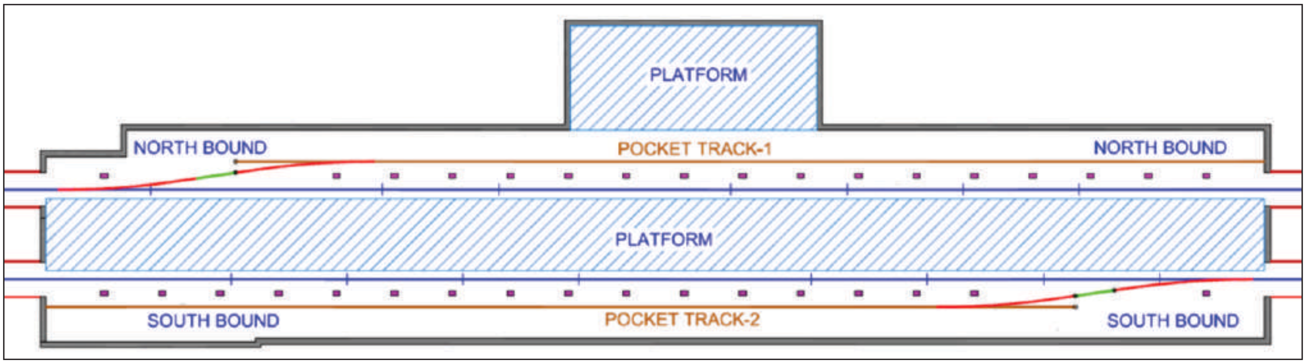

Fig 3.1 : Option-1 station with Island platform.

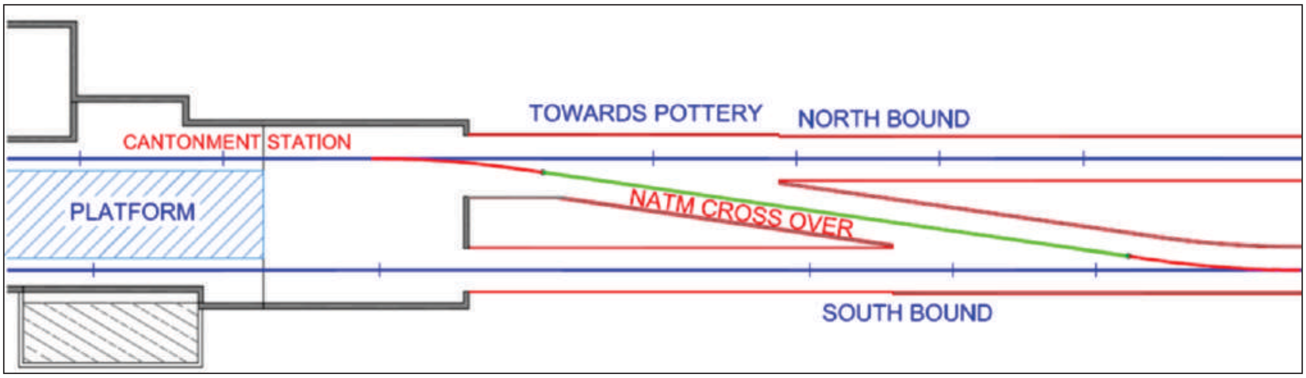

Fig 3.2 : Option-1 Cross over in Cantonment station.

construction of the platform slab. Because the arrangements for station staircases, escalators, and lifts have been relocated to the island platform, the construction work will commence only after the completion of TBM shifting activities. Consequently, this will result in additional timelines and a potential delay in project completion. Another concern arises from the need for approval from the architecture team, as the modification in column arrangements has implications for the layout of the operation room. This arrangement necessitates extensive modifications for the Environmental Control System (ECS) team due to the alterations in openings. In all scenarios, Option-1 offers the advantage of eliminating NATM construction in Pottery Town station. However, it comes with various drawbacks, including project timeline delays and additional work requirements in cantonment station location. Hence, the team has collectively decided to not to pursue Option-1 due to its significant impacts.

Option-2- Side platform with additional columns.

Upon examination, the primary issue with the Option 1 was identified as a delay in constructing the platform and the staircases. Fig 3.3 shows the arrangment of option-2. In response, Option 2 proposed a modification by introducing a side platform with additional columns positioned in the middle of the station. However, Option 2 brings its own set of challenges, including increased column construction, leading to additional construction activities in terms of time and cost. As per architectural acquirement, position of the columns could adversely affect passenger movement due to the presence of additional columns at the station's center in concourse area. As a result, option 2 could not proceed.

Option-3 Reduced NATM lengths

Given the client's directive to consolidate the crossover and stabling yard at the Pottery Town location, Option 3 was approached. This option closely aligns with the initial tender conditions. However, to accommodate TBM (Tunnel Boring Machine) operations, adjustments have to be made. In doing so, the length of the NATM (New Austrian Tunneling Method) has been reduced on the south side by 35m instead of 100m and extended on the north side by 101.97m as shown in Fig 3.4. While this modification facilitates crossover

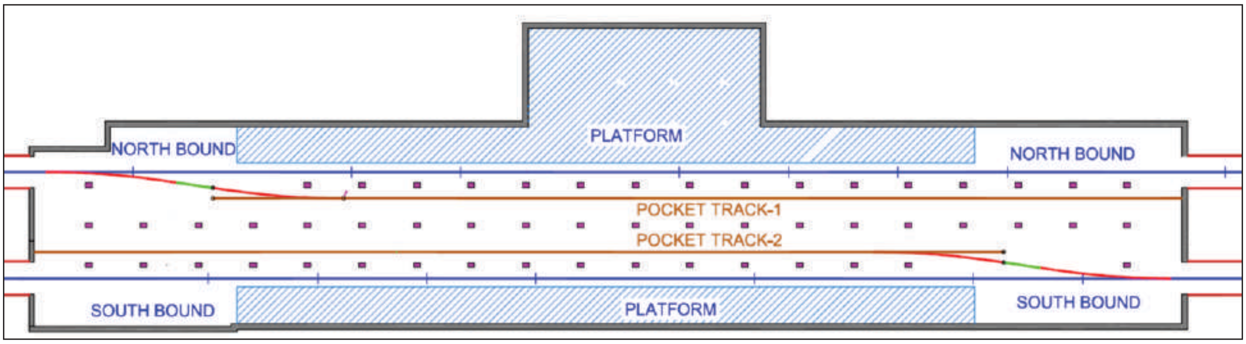

Fig 3.3 : Option-2 station with side platform.

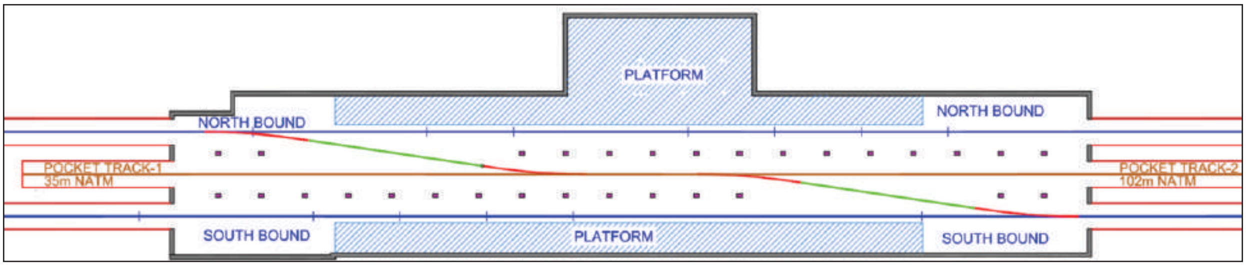

Fig 3.4 : Option 3 Cross over and station within the station with reduce NATM tunnel in south zone.

operation, it results in larger station spans between Grids 2-7 and Grids 12-17. Consequently, additional thickness is required for both the concourse and roof slabs including increase in station columns. Furthermore, this option necessitates NATM length of 35 meters on the south side. Considering the previously mentioned unfavorable soil conditions with poor fill, there is contemplation to exclude the NATM tunnel in the southern zone. To avoid the NATM construction at south side it has decided to prepare the another option to construct the NATM tunnel as cut & cover box with bottom up method to resolve the issue. Hence the increasing the cut and cover box length in south side as 40m.

3.2 *Property Development*

During the process of alignment modification (Option-4), the client has proposed incorporating property development above the station location. Specifically, the entry structure for Pottery Town Station spans across Grids 1-4 (Entry B) and Grids 15-19 (Entry A). The client's requirement is to construct G+4 buildings at each of these entries. To meet this demand, the station must be designed to bear the additional loads imposed by the above-ground structures.

In light of the previous challenge (option-3) concerning the pocket track requirement, careful consideration has been given to the placement of station columns at the station. These columns must be strategically located to support the loads from the structures above without interfering with the track layout. To address these requirements, a new proposal has been developed as shown in Fig 3.5. Both the columns for property development and those for the station have been aligned in the same positions to ensure that the loads on the station's roof slabs are adequately supported. Fig 3.6 and Gig 3.7 explains the condition of station column and Property development columns arrangments.

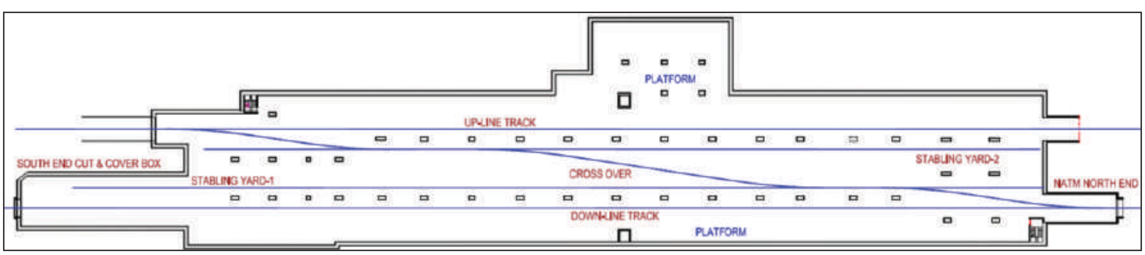

Fig 3.5 : Option-4 Cut and Cover Box with PD column position.

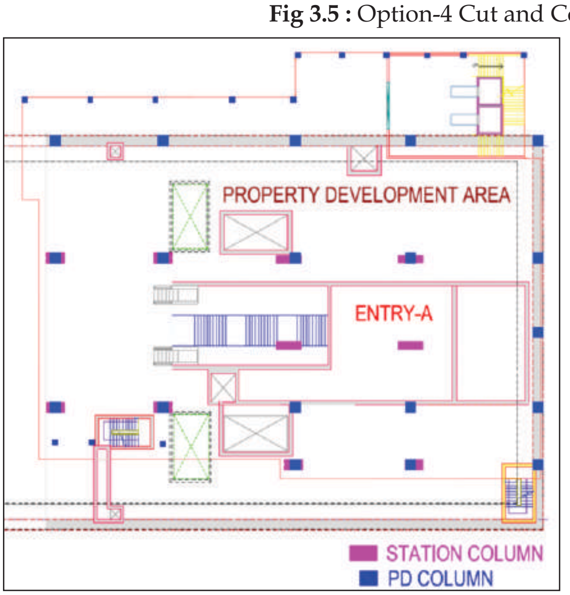

Fig 3.6 : Entry A with Property Development agreement.

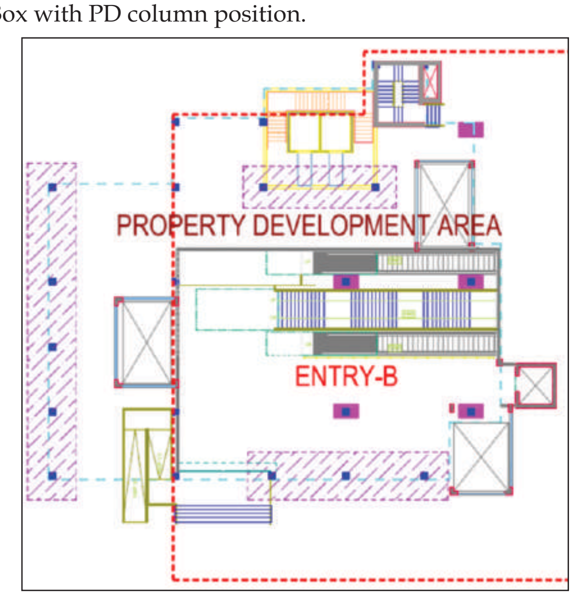

Fig 3.7 : Entry B with Property Development agreement.

As per the image blue color columns are PD columns and Magenta color columns are PD columns. To the max Columns are placed in existing station column and station walls.

As a result, the conclusion has been reached that the NATM (New Austrian Tunneling Method) tunnel should be constructed as a cut-and-cover box structure as per the Option 3 of the proposal. This approach allows for an extension of the cut-and-cover section at south side and a reduction in the length of the NATM tunnel in the north. This proposal not only enables the inclusion of the crossover and stabling yard within the station's confines but also maintains the station column locations in accordance with the conditions outlined in the tender documents and preliminary approved general arrangement drawings. This challenge leads the provision of 2 stabling yard and cross over with in the station location with reduced NATM construction. The time line of construction of cut and cover location has made within project schdeule.

3.3 TBM Drag Operation

In the TBM drag-through scenario, the original plan was to construct the full base slab and subsequently, the concourse and roof slabs were intended to be built after the TBM drag-through operation was completed for grid 1-3 and 17-19 However, due to tunneling activity condition, there is now a desire within the construction team to proceed with the construction of the concourse and roof slab in Grids 1-3 and 17-19 before TBM draging operation. This change would impact the location of the station columns.To address this challenge, the decision has been made to construct the concourse and roof slab in Grids 1-3 and 17-19 using temporary columns. Notably, both the up-line and down-line have different timelines for reaching the station location, necessitating two distinct schemes for TBM dragging operations. To accommodate these changes, separate STAAD analyses have been conducted, considering both permanent and temporary column arrangements in the design of the concourse and roof slab. When the TBM reaches the station portion columns in the grid 3,4,5 made hindernce to shifting process, hence temorary column arrangement proposed in grid 3,4,5. Similarly same kind of arrangement has made in the grid 17-19 columns. Both the cases are shown in fig 3.8. In the same condition backup gantry arrangments also staisfied as shown in fig 3.9. These modifications present an opportunity to work within constrained conditions and explore innovative methods for station construction.

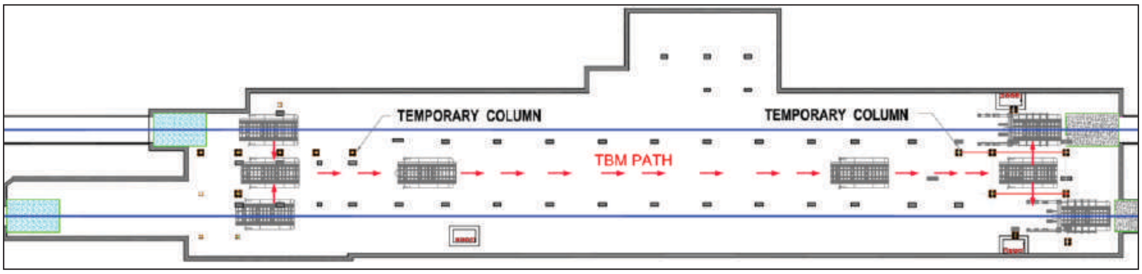

Fig 3.8 : TBM drag through with temporary column.

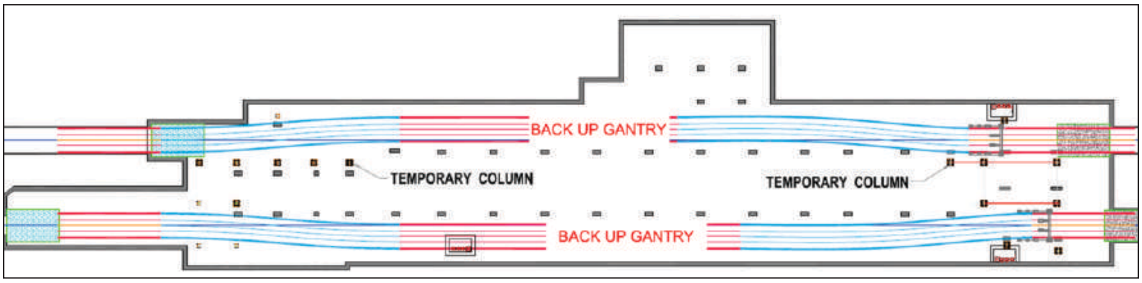

Fig 3.9 : Backup Gantry drag through arrangement.

4. Conclusion

This case study of Pottery Town Station offers a comprehensive perspective on the multitude of opportunities and challenges inherent in the design and construction of underground stations. Notably, changes in the geotechnical profile represent a significant hurdle for all underground related projects, particularly since the selection of construction methods directly impacts project timelines. In the context of underground stations, any modifications made during the project's course necessitate full concurrence from the architectural, track, ECS (Environmental Control System), and site teams. Each solution must align with the unique requirements of these domains. Within this study, the initial concept for the stabling yard and crossover provision revolved around separate locations for each within the station as a preliminary proposal. However, evolving demands, such as geological impact, property development, client requirements and construction schedules, gave rise to a fresh opportunity: the reduction of NATM construction and the integration of additional stabling yards and crossovers within the station's area. These constraints, while initially challenging, unveil new prospects in every underground project. With experience and proper guidance, they serve as catalysts for innovative solutions that enhance the overall success of underground projects.

5. Acknowledgement

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Precast in Underground Station Construction

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Abstract

Construction of underground metro rail stations in densely populated urban areas presents a myriad of unique challenges. These locations are often characterized by congested road and pedestrian traffic, following traditional construction methods could be both time-consuming and disruptive. In such demanding environments, the utilization of precast solutions emerges as an exceptionally advantageous approach. By incorporating precast elements into the underground station's design, essential components like Fire Fighter and Fire Escape stairs, platform slabs, Under Platform Exhaust (UPE) walls, Over Track Exhaust (OTE) ducts, and utility galleries can be efficiently manufactured off-site. This not only reduces construction timelines but also minimizes the need for repetitive formwork construction and avoiding staging works in congested metro areas and busy city roads.

Once the station layout is defined, careful consideration is given to the selection of precast elements. While major components like the concourse slab can potentially be precast, this decision necessitates meticulous coordination with various disciplines. The interface with other architectural and structural aspects must be closely examined and confirmed in advance before finalizing the construction arrangements. The goal is to ensure seamless integration between precast elements and other station features, optimizing both functionality and aesthetics.

This paper delves into the diverse array of options adopted in the Bangalore Metro RT 02 project, shedding light on the challenges and opportunities encountered throughout the project duration. By exploring these experiences, it provides valuable insights into the innovative use of precast solutions for various indicated elements in metro station construction, emphasizing their potential to streamline processes and enhance the overall efficiency of urban rail projects in bustling metropolitan settings.

Keywords: Underground stations, Precast works, Construction Methods, Precast Staircase, Bangalore Metro.

1. Introduction

Underground metro station, also referred to as a subway station or rapid transit system, operates through a distinct grid power source and functions on a dedicated right-of-way. The station comprises three main levels: the roof level, concourse level, and base level. Entry and exit points are strategically designed to facilitate the seamless movement of the public between street level and the underground station, ensuring convenient access for commuters.

Station Box is constructed either by Cut & cover methodology or New Australian Tunnelling Method (NATM). The box type section is constructed with external retaining walls as RCC wall, Diaphragm wall, or secant pile with required depth into the firm strata. Platform slab, which is supported by the Under Platform Exhausting Wall (UPE), and Plenum slab, which are ducts above suspended from the soffit of concourse level make up the station's base level. Over track Exhaust (OTE) duct system runs at the soffit of concourse level for removing the hot air from the rolling stock rails exhaust system at top and under chassis engine heat is handled by UPE ducts. Both the OTE & UPE are the part of Ventilation system for the Stations.

Concourse level is constructed with Elements such as Column, Staircase, Lift, Escalators, stub column and internal rooms. At roof level the staircase is used as main utility service to access station from Road/public areas which has been located on ground. Fig.1 represents the structural components of the underground metro station.

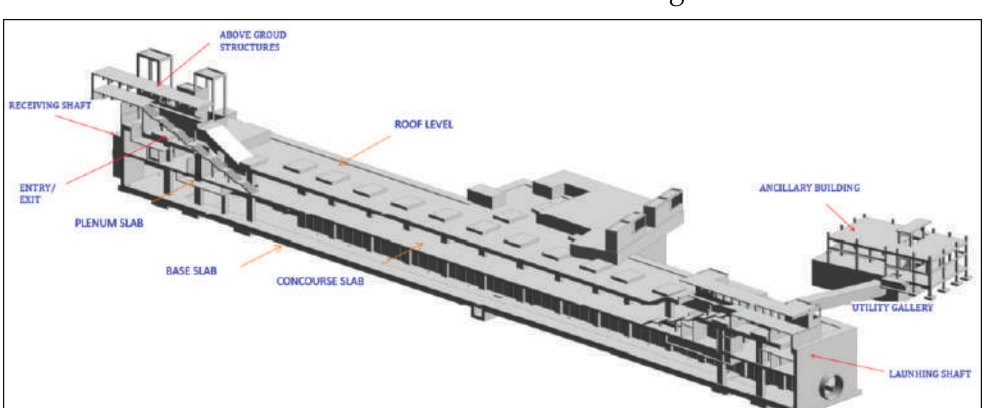

Fig.1: Salient features of UG metro

2. Method of Construction

Since the non-availability of required work area in the Metropolitan roadways, the construction of Underground metro projects largely demanding and becomes more challenging. It is essential from both time saving and convenience standpoints in selection of type of construction. The traffic flow within the construction zone is restricted due to metro construction, making the selection of an appropriate construction methodology more relevant and crucial under these circumstances.

Conventional method of cast-in-situ technology being used widely in metro construction. When the workspace is more than sufficient to produce concrete on site, this traditional method is preferred. The concrete is poured into the formwork and then cured. This process is required more manpower and time consuming.

Whereas Precast concrete offers definite advantages over cast-in-place construction, Precast Elements are manufactured by Pouring the concrete into the reusable mould and cured at casting yard transported from there to required Site area. The manufacturing process is being done away from the work boundary and it requires half of the workspace and very minimal manpower. This methodology has major advantage in time saving and the quality of the work is ensured with very less supervision.

3. Precast Construction in Bangalore Metro Underground Station

Bangalore Metro Rail Corporation has been set up for the implementation and Operation of Bangalore MRTS Project. To facilitate the transportation, need of the people, an MRTS of (Tunnels & Stations) from South ramp to North ramp of UG.

Even though, the Underground station is constructed by cut and cover methods, after analysing the site availability, manufacturing yard facility, it is decided that few internal Elements are to be constructed by precast method.

Precast Elements are implemented at BMRC,

1. OTE Duct - Over Track Exhaust
2. UPE wall - Under Platform Exhaust
3. Platform slab
4. Fire Escape (FES) & Fire fighter Staircase (FFS)

3.1. *Precast Over Track Exhaust (OTE)*

The Trackway Exhaust System (TES) is installed in the trainways of each station to directly capture heat ejected by the vehicle heat exhaust system, braking, auxiliary and air conditioning systems as the train dwells in the station. The TES includes both an Over-trackway (OTE) exhaust duct and an under-platform exhaust (UPE) duct.

The OTE is designed to extract heat from roof-mounted air conditioning system in normal mode. During fire accident the same OTE can extract the smoke to street level. Over track Exhaust ducts are formed above the track which is hanging from the concourse soffit. The arrangement of each station consists of a single central platform 165 m in length, with a 4-sided OTE duct located approximately 5 m above the full length of each track on either side of the platform. These would be connected by a crossover plenum ceiling at each end of the platform above the Tunnel Power Supply (TPS) room, which returns to the Tunnel Ventilation System shaft. This shaft contains a series of extraction fans, which then exhaust the smoke or hot air up to ground level. Fig.2 showing the picture of completed precast OTE duct with sleeves.

Fig. 2: Precast OTE Duct

Challenge: Due to its large size, the OTE would also need to be prefabricated on the track level, and then lifted and installed from mobile scaffolding and scissor lifts. This decision was made in careful consideration for the lifting and fixing methodology and best practices. The Precast ducts are delivered to the track level, by a large opening in the concrete slab midway along the track area on each OTE. Each Precast panel having a dimension of 3.15 m wide x 2.2 m high x 2.45 m long with 160 mm thick and fire-rated will be erected below concourse slab by using fabricated bolts embedded in OTE Panels during casting. The U-shape cross section length varies based on the opening and types as per requirement. The mould size is repeated for almost 70 panels among 100 panels and the precast system required only 10 days which is many times less than an alternative cast in situ concrete solution would need to achieve the same performance.

