Silkyara Tunnel Section Collapse:

A Case Study

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EXECUTIVE SUMMARY

The Char Dham all-weather road project, a significant infrastructure initiative by the Central Government of India, aims to enhance connectivity to the Char Dham pilgrimage sites in Uttarakhand. The Silkyara-Barkot tunnel, part of this project, is a 4.531 km long 2-lane bi-directional tunnel that promises to cut travel time by about an hour and improve accessibility, particularly during adverse weather conditions. However, on November 12, 2023, a section of the tunnel collapsed, trapping 41 workers inside.

The collapse was attributed to a combination of geological and structural factors, including hidden loose patches of fractured or weak rock, water seepage, and undetectable issues during construction. Despite advanced safety measures, the collapse underscored the inherent challenges of tunnel construction in such terrain.

In response, a coordinated rescue operation involving multiple government agencies, private resources, and international experts was launched. Notably, Government of Uttarakhand, the National Disaster Response Force (NDRF), State Disaster Response Force (SDRF), Uttarakhand Police, Indian Army Corps of Engineers, and Project Shivalik of the Border Roads Organisation were pivotal in the rescue efforts. Additionally, Australian tunnelling experts Mr. Arnold Dix and Dr. Chris Cooper provided valuable assistance.

The rescue operation unfolded in several stages, beginning with initial muck removal and alternative plans for machine mobilization. Horizontal drilling, vertical drilling and manual excavation by rat hole miner's efforts were employed to establish a lifeline for the trapped workers, ensuring a continuous supply of food, air, water, and communication. The site team at Siulkyara portal utilized pipe-pushing techniques with safety measures and strategic placement of precast concrete blocks. Sutlej Jal Vidyut Nigam Limited (SJVNL) initiated vertical drilling operations, while Rail Vikas Nigam Limited (RVNL) combined perpendicular-horizontal drilling and vertical drilling techniques, employing micro-tunneling. Oil and Natural Gas Corporation (ONGC) initiated vertical drilling with a 24-inch diameter, and Tehri Hydro Development Corporation Limited (THDC) started constructing a rescue tunnel from the Barkot end. Additionally, a joint team comprising THDCL, the Army, Coal India, and NHIDCL employed manual-semi mechanized methods for drift tunnel construction. Despite challenges such as obstructions and machinery failures, innovative solutions and manual mining were devised, leading to the successful rescue of all 41 workers on November 28, 2023, after 16 days.

Following the rescue, a thorough review of the incident was conducted, emphasizing the need for on-going monitoring and support for the well-being of the rescued workers. Medical examinations were carried out, and the workers were airlifted to AIIMS Rishikesh for further assessment. A six-person committee was formed to investigate the cause of the collapse, highlighting the commitment to preventing similar incidents in the future.

Throughout the operation, district and state governments played a crucial role, activating emergency response plans, establishing onsite command centres, and coordinating various agencies' efforts. The involvement of state police, medical teams, and public works departments ensured a comprehensive and efficient response.

Despite the challenges posed by the tunnel collapse, the successful rescue operation exemplified the resilience and collaboration of all stakeholders involved. Moving forward, lessons learned from this incident will inform future tunnel construction projects, emphasizing the importance of thorough geological assessments, robust safety measures, and coordinated response plans.

The team from the Disaster Management Cell at Dr. R.S. Tolia Uttarakhand Academy of Administration, Nainital visited the incident site from January 5th to January 6th, 2024. Their study focused on observations and included visits to both the tunnel portal on the Barkot side, where 1708 meters of tunnel work had been completed, and the Silkyara portal side, where a section of the tunnel had collapsed. The team conducted descriptive and explanatory interviews with site project managers, as well as Dunda & Barkot Tehsil and district authorities in Uttarkashi, to gather information on the tunnel collapse incident and the response process. Additionally, they utilized secondary data from published journals, reports, articles, and documents obtained from the district office to further develop their research base.

In conclusion, the Silkyara-Barkot tunnel collapse was a testament to the complexities of infrastructure development in challenging terrains. However, the swift and coordinated response demonstrated the government's commitment to ensuring the safety and well-being of its citizens. As the project moves forward, on-going vigilance and adherence to best practices will be paramount to its success.

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1.0 INTRODUCTION

The history of tunnels dates back even before early civilizations, with ancient societies carving rudimentary tunnels for religious, hydraulic work and strategic security purposes. According to modern historians, the earliest recorded tunnel excavation by human dates back to 2200 BC, connecting the palace with the temple of Belos in Babylon. However, the first tunnel whose engineer is known was constructed on the island of Samos. The engineer, Eupalinos of Megara, built this 1-kilometer-long tunnel in 530 BC to supply water to the island's capital. (1).In ancient India, the history of tunnel construction dates back to the time of the Mahabharata. According to Mahabharata, the Pandavas constructed an escape tunnel, which served as a refuge during times of peril or conflict. Later on tunnels were initially constructed for religious use, as seen in the tunnel-like monastery caves of Ellora and Ajanta, and by many kings also constructed escape tunnels from their forts to safer places to be used during emergencies. These historic tunnels bear testimony to the early engineering prowess of civilizations. originally, to oversee canal construction in Roorkee, two specialized facilities, the Iron Foundry and Canal Workshop, were established. Today, they are known collectively as the Irrigation Workshop. This workshop's tunnel served as a refuge for several families of diverse religious backgrounds and British officers during the Revolt of 1857(12). Jamalpur Tunnel constructed in 1861 which is the oldest tunnel in Indian Railways ion India (2). Parsik Tunnel was constructed in 1916 for connecting Thane to Kalyan — lies between Thane and Diva and cuts across the Parsik Hill (3). In contemporary times, tunnel construction has evolved significantly, incorporating cutting-edge technologies and engineering techniques. Today, tunnels serve a myriad of purposes, from transportation and urban infrastructure to underground utilities. Modern tunneling projects utilize advanced machinery, including tunnel boring machines (TBMs), and adhere to stringent safety and environmental standards. The evolution of tunnel construction from ancient rudimentary structures to sophisticated modern engineering reflects the on-going significance and adaptability of this underground infrastructure in meeting diverse societal needs.

In tunnel construction planning, three key aspects are extremely important: geological assessments, continuous monitoring, and surveying. The first cornerstone lies in the meticulous scrutiny of the rock strata, where the objective is to comprehensively fathom the strength and composition of the geological formations. Engineers employ an arsenal of methods, ranging from seismic waves to petrographic analysis, extracting vital information about load-bearing capacities and stability. This rock investigation proves indispensable, guiding the design process to adeptly navigate geological challenges, including the identification of potential hazards such as fault lines or weak rock formations. The second pillar revolves around the imperativeness of continuous monitoring and robust support. Stress and deformation meters become vigilant

sentinels, tirelessly scanning for any subtle shifts in the structural integrity of the tunnel. Simultaneously, a suite of support mechanisms, encompassing shotcrete, rock bolts, steel ribs, and tunnel pipe umbrellas, fortifies the structure against the unpredictable dynamics of the surrounding geological conditions. This dynamic synergy ensures the early detection of potential issues and bolsters the tunnel's resilience. The third keystone involves the indispensable role of independent geologists, entrusted with the task of providing unbiased expertise in assessing geological features, predicting potential failures, and evaluating the overall stability of the rock mass. Engaged in site investigations, geological map evaluations, and field studies, geologists act as stalwart guardians, offering valuable insights into the long- term stability of the tunnel. Collectively, these integrated facets form a comprehensive approach that enhances the safety and resilience of tunnel infrastructure, addressing challenges inherent in the ever-shifting and occasionally unpredictable conditions encountered during the meticulous process of tunnel excavation.

Methodology

The incident site was visited from 5th January to 6th January 2024. It is an observation-based study; the team first visited the site at the tunnel portal on the Barkot side, where around 1708 meters of the tunnel work is completed from the portal. In the second half, team visited the

Silkyara portal side where a section of the tunnel collapsed. Descriptive and explanatory interviews with site project managers and Block and district authorities were conducted to retrieve information on the tunnel collapse incident and the response process. Secondary data were used to develop the research base. This includes published journals, reports, articles, and documents collected from the district office.