3.2 *Precast Under Platform Exhaust*

Under platform Exhaust (UPE) duct system is formed under the platform void. Exhaust intakes are to be located to coincide with the train-borne heat sources. The UPE system is only designed to capture heat from the Brake resistor Grid during normal mode. It will remain closed during any fire emergency mode, including undercar fires, so that smoke buoyancy is utilized and OTE smoke capture maximized.

Challenge: As the UPE & platform slab edge is projected towards track side. The other construction activities like precast segment transportation, movement of ready-mix concrete vehicle, railroad vehicle movement and OTE duct erection are impacted. Hence, the casting of in-situ UPE is to be postponed until all these activities are completed.

Also, the UPE wall height is restricted to up to 2.1 m, it is recommended to cast the UPE wall as precast Element. The mould size of 1.5 to 2 m length x 1.2 m wide with 200 mm thick and fire-rated segment manufactured partially with platform slab alongwith temporary hooks. The shear pin @ 500 mm c/c are to be placed while installing precast panel. The dowel length of 650 mm should be maintained at base slab. Precast panel is manufactured with sleeves for grouting. Fig.3 showing the picture of precast UPE duct with lifting hooks and ducts.

Fig. 3: Precast UPE Duct

3.3. *Precast Platform slab*

For boarding and exiting of passengers, the platform slabs are constructed at track level of the underground station. The platform slab should have at least 200 mm thickness and 12 m wide, and 165 m long based on the number of cars. This platform slab area is divided into bell mouth portion and non-bell mouth portion. To satisfy the service condition, usually it is constructed as Cast-in-situ method. Since this slab is supported by Precast UPE wall at base slab level leads to the precast construction of platform slab also.

The Precast platform slab construction steps are as follows:

Step 1: Provide groove and couplers with shear pin at base slab for connecting precast UPE duct. Fig.4 showing, the pictorial view of the initial step of the precast platform slab construction.

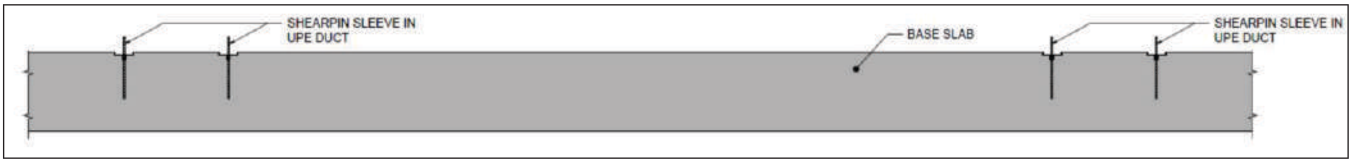

Fig. 4: Showing details of shear pin at base slab

Step 2: Casting of UPE duct with Bolt embedded in the corbel along with provision of sleeves at bottom of couplers. Fig.5 represents the casting of UPE duct construction.

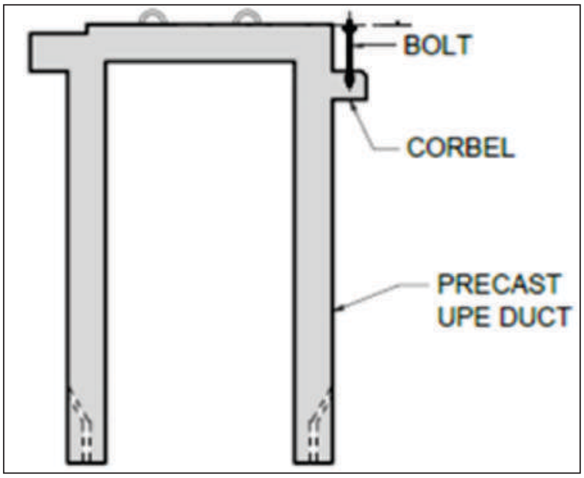

Fig. 5: Casting of UPE duct.

Step 3: Duct wall with the precast UPE duct being erected above the cast- in- situ base Slab. Ensuring the shear pins are embedded in sleeves and the non-shrinkage grout is poured.

Step 4: Construction of cast-in-situ stub column and beam with embedded bolts in corbels.

Step 5: Construction of slab with slotted holes at predetermined locations to fix over the corbels at supporting. ends. Fig.6 - 8 represents the details of the precast platform slab construction.

Step 6: Erection of precast slab in position and fasten the Bolts with washer plate. Precast Slab is erected. simultaneously at both sides of central beam.

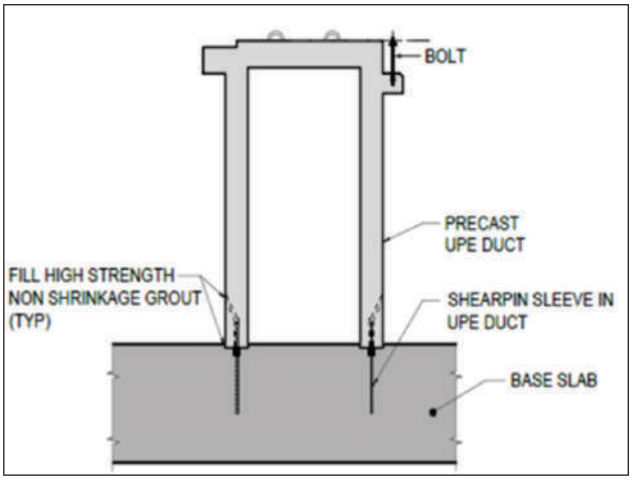

Fig 6: Duct wall embedded into base slab.

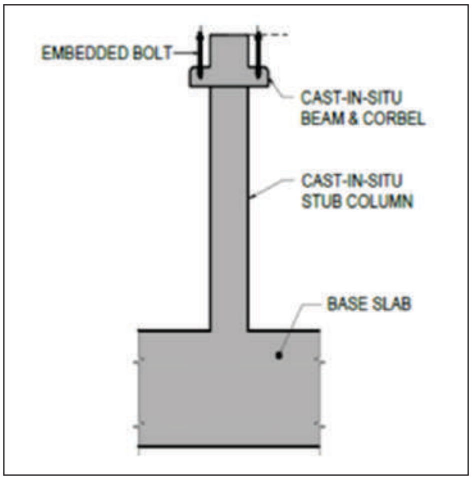

Fig 7: Cast-in-situ stub column and beam with embedded bolts in corbels

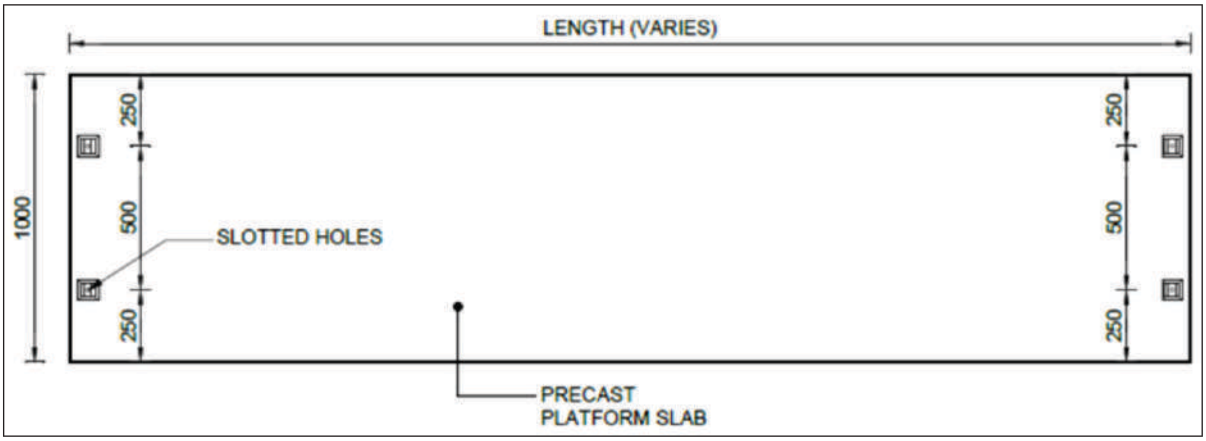

Fig 8: Construction of Precast slab with slotted holes

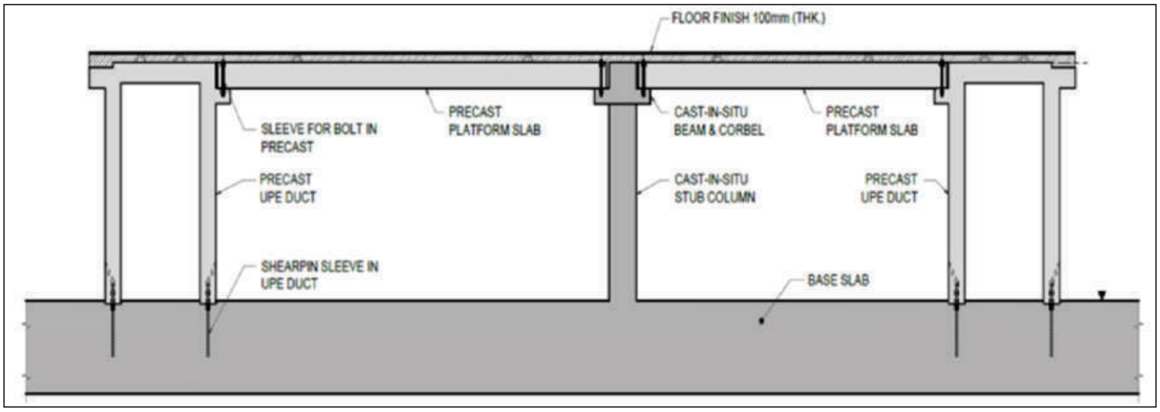

Fig. 9: Showing details of Precast slab & UPE Duct

Step 7: Erection gaps between the precast segments with non-Shrinkage grout & lay screed for floorings. Fig.9 represents the detailed view of the precast platform slab & precast UPE duct construction.

3.4. *Precast Fire Escape (FES) & Fire Fighter staircase (FFS)*

Staircase is the important structural component in a station and passenger movements shall be based upon forecast passenger flow rates, vertical travel distance, structural limitations, and the availability of space. In the underground Station, 3 different staircases such as Public, Fire Escape & Firefighter staircase. Public staircase is wider staircase for public use on day-to-day basis.

Precast Fire Escape are designated emergency escape routes provided for guiding passengers to point of safety. Firefighter staircase is access for fire brigades to reach the required location in case of emergency. Fire escape staircase starts from the Base level and runs up to Concourse level. Precast Fire Fighter staircase is required to run from Ground level with exit / entry at concourse, platform & Under Platform levels. Staircase consists of landing slab, Waist slab and Steps. The steps are associated with waist slab is referred as Flight. Self-weight of super imposed load, live load, handrail, and few construction handling loads are considered for design. Based on the Geometry, usability, and location there are 2 types of Precast type identified.

Type -1 Precast Staircase (FES) consists of Precast Flight and Cast- in -situ Landing slab with RCC corbel up to concourse level. The whole setup is applicable for Scissor Cross staircase. Type-2 Precast Staircase (FFS) consists of Precast Flight and Landing slab with RCC corbel up to Roof level. This setup is applicable for well type Staircase. Fig.10 represents the 3D view of the precast Fire escape staircase flight with lifting hook and precast landing. Similarly, Fig.11 represents the 3D view of the precast Fire fighter staircase flight and landing with lifting hook.

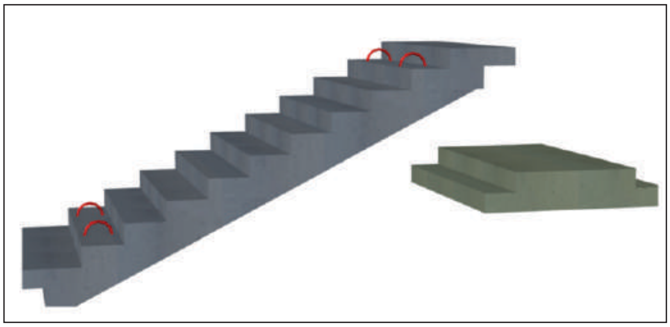

Fig. 10: Type-1 Precast Fire Escape Staircase (Scissor cross stair)

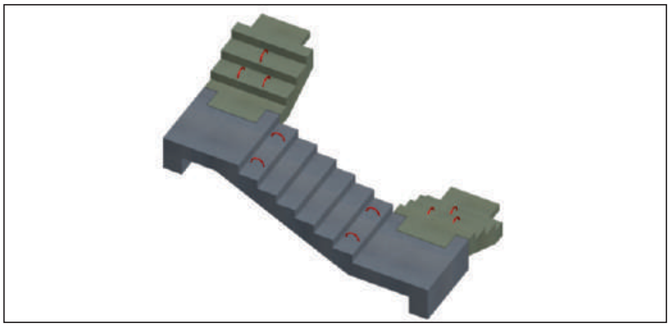

Fig. 11: Type-2 Precast Fire Fighter Staircase (Well type stair)

Challenges in construction stage: Since precast members are to be constructed away from the site, it promotes high quality control and enhances speed of construction. Precast element dimensions are decided based on the lifting, handling, storage, leading and erection constraints. Precast flight to be constructed with lifting hook and erected by heavy crane. The segments are placed carefully at the desired location with 50 - degree angle to avoid collision between landings or another flight. The handling loads and percentage of safety aspects are considered while designing the staircase segment. Typical Precast flight segment of 6.02 MT approximate weight. Similarly, Fig.12 showing the 3D view of the lifting of precast staircase segment at construction stage.

4. Comparison

The actual time schedule and planning time schedule plays main role in the construction progress. Conducted a comparative study between prefabrication construction and conventional construction of, Precast OTE Duct & UPE Wall are taken, and the study is based on quantity estimation, determination of Construction duration and data collection from the Project Site. The cost for individual OTE Duct & UPE Wall is 12% higher when it is built using precast form, the time for completing the Erection is reduced by 75 days when it is done by precast elements.

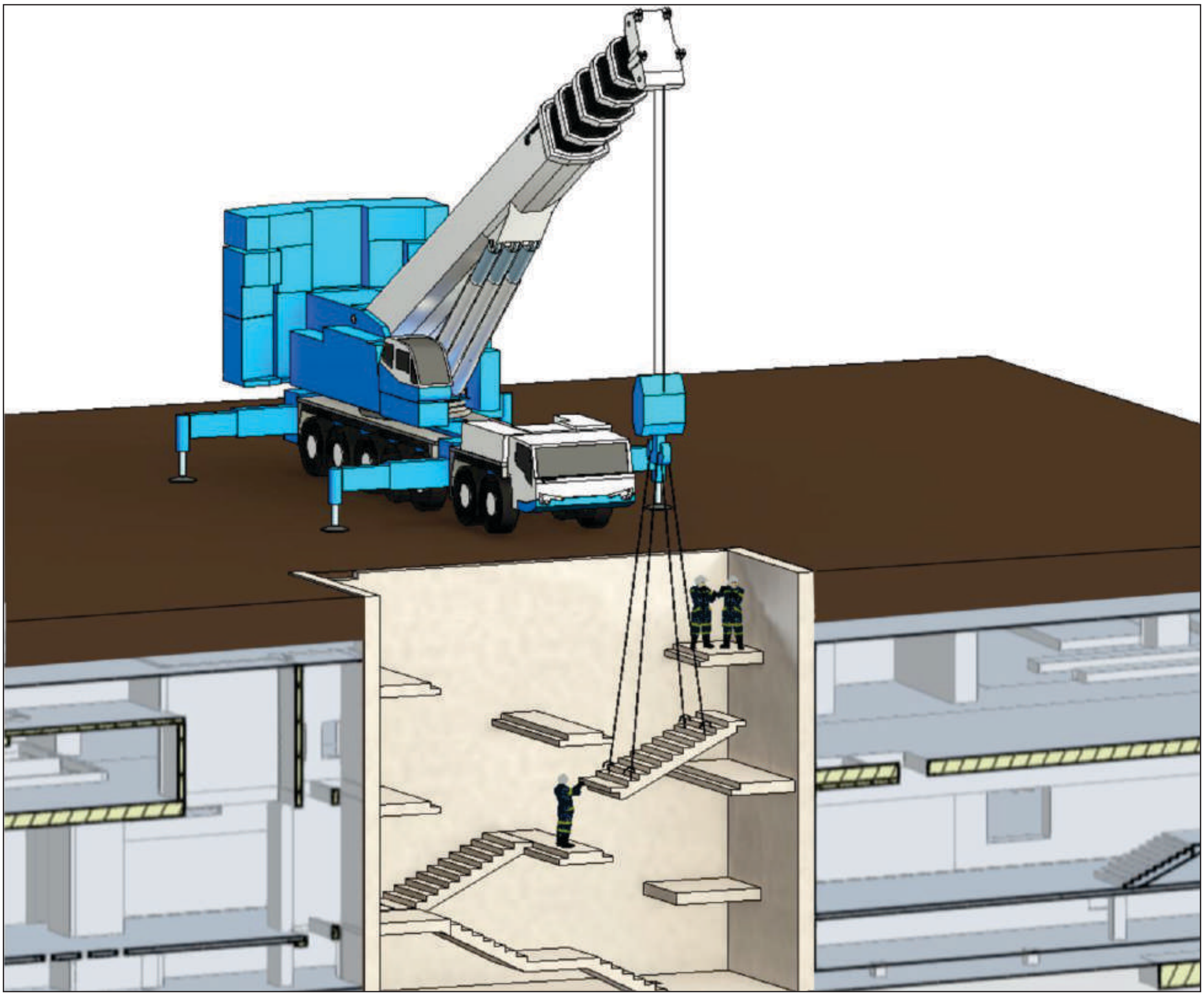

Fig. 12: Lifting of Precast Staircase Segment at Construction stage.

5. Conclusion

Although, the cost for completion of Conventional UPE Wall is less than 8 % which is comparatively less than Pre-Cast Segments, the days to complete casting exceeds 100 days. By the time of constructing 1m conventional Cast-in-situ UPE Wall, can do 4 m pre-cast construction, which eventually increases the profit. The Construction of Precast staircase at underground station building is possible with precautions and safety measures. The major outcome of this study is, although the initial amount of precast construction is high, it has advantage over cast in-situ as time consumed is less leads to faster in construction with least repetition formwork which is a huge beneficiary in the Underground station Construction. Despite these challenges, careful planning, coordination with transportation authorities, and using appropriate equipment and strategies for delivery can help mitigate disruptions to traffic.

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Settlement Analysis Due to EPB Tunneling: A Case Study from High Speed Underground Metro Project

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Abstract

The paper presents a case study from the NCRTC Project of the settlement analysis of the tunnel that already made a breakthrough. It summarizes the geological setting of the region in brief, estimates of design operational range of the TBM key parameters such as face pressure, TVG & volume loss, monitoring frameworks planned along the tunnel profile, and compares the designed settlement with the actual settlement and volume loss observed.

Results of the monitoring show that settlements and the volume loss of the ground are generally well controlled; however, there were occasional large settlements, exceeding the design estimates. Most of the larger surface settlements can be related to the sub-surface at shallow depths often consisting of loose soils, granular alluvial deposits, or man-made fills. The factors associated with such settlements are compared with some other documented tunnel experiences that observed excessive settlement and volume loss over the EPB shield tunnel.

Keywords: EPB Tunneling, Face Pressure, Settlement, Volume Loss.

1. Introduction

In recent years, the growing need for transportation infrastructure has led to a rapid increase in the utilization of underground space. In urban tunnels bored mainly at shallow depths, prediction and control of ground movement around the tunnel are critical and the concept of tunnel design involves the need to revalue the classical concepts of deformation response to the excavation and the control priorities[1].

The design practice commonly involves the estimate of the vertical and associated lateral extent of the settlement due to tunneling [2]. To control the excessive settlement that may have severe hazard consequences, necessary countermeasures in the TBM operation parameters such as face pressure, grouting, and extensive monitoring plan are to be considered in the tunnel design. In this paper, the results of the monitoring data of the settlement are presented from the tunneling of the NCRTC Project in India. A summary of experience from this project is critically analyzed after taking into account the case study of some other metro projects to identify the key TBM parameter that would be crucial to control these ground settlements.

2. Project Description

The proposed 82km long RRTS Mass Rapid Transit System (MRTS) corridor that connects regional nodes in Delhi NCR as part of the National Capital Region Transport Corporation (NCRTC) plan for a MRTS is under construction. The present case study is made for the Delhi-Ghaziabad-Meerut Corridor that starts at Sarai Kale Khan in Delhi and ends at Modipuram in Uttar Pradesh and is passing through one of the most densely populated sections of the National Capital Region connecting Delhi to Uttar Pradesh. Out of the 82km long corridor, around two-thirds are elevated while the remaining is underground. The project is designed as Regional Rail Project, calling for a larger finished internal diameter (ID) of 6.65m for the tunnels and a higher top design speed of 180kmph, as compared to Metropolitan Light Rail (Metro) Projects, where the tunnel finished ID is 6.65 m with a design speed of 160 kmph. The tunneling for the RRTS project corridor is being carried out using TBMs with earth pressure balance (EPB) shields.

The entire length of the project is subdivided into various packages. The present case study discusses package 8 which broadly comprised a ramp of around 873m, two launching & retrieval shafts, one cut & cover tunnel of around 458m, and TBM/NATM tunnels with three UG Stations in between viz. Meerut Central, Bhaisali, and Begumpul. The total length of tunneling by TBM in this package is approximately 3.56km. The route of the RRTS Delhi- Meerut corridor is shown in Fig. 1.

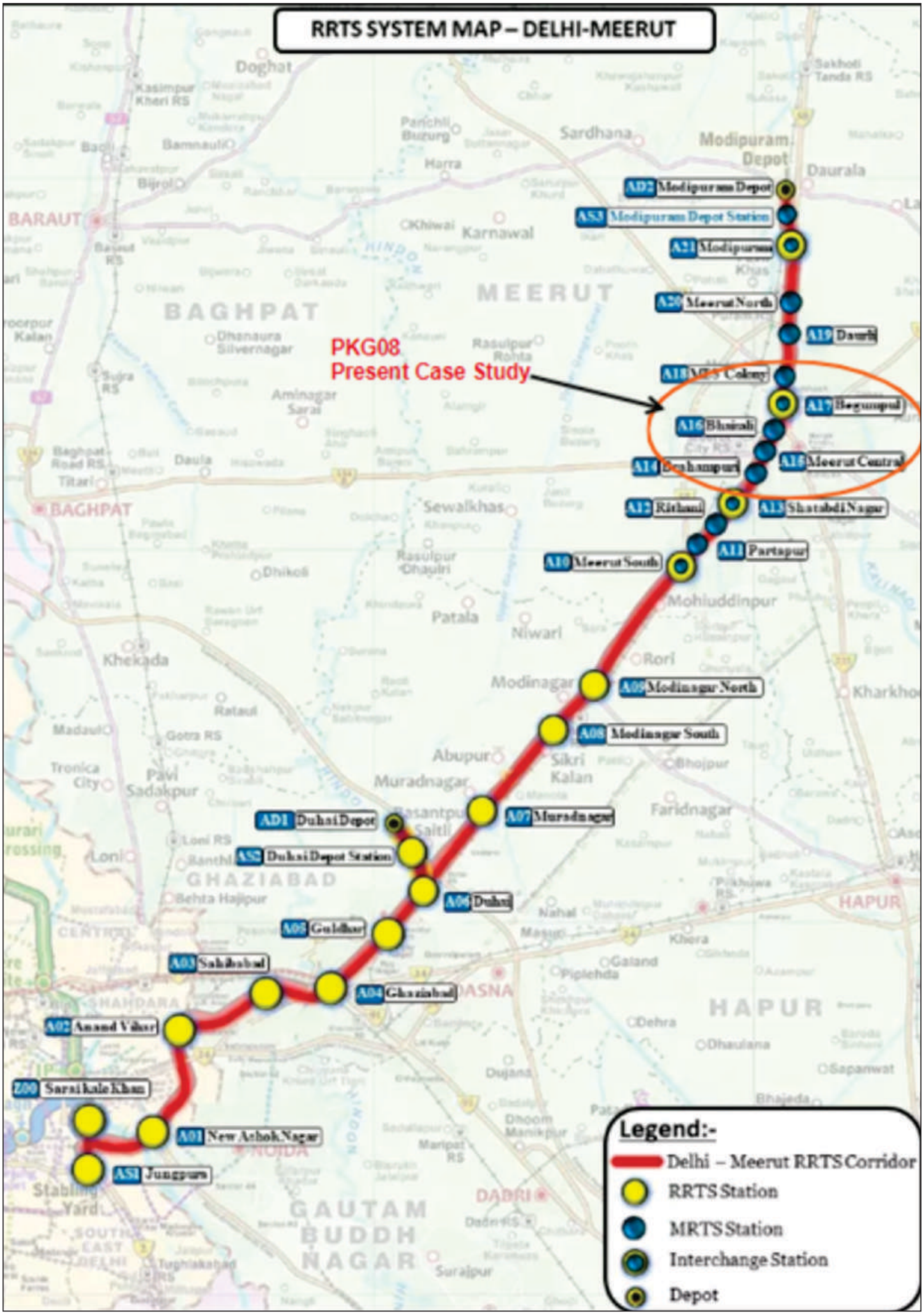

Fig. 1 : Route Map of the Proposed RRTS Delhi-Meerut High-Speed Corridor

3. Geology and Ground Condition

The proposed project site is generally part of the Indo-Gangetic plains and located in between the divides of Ganga and Yamuna Basin, with relatively flat elevation ranging between 215 to 225 m AMSL. The river Hindan, a tributary of Yamuna drains Meerut District towards the West, while the river Ganga drains it towards the East. The regional geological stratigraphy (closer to Delhi) follows the general sequence of recent to sub-recent alluvium (underlain by the Delhi system-precambrian rocks). The overlying horizon of alluvium, Meerut, is identified as the Varanasi Older Alluvium and is understood to have been mostly deposited from the rivers Ganga and Yamuna, which is composed of medium sands, silts, gravels, clay, and kankar (calcareous nodules). Nearer the surface, aeolian deposits of recent age are expected to be found intermixed.