Objective of Silkyara Tunnel:

The Silkyara Bendno–Barkot tunnel was constructed by contentious Navayuga Engineering Construction Limited (NECL) under National Highways and Infrastructure Development Corporation Limited (NHIDCL) as part of the Char Dham project, intended to connect important Hindu pilgrim sites in Uttarakhand, North India, with two-lane, to solve the issue of traffic congestion on the Char Dham road. The tunnel was located on the Yamunotri end of National Highway 134, which is planned to connect Dharasu on the south end to Yamunotri on the north end. The tunnel is 4.5 K.M. long and will shorten the route by about 20 K.M.

Tunnel disasters are relatively rare but can have severe consequences due to the enclosed and confined nature of these structures. Here are a few notable tunnel disasters from around the world (11):

Mont Blanc Tunnel Fire (France and Italy, 1999), a truck carrying flour and margarine caught fire in the Mont Blanc Tunnel, which connects France and Italy under the Alps. The fire burned for 53 hours, and 39 people lost their lives due to intense heat and toxic smoke inhalation.

Gotthard Road Tunnel Fire of Switzerland in the year 2001, a collision between two trucks in the Gotthard Road Tunnel resulted in a fire that killed 11 people and injured dozens. The fire burned for two days and led to significant damage to the tunnel.

In **France & UK Channel Tunnel** Fire incident in the year 2008 where a truck on a freight train caught fire in the Channel Tunnel connecting France and the United Kingdom. The incident led to the evacuation of passengers and significant damage to the tunnel infrastructure.

In **Hokuriku Tunnel Collapse (2012),** Japan, the Sasago Tunnel on the Chuo Expressway suffered a collapse. Concrete ceiling panel fell onto moving vehicles, resulting in the death of nine people.

1.1 Location Map :

The Silkyara Tunnel is located in Dunda Tehsil of District Uttarkashi. The geographical location of Site is 30°45´26"N latitude and 78°15´48"longitude.Distance wise the nearest headquarters from tehsil level to state level from Silkyara Portal are:

1. Dunda Tehsil _ 36 Km.
2. Barkot Tehsil 32Km.
3. Uttarkashi Collectorate 49Km.
4. Dehradun 140Km.

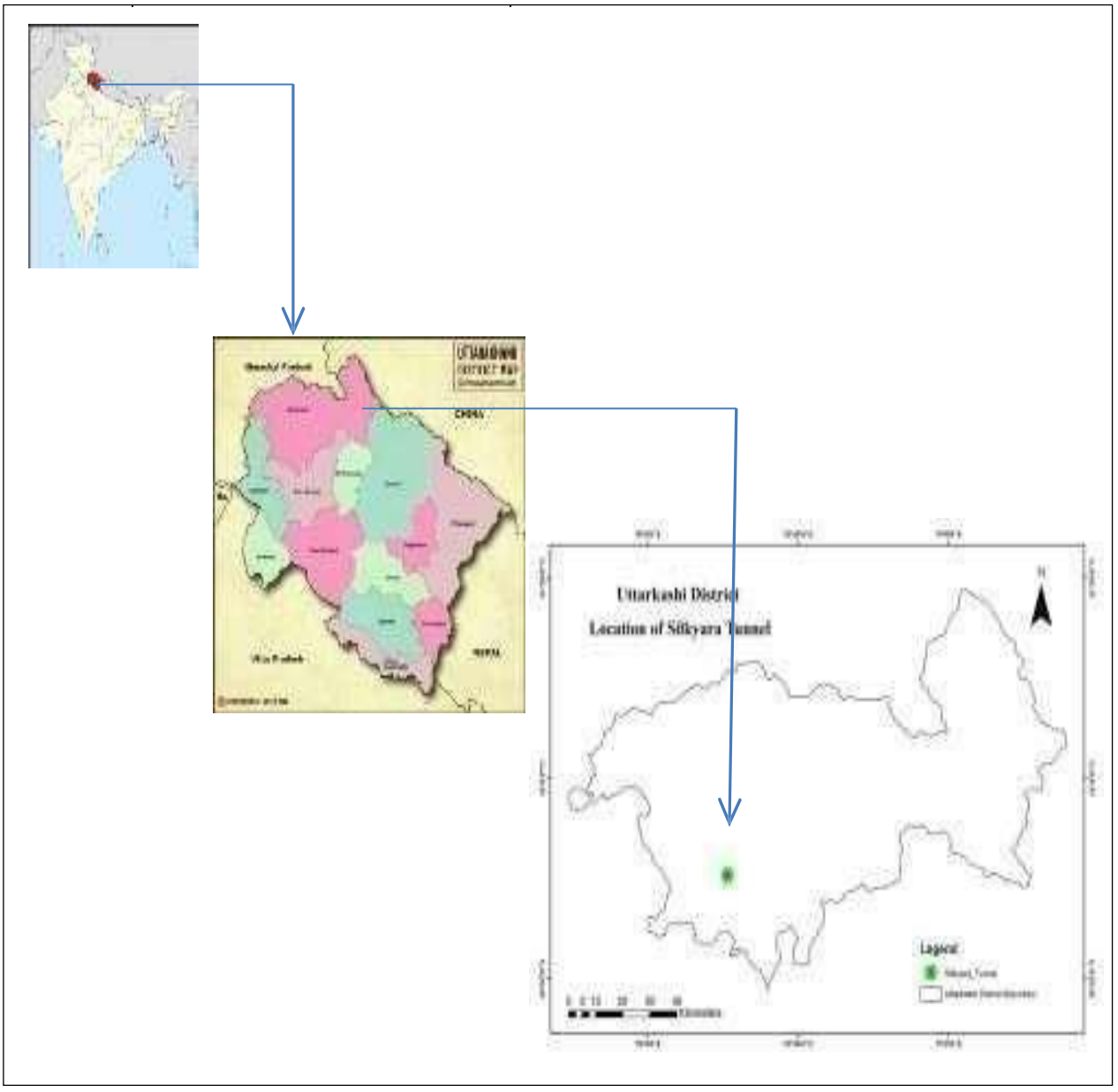

Fig-1: Location of Silkyara tunnel with reference to India and Uttarakhand.