The Meerut area in Uttar Pradesh is located at the divide of the two river basins as shown in Fig. 2 and is expected to be marked by the predominant occurrence of coarse (sands and gravels) over the fines (silts and clays), which may occur locally and/or as minor lenses [3]. The deposits further below are expected to exhibit structures associated with sedimentation processes, including stratifications.

Investigations in the project area have reported that the dominant soil along the tunnel alignment is mainly silty sand (SM) of medium dense to dense granular nature, with the soil at the overburden depth varying between around 10m to 18m. The groundwater level is reported to be approximately 21.0±3 m below ground level (bgl) thus indicating that except at a few locations of low overburden that is near the launch & retrieval shafts along the tunnel, and near the station area, the drive of the TBM shall mostly remain under the dry condition.

Fig. 2: Geology Map of Meerut Area

4. Elements of Tunnel Design

The following are the key elements considered in the tunnel design:

4.1 EPB Tunneling Methodology

The bored tunnel of the underground stretch shall be excavated through the earth pressure balance (EPB) Tunnel Boring Machine (TBM). The basic principle on which the EPB machine works is that it turns the excavated soil into the mud and holds it under soil pressure to stabilize the cutting face [1]. It has an excavation system to cut the soil, a mixing system to mix the excavated soil into the mud, a soil discharge system to discharge the soil, and a control system to keep the soil pressure uniform. As per standard practice of the TBM machine, the annular space between the excavated surface and segment liner shall be filled with cement grout as part of the construction methodology. This is done by backfill grouting through tail tube grouting and/or through grout ports in segment lining. The combined effect of balancing face pressure and backfill grouting controls the loss of ground and settlement at the surface. There are four main sources of settlement during EPB Tunneling, as explained hereunder:

(a) at the face of the machine.

(b) the overcut due to the void created by the difference in the size of the hole cut by the machine and the size of the tail skin.

(c) tail void closure due to the partial or complete closure of the gap at the tail of the machine resulting from the difference between the size of the tail skin and the permanent lining through primary and secondary grouting.

(d) consolidation due to the changes in pore pressures resulting from the construction of the tunnel.

Sources of the settlement in the EPB tunnel are schematically shown in Fig. 3. The first three of these sources result in the immediate settlement that occurs as the machine moves under and away from the measurement points.

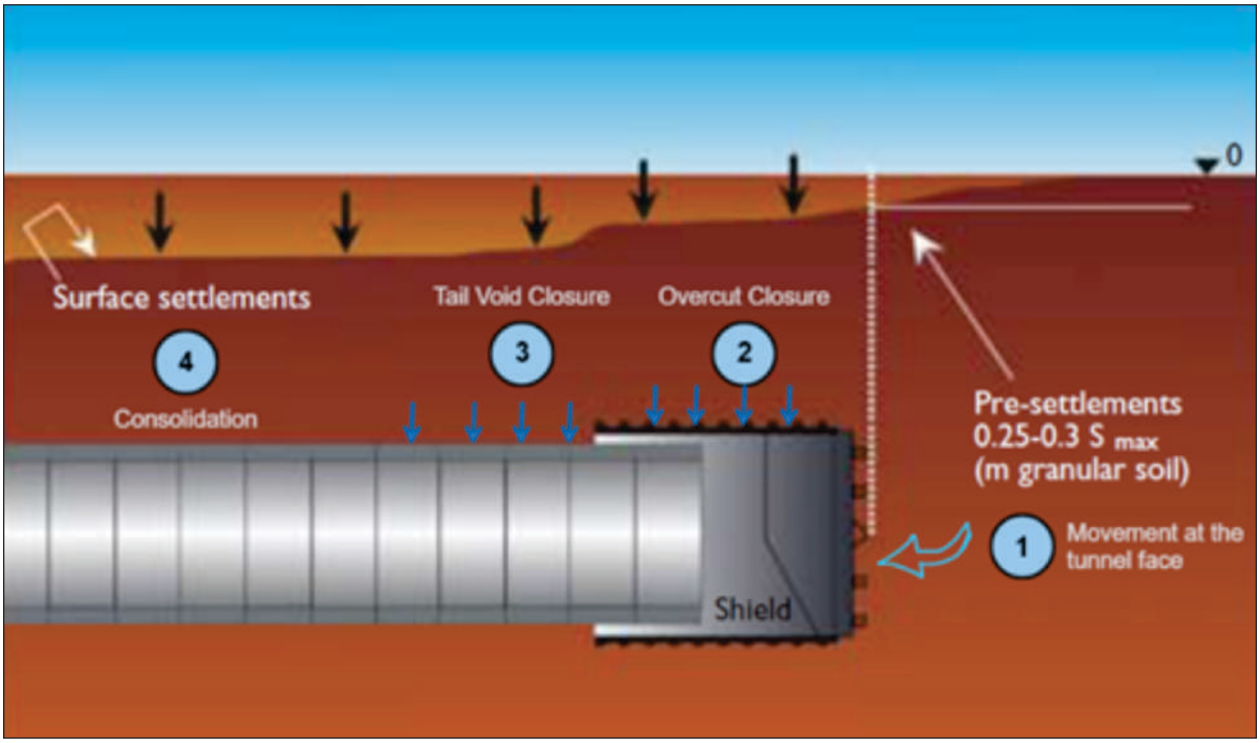

Fig. 3: Development and causes of ground movement during EPB tunnelling.

4.2 *Estimate of Ground Settlement*

Surface settlement is calculated through an analytical approach as per the procedure adopted by Peck (1969) [4]. It describes the resulting surface settlement occurring due to tunnel excavation through the Gaussian distribution curve as shown in Fig. 4 and is estimated as:

$$S_v = S_{max} \exp[-y^2/2i^2] \qquad (1)$$

Where, S_v = settlement, S_{max} = maximum settlement on tunnel centerline, y = horizontal distance from tunnel centerline, i = horizontal distance from tunnel centerline to the inflexion point on the settlement trough which is estimated from a simple approximate relationship [5] :

$$i = kZ_0 \qquad (2)$$

Where K = trough width parameter (assumed 0.5) and Z_0 = depth from ground level to tunnel spring line. The volume of settlement trough (per meter length of the tunnel) V_s can be calculated as

$$V_s = \sqrt{2\pi}\, i\, S_{max} \qquad (3)$$

Where V_s = percentage ground loss volume due to tunnel excavation

However, the analytical approach shows that the near settlement is an approximately linear function of the depth and is independent of the construction method and assumed that the predicted ground movement for each tunnel acts independently in the case of twin tunnels.

Theoretical maximum surface settlement is estimated at around 16mm considering the volume loss of 0.6% in SM/SP-SM (silt sand) with a trough width parameter of 0.5. The exact settlement values vary as a function of overburden and horizontal curve of the alignment and are to be referred from chainage-wise face pressure calculation.

4.3 *Trough Width Parameters*

The choice of the trough width parameter requiresd judgment since it depends on the ground types [2]. Table 1 summarizes the trough width parameters considered in the other metro projects in India and Singapore.

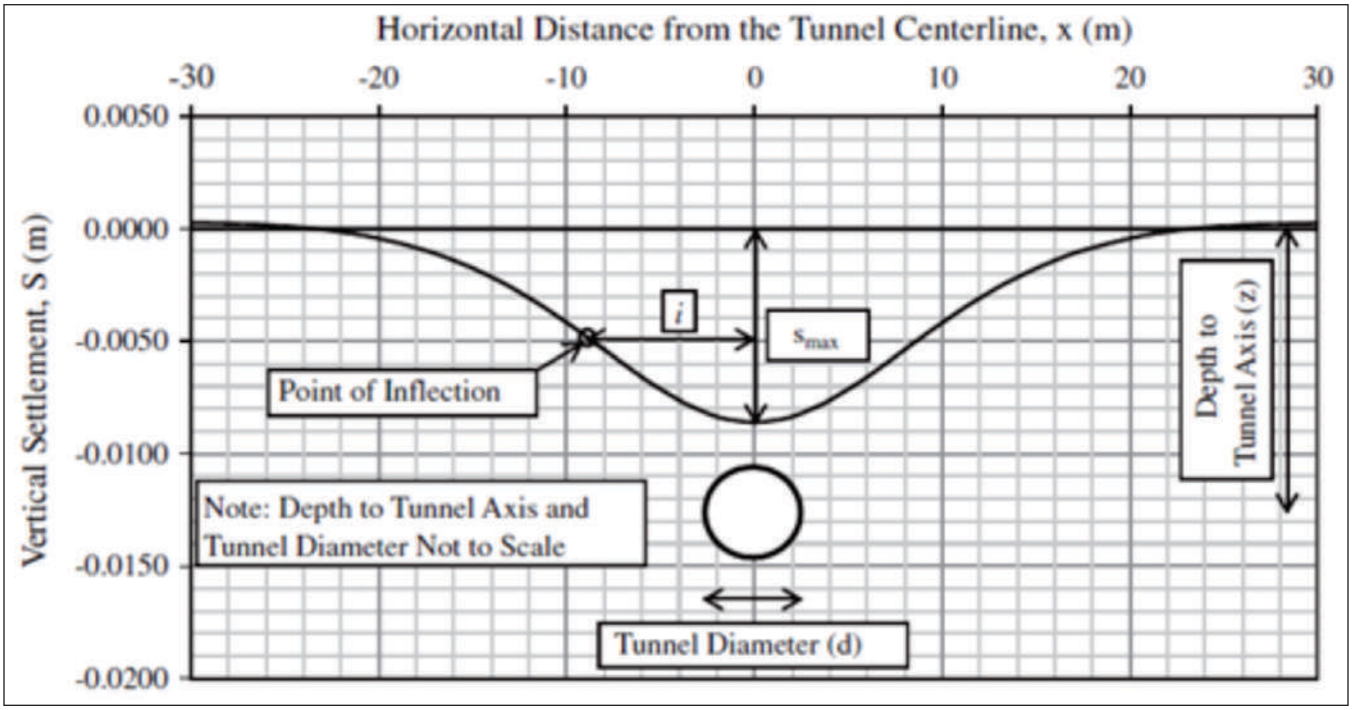

Fig. 4: Transverse Settlement Trough

In the present analysis, the trough width parameter (k) for the settlement estimate has been considered as 0.5. This is taken by performing a numerical analysis by taking the actual site-specific ground type properties and corresponding to the volume loss obtained from the recommended tail void pressure. The approximate trough width parameter suggested in the literature are either for uniform sands, gravels, or clay strata and are for the initial estimate and are suggested to be adjusted by performing a set of numerical analysis, [1], [2]. As the ground stratification of the project site is showing different layers with varying fine contents over the depth, a detailed site-specific parametric study has been performed to predict the settlement of the ground and the width of the transverse settlement trough.

4.4 Face Pressure

Tunnels excavated using EPB-type TBMs can counteract the pressure exerted by the soil along the tunnel face by exerting pressure against the excavation face. It has been shown that with the counter-pressure between 0.9 and 1.2 times the total vertical stress at the tunnel axis level, surface settlement is minimized [1].

The approach for the estimate of face pressure is based on Anagnostou and Kovari [6] and is widely accepted and commonly used. The imposed loads comprise the gravity loading of soil above the sliding wedge and the possible surface surcharge load.

The average recommended face pressure in the present case for the varying overburden of 9 to 12m on the tunnel face at the axis of the tunnel is estimated at around 110 KPa with a pressure deviation of 20 KPa in the target/recommended face pressure.

Compressed air pressure during the intervention is kept at 50KPa. The average volume loss of 0.6% is estimated from the displacement using Pender's

Table 1 : Typical Values of trough width parameters in various ground conditions

Projects	**Ground Type**	**k**
North East Line Tunneling, Singapore	Marine clay	0.5
North East Line Tunneling, Singapore	Fort Canning Boulder Bed	0.5
North East Line Tunneling, Singapore	Grades V and VI Jurong F.	0.45
North East Line Tunneling, Singapore	Grades V and VI granite	0.45
Delhi Metro Projects, India	Dense Delhi Silt	0.5
Lucknow Metro Projects, India	Clayey Silt & Sandy silt	0.5 & 0.4
Jaipur Metro Projects, India	Silty Sand	0.4
Ahmedabad Metro Projects, India	Silty Sand	0.35
Mumbai Metro Projects, India	Rock (Breccia)	0.80
Pune Metro Project, India	Basalt	0.8 0
Bangalore Metro Project, India	Soil (Silty sand & clayey sand) & Rock (Granite)	0.5
NCRTC Project, India (Present Case Study)	Silty Sand	0.50
Kanpur Metro Project, KNPCC 06	Clayey silt/Sandy Silt	0.40

equation [7]. This volume loss is targeted by controlling settlement by maintaining adequate pressures against the excavation face which is large enough to inhibit any plasticization of the ground i.e. maintaining the elastic state and by backfilling the free annular space between the ground and the outside of the liner with grouting as soon as the shield releases the liner. It is estimated that the settlement due to excavation (adding that produced by the EPB before reaching the vertical of the measuring point and that produced at the time of excavation) is reduced to 10% of the total settlement and the rest is produced after excavation, the release of lining and backfilling of the gap.

The average tail void grouting pressure is recommended to be around 200 kPa. The volume loss during the tunneling is to be minimised by increasing the required tail void grouting pressure. However, it is to be kept lower than the existing octahedral stress regime to avoid ground fracturing and heaving. Thus, the tail void grout pressures are to be adjusted at the site and varied in the range between minimum and maximum depending on the site geology and to control settlement. The theoretical grout volume is estimated to be on an average about 5.4cum considering the excavation diameter of 7.56m and the finished tunnel outer diameter of 7.25m, in case of NCRTC package 8.

4.5 Monitoring and Instrument

Extensive instrumentation and monitoring plan have been proposed to monitor the effects of construction work on the ground and adjacent buildings. The typical monitoring instruments include (a) Standpipe Piezometers to monitor fluctuation in the groundwater table in the new/existing boreholes, (b) Surface Settlement Points to monitor the vertical movement of existing surfaces, (c) Building Settlement points to monitor the vertical movement of the existing buildings and structures(EBS), (d) Borehole Extensometer to monitor vertical deformation (relative) at a different designated level below ground level, (e) Inclinometer to monitor lateral deflection(relative) at different depths below ground level, (f) 3D Optical/Sticker Targets to monitor three directional deflections of EBS, (g) Tilt Plate/Meter to monitor unidirectional or bi-directional angular distortion of EBS, (h) Crack meter to monitor existing/new cracks in EBS and (i) Vibration Meter to monitor the vibration of EBS or ground due to TBM construction.

The movement control levels for monitored elements shall be defined in accordance with the following criteria:

(a) Alert Value: set at 0.5 times serviceability limit

(b) Action Value: set at 0.8 times serviceability limit

(c) Alarm Value: set at the serviceability limit.

5. Results of the Monitoring

5.1 Observed Settlement and Volume Loss

There are 3 tunnel stretches in the project. Tunnel 1 is along the route between the Meerut Central to Bhaisali and is the longest tunnel drive around 1.824 Km than the other two tunnel stretches. Tunnel 2 from Bhaisali to Begumpul is around 966 m long and the third Tunnel 3 from NLS to Begumpul station is around 759m long. Currently, tunnels T1 and T3 are completed.

Results of the monitoring instruments show that the behaviour of settlement observed in tunnels T1 and T3 are broadly the same which is on the expected line due to the uniform ground condition that is medium dense to dense granular silty sand SM and SP-SM. A typical monitoring plot of a surface settlement marker for one of the array stations is shown in Fig 5. The maximum settlement of the tunnel upline and tunnel downline is 15mm and 19mm nearing the design action and alarm level.

Mapping the results of the monitoring instrument of the entire stretch of tunnel T1 & T3 show that the surface settlement is well-controlled throughout the drive. The recorded vertical settlement varies in the range between 15mm to 27mm and the average settlement is 21mm which is equivalent to an average volume loss of around 0.8%. The observed volume loss is slightly higher than the estimated design volume loss of 0.6% but within the range of the contract requirement of 1%. There were a few occasions when the settlement was recorded up to 36mm and 45mm equivalent to a maximum ground volume loss of 1.8%. The number of occurrences of volume loss for both tunnels T1 & T3 is shown in Fig. 6.

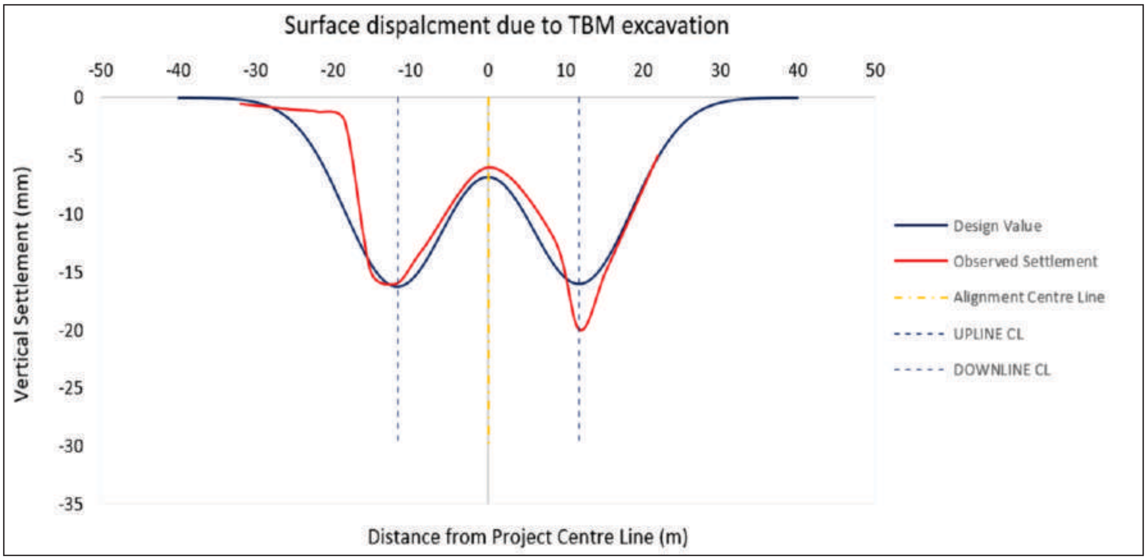

Fig. 5: Recorded settlement trough

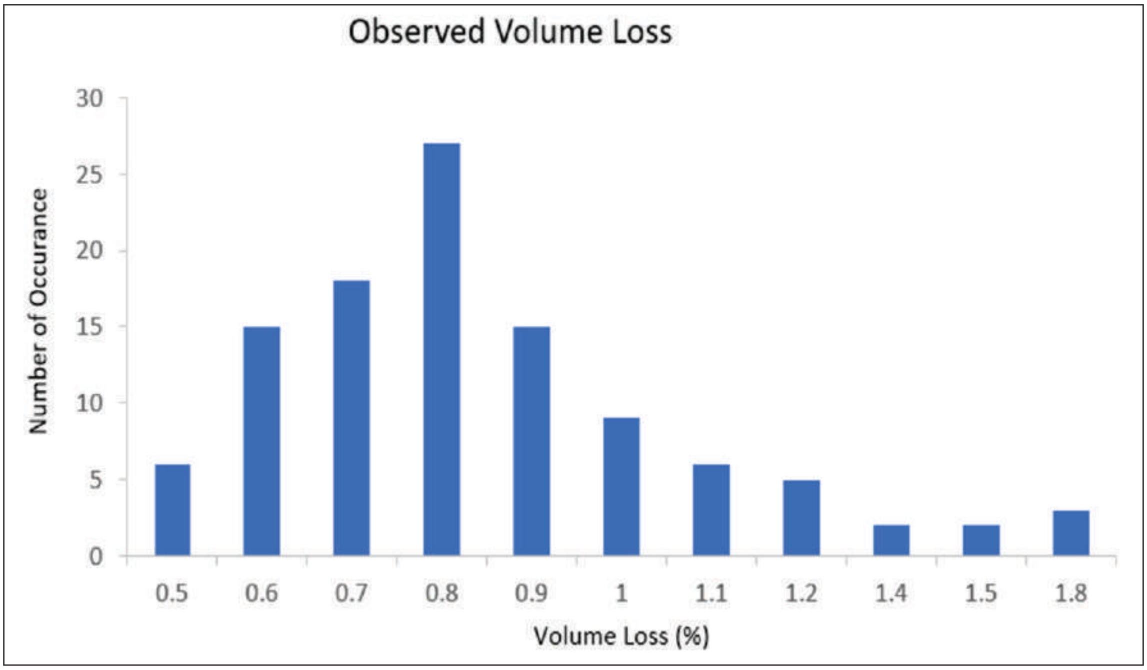

Fig. 6: Occurrence of volume loss

5.2 *Comparison With Other Metro Projects With EPB Shields*

Some case studies of different tunnel work in India and other countries have been analyzed to examine the observed settlement and volume loss in the present tunnel. After the analysis of 14 case studies in the Delhi Metro Tunnel, Chitoshi Izumi et al. reported settlements between 5mm to 20mm and a volume loss between 0.3% to 0.8% in dense Delhi silt from alluvium origin [8]. About 3% of volume loss up to 3% (excluding consolidation) was recorded in the soft marine clay of Singapore [2]. For tunnels in London Clay volume losses are generally likely to be in the range of 1-2% for shield tunnelling and with the use of sprayed concrete linings, the volume losses were in the similar range of 1-1.5% [5]. Similar results of the volume loss are reported during the construction of the Jubilee Line Extension.

Table 2 lists the summary of the probable reasons for the excessive settlement in some other tunnel projects with EPB machines [9]. In some of the cases, the ground settlement exceeded up to 1.0m and the volume loss of over 20%. The learning experience shows that the settlement that exceeded the design value or the sinkholes and ground losses generally resulted due to various factors such as:

- inadequate face pressure,
- launching of the shield,
- change in the ground condition that requires a change in necessary face pressure,
- a mixed face condition comprising one type of ground that requires a support pressure, and another inherently stable material,
- long stoppage with the head empty or partly empty during TBM intervention, and
- docking of the shied at the end of the drive.

Less common factor includes mechanical problems with the shied and the problem with the tail void grouting. One uncommon factor reported in Northeast line Singapore is that of an experienced shield operator handing over temporarily to an inexperienced operator [9].

Table 2 : Reason for observed excessive settlement in some other metro projects

Project	Ground type	Max. settlement	Remarks for excessive settlement
Changi Line tunnels, Singapore	Old Alluvium except for a local valley, infilled with Kallang Formation soils.	300mm Vol. loss of 20%	Passed from the Old Alluvium into the Kallang Formation soils.
Anacostia River tunnels, Washington DC, USA	Mixed face of sand or sand and gravel overlying clay.	150mm	Severe problems with ground control occurred each time mixed ground conditions were encountered.
Taipei RTS, Taipei City, ROC	Soft Ground	Number of a very large settlement	An old tree trunk in the face, which was pushed ahead by the machine, rather than cut a lost borehole casing encountered during the tunnelling loss of ground during the launching and docking of the EPB machines.