1.2 Geology :

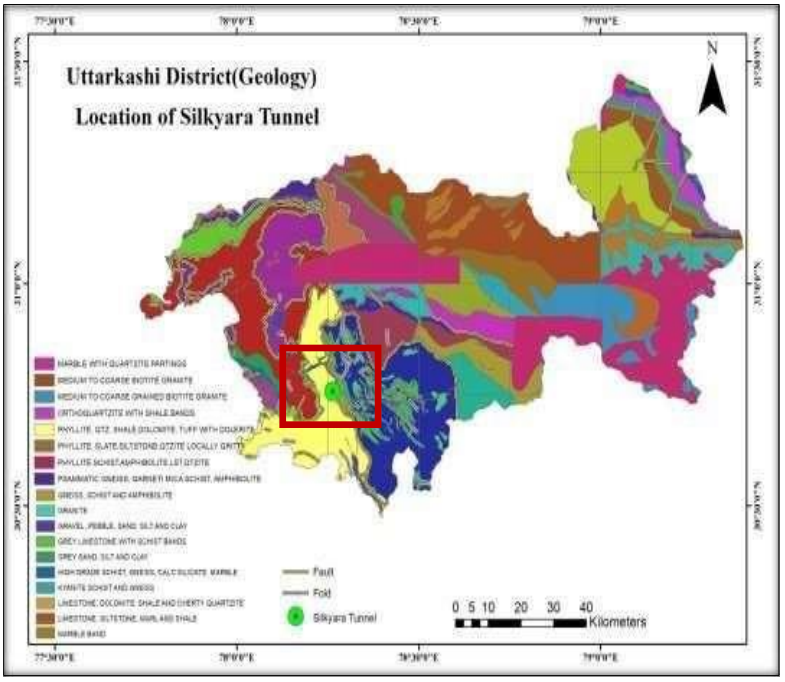

Fig-2: Geology of the District Uttarkashi and Silkyara Tunnel

Source: Bhukosh, Geological Survey of India

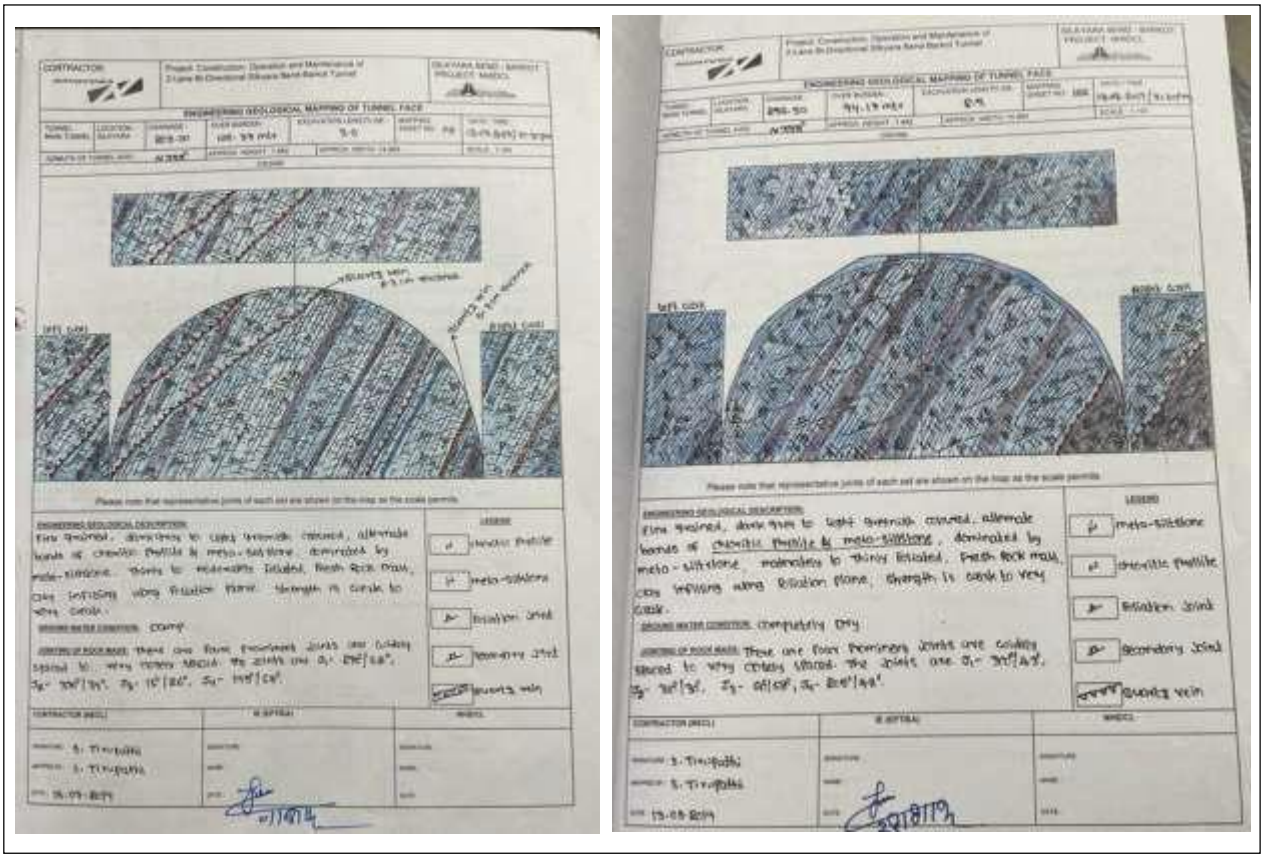

Fig-3: Geology of section from the mouth of Silkyara Portal

The tunnel's location is in proximity to the Main Central Thrust of the Himalayas which is a major geological sheared fault zone composed of an extremely weak rock mass constituting meta-siltstone and phyllites.

The area belongs to part of Lesser Himalayan Sequence of rocks of the Garhwal Himalayans of northern India.The geology of Silkyara tunnel area represent both meta-sedimentary rock of lesser Himalaya and crystalline metamorphic of Higher Himalaya. North Almora Thrust passes near the site of Silkyara tunnel which separates Chandpur formation which is exposed near Dharsau bend and The Jaunsar group which is lithological composed of phyllites, slate, schistose quartzite and Dharasu-Fault is just a few kms away. As shown in Fig-2 and geological report submitted to Ministry of Road Transport & Highways (GoI) by Technocrates Advisory Services Pvt. Ltd., highlighted that major rock types near the silkyara tunnel portal are Phyllite, is weak and fragile and Meta silt stone is of comparatively a greater strength but weak which present a unique challenge while opportunity for dynamic and adaptable construction approachin tunnel construction.

1.3 Silkyara-Barkot Tunnel Project:

The Char Dham all-weather road project is a significant infrastructure initiative by the Central Government of India, aimed at improving connectivity to the Char Dham pilgrimage sites in the state of Uttarakhand. These pilgrimage sites include Yamunotri, Gangotri, Kedarnath, and Badrinath. The tunnel will additionally serve the local community by addressing the issue of disconnection during snowfall at Radi top, especially for Barkot. Acting as an all-weather road, it will offer a reliable and comfortable transportation route for the local residents. The Silkyara-Barkot tunnel, being part of this project, would likely contribute to better accessibility and transportation in the region. The National Highways and Infrastructure Development Corporation Ltd (NHIDCL), a fully owned company of the Ministry of Road Transport & Highways, Government of India, has been overseeing the development of this project. The tunnel is 4.531 km long 2-Lane Bi- Directional Silkyara Bend - Barkot Tunnel along with 328 m approach road. The suggested tunnel will cut down the travel distance between Dharasu and Yamunotri by approximately 25.6 km, resulting in a reduction of travel time by about an hour. Additionally, the proposed tunnel is expected to preserve a significant number of trees, which would have otherwise needed removal for the road improvement covering a distance of 25.600 km if the initial alignment had been adhered to.

The project is situated along NH-134 (formerly NH-94) in the state of Uttarakhand. The total

project cost is INR 1383.78 crore, which is inclusive of the cost towards Land Acquisition & Rehabilitation and other pre-construction activities as well as Maintenance and Operation cost of tunnel for 4 years. According to project managers on both sides of the tunnel, as of the date of the collapse, progress had been made from Silkyara side about of 2350 m and from Barkot side about of 1708 m. It is a D- shaped and carriageway width 7m. The tunnel incorporates vehicle passages at intervals of 565 m and pedestrian passages at intervals of 300 m. This design is implemented for safety (escape facilitates), maintenance purposes in the situation of evacuation. The tunnel has water mist system for fire protection. However, a section of the tunnel, specifically at a distance of 203-240 m from the mouth, experienced a collapse on 12 November 2023.

1.4 Possible Reasons of Tunnel section Collapse:

After survey of the area and taking into consideration the discussion with project team on construction site and local administration that combination of geological and structural factors can be the potential causes where a tunnel section collapsed:

A. Hidden Loose Patch of Fractured or Weak Rock: During the construction of the tunnel, geological surveys and assessments are typically conducted to identify potential hazards such as loose or fractured rocks. However, it's possible that a specific section, located around 200-300 meters from the tunnel mouth, contained a hidden loose patch of fractured or weak rock that went undetected during the initial assessments. Geological conditions can vary, and sometimes, the full extent of rock stability issues may not be apparent until excavation work begins. According to the geological report provided by Technocrats Advisory Services Pvt. Ltd., the composition of rock types along the diversion tunnel is outlined as follows: 20% falls under the classification of good quality (Class II), 50% is categorized as fair quality (Class III), 15% is deemed poor quality (Class IV), and the remaining 15% is classified as very poor quality (Class V). Additionally, the report notes that exploratory drilling was conducted at only three specific locations, namely Silkyara Portal, Radi Portal, and Barkot Portal, indicating a limitation in the scope of the study. Expanding the scope of exploratory drilling to encompass diverse locations along the proposed tunnel route could have significantly enriched our understanding of subsurface conditions, potential hazards, and variations in rock formations. This comprehensive insight would have been invaluable for refining engineering designs, mitigating risks, and accurately estimating project costs for the tunnel construction endeavor. Furthermore, exploring a broader range of locations could have unveiled alternative routes or allowed for the optimization of tunnel alignment, thereby minimizing environmental impacts and bolstering the

overall resilience of the project. Although implementing a more extensive exploratory drilling program would have necessitated additional investment, the potential benefits in terms of project robustness and success would have been profound. The rock type around the area is Phyllite which is mostly contains clay and micaceous mineral, considered a very weak rock. Although all the different support measures were prescribed for different rock mass classes. This includes shotcrete, rock bolts, lattice girders, and pipe roofing in the DPR considering the rock mass aspect but the incident occurred.

B. Water Seepage and Erosion: If there was indeed a hidden loose patch of rock, water seepage could have played a crucial role in the collapse. Water infiltration into the rock mass can weaken it over time, especially if the rock is susceptible to dissolution or erosion as both the rock type present near the construction site are weak metamorphic rocks i.e. chloritic phyllite and meta silt stone. The compromised rock might have allowed water to seep through, creating an unseen void above the tunnel structure. Over time, this void could have expanded, weakening the structural integrity of the rock mass and the tunnel.

C. Undetectable Issues during Construction: Despite advanced construction methods and technologies, certain geological features can be challenging to detect or predict accurately. Some weaknesses may not be evident until excavation work is underway.

In the case of the collapsed tunnel section, the combination of a hidden loose patch of rock and on-going water seepage might have created conditions that were difficult to identify during the construction phase.

2.0 RESCUE OPERATION OF THE TRAPPED WORKERS:

2.1. Chronology of Events & Efforts for Rescue:

Rescue operations were immediately launched, with a number of government agencies involved, including the National Disaster Response Force, the State Disaster Response Force, Uttarakhand Police, engineers from the Indian Army Corps of Engineers, and Project Shivalik of the Border Roads Organisation. Numerous private resources were utilized in the rescue efforts as well, including Australian tunneling experts Arnold Dix and Chris Cooper. Though the initial attempts at a rescue were complicated because of the kinds of debris created in the collapse, the government brought in "rat-hole" miners who were able to use manual mining methods to get an access pipe to the trapped workers. All 41 workers were rescued, and the collapse triggered a safety audit of other tunnels in the area.

This details chronological sequence of events and effort made during the rescue mission at the

Silkyara-Paulgaon (Barkot) Tunnel Project. The successful rescue of all 41 trapped workers was achieved through collaborative efforts of NECL, local/state administration officials, PMO, MoRTH, NHIDCL, and other agencies. There is an overview of the response system focusing on the district level for the tunnel collapse incident:

1. **Initial Response (12th Nov, 2023):**

   - **Incident Identification:**

   Night shift operations led to a sudden collapse around 05.30 IST in the tunnel at Ch 203 m to Ch 240 m.

   - **Notification:**
     - Local administration and police were informed immediately.
     - Rescue efforts initiated by Navayuga Engineering Company Limited (NECL) ground staff.

2. **Communication and Resource Mobilization:**

   - **Communication Channel:**
     - Established through the existing 100 mm water supply line.
     - Dry ration/food supplied through a 4-inch pipeline.
   - **Resource Mobilization:**
     - Horizontal drilling machine, compressor, and shotcrete machine mobilized.
     - MS plates, Hume pipes, and other equipment moved to the site.

3. **Rescue Operations (13th Nov - 28th Nov, 2023):**

   - **Initial Muck Removal:**
     - Excavators deployed to remove muck from Ch 203 towards Ch 250.
     - Shotcrete applied for protection.
   - **Alternative Plans and Machine Mobilization:**
     - Coordination with IRCON and Trenchless Engineering Services.
     - Mobilization of horizontal drilling and auger machines.
   - **Organizations/Agencies Involvement:**
     - RVNL, THDC, ONGC, SJVNL roped in for specialized rescue operations. High-level meeting chaired by PMO Advisor to discuss options.

4. **Auger Machine Challenges (17th Nov - 26th Nov, 2023):**

   - **Auger Issues:**
     - American Auger machine faced challenges and required reinforcement.

- Navayuga mobilized an additional auger machine.

On 19 November, the Border Roads Organisation constructed a 1.15 K.M. road to a location on a hillock above the tunnel as plans for drilling a vertical shaft to enable a rescue were made.

5. Vertical Drilling Attempts:

- Vertical drilling operations considered but halted due to concerns.
- Manual excavation through a mining team proposed .

Problems with the consistency of the rubble and with obstructions caused drilling delays on 22 and 23 November, with significant repairs required to the drilling machine and its mounting platform on 23 November; at this stage, it was believed that the operations had reached 75% of the way through the obstructing debris.

On 25 November, the rescue operation faced another setback as the tunnel drilling machine broke and became stuck inside the tunnel after successfully drilling 47 metres hampering the drilling's progress. The rescue team decided to use manual tools such as hammers and chisels to break the debris and reach the trapped workers. It was believed that the drilling had reached a point approximately 9 metres (30 ft) short of breaking through. Meanwhile, Australian tunneling expert Arnold Dix, who was part of the rescue operation, informed them that they needed to approach cautiously.

6. Successful Rescue (27th Nov, 2023):

On 27 November, alternate methods to gain access to the workers were intensified. Vertical drilling by Satluj Jal Vidyut Nigam at the Silkyara end reached a depth of 32 metres (105 ft) and a third pipeline for the supply of necessities to the workers was also being laid by Rail Vikas Nigam. On the Barkot end of the tunnel, THDC India Limited had executed asuccessful drill up to 12 metres (39 ft) while Oil and Natural Gas Corporation was preparing for vertical drilling.

- Pipe Insertion and Manual Excavation:
- Drilling of additional lifeline pipes attempted successfully.
- Manual excavation conducted parallelly (by the ―Rat Miners.).

7. Communication and Evacuation: Communication with trapped workers maintained.NDRF/SDRF rescued workers in batches.

On 28 November, "rat-hole" miners in the rescue team broke through the remaining length of debris and pushed a pipe to the trapped workers manually.The rescue team evacuated the

workers one-by-one on stretchers, throughout the day, in a process that was expected to take several hours.Later at around 20:50 IST on the same day, it was confirmed by the Government of Uttarakhand that all 41 workers had been successfully rescued.The chief minister of Uttarakhand Pushkar Singh Dhami and Minister of State of Road Transport and Highways V. K. Singh were present at the site welcoming the rescued workers.

8. Aftermath and Review (28th Nov, 2023):

- **After-Action Review:**

  Evaluate the response and identify areas for improvement.

- **Medical Support:**

  Transfer rescued workers to a temporary hospital for further medical attention.

Follow-up Actions:

Continue monitoring and supporting the well-being of the rescued workers at Chiniyalisaur CHC and then to AIMS, Rishikesh for detailed check-up. Forty-one ambulances were arranged for the individuals. The rescued workers were reported to be in good health, and they were taken to a medical facility in Chinyalisaur for initial assessment.

On 29 November, the 41 rescued workers were airlifted to AIIMS Rishikesh aboard an Indian Air Force CH-47 Chinook helicopter for further assessment. Following a medical examination, 40 of those workers were declared fit and cleared to return home.

The construction work is on hold, and a six-person committee has been formed by the state government to look into it in detail.