Sheppard Subway tunnels, Toronto, Canada	Glacial soils, including hard clay till and granular fluvioglacial deposits.	Upto 100mm	(a) extended stoppages (b) over mining in mixed-face conditions, typically consisting of a mixed face of sand overlying stiff or hard clay till (c) at the launching of the shields, (d) problems with the simultaneous grouting system, leading to poor grouting.
Allen Sewer tunnel, Toronto, Canada	Very dense fine sand (a fluvioglacial deposit)	180mm	Near launching area
Storebaelt tunnels, Denmark	Under Sea bed	"Fairly frequent" large depression in the sea bed	(a) extended stoppages of the machine, presumably for maintenance (b) over mining while tunnelling through a mixed face of sand overlying hard clay till.
Railway tunnels, Japan	Granular material	Major losses of ground	change in the face conditions
St Clair River tunnel, Canada	Under River	1m	Seals of the main bearing were damaged and only a quarter of face pressure was applied.
Lille Metro, Belgium	Weathered layer, which lay under clayey sandy silt.	Sinkholes	Insufficient face pressure to control the stability of the tunnel under low cover
North-East Line, Singapore	Old Alluvium except for a local valley, infilled with Kallang Formation soils.	20 incidents of very high, local ground losses or sinkholes	Inadequate face pressure, Temporarily inexperienced TBM operation.

6. Assessment of the reason for settlement and ground loss

Results of the surface monitoring instrument observed in the present case study show that settlement and the volume loss of the ground are generally well controlled; however, there were occasional large settlements, exceeding the design estimates. Most of the larger surface settlements can be related to the sub-surface at shallow depths often consisting of loose soils, granular alluvial deposits, or man-made fills. Also, the occurrence of higher volume loss is reported near the launching area or close to the end of the tunnel drive where there was a relatively low cover.

Some of the major key parameters are critically analyzed to restrict the ground settlement during the tunnel drives and are summarized below:

6.1 TBM Operation:

Careful TBM operation is the key to minimizing surface settlement. For the TBM operation, it is to be noted that TBM parameters such as cutter head speed, TBM thrust, face pressure, and spoil volume need to be stabilized and regularly monitored and the tunnel operating team should check the consistency of these TBM operations. Maintaining these parameters is critical. Any deviations from the target values are to be corrected immediately. An unnecessary stoppage is to be avoided, particularly when the TBM operation is near a critical building or any heritage structure.

In the present case study, during the TBM operation, the cutter head speed was maintained between 1.5 to 1.7 rpm, and the peripheral penetration rate was kept at 30mm/minute. Face pressure of around 1 bar was maintained and found to be adequate.

6.2 Primary & Secondary Grouting:

During the tunnel execution, the mode of TBM operation was maintained so as to ensure the second stage grouting of at least three rings behind the tail skin, and to close voids, if any, above the crown. This measure worked well in generally reducing/minimising the ground settlement. The intake of primary grout varied from 110% to 120% of the annulus space between the excavated surface and segment liner thus indicating some overcut during the tunneling process. The theoretical volume of grouting per ring amounts to 5.4 cum, which means that the average primary grout consumption was around 6 to 6.5 cum. The intake of the secondary grouting amounts to an average of 15 litres and was less. Tail skin brushes were changed in one of the tunnels as the backflow of the primary grouting was observed.

6.3 Monitoring:

Monitoring is another key element to control the residual risks in urban tunnelling to ensure that construction shall process as a controlled process [1]. The extensive monitoring program that was implemented during the tunnelling process enabled to observe all the critical parameters.

Following is a summary of the list of monitoring aspects:

Monitoring of the actual extent of the tunnelling-induced ground movement and the associated impacts.

Monitoring and adjustment of the face-support pressure, considering that the potential instability of the excavation face is the major source of risk or severe damage to the properties and/ or infrastructure on the surface.

Monitoring and control of the backfill process considering that an inefficient and untimely, or an ineffective, backfilling of the tail void is another major source of risk of instabilities and damages.

Monitoring and control of the excavation by an EPB Shield.

6.4 Advance Ground Improvement:

Since minimum ground settlements were observed because of careful TBM operations (through mass balance and face pressure), no an advanced ground treatment, such as pregrouting, was found necessary The average grout intake which was performed during the compensation grouting after the excavation in some of the buildings' foundations and the open field (before and after the tunnelling) was around 200 litre per borehole of 4m depth which may be considered as low.

In the given ground conditions, only jet grouting or soil face/compensation grouting is possible with cement grout. Both methods can adversely affect the stability of the ground below the foundations, leading to instabilities and excessive settlement. However, the grout material was kept ready for compensation grouting so that in case there are issues during the driving, focused action can be taken.

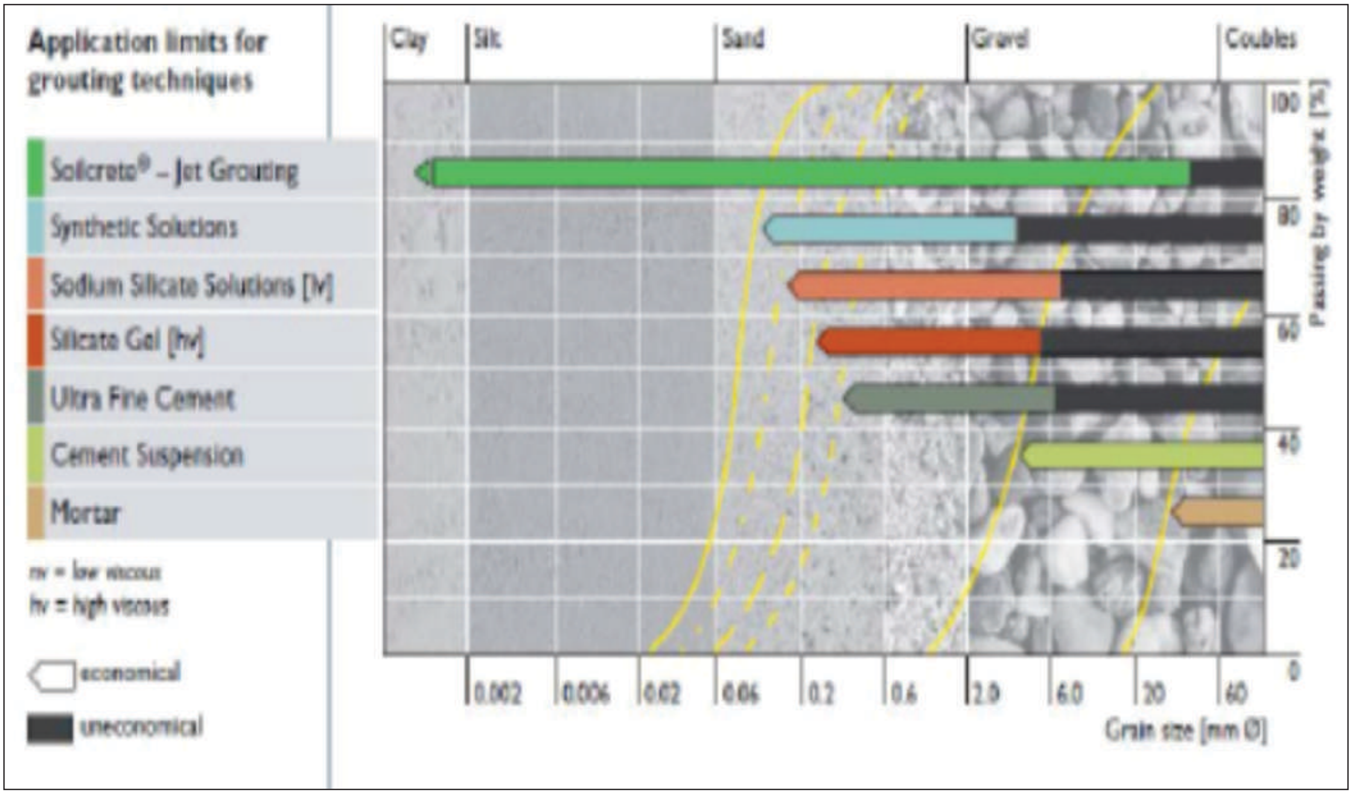

Fig. 7: Application limits for grouting techniques (© Keller Group)

7. Summary and Conclusion

The paper presents a case study of the observed surface settlement from the tunnelling of the NCRTC Project in India. So far out of 3 tunnels, boring in 3 tunnels through closed EPB TBMs has already been completed.

During excavation, the degree of effectiveness of the face support and the lining back-fill is provided by the subsidence response which is continuously monitored and interpreted by using adequate monitoring stations along the tunnel alignment. Results of the monitoring data show that the settlements and the volume loss of the ground are generally well controlled and vertical settlement varied in the range between 15mm to 27mm and the average settlement is 21mm which is equivalent to an average volume loss of around 0.8%. There were a few rare, isolated cases when the settlement was recorded up to 45mm, equivalent to a maximum ground volume loss of 1.8%. The larger settlements can be attributed to the low cover often consisting of loose soils, granular alluvial deposits, or man-made fills. The occurrence of higher volume loss is mainly reported near the launching area or close to the end of the tunnel drive. The probable reasons for higher settlement is critically analyzed after taking into account the case study of some other metro projects to identify the key TBM parameter that would be crucial to control these ground settlements.

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A Case Study on Damage Assessment of Brick Sewer due to TBM Tunnelling

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Abstract

Underground metro alignment through the central part of Kolkata, is likely to encounter brick sewer lines, which were built during the British era are mostly deteriorated due to the ageing effect, lack of adequate maintenance and upgradation. The brick sewer from C. R. Avenue to Sealdah Railway station along B. B. Ganguly Street is one such case. In East-West Metro Project, both the TBM tunnel alignments are passing below B.B. Ganguly Street from Bow-bazar to Sealdah and thus having impact on the existing brick sewer line.

The present study covers the damage assessment of age-old brick sewers and the computation of surface settlement due to the impact of TBM tunnelling. The impact has been monitored through installed instrumentations during and post tunnel construction, to capture the immediate and consolidation settlement. Settlements have been calculated at ground surface, for single tunnelling effect considering the volume losses of 1%. Accordingly stresses on the sewer have been computed. Mitigation measures have also been carried out to eliminate the impact of surface settlement on traffic movement.

Keywords: TBM tunnelling, age-old, brick sewer, damage assessment, subsurface settlement, Immediate and Consolidation settlement, volume loss, mitigation measures.

1. Introduction

Kolkata, the earlier capital of British India, has its current importance as a metropolitan city in eastern India due to its geographical position. Thereby, the age-old city of British era needed modernization of transportation for its steady growth and development. Kolkata East-West Metro Corridor Project, which comprises of underground tunnelling within the city, contributes to the development of transportation. The underground tunnel boring machine (TBM), while mining below the B. B. Ganguly Street runs along the age-old brick sewer, during tunnelling from Esplanade to Sealdah Station. This sewer network in the older part of Kolkata, which was built during British era, are with brick masonry, and has now been deteriorated due to lack of adequate maintenance and upgradation. Consequently, ground deformation, on account of volume loss caused by TBM tunnelling activity, inevitably impacts the existing sewer lines.

Present study elaborates a case study on the ground deformation caused by the TBM tunnelling and its impact on the age-old brick sewer line along the B. B. Ganguly Street. Further, the damage assessment and suitable mitigation measures of the brick sewer has been proposed in the study. Surface settlement trough has been computed by using soil structure interaction (SSI) analysis and are compared with field instrumentation values. Stresses on the brick sewer have been calculated using the settlement curve obtained from SSI analysis. Accordingly, necessary precautionary measures have also been worked out to ensure smooth traffic movement through the street during tunnelling operation beneath.

2. Volume Loss due to TBM Tunnelling

Volume loss is the most inevitable phenomenon of any tunnel construction by TBM, which results in ground deformation with subsequent deformation on the surface and impacts sub-surface structures and utilities. Volume loss may be defined as the volume of ground material that has been excavated, in excess of the theoretical requirement, for the construction of tunnel segments. Several modes of losses during TBM operations, that are attributed to volume loss are face loss, shield loss, trail loss, losses due to time-dependent consolidation etc.

In the present study, 1.0% volume loss has been considered to calculate surface settlement and the corresponding impact on the brick sewer.

3. Ground Profile

Within the stretch covered under the present study, the following soil layers are encountered as below:

(a) Stratum-1: Filled-up soil consisting of brick pieces, coal ash etc. mixed in silty clay.

(b) Stratum-2: Silty clay/brownish grey to greyish brown silty clay to loose clayey silt.

(c) Stratum-3: Silty clay with decomposed/ semi-decomposed wood pieces and peat.

(d) Stratum-4a: Clayey silt/silty clay with calcareous nodules and pockets of silt and sand.

(e) Stratum-4b: Silty sand with occasional clay.

(f) Stratum-5: Silty clay with occasional traces of sand.

The geological profiles are presented below in Table 1.

4. Brick Sewer Parameters

Table 1: Geological Profile of the stretch covered under the present study

Stratum	Strata	From Depth (m)	To Depth (m)	From MSL	To MSL
Made Ground	Strata 1	0	2	4.5	2.5
MH	Strata 2	2	8	2.5	-3.5
MH	Strata 3	8	12	-3.5	-7.5
MH	Strata 4a	12	14	-7.5	-9.5
SM	Strata 4b	14	22	-9.5	-17.5
MH	Strata 5	22	44.5	-17.5	-40.0

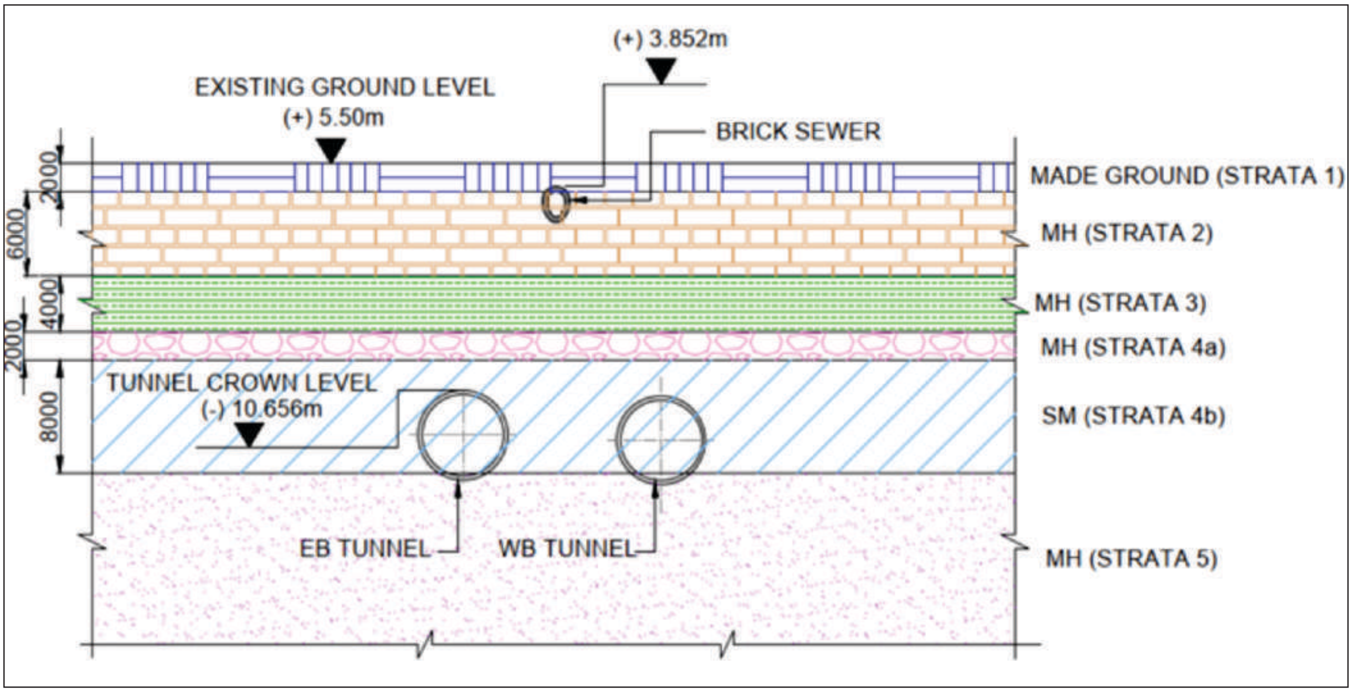

Fig. 1 : Ground Profile

The following parameters of brick sewer have been considered in the assessment study.

Modulus of elasticity of brick	=	1068.48 MPa [5].
Allowable tensile stress	=	0.55 MPa [3-4].
Horizontal dimension	=	1200 mm
Vertical dimension	=	1800 mm
Thickness	=	376.5 mm

5. Design Philosophy

The analysis has been performed using empirical formulas by Gaussian distribution method to plot the ground settlement contour along longitudinal direction of the Tunnel as the settlement contour obtained from Gaussian distribution method is developed all around the TBM cutterhead. Further, in order to compare the Gaussian distribution curve with Instrumentation & Monitoring (I&M) data, longitudinal ground settlement trough is plotted considering volume loss at certain location instead of plotting the progressive deformation of ground due to passage of TBM with time. Therefore, in the present study, settlement trough obtained from I&M data is mirrored to compare with settlement trough obtained by Gaussian distribution method.

To assess the stress in brick sewer, SSI analysis proposed by Hetenyi has been used and the settlement trough of brick sewer passing longitudinally is plotted considering the maximum ground deformation as obtained from Gaussian distribution method. The settlement contour of brick sewer obtained from Hetenyi equation is then compared with the ground settlement contour from Gaussian distribution method and bending stresses have been computed based on the equations proposed by Hetenyi.

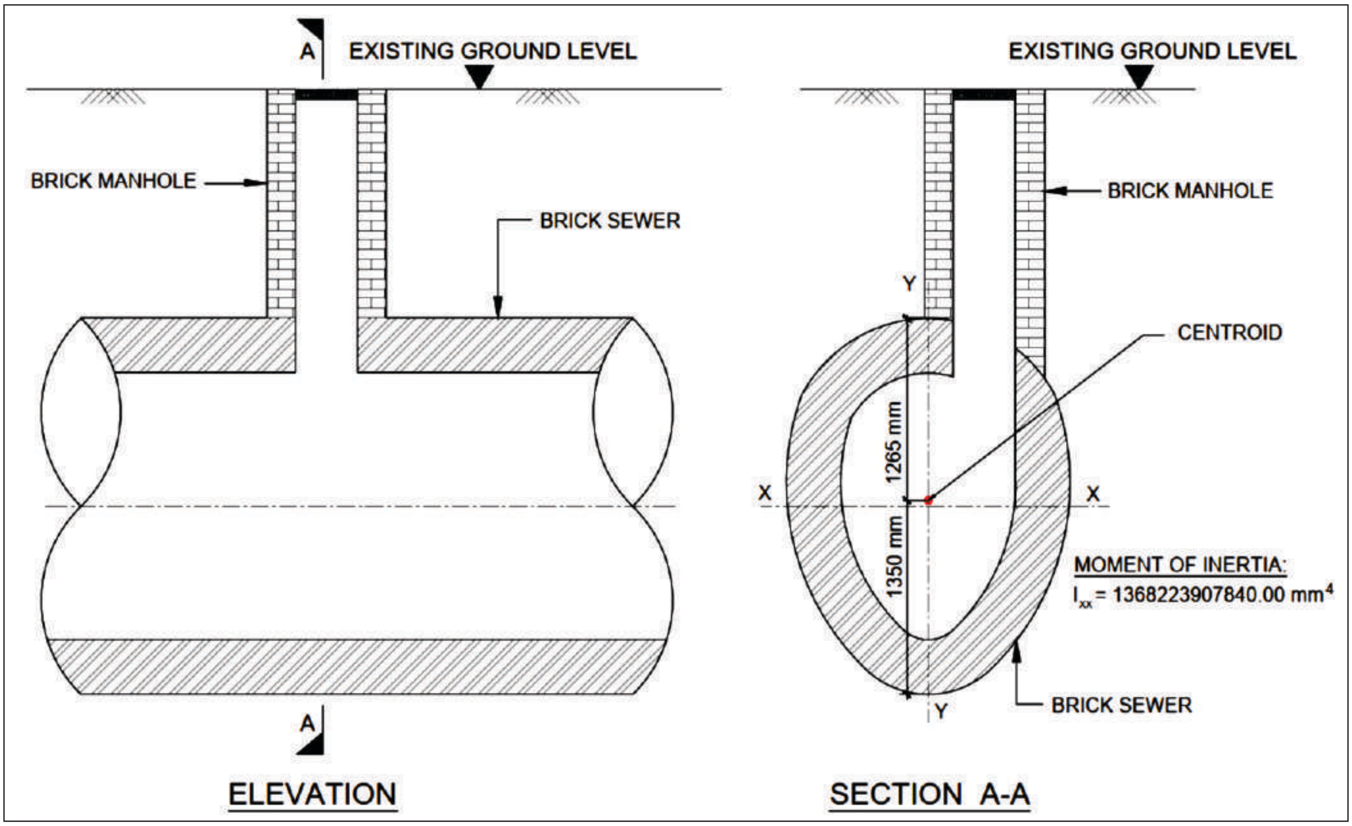

Fig. 2: Brick Sewer dimension

6. Analysis using Empirical Method

To evaluate ground settlement during TBM tunnelling, the Gaussian distribution proposed by Peck [1] has been used as presented in (1) [1-2].

$S(x) = Smax * e^{((-x^2/2i^2))}$ (1)

$S_{max} = 0.313 * (V_L * D_2)/i$ (2)

Where,

S = vertical settlement at a horizontal distance x.

S_{max} = maximum vertical surface settlement.

V_L = volume Loss.

D = diameter of tunnel.

X = horizontal distance between tunnel centre line and the point where settlement has been evaluated

i = horizontal distance between tunnel centre line and point of inflexion along the settlement trough and has been suggested by Attewell as described in (3).

$$i = K * Z_0 \quad (3)$$

Where,

Z_0 is the depth of the tunnel axis.

K = trough width parameter depending upon soil type and behaviour.

Therefore, with the help of (1), (2) and (3), a transverse settlement contour has been obtained perpendicular to the brick sewer due to TBM tunnelling.

To consider the effect of soil structure analysis on the brick sewer, the empirical equation proposed by Hetenyi has been considered assuming the sewer as an infinite beam subjected to uniformly distributed loading.

In the Hetenyi Model, deflections of beams are obtained at surface level. Brick sewer is at a depth of 1.5m below ground level only and for the purpose of simplicity surface level deflection may be considered same as deflection at the brick sewer level. Hence, in the present study, deflections obtained from Hetenyi model has been used for calculation of stresses in the brick sewer.

Following equations have been used to obtain deformations of brick sewer at different points and thus the settlement contour along the sewer has been plotted [7].

$$w = (q/2k) * (2 - D_{\lambda a} - D_{\lambda b}) \quad (4)$$

Where, $D_{\lambda a} = e^{-\lambda a}$ (5)

In this case, cosine terms for calculating the factor $D_{\lambda a}$ has been neglected to capture the actual behaviour of the surface due to the tunnelling.

Again,

q = distributed force which has been calculated boundary condition using the maximum settlement obtained from the Peck's equation

k = Subgrade modulus.

λ = $\sqrt[4]{((k/4EI))}$,

Where,

EI = stiffness of the sewer.

a = distance of the point considered from the left end point of the loading length.

b = distance of the point considered from the right end point of the loading length.

Depending upon the position of reference point from the loading length (4) has been modified as follows:

$w = (q/2k) * (D_{\lambda a} - D_{\lambda b})$ (6)

$w = -(q/2k) * (D_{\lambda a} - D_{\lambda b})$ (7)

Finally, the settlement contour in both directions using Peck and Hetenyi equation has been plotted and shown in Fig 3 and Fig 5.

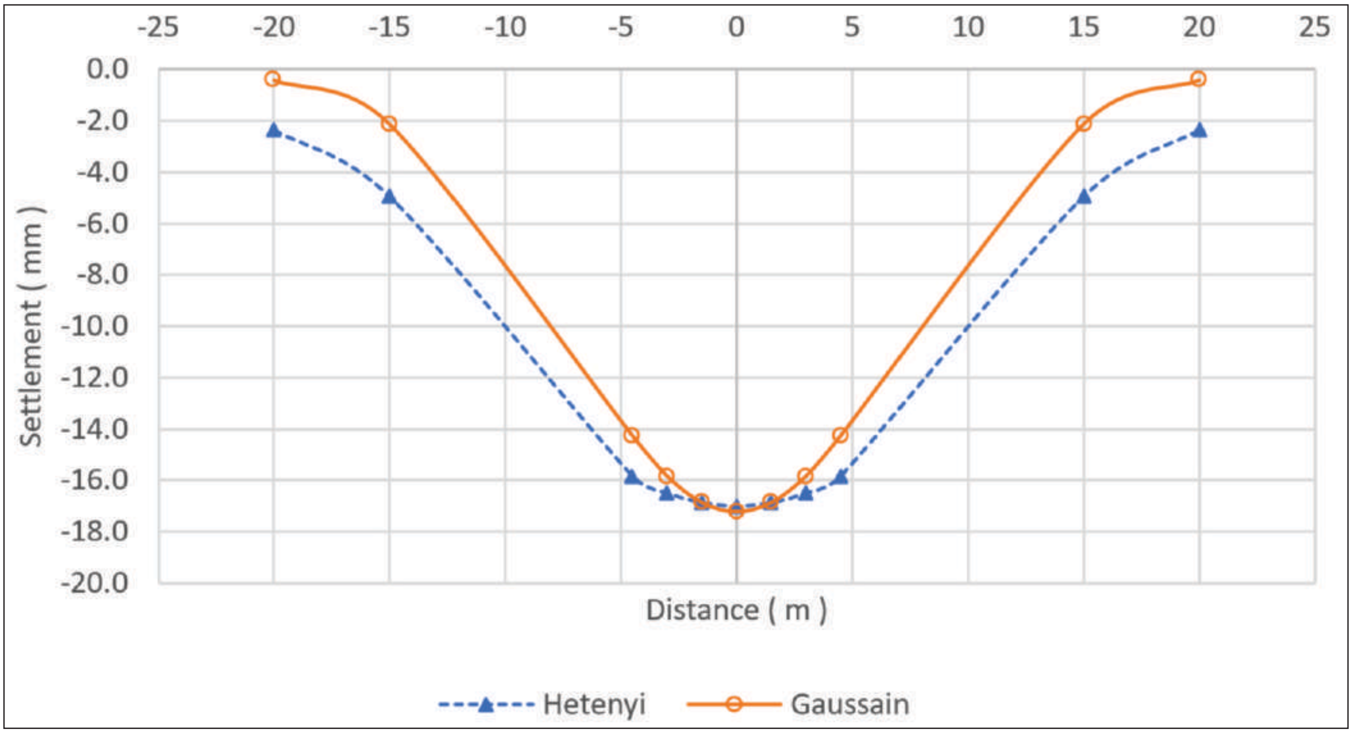

Fig. 3: Surface settlement Contour

It has been observed that both the contours are compatible and therefore settlement contour from Hetenyi has been used for assessment of brick sewer.

7. Impact Assessment of Brick Sewer

From the equations for beams on elastic foundation proposed by Hetenyi, bending moment at different points of the settlement contour has been calculated using (8), (9) and (10) as follows [7].

$$M = (q/4\lambda^2) * (B_{\lambda a} + B_{\lambda b}) \quad (8)$$

$$M = -(q/4\lambda^2) * (B_{\lambda a} - B_{\lambda b}) \quad (9)$$

$$M = (q/4\lambda^2) * (B_{\lambda a} - B_{\lambda b}) \quad (10)$$

Where,

$$B_{\lambda a} = e^{-\lambda a} \text{ and } B_{\lambda b} - e^{-\lambda b} \quad (11)$$

Bending stress at different points of the sewer has been computed using the section properties of the brick sewer and compared with the allowable tensile stress of the masonry structure as per codal specification [3-4].

Using the above equations, maximum bending moment comes around 405 kN-m and maximum bending stress calculated using sewer property and considering infinite elastic beam is around 390 kPa. This is well within the allowable limit as mentioned above i.e., 550 kPa. [3-4]

8. Instrumentation & Monitoring (I&M)

In order to obtain the ground settlement trough during tunnelling, ground settlement markers are installed at an interval of 10-12m along the tunnelling alignment. The ground settlement has been monitored during and after tunnelling so that the impact on substructures like brick sewer can be compared with the design settlement values and requirement of any mitigation can be assessed. Fig. 4 represents the location of ground settlement markers along with the tunnel alignment [8].

9. Comparison of Empirical solutions with I&M data

From Hetenyi model, the sewer settlement has been calculated considering the sewer settlement same as surface settlement due to its shallow depth. Now, the same has been compared with ground settlement contour obtained from instrumentation & monitoring data.

To compare the ground settlement obtained from empirical equations and the settlement trough as obtained from the field instrumentation data it is found that the settlement trough obtained from the field data is less steep than that has been obtained from empirical equations. The value of maximum settlement obtained from the empirical equation matches with the settlement obtained during single tunnelling which further increases after passing of second tunnel, but the extent of the settlement trough is more in case of field data, than that obtained by empirical equations. It can be observed that, the settlement contour from I&M record for both the tunnel is much flatter than the settlement contour obtained from empirical formulas. Hence, the strain obtained for stress calculation from empirical formulas gives conservative result. Following is the combined plot of ground settlement obtained from analysis and its comparison with field values which has been plotted as per methodology described in section 5 and is shown in Fig.5.

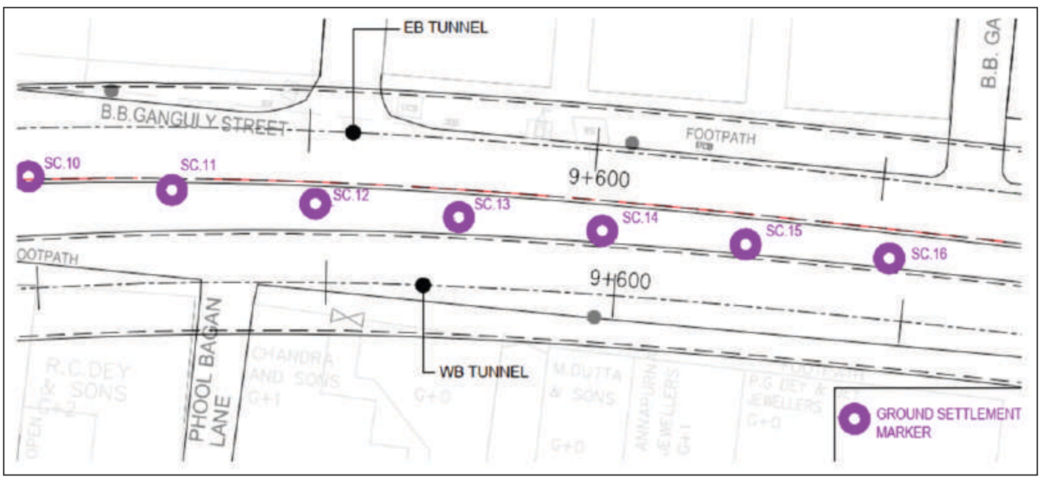

Fig.4: Location of ground settlement marker

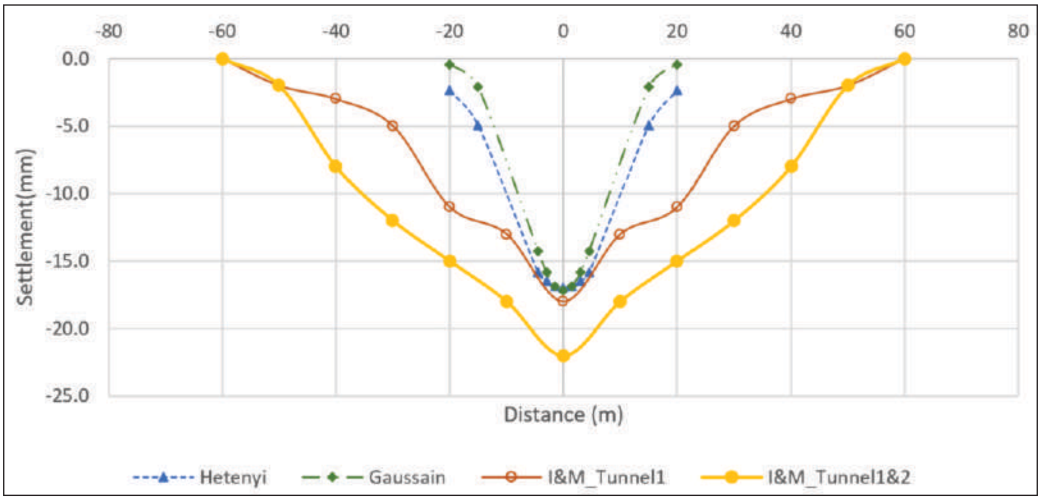

Fig.5: Comparison of Empirical values with I & M data

10. Mitigation Measures

Underground sewer lines of Kolkata are the main trunk of drainage system of the city thereby attains its importance of protection against any damage due to tunnelling. Moreover, the sewers are passing through shallow depth in the fill layer which may be comprised of voids or local air pockets. As the age-old sewer line is one of the main sewer lines in Kolkata and is inaccessible and existing as built condition of the sewer is poor, mitigation measures have been proposed during tunnelling operation, though stresses have been calculated conservatively using Hetenyi Model. Hence grouting with cementitious material at low pressure has been applied as a mitigation measure so that there remains no cavern in soil.

11. Conclusion

From the present study it is found that soil structure interaction analysis carried by Hetenyi can be used to assess the forces on the brick sewer in an effective way. The predicted maximum settlement obtained from Gaussian distribution curve matches with the field data, but the settlement trough obtained from Gaussian curve and Hetenyi model gives conservative values of stresses on brick sewer. However, as the age-old brick sewer is in distressed condition and no actual conditional survey is available, the conservative approach by Hetenyi model can be an efficient guideline for assessment of stresses on shallow structures due to underground tunnelling.

12. Acknowledgement

The support received from Kolkata Metro Railway Corporation (KMRCL) for allowing to use the project data through Consultative Collaboration is gratefully acknowledged. The guidance rendered by Mr. Shailesh Kumar, General Manager (CIVIL), KMRCL is also sincerely avowed.

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Following reports, codes and literatures were reviewed thoroughly and referred as per requirement and relevance.

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A Design overview on Steel Fibre Reinforced Concrete (SFRC) in Tunnel Segment Linings

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Abstract

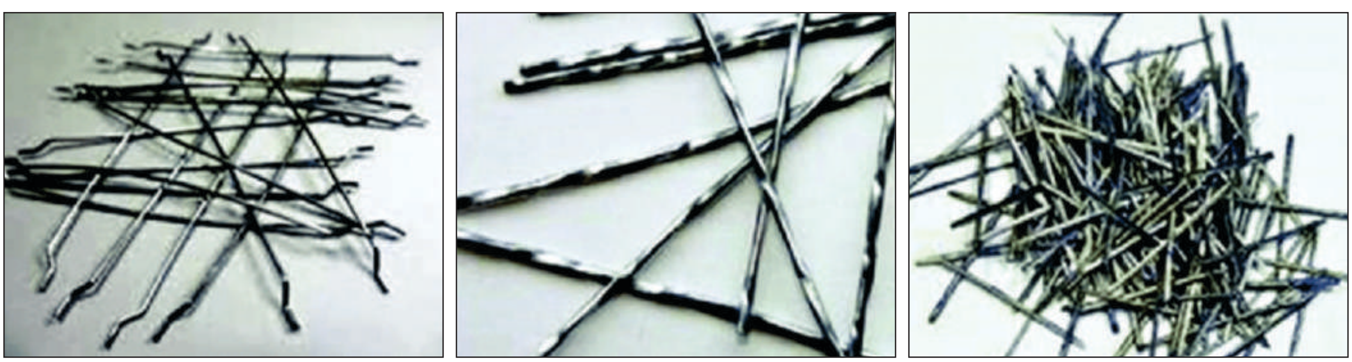
This abstract provides a comprehensive overview of the design considerations associated with the utilization of Steel Fiber Reinforced Concrete (SFRC) in tunnel segment linings, a notable departure from the conventional Reinforced Concrete segments used in such applications. SFRC is a composite material comprising concrete reinforced with steel fibres, enhancing its structural properties and durability. Recent advancements in SFRC technology have propelled it to the forefront of tunnel construction. In this paper, we will explore existing regulations governing the design and construction of SFRC segments, reflecting its expanding significance in the industry. This paper briefly describes the design methodologies employed to address various load conditions, showcasing SFRC's adaptability in tunnel segment applications. Notably, we will shed light on the analysis methods for tunnel linings and assessing the capacity of SFRC segments to withstand the substantial thrust forces generated by Tunnel Boring Machines (TBMs). Additionally, this paper will explore scenarios where exceptionally high loads necessitate the incorporation of additional reinforcement in SFRC segments. These hybrid segments represent an innovative approach to combining the advantages of SFRC with supplemental reinforcement. The principles behind the design of these hybrid segments will be briefly described, offering insights into their potential applications in tunnel construction. This paper will provide a review of how SFRC technology is developing and how it is being incorporated into tunnel segment design, considering both established practices and recent advancements in the field. A brief case study on the usage of SFRC in Indian Metro is also covered.

Keywords: SFRC, ACI-544, Fib Bulletin 83, Model Code 2010, TBM, Bursting, Spalling, Stacking, Circumferential joint, Radial Joint.

1. Introduction

The mechanisation and automation in construction industry has made rapid progress in recent years and certainly raised expectations in mechanised tunnelling works. Mechanised tunnelling using a shield Tunnel Boring Machine (TBM) commonly employs precast concrete segmental linings. These segmental concrete linings support tunnelling work in soft ground, weak and fractured hard rocks. These are generally reinforced with rebars that are placed in reinforced concrete (RC) element to resist tensile stresses. However, in last two decades, fibre reinforced concrete (FRC) has gained much attention and used in segmental linings alone or alongside conventional rebars [1,2,3].

FRCs are composite material with cementitious mix and discrete reinforcement which can be made of metal, glass, synthetic, or natural materials [4] as shown in Figure 1 1. The main reason to add such reinforcements is to improve the tensile capacity of



Steel Fibres

Synthetic Fibres

Figure 1.1 : Types of fibre

concrete. As fibres are uniformly distributed throughout the segment, fibre reinforcement effectively counteracts the bursting and spalling stresses that develop during the TBM jacking process. Fibres present in cementitious gel enhances fatigue and impact resistance which might occur at the time of handling or installation of segmental lining [5]. Some of the advantages of FRC are listed below:

1. Improves post cracking behaviour.
2. Better crack control when used with conventional reinforcement resulting in increased durability.
3. High resistance to impact loading.
4. Enhances use of structural concrete due to low environmental impact.
5. Fibre reinforcement is distributed, leads to increased fire protection.

If FRC is used alone, without conventional rebars, offers additional benefits:

1. Reduce handling time - eliminating the need to handle and position conventional rebars.
2. Reduced reliance on skilled labour to create curved reinforcements.
3. Space savings - storage space demand for rebar cage will be minimized.

In Chapter 2, most important standards are listed. Many standards are available for design of FRC elements, but no specific recommendation or design procedure is available for tunnel segmental lining. Since curved elements of segmental lining are subjected to various levels of stresses throughout the process of manufacturing to placement at required location, design of such elements becomes more critical specially when these are reinforced with only fibre reinforcement.

Chapter 3 will shade light on the analysis methods to determine design forces in segmental tunnel lining. Chapter 4 provides insight on the design approach and methodology for designing of segmental tunnel linings. The approach mainly considers increased post cracking residual strength resulting in increased resisting capacity of element casted with FRC. Forces experienced by segmental tunnel lining are also briefly discussed in this section. This section also gives insight into hybrid segment concept where conventional rebars are used along with FRC to achieve desired resistance demand.

Finally, chapter 5 will talk about conclusions and key take aways from this paper and chapter 6 will give idea about references referred while preparing this paper.

1.1 Scope and Limitations

This paper's focuses on concrete reinforced with steel fibre. In the subsequent sections, we look into the analysis and design methodology for Steel Fibre Reinforced Concrete (SFRC) precast tunnel segmental lining considering a variety of load conditions. These design methodologies are based on the design standards, norms, and guidelines that are used currently.

This paper does not address effect of temperature variation, loads due to TBM Gantries and fire related considerations. This paper also does not explore usage of synthetic or other types of fibres. The procedure outlined in standards shall be followed, together with experimentation on small- and full-scale tests, to determine the specific increase in tensile strength caused associated with use of various types of fibres.

2. Review of References

The design of fibre reinforced concrete (FRC) was not covered by international standards (Eurocode 2 [6], ACI 318 [7]), but after looking at growing use of FRCs, ACI 544 [8] and Fib bulletin 83 [10] have developed standard for design of tunnel segment lining recently. Key component of strength in FRC is post cracking residual strength provided by the fibres and to incorporate this in design, different methodologies and approaches have been published in guidelines for the design of FRC elements on the contrary, design of reinforced concrete elements is based on elastic approach.

Generation of cracks represented by an approach based on Non-Linear Fracture Mechanics (NLFM). General and simplified design approach has been published in FIB bulletin 83 [10], FIB Modal Code-2010 volume 1 & 2 [11] which follows ITA Guidelines [12], ITES Guidelines, RILEM Guidelines-2003 [13], DafStb Guidelines-2012 [14], CNR-DT 204-2006 [15], Recommendations of German Society for Concrete Technology. These recommendations and guidelines propose linear stress-strain constitutive laws for FRC after cracking.

AFTES recommendation-2016 [16] gives basic concepts used in FIB Model Code-2010 [11] but fails to explain about boundary condition and material irregularity to be used while replacing reinforcement partially or totally.

ACI 544 [8] uses results of standard beam tests such as ASTM C1609/C1609M [17]and BS EN 14651 [18] to determine residual tensile strength after cracking.

3. Analysis Methods

There are number of analysis models developed over a period. Figure 3 1 shows the complete flow chart for the methods adopted since 1920's. The most used method is based on the continuum model based on elastic theory developed by Muir Wood (1975) for the lined segmental tunnels. In recent years this analysis is also backed up with the help of numerical analysis and finite element method. The beam-spring model, finite or discrete element methods are also used in practice by the designers. These methods are briefly discussed below.

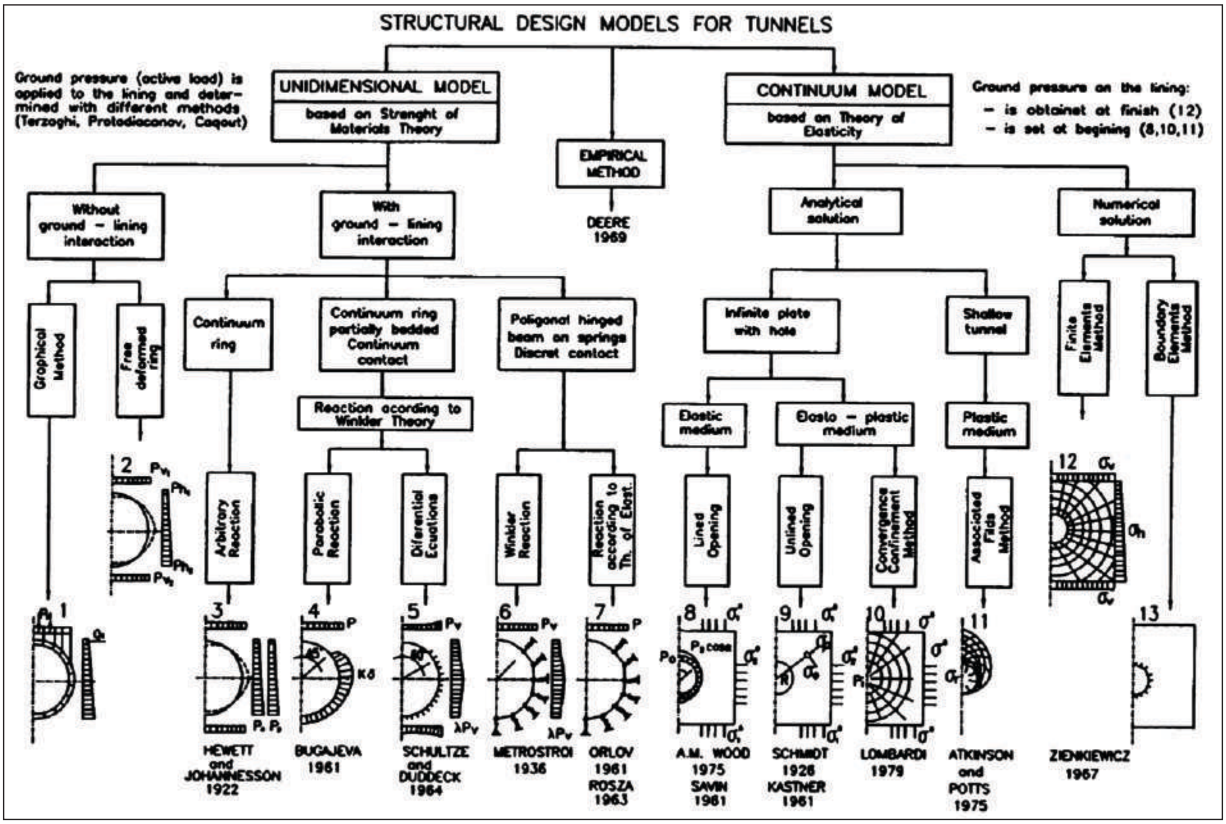


Figure 3.1 : Methods for analysis of Tunnels

3.1 Muir Wood's Continuum Model

It is an elastic analysis in which competence factor, ratio of ground strength in compression to vertical overburden pressure, is used for two-dimensional tunnel analysis. Reduced young's modulus is used to demonstrate quasi-elastic creep effect. Tunnel lining is made of segments, hence stiffness at joints is lesser than anywhere else. Effective second moment of area is calculated as given in formula 1.

$$I_e = I_j + (4/n^2)\ I_g \qquad \ldots(1)$$

I_j = effective second moment of area at joint,

I_g = second moment of area at tunnel lining,

n = no of segments

3.2 Elastic Equations Method

In this method, uniformly distributed load is applied vertically at ground level and linearly varying lateral earth pressure and self-weight of lining segments and triangularly distributed horizontal ground reaction. Member forces are calculated by elastic equations and segmental linings are modelled with reduced flexural rigidity to consider effect of longitudinal joints.

3.3 Beam-Spring Model

Segmental lining is modelled as a series of beams spanning between longitudinal joints. The interaction between ground and lining is modelled with help of translational springs (linear) in radial, longitudinal, and tangential directions. Stiffness of springs is calculated as specified in USACE EM 1110-2-2901 [19]. To consider effect of segmental joint either ring model with reduced flexural rigidity or ring model with multiple hinged joint or ring model with rotational springs are used.

Coupled ring analysis is slightly advanced method where the stiffness between the adjacent rings is also considered in the analysis. The coupling spring stabilize the system increasing the global stiffness and therefore there will be slight increase in the bending moments when compared to an uncoupled system. Diagrammatic representation of beam spring model for coupled ring analysis is shown in Figure 3.2.

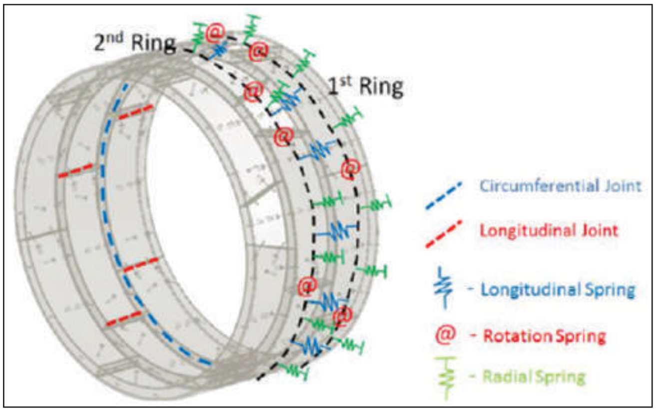


Figure 3.2 : Idealisation of the coupled ring analysis method

3.4 Finite Element Method and Discrete Element Method

FEM is generally used in soft ground, loose rock, and partially homogeneous solid rock as per recommendation in ACI 544 [8] whereas DEM is generally more accurate for fractured rock. For continuous linear alignment two-dimensional approaches are reliable but for more complex geometry or loading conditions three-dimensional approach is preferred. These techniques can provide, non-uniform and anisotropic stresses and forces experienced by segmental lining, to a degree of accuracy.

4. Design Approach and Methodology

4.1 Material Characterization

SFRC has its advantages in terms of sustainability, productivity, and economy. It is important to know the mechanical properties and limitations of FRC. Fibres help to increase residual flexural capacity for cracked concrete. Enhancing performance in manufacturing of segments and its behaviour under accidental loads are some of the other reasons to add fibres to concrete.

The introduction of the Model code 2010 [11] has initiated the use of FRC segments. It has been used as the basis for design of SFRC tunnel linings. Fibres which fulfil the following requirements are suitable for FRC production and these requirements are explained in FIB Modal Code-2010 volume 1 & 2 [11]. Some of the requirements are as follows:

Fibre shall not deteriorate in concrete in uncracked or cracked state.