This is the comprehensive chronological events and actions taken to address the tunnel collapse, involving multiple agencies, specialized equipment, and coordination efforts.

2.2 Life Support Solutions:

Following the collapse of the tunnel, the primary objective was to establish a life support system for the stranded workers. Horizontal directional drilling (HDD) machines were deployed to create a pilot tunnel through the debris, facilitating the insertion of 100mm/150mm/200mm MS pipes. These pipes served the critical purposes of maintaining a continuous supply of fresh air, providing drinking water, and establishing communication with personnel inside the tunnel. The successful insertion of a 4-inch/100mm pipe enabled the delivery of water, food, and oxygen to the trapped workers, ensuring their safety through effective communication. Recognizing the prolonged rescue operation and potential challenges ahead, construction commenced on November 18, 2023, for an additional pipeline (6 inch/150mm) on the right side

of the Silkyara end of the tunnel. After the third attempt, on November 21, 2023, another 150mm diameter steel pipe lifeline service was successfully pushed through the debris. This new life support line facilitated video connections, and regular deliveries of essential items such as dal, rice, roti, sabji, dry fruits, and medicineswere provided to the stranded workforce through this innovative pipeline system.

2.3 Suggestive Methodologies & Plans for Rescue

The chosen method for the earliest rescue attempt involves horizontally drilling a MS steel pipe through the debris at the Silkyara end tunnel. A decision has been made to utilize a 900 mm/800 mm diameter MS Steel Pipe with the aid of a Hydraulic Jack to establish a pathway for evacuating the trapped workforce. Various auger machine options have been explored, and the first one was deemed incompatible with horizontal drilling. Subsequently, a high- power drilling machine was airlifted from New Delhi. The base for installing the auger machine has been fabricated to facilitate the proper pushing of pipes with minimal vibrations.

On November 17, 2023, during the positioning of the fifth pipe after a 22-meter push, it was reported that the auger machine could not proceed further as it was getting lifted, and the machine's bearings were damaged. To address this, a decision was made to fix the machine with anchors to prevent uplifting. After a detailed discussion, it was agreed that the feasibility of pushing the 900 mm diameter pipe hinges on aligning the auger machine and pipe at the same inclination. Additional plates were added below the platform to modify the machine mounting platform accordingly. However, during further drilling at mid-day, a large-scale cracking sound caused panic among the workforce, security personnel, and local police. Consequently, pipe-pushing activity was halted.

In response to the incident, a meeting was convened with officials and experts from various organizations to determine future actions. On November 18, 2023, senior officers from PMO, MoRTH, State Government, and NHDCIL visited the tunnel and it’s top to assess the situation. A meeting under Shri Bhaskar Kulbe (IAS) was then organized, including senior officers from Gol and the State, representatives from various organizations (BRO, RVNL, RITES, SJVNL, THDC, etc.), and tunnel experts. After discussing various rescue operation options, five plans/ways were suggested to expedite the evacuation of the stranded workers.

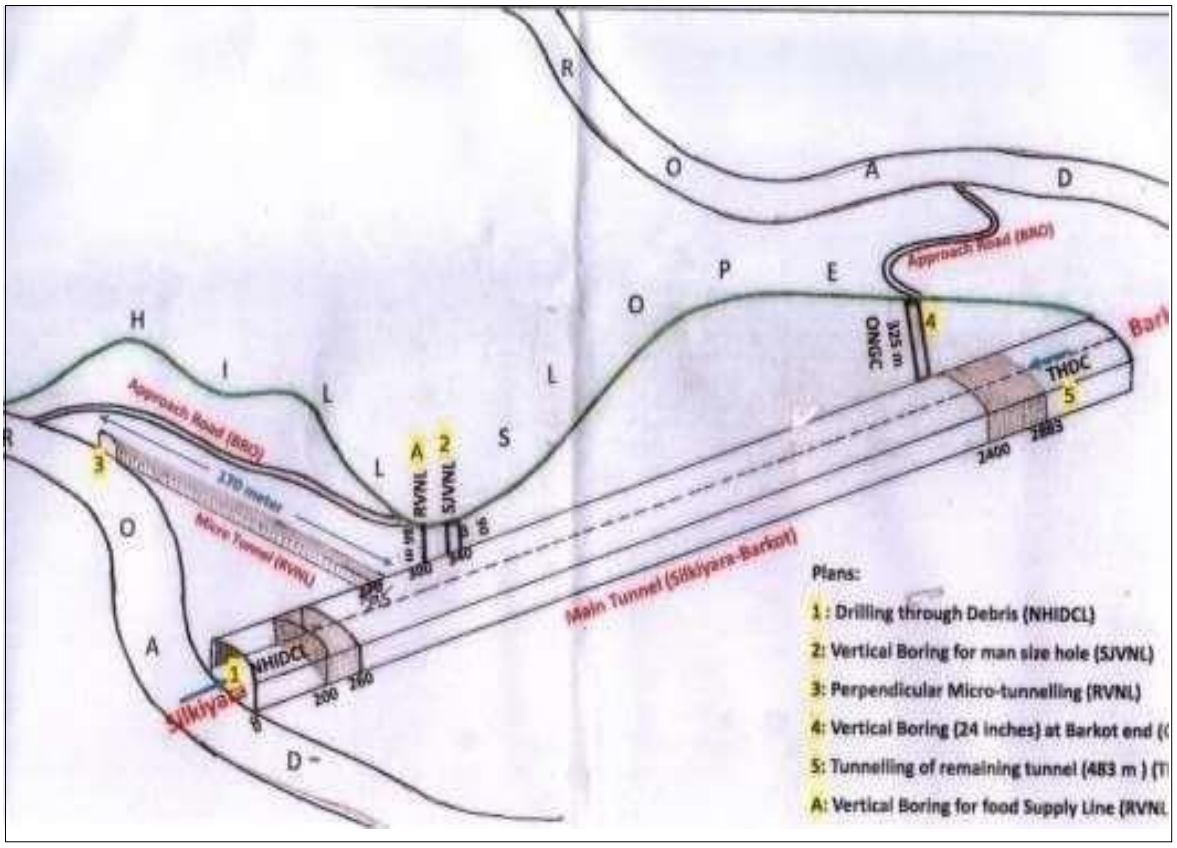

Fig-3: Presenting suggestive methodologies by various organizations and different places.
Source: Procured from Silkyara Site, Project Manager.

Rescue Method/Plan-1:

The initial plan proved highly optimistic, with a 22-meter length of pipe successfully inserted within a week. Building upon this progress, the rescue operation advanced with an increased emphasis on safety and precautionary measures. To ensure a secure passage for the workforce engaged in pipe-pushing activities, a series of safety measures were implemented. Precast concrete blocks, Hume pipes, and steel pipes were strategically placed, creating a pathway spanning approximately 87.2 meters up to the safe zone, covering an area susceptible to potential collapse. Additionally, a parallel gantry structure was constructed in situ to shield the pipe drilling machine, further enhancing safety. The erection of false ribs from the face of the tunnel towards the tunnel exit on the Silkyara side was also undertaken to safeguard the operational area.

Noticing heavy vibrations during the pushing of the 900 mm pipe after a 22-meter insertion, adecision was made to construct a solid platform and reduce the pushing pipe size to 800 mm diameter for subsequent auger drilling. Progressing smoothly from 22 to 44.10 meters (8^{th} pipe of 6 meters) in length, the insertion of 800 mm pipes encountered no obstructions until November 22, 2023. However, while inserting the 9^{th} pipe, a metallic object (Lattice girder rib)

impeded further progress. The NDRF/SDRF team was deployed to cut the rib with gas cutters, completing the operation on the afternoon of November 23, 2023. Following this, the trenchless team manually entered the pipe twice to confirm the clearance of the rescue pipe. The pushing of the 9th pipe commenced, reaching an additional 1.8 meters. However, vibrations prompted a cautious reassessment, revealing obstructions. A bent part of the fore pole (pipe) from the tunnel lining had become entangled in the auger assembly, causing vibrations. Strengthening the platform for the auger machine was addressed by using an accelerating agent for the rapid hardening of concrete.