Fibre shall not have negative impact in fresh state of concrete (workability, air content, etc) and in hardened state of concrete (compressive strength, static elastic modulus, creep, shrinkage, and bond to reinforcing steel).

Fibres shall not settle in mixing, transport and placing operation.

Composite material generally shows strain softening effect, but strain hardening can be achieved by using high performance fibres. Fibres added to concrete will not influence the mechanical properties of uncracked concrete section. There are several different test techniques available for assessing the post cracking behaviour of FRC. Uniaxial tensile tests enable to directly evaluate post cracking tensile strength, but they are challenging to carry out. Design recommendations are based on flexural test that can analyse flexural response of heterogeneous mixture after cracking.

The fibre reinforcement can be considered to replace the conventional reinforcement at the ultimate limit state (ULS) if the following two conditions are satisfied:

$$f_{R1k}/f_{Lk} > 0.4 \qquad \text{...(2)}$$

$$f_{R3k}/f_{R1k} > 0.5 \qquad \text{...(3)}$$

f_{Lk} = Limit of proportionality at which material stress is directly proportional to strain

f_{R1k} = Characteristic residual flexural strength corresponding to Crack mouth opening displacement (CMOD) 1 = 0.5mm

f_{R3k} = Characteristic residual flexural strength corresponding to Crack mouth opening displacement (CMOD) 3 = 2.5mm

According to the Model code 2010 [11] the post-cracking residual strength can be classified by using two parameters, namely f_{Rjk} (representing the strength interval) and a letter a, b, c, d, or e (representing the ratio f_{R3k}/f_{R1k}) as given in below table. For instance, concrete with a cylindrical compressive strength f_{ck} higher than 40 MPa, a residual tensile strength f_{R1k} higher than 4.0 MPa and a tensile strength f_{R3k} ranging between 3.6 MPa and 4.4 MPa is classified as FRC 40 4c.

a	$0.5 \leq f_{R3k} / f_{R1k} \leq 0.7$
b	$0.7 \leq f_{R3k} / f_{R1k} \leq 0.9$
c	$0.9 \leq f_{R3k} / f_{R1k} \leq 1.1$
d	$1.1 \leq f_{R3k} / f_{R1k} \leq 1.3$
e	$1.3 \leq f_{R3k} / f_{R1k}$

4.1.1 Flexural test on beam

BS EN 14651 [18] and FIB Modal Code-2010 volume 1 & 2 [11] provides guidelines for beam testing for 3-point flexural test on a notched beam.

Notch is introduced at the point A in Figure 4.1. This notch is used to measure CMOD. Dimension of test beam are given in Figure 4.1 as shown and all dimensions are in mm. Figure 4.2 shows typical graph of applied force (F) versus deformation expressed in CMOD. Equivalence between CMOD and deflection can be given by formula 1.

$$\delta = 0.85 * CMOD + 0.04 \qquad \text{...(4)}$$

Nominal residual flexural tensile strength based on F-CMOD graph is given by formula 2.

$$f_{R,j} = (3*Fj*l)/(2*b*h^{2}_{sp}) \qquad \text{...(5)}$$

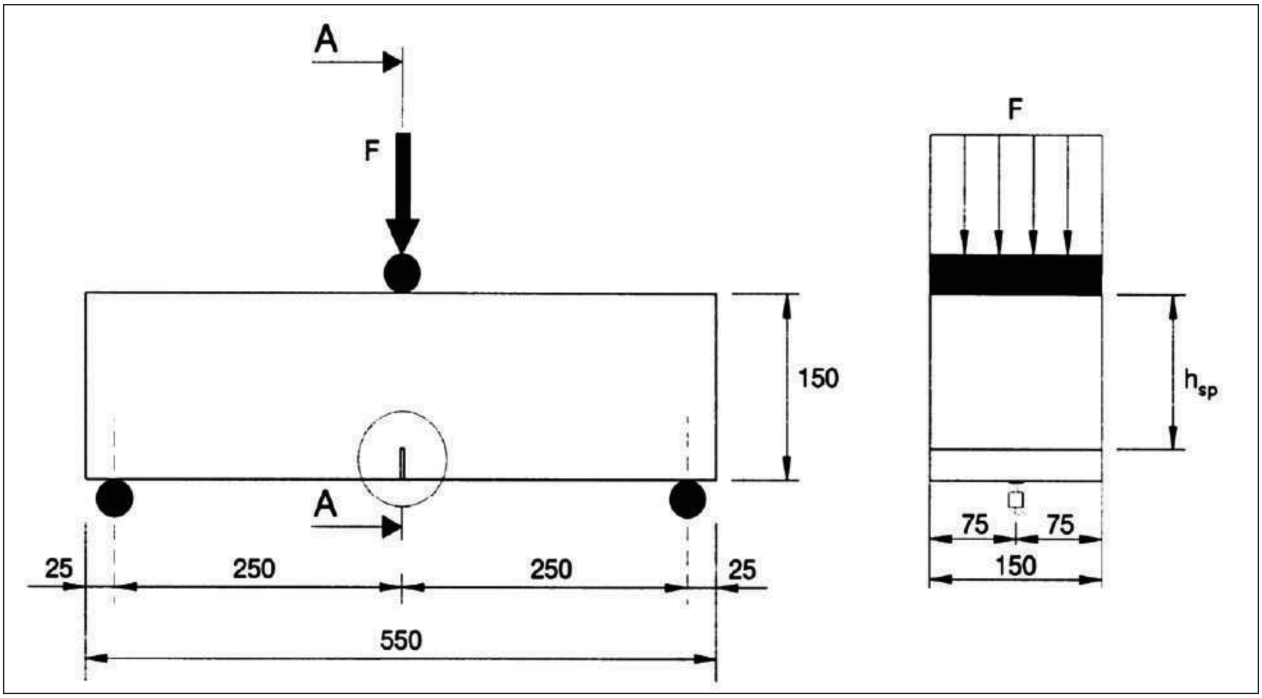


Figure 4.1 : Typical arrangement for measuring CMOD

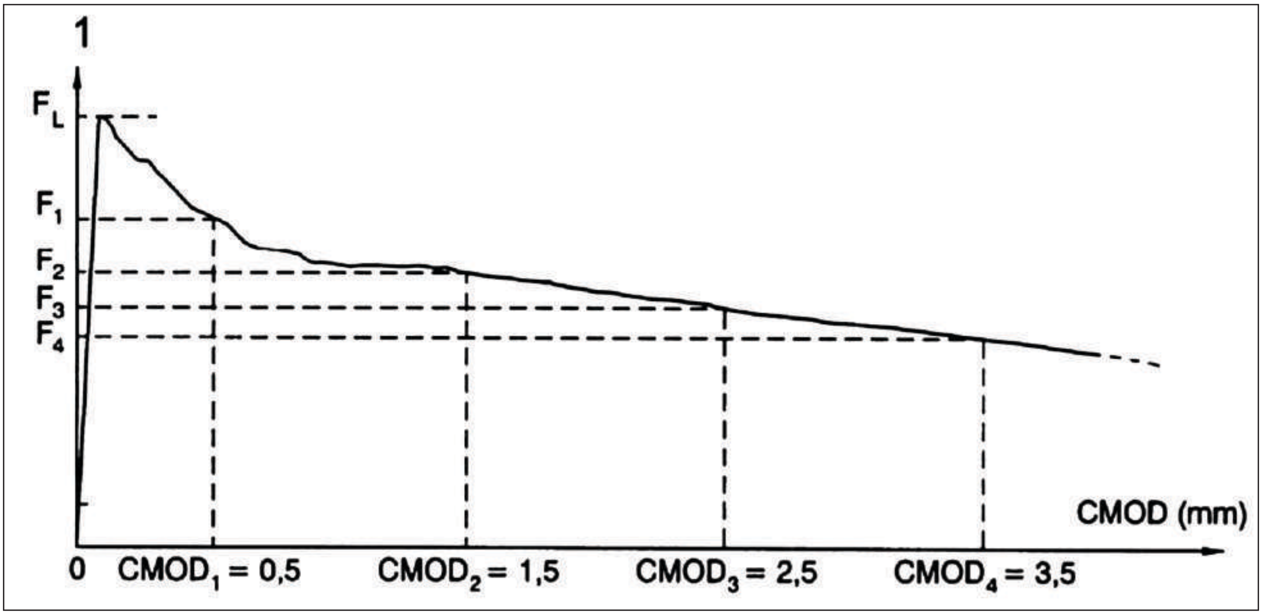


Figure 4.2 : Load-CMOD diagram and Fj

4.2 Stress-strain relationship

When plain concrete is compared to FRC in compression, fibres does not display any significant change in behaviour and because of this reason stress-strain relation given in codes are used without any modifications. Until the point of tensile failure of the concrete, the direct tensile capacity of plain or reinforced concrete follows a linear elastic behaviour. As this failure occurs at extremely low stresses, fibre reinforcement does not increase the tensile resistance up until this point and because of this reason, peak tensile strength of FRC is taken as least matches with direct tensile strength of plain concrete.

In Figure 4.3, behaviour of ordinary concrete and FRC under load is shown. Dashed line shows Plain cement concrete's behaviour and solid green and red lines indicates behaviour of FRC at single and multiple cracking. At single cracking it shows softening effect whereas at multiple cracks hardening behaviour is shown.

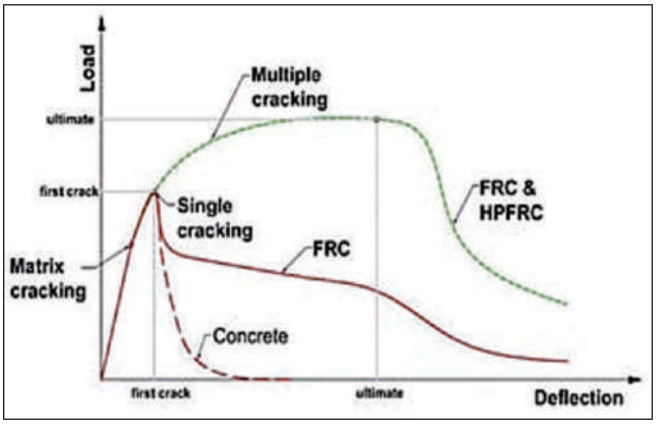


Figure 4.3 : Classification of concrete behaviour under load

Figure 4.4 shows, stress- strain behaviour of FR Concrete. Below strain axis compressive stresses are shown whereas above strain axis tensile stresses are shown. All important points shown in Figure 4.4 are mentioned in RILEM Guidelines [13].

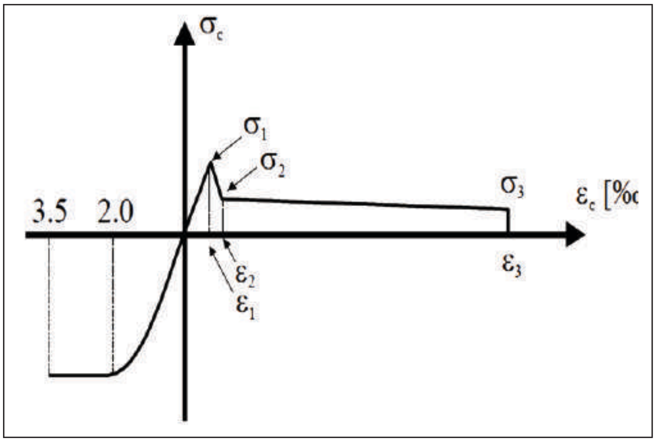


Figure 4.4 : Stress-strain graph for Fibre Reinforced Concrete

$$\varepsilon_1 = \sigma_1 / E_c \quad ...(6)$$

where, $\sigma_1 = 0.7 * f_{ctm,fl} * (1.6\text{-}d)$, $\varepsilon_2 = \varepsilon_1 + 0.1$ %0, $\varepsilon_3 = 25$ $\%_0$.

The model code 2010 [13] also specifies the determination of the σ-ε by assumed multilinear curves based on f_{LK}, f_{R1k}, f_{R3k} values based on the material testing.

4.2.1 Inverse Analysis

The inverse analysis procedure is an iterative process which is used to find parameters to fit experimental data which defines σ-w curve. This procedure is for the determination of tensile stress-crack opening curve from the flexural response of FRC by taking inelasticity and nonlinearity into account. It is used for determining the tensile constitutive parameter of SFRC, showing both softening and hardening type behaviour. The tensile curve of FRC has an initial linear elastic region until crack is formed. Then, a gradual drop in stress until failure in case of ordinary concrete as shown in Figure 4.3. Fibres reduces cracks and curve becomes flat or rises as per fibre's dosage.

To simulate 3-point bending test of FRC, nonlinear hinge concept is used. In a centrally loaded notched beam maximum bending moment occurs at mid-span. A hinge placed at midpoint at half of the depth of section, demonstrates linear elastic behaviour until stress reaches tensile strength point. After the initiation of cracks hinge demonstrates non-linear behaviour. The shape of σ-w curve is because of fibre yielding and pulling out from matrix. The bilinear/multilinear crack opening curve is assumed as straight in each branch of curve as shown is Figure 4.5. The parameter is found by reiterating process of finding CMOD and comparing with analytical value.

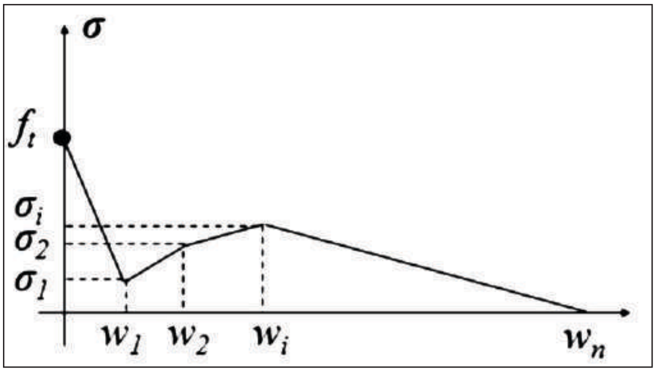


Figure 4.5 : Multilinear crack model with assumed curves

4.3 Design Approach

Loads carried by precast segmental linings can be broadly classified in 3 categories: Production and transit stage, construction stage, service stage.

4.3.1 Production and Transit Stage Loading

Vacuum lifting or mechanical lifting loads occurs at the demoulding stage of production. Demoulding induces bending in the segment and residual tensile strength of FRC is of importance in early 4 hours of production.

Demoulded segments are stacked on wooden blocks with 2-point support. The supports shall be spaced such as to minimise bending between the point of support distance is calculated from free end. All segments are supported at aligned supports however in practice, the segments may not be seated with blocks in the same line, eccentricity is to be considered while calculating design moment for this stage.

During transport, segment experiences dynamic shock loading and while shifting on TBM trailing gear it experiences forces when lifted by forklift.

4.3.2 Construction Stage Loading

TBM moves forward by applying pressure against newly constructed segment.

Very high compressive stresses are generated under thrust pads causing generation of significant bursting stresses within segments. Spalling tensile stresses are generated between the TBM jack location as shown in. Figure 4.6 (a) indicates shows location of stresses under double TBM jack and Figure 4.6 (b) shows location of stresses under single TBM jack. Thrust generated by TBM consist of force required for boring, friction between ground and shield of TBM, and force required to carry trailing gears. The bursting stresses are generated directly below the jack and farther from the jacking point, whereas the spalling stresses are generated in between the jacks, near to the circumferential face of the segment. Simplified

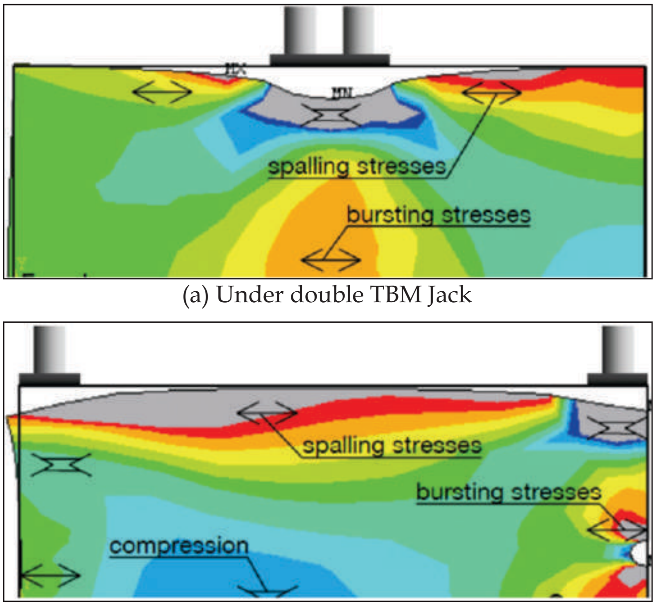


Figure 4.6 : Bursting and spalling stress regions due to TBM trust

equations are available to determine Bursting and spalling stresses are given in ACI 544 [8], DafStb Guidelines-2012 [14], DAUB [20]. Analytical methods proposed by Iyengar [21] in form of charts are also referred by designers to assess the bursting stress, however the method does not consider the resistance provided by the fibres as they have been considered only as an elastic material. Finite element can also be adopted to assess the actual stresses occurring in the segments as shown in Figure 4 7 If the stress obtained exceed the limit of proportionality (thereby the cracks will activate the fibres) then Nonlinear analysis shall be carried out to determine the depth and width of the cracks and ensured that they are within the limits.

Rings of tunnel segment are placed at designated places, but the void is created between actual excavated portion and ring of tunnel segment. This void is continuously filled with grout slurry under high pressure to ensure complete contact between tunnel segments and ground. It also helps in reducing settlement that can potentially occur due to void. Optimal grout pressure is higher than groundwater pressure but less than overburden pressure.

Secondary grout/check grout is filled through holes manufactured in segments. Grout sockets are closed with non-return valve during ring installation. This effect is considered by applying triangular load at joint location where maximum value occurs at joint and then reduces in circumferential direction. This can result in high bending moment with small axial force.

4.3.3 Service Stage Loading

Soil load, ground water pressure and surcharge from vertical or horizontal direction can be applied on tunnel segment. These forces depend on actual ground level, ground water level, and surcharge due to live load or any other structure along the tunnel alignment.

Longitudinal joint burst can occur due to permanent earth and ground water pressure causing hoop forces to generate in reduced cross-sectional area. Maximum normal/hoop forces can be taken from primary analysis and by using simplified equations mentioned in ACI 544 [8] force calculation and its design can be carried out.

Sometimes tunnel segment may experience forces due to additional distortions that may arise during construction activities such as joint misalignment, yield of connectors, excessive grout pressure or due to construction of adjacent tunnel. Extra moments generated due to such distortions can be calculated by formula given in ACI 544 [8].

Other loads that can occur on tunnel segments are earthquake, fire, explosion, or excess longitudinal bending. Earthquake load can be given in term of time histories or numerical models based on free field deformations and combined axial and bending strains are calculated. Fire load can be given as temperature gradient between intrados and extrados of tunnel segment lining. Explosion load can be applied as excess radial pressure at service condition.

Precast segmental lining designed with LSM approach. Load factors and strength reduction factors are given as per ACI 544 [8] by considering recommendations from ACI 318 [7], EN 1992-1-1 [6], FIB bulletin 83 [10]. Below table 4.1 gives load factors for ULS condition.

Table 4.1 : Load Factors for ULS Condition

Sr. No.	**Load**	**Partial safety factor for loads**	
		ACI 544.7R-16	**FIB Bulletin 83**
1	Stripping of segment	1.4 w	1.35 w
2	Storage	1.4 (w+F)	1.35 (w+F), 1.0 (w+F) for accidental case
3	Transportation	1.4 (w+F)	1.35 (w+F) 2-additional for dynamic load
4	Handling	1.4 w	
5	Jack Force	1.2 J	1.5 J , 1.0 J- for max load of jacks
6	Tail skin grouting	1.25 (w + G)	-
7	Secondary grouting	1.25 (w + G)	-
8	Earth Pressure and ground water load	$1.25(w+WA_p) +$ $1.35(EH+EV) + 1.5ES$	-

9	longitudinal joint bursting	1.25(w+WAp) + 1.35(EH+EV) + 1.5ES	-
10	Additional distortion	1.4 $M_{distortion}$	-

Note : *w is self-weight; F is self-weight of segments positioned above; J is TBM jacking force; G is grout pressure; WA_p is groundwater pressure; EV is vertical ground pressure; EH is horizontal ground pressure; ES is surcharge load; and Mdistortion is additional distortion effect.*

From these load and load factors, tunnel segment lining thickness is determined. After determining thickness, moment - axial force (M-N) interaction diagram is generated for the capacity of designed thickness. Typical interaction diagram for SFRC Tunnel lining segment is as shown in Figure 4.8 Horizontal axis represent axial force (N) in kN and vertical axis represent bending moment (M) in kNm. Points mentioned on N-M diagram have significance as follows:

At point 1, ε_{cu} = 0.0035 at both top and bottom fibre of section, only axial force, and no bending moment.

At point 2 and 8, N = $N_{max,compression}$ - $N_{max,tension}$ and M ≠ 0, $\varepsilon_{top\ fibre}$ = from equilibrium and $\varepsilon_{bottom\ fibre}$ = min (0.002, crack width / depth of specimen)

At point 3 and 7, N = compression - tension + axial force and M = ∑ (forces * lever arm), $\varepsilon_{top\ fibre}$ = 0.0035 and $\varepsilon_{bottom\ fibre}$ = min (0.002, crack width / depth of specimen)

At point 4 and 8, N = 0 and M = ∑ (forces * lever arm), $\varepsilon_{top\ fibre}$ = from equilibrium and $\varepsilon_{bottom\ fibre}$ = min (0.002, crack width / depth of specimen)

At point 5, N_{max} = Tension, M = 0

4.4 *Hybrid Tunnel Segmental Lining*

In hybrid tunnel segmental lining, precast FRC segmental lining is used along with conventional reinforcement to obtain the required flexural strength of the lining at (ULS) and to enhance the crack control at (SLS). The bursting stresses developed under the tunnel-boring machine

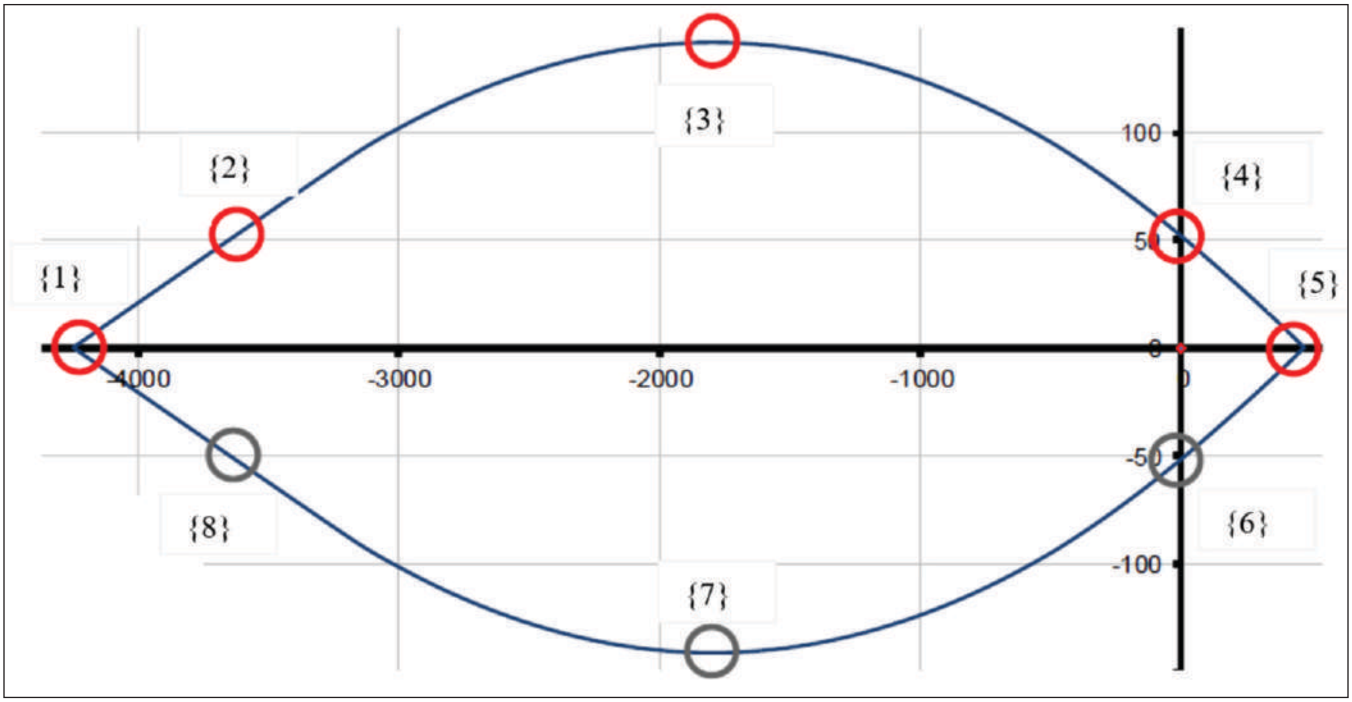


Figure 4.7 : Typical axial force - Bending moment interaction diagram for tunnel segmental lining

(TBM) jack shoes can be resisted using fibres that provide localized capacity to redistribute the stresses. During the construction, TBM thrust jack forces are applied to the segments in addition to local effects such as the bursting or spalling stresses. Eccentric radial placement can also occur due to the misalignment of TBM jack shoes may cause cracks in middle section to due additional tensile stresses. Hence to enable segment to take up these additional stresses conventional reinforcement is provided. When reinforcing bars are placed along longer sides to resist flexural stresses arose from imperfect construction or eccentricity, it behaves as deep beam. Main design principle for the design of hybrid segment includes:

- In addition to fibres, adequate transverse reinforcement to be provided to give sufficient flexural strength in ULS.
- Adequate transverse reinforcement to be provided to control spalling cracks.
- Concentrated transverse reinforcement to resist flexural stresses in construction stage.
- Adequate longitudinal joint reinforcement to resist bursting stresses.
- Adequate circumferential joint reinforcement to hold transverse reinforcement in place.