On November 24, 2023, the auger had to be fully retracted to assess any additional damage to the pipe. After removing the auger, a Ground Penetration Radar (GPR) test was conducted to identify any other metallic obstructions in the pipeline. The welder's team re-entered the pipe to cut the damaged and bent section. Once the cutting was completed, the auger was reassembled, and all augers were reinserted. The insertion of the 10th pipe, measuring 4.7 meters in length, began in the afternoon of November 24, 2023. By evening, a length of 2.2 meters had been inserted, resulting in a total length of 46.9 meters. However, the pushing of pipes was once again halted due to an obstruction.

On November 25, 2023, the process of pulling back the auger commenced. After pulling back a 15-meter section of the auger, the auger joint broke. Various methods were employed to extract the remaining 32-meter auger inside the pipe. Initially, manual cutting of auger blades was attempted, but due to delays, alternative options were explored. A team from DRDO in Hyderabad was deployed with a plasma cutter machine on November 26, 2023, but operational challenges at the site prevented the use of plasma cutters. ONGC arranged a Magna Cutter machine to assist in cutting the auger blades and shafts, and the identified workforce from Rajahmundry was mobilized to the Silkyara site for the cutting process.

During the cutting procedure, it was observed that manual cutting using gas cutters was the most efficient method. Therefore, the gas-cutting process was resumed on November 27, 2023, leading to the successful removal of the entire length of the auger. Subsequent visual inspection revealed that the auger cutter had become entangled with lattice girder bars, causing damage to a 1.5-meter section of the 800-meter passage pipe. Gas cutting was employed to remove the remaining pipe length, along with the obstruction caused by lattice girder and reinforcement. The entire process was completed by the evening of November 27, 2023. Additionally, the shotcrete lump in front of the pipe was manually broken into pieces using a rock breaker.

Recognizing the risk of continuous obstructions damaging the auger machine during the pipe- pushing process through debris, officials and experts opted for a strategic approach to avoid further delays in the rescue operation. It was decided that the remaining length of pipe pushing would be accomplished through manual excavation before resuming the pipe- pushing phase. A specialized team of manual excavators, known as 'Rat Miners,' was deployed to excavate through the 800 mm pushing pipe. By the evening of November 28, 2023, the desired length of pipe insertion and breakthrough necessary to reach the trapped workers was successfully achieved. All 41 stranded workers were safely rescued by the NDRF and other response agencies.

Rescue Method/Plan-2: Vertical drilling operations with a 1.0-meter diameter were initiated for rescue efforts by **Sutlej Jal Vidyut Nigam Limited (SJVNL).** The necessary drilling machineries were successfully transported to the site, and the platform for launching the drilling machine was meticulously completed. The drilling point, determined in consultation with **Geological Survey of India (GSI)**, **Rail Vikas Nigam Limited (RVNL),** and **Oil and Natural Gas Corporation (ONGC),** was marked at Ch. 300 L/S. The primary drilling machine reached the designated site, and the drilling rig was efficiently transported from the tunnel portal to the drilling site. The drilling process was initiated at 12:05 PM on November 26, 2023. According to the latest report, a substantial depth of 30.80 meters was achieved, marking significant progress in the rescue operation. The coordinated efforts of the involved parties and the adherence to the planned schedule signified a dedicated approach to the challenging task at hand.

Rescue Method/Plan-3: RVNL (Rail Vikas Nigam Limited) has undertaken a comprehensive rescue operation at Silkyara end, employing a combination of perpendicular- horizontal drilling and vertical drilling techniques. To facilitate horizontal drilling for the rescue of laborers, micro tunneling equipment has been transported to the site from Nashik and Delhi. Concurrently, efforts are underway to construct a platform, a crucial element in the horizontal drilling process. The drilling for the horizontal section is aimed at creating a safe passage and has commenced with the use of specialized equipment. In tandem with the horizontal drilling activities, vertical drilling with an 8-inch diameter is being carried out by RVNL at the Silkyara end. The Border Roads Organization (BRO) has played a pivotal role in preparing the site, completing an 1150-meter access road and handing it over to RVNL. The drilling machine has been efficiently towed to the location by BRO, ensuring the necessary equipment is in place for the vertical drilling process. Significant progress has been made in establishing the

infrastructure required for vertical drilling. The access road has been successfully completed, and an electric connection has been provided to RVNL, ensuring uninterrupted power supply for the drilling operations. Furthermore, the construction of the platform for vertical drilling has been finalized, providing a stable foundation for the drilling activities.

The vertical drilling commenced on November 26, 2023, at 04:00 am, with 72 meters successfully completed as of that time. The collaborative efforts of BRO and RVNL showcase a coordinated and efficient approach to address the challenges at hand, emphasizing the commitment to the timely and safe completion of the rescue operation.

Rescue Method/Plan-4: On November 20, 2023, the **Oil and Natural Gas Corporation (ONGC)** drilling team visited the drilling site at Barkot End to initiate vertical drilling with a diameter of 24 inches. At that time, the Air Drilling Rig, sourced from Indore, had already reached the site. ONGC had mobilized all the associated materials for the Air Hammer Drilling Rig, and these were placed on standby at Rishikesh. The preparation of the road and location for the placement of the rig for drilling was in progress, carried out by the Border Roads Organization (BRO). As the road and location were being readied, the drilling equipment and materials were in anticipation of the upcoming drilling operation. The BRO team has finalized 1050 meters of the approach road as of November 28, 2023, out of the total 5000-meter road stretch. However, operations were halted due to a breakthrough at Silkyara's end.

Rescue Method/Plan-5: The construction of a rescue tunnel from the Barkot end was initiated by **Tehri Hydro Development Corporation Limited (THDC)**. In a significant development, the sixth blast was executed at 06:15 am on November 27, 2023. During the course of the project, the total executed length of the drift reached 12 meters, showcasing notable progress in the tunnel construction. Simultaneously, the fabrication work for 18 ribs was successfully completed, underscoring the meticulous planning and execution of crucial structural elements for the tunnel's stability. THDC's proactive approach and dedication to the rescue tunnel project are evident in these accomplishments, reflecting a commitment to overcoming challenges and advancing construction efficiently. The completion of the sixth blast, coupled with the achieved length of the drift and the fabrication of ribs, signifies significant milestones in establishing a vital rescue pathway from the Barkot side.

Rescue Method/Plan-6: The drift tunnel project, which employed a manual-semi mechanized method and was executed by a joint team comprising **THDCL, the Army, Coal India,** and **NHIDCL**, reached significant milestones. The drift design, delineated in 1.2m X 1.5m sections,

was successfully completed. The requisite materials were readily available at the project site, facilitating smooth progress. Commencing on November 21, 2023, skilled **Army welders** initiated the fabrication process. As of then, 22 frames had been meticulously fabricated and were marked as completed. This achievement underscored the collaborative effort and efficiency of the joint team, marking substantial progress toward the successful realization of the drift tunnel project.

The Border Roads Organisation (BRO) achieved significant milestones in road cutting and supportive work, playing a crucial role in infrastructure development. One notable accomplishment included the successful completion of the approach road for vertical drilling projects undertaken by SJVNL (Satluj Jal Vidyut Nigam Limited) and RVNL (Rail Vikas Nigam Limited).Furthermore, BRO was actively involved in constructing an approach road for ONGC (Oil and Natural Gas Corporation) based on geological surveys conducted by ONGC. At that time, a commendable 1050 meters of the planned 5000 meters of the approach road had been successfully constructed.