Generally, hybrid tunnel segments are used in places where there is soft soil is present also it is used junction of tunnels or junction of cross passage and tunnel.

4.5 Sacrificial Segments for an Indian Metro tunnel

SFRC for Precast tunnel segments were proposed in one of the Indian Metro. Initially it was envisaged to be used for sacrificial segments at the blind rings during launching of the TBM. Following are the characteristics of the tunnel.

Internal diameter	- 5.8m
Outer diameter	- 6.35m
Lining Type	- segmental
Ring Type	- Universal ring
No of Segments	- 3 standard segments, two counter-key segments and one key segment.
Segment width	- 1.4m
TBM Type	- EPBM shield machine
No of Jacks	- 24 jacks
No of Shoes	- 16 shoes (8-twin jack, 8-single jack)
Max Thrust	- $8\times2\times1858 + 8\times1858 = 44592$ kN

The material characterisation of the SFRC mix was determined based on 2 trial mixes with dosage of 40 kg/m^3 and 60 kg/m^3 of Dramix 4D 80/60 BG hooked-ended steel fibres, termed as BG40, BG60. In addition, the test was also carried out with Dramix 4D 80/60 BGP hooked-ended steel fibres and dosage of 40 Kg/m^3 termed as GP40. The Material properties and the SFRC classification for the different mixes are provided in Table 4.2 and Table 4.3 respectively.

Table 4.2 : Material Properties of SFRC

Concrete mix	Strength (MPa) Compressive strength, in cubes					Splitting tensile strength	Elastic modulus (GPa)
	*SC**	*1- day*	*3- day*	*7- day*	*28- day*	*28*	*28*
BG40	42.9±0.4 (7 hours)	30.5±1.3	45.9±0.5	56.4±1.1	69.2±3.7	7.8±0.4	42.9±0.3
BG60	32.1±0.9 (4 hours)	23.5±0.9	49.8±2.0	56.8±4.3	78.5±1.9	8.9±0.7	42.6±0.1
GP40	-	-	-	55.9±3.7	73.3±2.0	6.9±0.38	-

**Steam curing carried out on the specimens*

Table 4.3 : Concrete classification based on strength and toughness.

Mix	$f_{L,k}$ (MPa)	$f_{R,1k}$ (MPa)	$f_{R,3k}$ (MPa)	$f_{R,3k}/f_{R,1k}$	Class	$f_{R,1k}/f_{Lk}$
BG40	6.6	5.66	5.85	1.03	6c	0.86
BG60	6.7	8.62	7.81	0.91	9c	1.30
GP40	7.07	5.75	8.32	1.45	6e	0.81

The slump of the SFRC mix is crucial to the workability and to the mechanical properties of the mix. An optimum Superplasticizer (SP) dosage was also determined for the mix. Although the slump of 45mm is preferable for the homogenous fibre distribution, it is practically not achievable for mass production. The slump of 90mm was ideal and is considered the maximum slump. An ideal slump for SFRC is considered between 50-70mm. This ensures that the fibres do not orient in the same direction upon vibration. The fibre density for the beams turned out to be 0.63, 0.6 & 0.39 fibres/cm^2 for mix with 45, 90 & 120mm slump respectively. Eventually the mix with slump 120mm had very poor fibre distribution. The fibre orientation also induces high variability in the flexural residual strength of the SFRC beams.

The design of SFRC segments was carried out with consideration of strength class 4c, however the strength class based on the beam test results turned out to be superior, with strength class 6c while using BG fibres and 6e (higher toughness) while using BGP fibres.

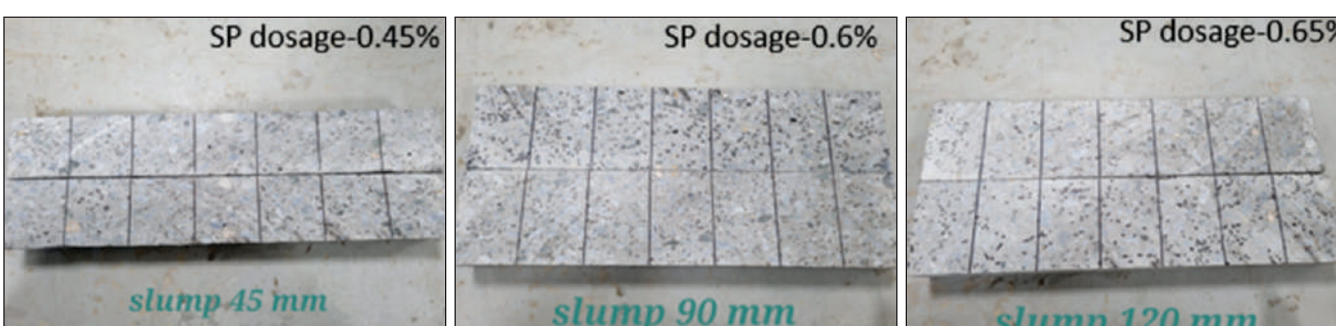
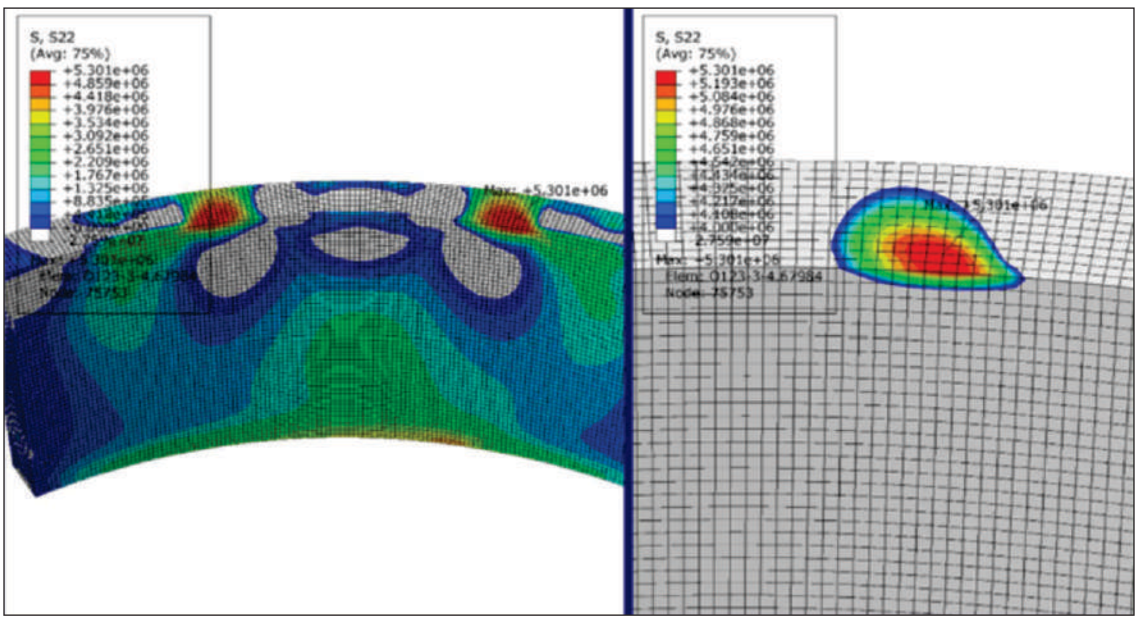


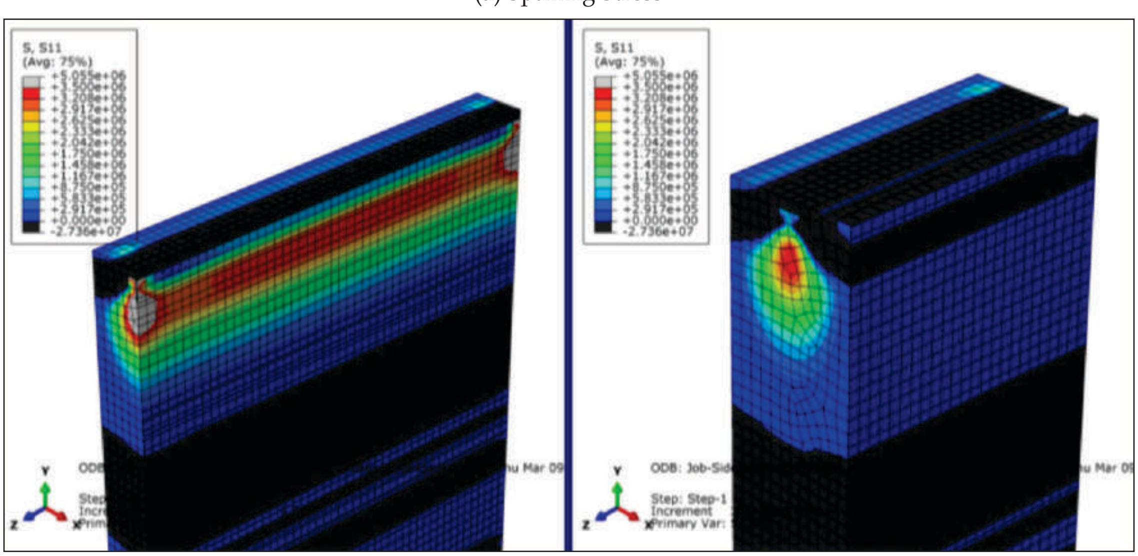
Figure 4.8 : Fibre distribution with different slump for design mix with 40kg/m3 of fibres.

The inputs for the design of segmental linings were the residual flexural strength at CMOD1 and CMOD3. The idealised tensile stress-strain behaviour was derived from the methods specified in Model code 2010. The stress-strain behaviour in compression was assumed to be the same as of the normal concrete, although the strain corresponding to peak stress was more than that of the normal concrete. The MN plot was generated using inhouse spreadsheets, and the design forces were found to be within the limiting boundary.

The local checks for bursting and spalling were verified using Abaqus software. The idealised stress-strain were provided in the material model. The Spalling stresses were dominant than the bursting stresses. The max spalling stress was 5.3MPa, and the maximum bursting stress was 3.6MPa. Further analysis was also carried out in DIANA with nonlinear analysis to verify that the cracks are within limits for the extreme case loading.



(a) Spalling Stress



(b) Bursting Stress

Figure 4.9 : Stresses as per FEM analysis in Abaqus software for a typical tunnel segment

5. Conclusion

This paper provides an insight into the usage of steel fibres in specific application to tunnel linings used in TBM mined tunnels. The material characteristics is unique for each concrete matrix and hence needs to be ascertained by trial tests that have been described in the paper. The inputs for the design of segments are from the residual flexural strength based on material characterisation. The paper discusses the philosophy in obtaining the section capacity for the SFRC. The splitting and spalling stresses due to TBM jack forces are critical loadings for the segment and shall be checked as per the methods discussed. Extreme loads may also require reinforcement bars to reinforce the local zones to increase the strength of the zones.

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Abbreviations

FRC	Fibre reinforced concrete
SFRC	Steel fibre reinforced concrete
TBM	Tunnel boring machine
NLFM	Nonlinear fracture mechanics
FEM	Finite element method
DEM	Discrete element method
CMOD	Crack mouth opening displacement
LSM	Limit state method
ULS	Ultimate limit state
SLS	Serviceability limit state
EPBM	Earth pressure balancing machine
SP	Superplasticizer

Challenges of TBM Tunnelling in DMRC Project, Phase – III, CC-04

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Abstract

In 2015 Delhi Metro Rail Project Phase-III, Line-7, Contract CC-04, two TBMs got stuck below the religious structure (Gurudwara) in highly dense built-up residential locality known as Rameshwar Nagar. Original plan was to retrieve both the TBM from Mukundpur retrieval shaft. Due to hard rock strata in both the alignments, further advancement was not possible as the TBM was EPB soil TBM. To complete the Metro tunnel, there was no alternate option to except intermediate retrieval shaft.

Keywords: Intermediate Retrieval Shaft, TBM Advancement, Geotechnical investigation, TBM Specification, unexpected geology, Hyperbaric Intervention, Ground exploration, real-time monitoring.

1. Introduction

Phase - III of Delhi Metro Rail Project, Contract CC-04, after successfully completion of 1st drive of both the TBM from Azadpur south side Launching shaft to Shalimarbagh retrieval shaft, both the TBM again launched at North shaft of Azadpur station towards Mukundpur retrieval shaft. In 2nd drive After (app.) 50% of advancement, due to unforeseen geology, both the TBMs got stuck below the religious structure (Gurudwara) in highly dense built-up residential locality known as

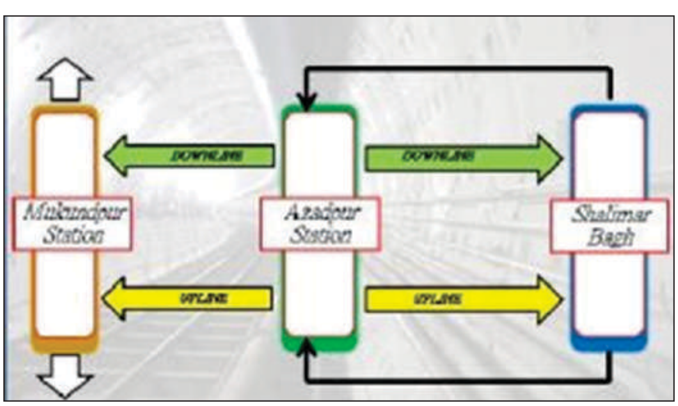

Fig.1: Original Planned TBM drive sequence

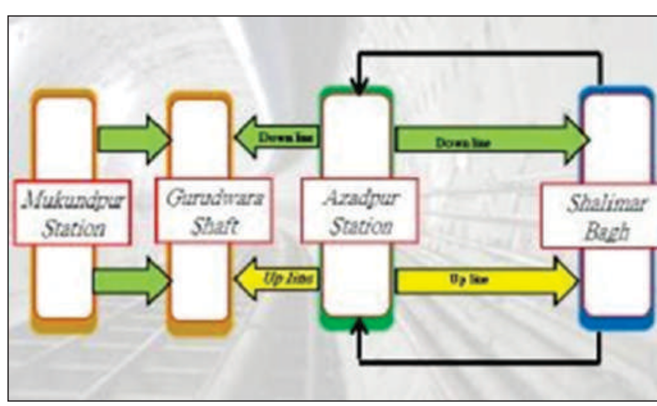

Fig.2: Actual TBM drive sequence

Rameshwar Nagar. Another two soil EPB TBMs were launched at Mukundpur retrieval shaft by converting to Launching shaft for drive of another two TBM towards intermediate shaft called Gurudwara Emergency Exit shaft, which has built below the Palace of worship of Sikh people community. From this small shaft 4 nos TBM retrieval was huge challenged.

2. Geology & Hydrology

Geotechnical investigation is done in the year of 2011-2012. The stratigraphy based on soil investigation divides the subsurface in to following geotechnical units with a top layer of manmade fill, silty clay with small kankar, poorly graded fine to medium sand, silty sand with trace of clay with small kankar, silty clay with small kankar, and silty sand with trace of clay with small kankar. Adjoining Bore Hole No. 16 core recovery drillings have investigated the stratigraphy of the soils. Additional in-situ test (SPT and Lefranc) and laboratory tests have allowed the geotechnical and hydrogeological parameterisation of the different soil units. For the determination of the soil properties, the following geotechnical laboratory tests have been carried out: specific gravity, dry and bulk density, natural moisture content, relative density, void ratio, grain size distribution and Atterberg limits. Further, for determining the geomechanical characteristics (resistance and deformability) lab tests have been carried out which included triaxial tests, direct shear test and consolidation test in soil. The soil description and the range of the geotechnical parameters adopted for the different geotechnical units detected along the TBM tunnel area are shown in the Geological and Geotechnical Interpretative Report. With the aim to particularize the response of each building in relation to the closer borehole, three zones were determined. The final characterization was derived from laboratory and in situ tests. The boreholes considered for the geotechnical characterization of the different zones are shown in the following figures. A confirmation of the laboratory test results is obtained from the SPT in situ test with interpretation with curved strength envelops, a Baligh criterion, and subsequent linearization with Mohr-Coulomb criterion. The Young modulus E was defined on the base of SPT results.

3. TBM Specification

Table 1: TBM Specification

Technical Data of 4Nos TBM			
Item	Name	Azadpur to Gurudwara Drive(2TBMs)	Mukundpur to Gurudwara Drive(2 TBMs)
		Parameter	Parameter
Design Condition	Minimum Curve Radius	250m	250m
	Maximum Gadient	3%	3%
	Lining Out Diameter	6.350m	6.350m
	Lining Inner Diameter	5.800m	5.800m
	Lining Length	1.200m	1.400m
	Type	5+1	5+1
Main Shield	Total length	8.000m	7.860m
	Total weight	400Ton	400Ton
	Excavation diameter	6.560m	6.610m
	Front shield diameter	6.540m	6.580m
	Middle shield diameter	6.530m	6.570m
	Tail skin diameter	6.520m	6.560m
	Shield thickness	45mm	60mm
	Tail clearance	45mm	40mm
	Maximum excavation speed	80mm/min	80mm/min
	Main Thrust Cylenders	30	32
	Thrust force	350bar	350bar
	Soil pressure cells	6	6
Cutterhead Drive system	Copy cutter	2	1
	Overcut	75mm	40mm
Articulation	Non-Artuclate		Artuclated

4. Challenges Faced in Drive towards Mukundpur from Azadpur

4.1 Azadpur to Gurudwara Drive

In the month of December' 2014 Two nos Soil EPB TBM launched from south shaft of Azadpur station towards Mukundpur retrieval shaft. In DN line upto ring No. 548 was successfully completed and on 1st April' 2015 suddenly TBM encountered gravel/cobbles mixed with reddish brown materials. 20% stone masonry in the muck was recorded. During advance no 550, unstable high torque and fluctuation in cutter head rotation observed with frequent tripping of the machine, which predicted that machine was overloaded. This resulted in reduction in TBM advance speed and thrust. The mucking period increased significantly to several hours, maximum 8 hours to complete the advance. Between advance no. 550 to 554, same issues observed. During the advance of 554, first 300mm took nearly 1.5 hours and one muck skip was filled. During this, high torque, difficult penetration and extreme operating conditions were observed. At the end of above shove, drastic change observed with suddenly huge ingress of water along with soil. The muck, coming out of screw conveyor, was low viscous sand (running sand) with cobbles. Two extra muck skips filled before the operator closed and sealed the screw conveyor gate over a period of 2 to 3 minutes after hitting the water inrush. Normal TBM operating procedure on encountering such ground is to immediately close the screw conveyer. Excavation immediately stopped. The observed settlement of 177mm across a 10m x 10m area at the surface indicates a potential ground restriction likely caused by unforeseen geological conditions.

After successful completion of the filling the depression on the Road and compensatory grouting on the Road, balance advance of TBM started on 28th April 2015 of advance no.554 and completed advance no.557 on 29th April 2015with great difficulty. TBM advance got stuck during advance of 550 on 1st May 2016; Excavation was put on hold for further investigation. Meantime Up line TBM also reached up to advance no.496. Both the Machines stopped for further investigation of geology and further improvement of works.

Fig.3: Alignment of 2nd drive from Azadpur station to Mukundpur Ramp

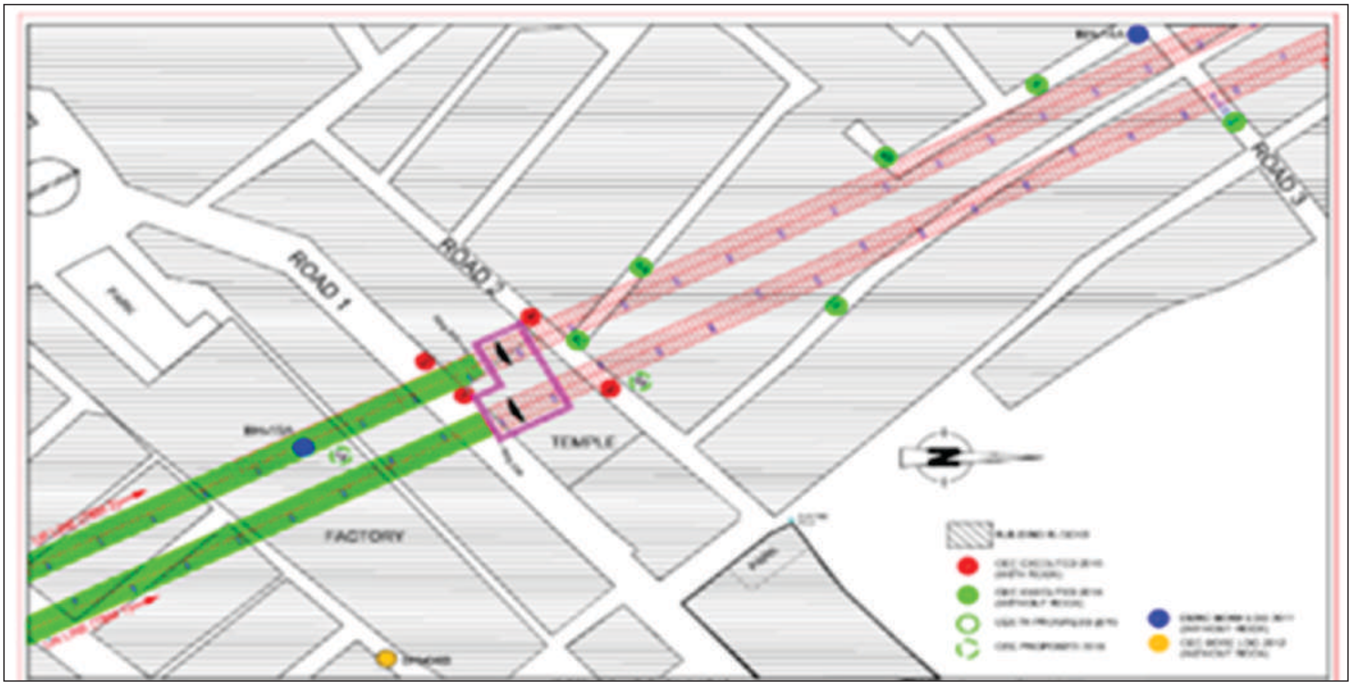

Fig.4: Geological sample and surface settlement during Tunnelling below shaft

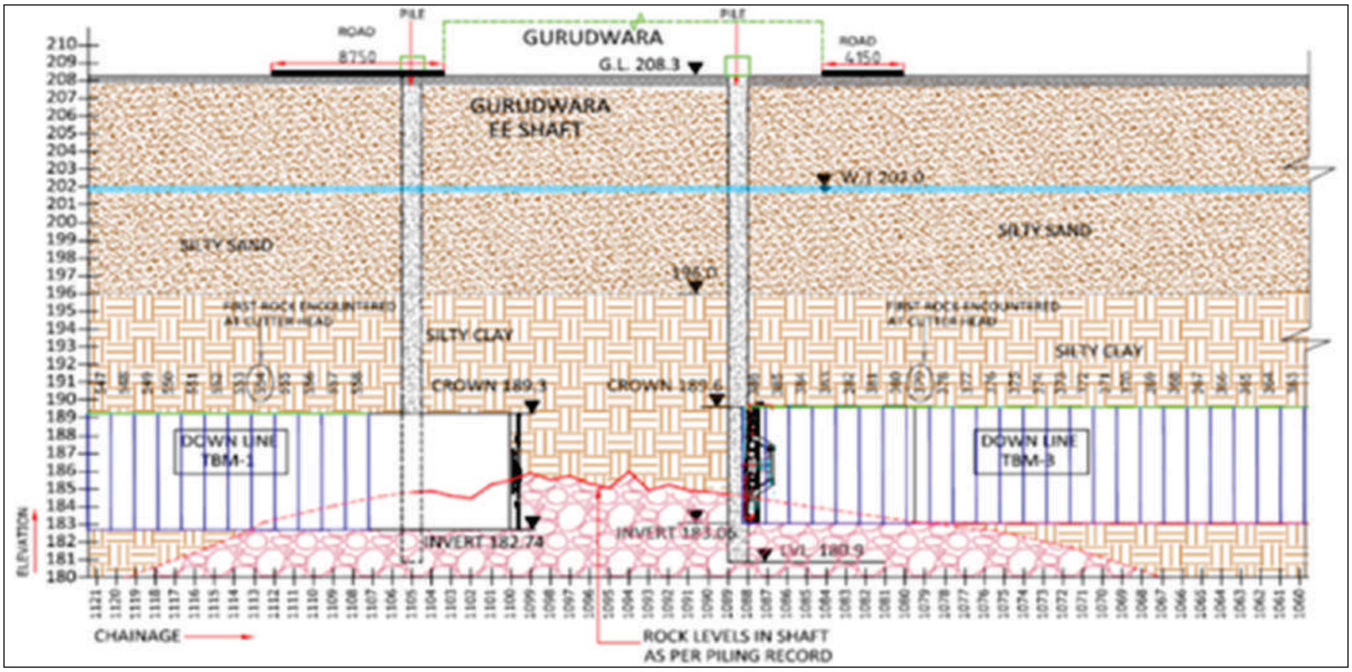

Fig. 5: L - Section of Tunnel advancement along with geological profile

Fig.6: Hyperbaric Intervention

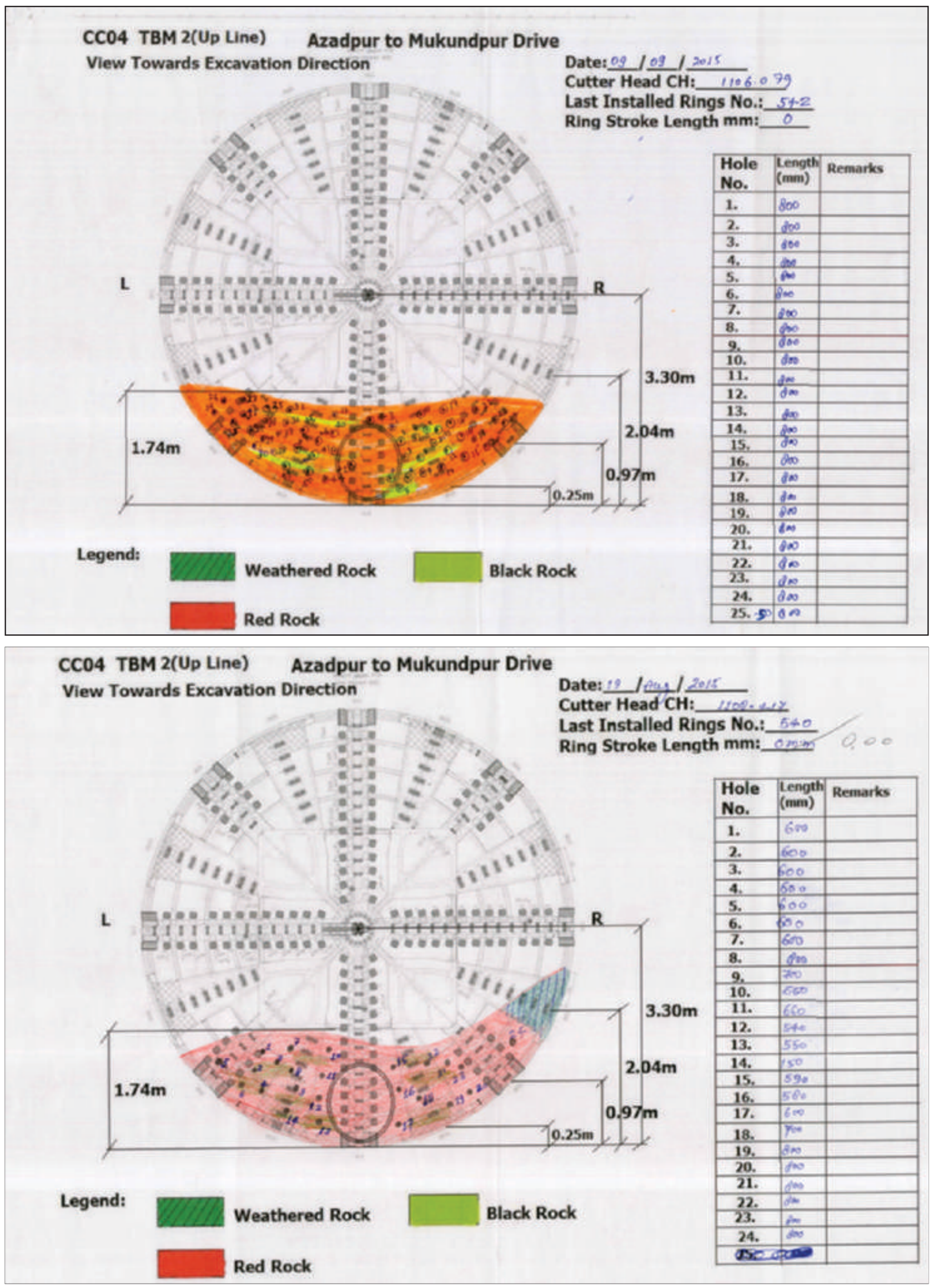

Fig.7: Mapping of rock profile

Ground exploration and investigation with triple core bore holes drilled near the TBM Locations and along the alignment up to the Mukundpur Retrieval shaft for investigation of the Geology were made. In the investigation observed the rock at invert portion of the TBM Cutter head at 2.0m height at length of 30-40m along the alignment. Decision was made to lift the vertical alignment as much as possible for the Up-line Tunnel and as well as down line Tunnel. In order to meet the design requirement of Schedule of Dimensions (SOD) with 1550m radius with 3.7% allowable in this case. Both the Tunnels realignment was done to overcome the rock encounter, as the both the machines were not designed for the Rock Cutting and don't have any Cutter Discs for rock breaking in the Cutting Wheels. Realignment only helped to lift the Up line TBM by lifting 1m. Still the Rock encountering chances are there. As the rock was mainly in the central invert area, it was great difficulty to access that area especially in front of the screw conveyor in the excavation chamber.

After interpretation from the borehole data, it was predicted that mixed face with sand strata at top and rock in the invert will be encountered. With 18m high water table, it was very high risk for hyperbaric intervention. For that bentonite mix was injected in the face for stabilization. Hyperbaric intervention arrangements were made ready for cutter head intervention to inspect the Cutting wheel for damage assessment and for the breaking the rock with crackmite chemical. Down line TBM started with advance No.558 after Cutter head intervention successfully but after the Ring building of the Ring No.558 it was observed that all the knifes and other cutting tools were worn out and not possible to drive the machine ahead with this unstable ground condition and high risk at surface with holy place for Sikh religion of Gurudwara. And after brainstorming with the experts, decided to stop the Downline TBM and overtake the Up line TBM with new alignment. After interpretation the geological investigation data, the rock profile for the up line was interpolated. From the investigation the rock depth was estimated at approximate 1.7m from the invert, as it was not possible to do ground investigation under the Holy Place Gurudwara. After the vertical re-alignment, the rock depth was reduced to 0.7m from the invert which was foreseen to be excavated with hyperbaric intervention with chemical rock breaking. So Up line TBM advancing started on 13th July 2015 with new lifted vertical alignment, reached beside the down line TBM on 28th July 2015 with advance no.539 which is below the Gurudwara. From Advance No.540 to 542 took long time to drive with hyperbaric intervention and breaking the rock from the chamber by using crackmite chemical. Unfortunately, after advance No.541, cutter head got severely damaged, and the rock strata was found higher than estimated. Finally Up line TBM stopped after very hard work on 6th September 2015 with the ring No.542. It would be near impossible to continue mining in such conditions for the next 400 rings to reach the Mukundpur Shaft. Both the TBMs cut short the drive at Gurudwara and decided to retrieve the machines from the Gurudwara by making intermediate shaft and launching the additional machines from the Mukundpur retrieval shaft by converting as Launching Shaft.

4.2 *Mukundpur to Gurudwara Drive*

Delhi Metro Phase-III has a proven network construction is progress, fortunately few TBMs completed the drive, hence 2 available TBMs were hired to complete the Mukundpur drive after meeting the geometry and technical parameters. Mukundpur shaft initially retrieval shaft later converted as launching shaft for additional 2 TBMs was also big challenge because the base slab was designed for retrieval only. Mukundpur Shaft is in Curvature and continued towards ramp towards elevated corridor. In order to meet the accuracy of the Tunnel Final lining, the launching cradle for TBM was kept slightly inclined to the alignment, so thrust frame for the inclined alignment kept perpendicular by providing the Thrust block behind the frame with vertical support on the Roof slab as the base slab was not designed for such thrust from the TBM.

TBM drive started with 5.8m overburden and reached Gurudwara Shaft with overburden of 18.5m through the dense built-up urban area. Precautionary measures taken by providing the props to all structures and extensive instrumentation monitoring done during the drive of both Tunnels from Mukundpur to Gurudwara Shaft.

Down line TBM started on 23rd March 2016 and up line Started on 18th April 2016. Successfully Down line TBM reached Gurudwara on 04th July 2016 and hit the Gurudwara Piles, up line on 14th July 2016.

Fig.8: Launching of TBM at Mukundpur Launching Shaft

4.3 Gurudwara Shaft

The religious place Gurudwara was under construction partially where the TBM got stuck below, but prayer continued. It was difficult situation to convey the message that a religious place has to be demolished and will be restored later, after retrieval of the TBM. After engaging in multiple meetings with members of the community and effectively communicating the message, a request for support from the public was made. Eventually, an agreement was reached to hand over the Gurudwara, subject to certain conditions. These conditions include establishing a temporary Gurudwara in close proximity to the original location to ensure the continuity of prayers and other related activities.

At end of the Gurudwara Street found a small park for Temporary Gurudwara, after frequent meetings with MCD officials, completing the formal documentation with the officials, the park was handed over to construct the Temporary Gurudwara.

Fig.9: Both the TBM stuck below Girudwara at Rameshwar Nagar

Fig.10: Project location of DMRC map

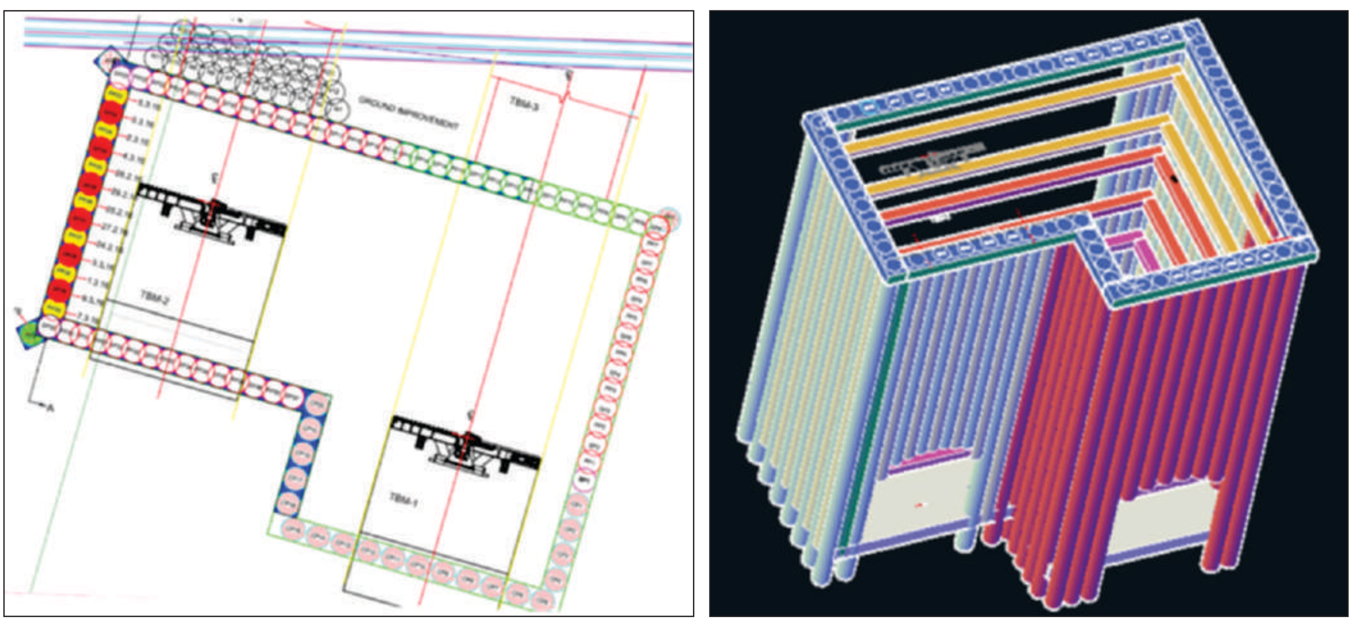

Fig.11: Contiguous and Secant pile arrangement of shaft

In addition to that, diverting all the utilities from the Gurudwara Shaft by coordinating with concerned Govt. Officials like Delhi Jal Board for Water line diversion, MCD for Sewer line diversion, TPDPL for Electrical cable Diversion played a key role and was a time-consuming task before taking the works at Gurudwara Shaft. DMRC officials played a key role in coordination with the Public, Gurudwara Management, and other Govt. Agencies to avail the permissions and land. To minimize disruption to the nearby Gurudwara, the demolition activities were restricted to daytime hours only. The demolition of the Gurudwara and three adjacent houses was successfully completed within a three-month period. This was necessary to create a shaft for the retrieval of four Tunnel Boring Machines (TBMs).

Fig.12: Dismantling of Gurudwara for construction of shaft

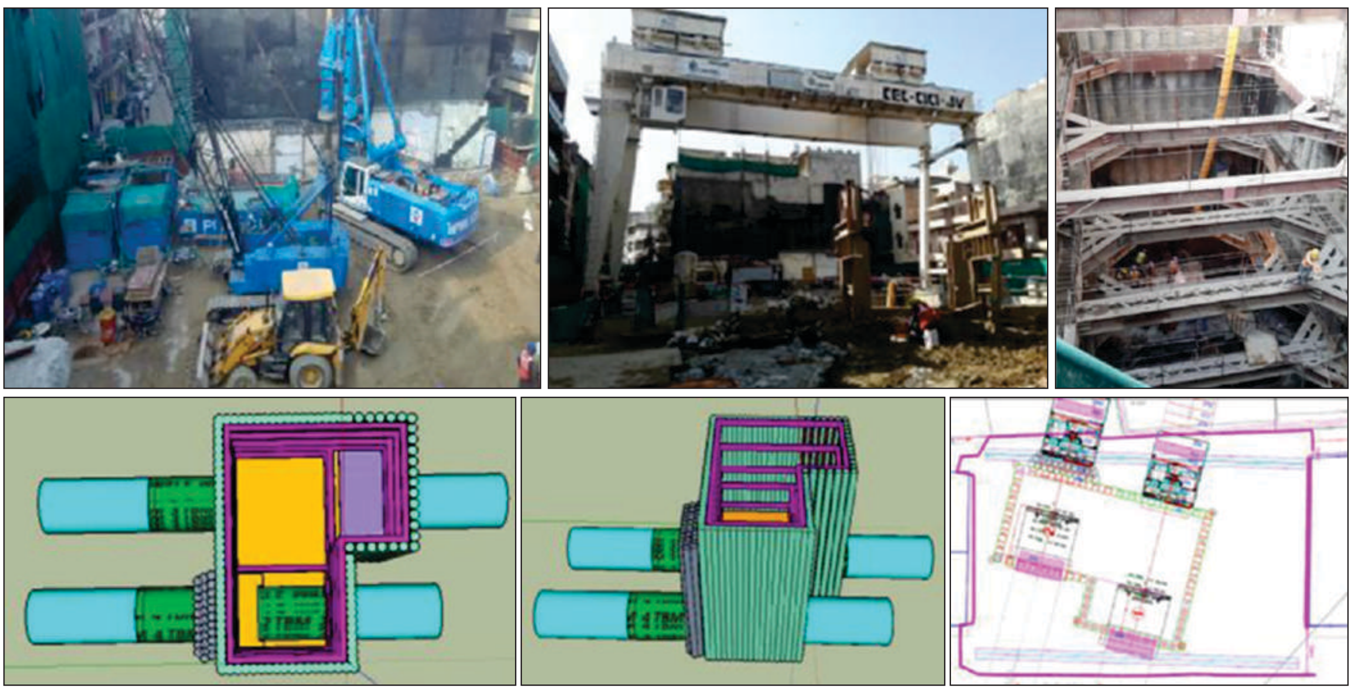

Fig.13: Construction of shaft

Meanwhile the design of the Gurudwara was ready, all the equipment's for the Gurudwara mobilised through the narrow roads in this colony.

In order to understand the ground movement and structures behaviour during the excavation of the shaft, an extensive instrumentation and monitoring played the role. Soil settlement markers, crack meters, 3D Optical Targets, Building Settlement Points, Multi rod extensometers, installed the entire influence zone around the Shaft. In Addition to that real time online monitoring also carried out to find the deformation of the structures real-time.


Fig.14: Real-time monitoring

Excavation of the Shaft started after successful completion of the Piling work for the Shaft. Again, excavation was not an easy task considering the excavation in high water table area, as the Dewatering wells not allowed drawing down the water table, which may lead to the Hugh settlement in the highly dense urban environment. The assembly of 150ton capacity Gantry Crane simultaneously during first layer of excavation of shaft was very critical job in dense urban area. Every cubic meter of muck disposal speaks the story about water ingress in the shaft, making the shaft water tightness by providing steel plates welding between the steel casing piles, injecting grouting both from surface and shaft all the day's work.

Till fourth layer of strut level, shaft excavated full size by controlling water, later it was very difficult to control the hydrostatic pressure, decided to sacrifice the Down line TBM in the ground, cast the PCC Slab over the TBM and reduced the Shaft size by providing the Sheet piled wall. Further Excavation continued till Rock was exposed, rock was removed manually by breaking into the pieces in a small shaft where the excavators cannot move there to break the rock.

4.4. Retrieving the Four TBMs from Small Shaft

Upline TBM from Azadpur to Gurudwara drive (TBM2) Cutter Head was disconnected from the Shield and removed from the Shaft on 26/11/2016, and other parts of the TBM were disconnected and retrieved from the Shaft followed by Cutter Head within period of 10 days. Transporting the TBMs to the Yard through the Narrow Roads was the critical situation. Up line TBM from Mukundpur to Gurudwara drive (TBM4) breakthrough on 19th December 2016 was successfully. Prior to the breakthrough preparation work was done very precisely to avoid the water ingress to the shaft as the water table at Gurudwara is very high. As on date 2 TBMs of Up line successfully retrieved in the Shaft.

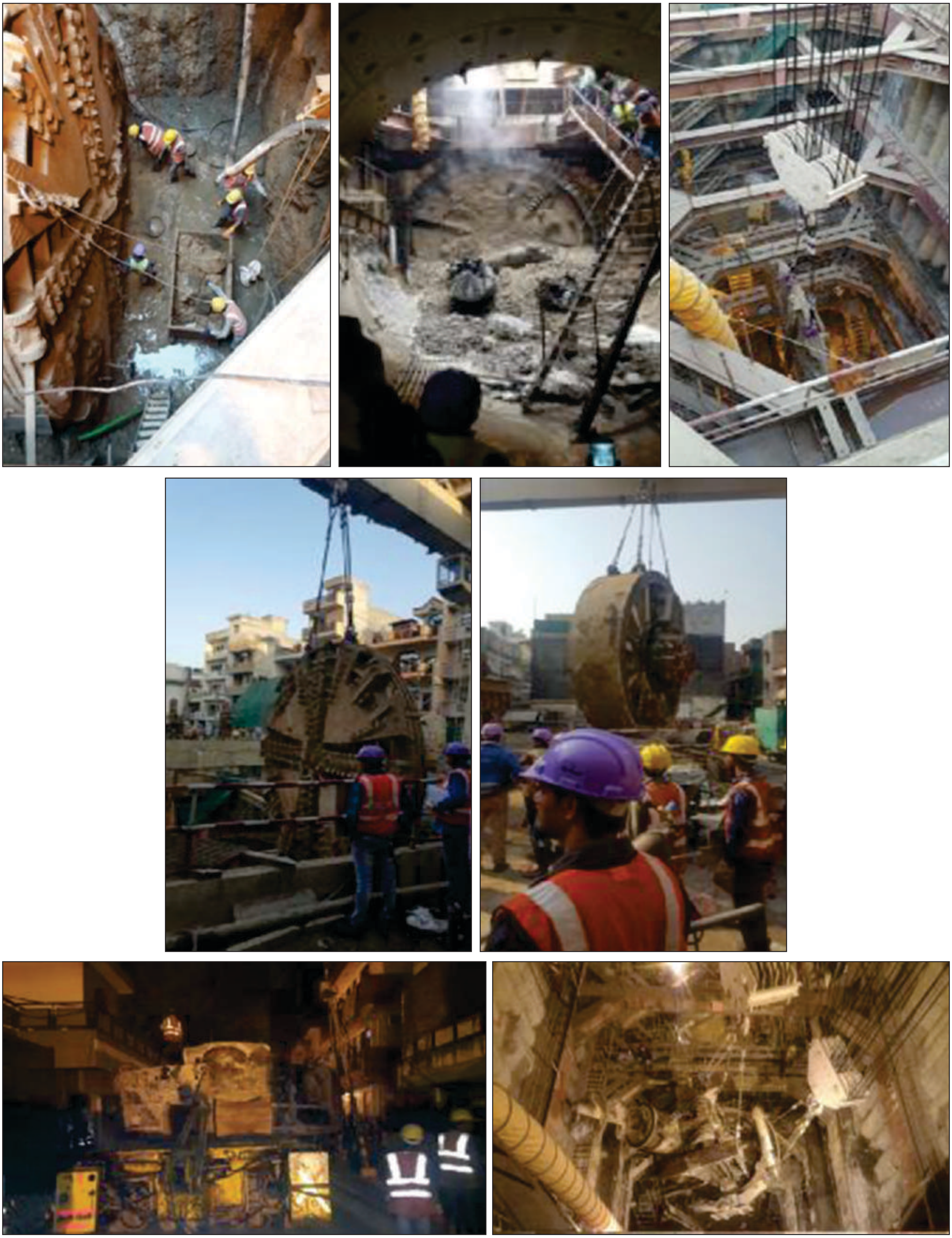

Fig. 15: Removing of 4 TBM from Gurudwara shaft

5. Conclusion

Geotechnical risks, in the form of unforeseen geological conditions, are a serious factor in the cost and schedule control on all the tunnelling works. The amount of time lapse, money, risks involved in arising from these geotechnical problems, is enormous and needs to be taken very seriously by engineering organisations. Inadequate site investigations rank as one of the major contributors to geotechnical risk. More realistic allocations of time and money have to be made to these site investigations. These conditions then become major construction problems because no one is prepared for them. The circumstances raise the question of whether these problems could have been avoided, or their impacts minimized, with a more thorough or different preconstruction geotechnical site investigation. But there are always some limitations in performing thorough investigations depending upon the geography or the local issues (like insufficient space for performing the investigations, or resistance from the nearby residents in performing the activity). In this project the hard rock strata was found for a length of 25 to 30 meter which is comparatively very small distance and due to unavailability of the space the bore holes were done at a larger distance from this location which gave the normal strata. The preparation of contract is a vital step in minimising cost and schedule overruns. The inclusion of a Geotechnical Baseline Report in a contract and the development of Risk Sharing Packages are amongst the contractual arrangements being explored to minimise the problems of unforeseen geological conditions. The possibility of rock was not anticipated, otherwise the contractual requirement of mixed strata cutterhead would have helped. Constructive approaches to handling risk in a design-build contract.

6. Reference

Mechanized Tunnelling in Urban Areas - Design methodology and construction control by Vittorio Gulielmetti, Piergiorgio Grasso, Ashraf Mahtab & Shulin Xu.