2.4 District & State Govt. Efforts:

In response to the Silkyara tunnel collapse, the state government swiftly activated its incident response plan, mobilizing the **State Emergency Operation Centre (SEOC)** and **District Emergency Operation Centre (DEOC)** to coordinate with NHIDCL and contractor MIS Navyuga Construction. The rescue operations focused on a 2 km section of the tunnel, where completed concrete work ensured the safety of workers. **National and international experts** were engaged to advise on the rescue efforts. The government launched **Operation "Zindagi"** to save the 41 trapped workers, showcasing the joint commitment of the Central and State governments. The Uttarkashi district administration established an onsite disaster operation center, with the **District Magistrate** and **Superintendent of Police** closely monitoring the situation. The Secretary of Disaster Management & Rehabilitation from the Government of Uttarakhand promptly reached the site. Various agencies, **including SDRF, BRO, JTBP, Health, and Police,** were deployed, and a six-member expert committee was formed to investigate the cause of the collapse. **SDRF** played a crucial role, deploying Commandant SDRF and 56 skilled personnel with machines and equipment to safely evacuate the trapped workers. The government's coordinated efforts reflect a comprehensive and urgent response to the tunnel collapse. The collaborative efforts of various authorities in response to the Silkyara tunnel collapse have been commendable. The **state police force**, led by the SP of Uttarkashi district, demonstrated exceptional performance in maintaining law and order and managing

traffic near the incident site. The establishment of a unified command center at the site further streamlined coordination. **State medical teams**, including specialist doctors and para-medical staff, were strategically positioned, and with near by medical facilities prepared for any adverse situations. There was 09 hospital bed, 41 ambulances, 15 Doctors and 90 other health worker/driver were deployed. Medical examination and observation was done at CHC facility at Chinyalisaur and then the entire rescued worker went through a detailed medical check-up including psychiatric assessment. The **Public Works Department (PWD)** played a crucial role, providing workforce and machinery support, road widening, and clearing operations. PWD also constructed a temporary helipad for efficient transportation. The water supply department contributed to drilling works, and senior officials were actively engaged in the rescue efforts. A multitude of central and state government agencies, along with international experts, closely monitored the operation. Notable figures such as **Mr. Arnold Dix from Australia** and **General (Dr.) V.K. Singh (Retd.)** personally oversaw the rescue operation. The collective involvement of **PMO, MoRTH, NIDDCL, Army, NDRF, SDRF, BRO**, and various other expert agencies underscores the comprehensive and concerted approach taken to ensure the safety and early evacuation of those trapped in the tunnel.

Table-1: Team Involved in rescue operations

Agency	Total Human Resource
Ex Advisor to PM	1
Personal Secretary to GOI	1
Uttarakhand Government	2
Nodal Officer From Other State	7
MoRTH	3
NHIDCL	17
NHAI	1
SJVNL	11
MEIL	1
RVNL	6
Indian Army	8
Indian Railways	2
IRCON	3
KRCL	1
THDC	3
BRO	5
NDRF	8
ONGC	11
Amberg Engineering	2
Squadrone	6
Engineers India Limited	4
DRDO	12
Geological Survey of India	2
International Expert	1
L&T	2
Max Infra	3
Cutters and Welders from Auger Team	17
Manual Excavation Team	6
Sandvick	1
ROBOZ	3
Coal India Limited	3
RODIC Consultant Pvt Ltd.	12
Trenchless Engineering Pvt. Ltd.	6
Parsan Overseas Pvt. Ltd.	7
Pay Jal Nigam	8
Dharani Geotech. Engineers India Pvt. Ltd.	14
Rat Miners	12
District Administration	29
SDRF	61
Geo Consultant India Pvt. Ltd.	1
CBRI	1

3.0 RISK/THREATS ASSOCIATED WITH TUNNELCONSTRUCTION

Following are the potential risks associated with road tunnel construction. It's crucial to identify and manage these risks to ensure the safety of workers and the successful completion of the project. Here are some possible risks associated with road tunnel construction:

3.1 Geotechnical Hazards:

3.1.1 Rock falls and Cave-Ins: As seen in the incident, the stability of the rock surrounding the tunnel can be compromised, leading to sudden collapses (and sometimes gradual creeping of sheared rocks), **for instance rock types found in the cavity area collapsed are chloritic phyllite is a weak rock and meta silt stone is comparatively a greater strength but weak.** Due to the different heights of mountains and the lengths of tunnels, the locations of the unfavorable geological sections cannot be fully determined before construction but needs a careful consideration of methods to treat the section to avoid disastrous events. For such conditions of tunnel area charged with groundwater, DRESS (drainage, reinforcement, excavation and support solution) Methodology appears to be an appropriate solution. To overcome the problem of weak rocks additional support such as fore poling, rocks bolt, steel ribs, lattice grinder have been made in Silkyara-Barkot tunnel.

3.1.2 Groundwater Ingress and Mud Gushing: The presence of groundwater in the formed of perched aquifers as well as the rainwater can weaken the surrounding rock and soil, increasing the risk of instability. **As communicated with the site manager, he identified one of the major causes of the collapse might be heavy rains last year and continuous groundwater ingress, which might have saturated the soil and led to the incident. When our team visited the incident location, the project manager emphasized the issue of groundwater ingress, stating that it could damage machinery and other parts of the tunnel if work does not resume soon.**

3.2 Construction Methodology:

3.2.1 Tunnel Boring Machine (TBM) Failures: Mechanical failures or malfunctions of TBMs can pose a risk to workers and the tunnel structure. This poses immediate safety risks to the workers present in and around the tunneling site. TBM failures introduce uncertainty about the project's future, causing stress and anxiety among the workers. Concerns about job security and the success of the project can affect morale on the construction site.

3.2.2 Blast-Related Risks:

The use of blasting for excavation in construction projects introduces several inherent risks, including misfires, flyrock, and vibration impact, all of which can pose serious threats such as rock fall, collapse, and potential worker injuries. For instance, consider a scenario where a

construction site is utilizing controlled blasting techniques to excavate rock for the construction of a tunnel. In this process, misfires may occur when the explosive charges fail to detonate as intended, leading to unpredictable outcomes. A misfire could result in unstable rock formations, increasing the likelihood of rock fall hazards within the tunnel. Fly rock, another significant risk, refers to the unintended projection of rock fragments beyond the blast area. For example, if blasting is conducted near the entrance of a tunnel, fly rock could travel beyond the designated zone, posing a risk of injury to workers or damage to nearby structures. This risk highlights the importance of meticulous planning and safety measures to contain the blast impact within predetermined boundaries. Vibration impact, generated by the shockwaves from blasting, poses a risk of ground movement that can lead to structural instability. Consider a construction site near existing infrastructure; excessive vibrations from blasting may compromise the integrity of nearby buildings or structures, potentially causing collapses or structural damage.

3.3 Equipment Failures & Material Handling Accidents: Equipment failures and material handling accidents pose significant risks in tunnel construction. Malfunctions or failures of machinery employed for critical tasks like face support installation, shotcrete application, and rock bolt grouting can have severe consequences. For instance, face support equipment malfunctions may lead to sudden collapses, endangering workers and causing project delays. Similarly, issues with shotcrete application equipment compromise the integrity of the tunnel lining, necessitating costly rework. Failures in rock bolt grouting equipment can weaken rock reinforcement, potentially resulting in collapses and requiring extensive remediation efforts. Additionally, mishandling of construction materials and equipment introduces another layer of risk. Improper lifting, transporting, or placement of materials may lead to accidents such as falling objects, crush injuries, or collisions with moving equipment. These incidents not only pose a direct threat to worker safety but can also impact the quality and structural stability of the tunnel.

3.4 Exposure to Hazardous Substances and Respiratory Risks: Workers may be exposed to hazardous substances present in the rock or construction materials. Dust generated during tunnel construction activities can pose respiratory health risks. Poor air quality due to vehicle emission, construction activities, or natural gases can create hazardous condition within the tunnel, necessitating effective ventilation system to maintain breathable air and mitigate the risk of asphyxiation or exposure to toxic fumes.

3.5 Logistical and Access Challenges:

3.5.1 Emergency Exit Access: In tunnel construction, the provision of adequate emergency exit routes is paramount for ensuring the rapid and safe evacuation of personnel in the event of

an incident. In the case of twin tunnels or parallel tunnel structures, having separate and strategically located emergency exit routes for each tunnel is crucial. These exit routes should be easily accessible, well-marked, and designed to lead personnel quickly to safe locations outside the tunnel. Additionally, other provisions, such as emergency communication systems, lighting, and signage, play a critical role in guiding evacuees to exits. There was no emergency exit plan was not available for Silkyara tunnel which caused delay in evacuation/rescue of worker.

3.5.2 Limited Accessibility for Emergency Services: Remote locations may impede the quick arrival of emergency services. The Uttarkashi tunnel collapse incident, particularly the Silkyara tunnel collapse in Uttarakhand, India, exemplifies the challenges associated with limited accessibility for emergency services in remote locations. A significant portion of the under-construction tunnel collapsed, trapping workers inside. The lack of immediate access hindered the quick deployment of rescue teams and equipment.

3.6 Communication and Coordination:

Lack of Communication Systems: Ineffective communication systems can delay response times and coordination during emergencies. GIS based information system is need of the hour for coordination and quick communication for such emergency operations.

3.7 Training and Competency: Inadequate training or lack of competency in tunnel construction can contribute to accidents. Training and competency play
pivotal roles in ensuring the safety of workers in tunnel construction, and their absence can significantly contribute to accidents. Tunnel construction involves complex tasks such as drilling, blasting, excavation, and the operation of specialized machinery. Workers need comprehensive training to understand the intricacies of these processes, including safety protocols, equipment operation, and emergency procedures. Inadequate training can lead to misunderstandings or ignorance of safety measures, increasing the risk of accidents. Moreover, the unique challenges of working in confined and underground spaces require a high level of competency. There was one tunnel worker stuck inside had previously survived the similar incident was a great help for the workers trapped inside by providing Psychosocial.

3.8 Weather-Related and Physical Hazards: Adverse weather conditions, such as heavy rainfall, can exacerbate geotechnical risks and impact construction activities. The construction site is near to Dhrasu fault. Constructing tunnels in locations near fault lines poses inherent risks due to the geological instability associated with seismic activity. Fault lines are zones where tectonic plates meet, and the potential for earthquakes exists. The dynamic nature of these geological features introduces the risk of ground movement and shifting, which can compromise

the integrity of tunnels. The seismic forces generated during an earthquake can induce ground shaking, surface rupture, and displacement, leading to structural damage and collapse of tunnel infrastructure. Engineers must implement sophisticated designs and construction techniques to mitigate seismic risks, including flexible tunnel linings and seismic retrofitting. Additionally, the potential for aftershocks following an earthquake adds complexity to ensuring the long-term stability of the tunnel. Adequate risk assessments, continuous monitoring systems, and adherence to stringent construction standards are crucial in mitigating the specific challenges associated with tunneling near fault lines, ultimately safeguarding infrastructure and the safety of those involved in tunnel construction and operation.

3.9 Failure to Comply with Regulations: Failure to comply with safety regulations and industry standards poses significant risks, potentially leading to a higher likelihood of incidents and legal consequences. Safety regulations and industry standards are established to ensure the well-being of workers, protect the environment, and maintain the integrity of infrastructure projects. Non- compliance can result in various adverse outcomes.

Firstly, inadequate adherence to safety regulations may jeopardize the safety of workers and others involved in the project. Failure to implement proper safety measures, provide necessary training, and enforce safety protocols increases the chances of accidents, injuries, and even fatalities on construction sites. It might be big issue in case Silkyara tunnel to restart the construction work.

Secondly, environmental regulations are designed to minimize the impact of construction activities on ecosystems and natural resources. Disregarding these regulations may result in environmental damage, pollution, and harm to local ecosystems. Such incidents can lead to legal actions, fines, and reputational damage for the responsible parties. As per EIA it is considered in case of Silkyara tunnel construction.

A track record of non-compliance may result in a loss of trust and credibility, impacting future business opportunities.

To mitigate these risks, comprehensive risk assessments, proper training programs, strict adherence to safety protocols, regular equipment maintenance, and continuous monitoring of geotechnical conditions are essential components of road tunnel construction projects. Regular reviews and updates of safety procedures based on lessons learned from incidents can also contribute to safer construction practices.

4.0 LESSONS EMERGING FROM THE SILKYARA TUNNEL COLLAPSE

After discussion with local authorities, Site managers and observational survey following are suggestions, and recommendations emerged:

4.1 Ensuring Safety and Stability: Constructing a road tunnel requires a detailed examination of the rock's behaviour to ensure the safety and stability of the structure. The process begins with comprehensive geological and geotechnical site investigations to understand the rock mass's characteristics, including strength, deformability, and permeability. Based on this information, an appropriate tunnel alignment, profile, and excavation method are chosen. Designing a robust support system, such as rock bolts and shotcrete, is critical to withstand anticipated stresses and deformations (5). Continuous monitoring of the rock's behaviour during and after construction, coupled with effective ventilation and drainage systems, helps address challenges like water ingress. Environmental considerations and emergency preparedness plans are integral components for a successful road tunnel construction project in rock, ensuring both structural integrity and minimal environmental impact.

4.2 Comprehensive Inventory Management for Seamless Tunnel Construction Operations: For tunnel construction projects, maintaining a comprehensive inventory of machines, medical facilities, and skilled workers is paramount to ensuring the smooth progression of operations and addressing potential challenges. The machines inventory entails a meticulous record of all tunnel construction equipment, such as tunnel boring machines, drilling rigs, and excavation tools. Each machine is assigned a unique identifier, and details like specifications, maintenance history, and usage logs are diligently documented (6). Concurrently, the medical facilities inventory encompasses information about healthcare resources available on- site, including first aid stations, medical personnel, and emergency response protocols. Additionally, a skilled workers inventory is crucial, documenting the expertise and qualifications of individuals involved in the tunnel construction process, such as engineers, technicians, and safety personnel.

4.3 Emergency Exit Planning for Road Tunnel Construction Sites: Ensuring the safety of personnel during road tunnel construction requires meticulous planning for emergency exits. Emergency exits serve as crucial evacuation routes in unforeseen events, such as accidents, fires, or structural issues. These exits should be strategically located and designed to provide quick and safe egress for workers such as ventilation strategies, incident detection, and emergency services response (7). They must comply with relevant safety regulations and standards,

featuring clearly marked exit routes, proper lighting, and regular drills to familiarize personnel with evacuation procedures. Adequate communication systems and emergency signage should be in place to guide workers to the exits efficiently.

4.4 Enhancing Precision in Tunnel Construction Detailed Project Report (DPR):

Tunnel construction is a complex and critical undertaking that demands meticulous planning and execution. The Detailed Project Report (DPR) serves as the foundational document outlining the project's scope, objectives, and methodologies. To enhance precision in road tunnel construction DPRs, a more thorough and detailed approach is imperative. This involves a comprehensive analysis of geological and geotechnical conditions along the tunnel alignment, considering factors such as rock strata, soil types, and potential geological hazards. Accurate surveying and mapping technologies should be employed to obtain precise topographical data, ensuring a realistic representation of the terrain. Additionally, a thorough risk assessment should be conducted, taking into account potential challenges such as water ingress, ground settlement, and seismic activity. The DPR should also provide a detailed breakdown of construction methodologies, materials, and equipment, along with a robust financial analysis to ensure cost estimates are as accurate as possible. By incorporating these elements, a more precise DPR will serve as a reliable guide for stakeholders, contractors, and engineers, minimizing uncertainties and contributing to the successful and efficient completion of road tunnel construction projects.

4.5 Post-Incident Medical Support, with a Focus on Psycho-Social Care: Post- incident medical support for workers trapped in a road tunnel requires a comprehensive approach with a particular emphasis on psycho-social care. Immediate attention should be given to physical injuries, with a dedicated medical team equipped for first aid (8). Simultaneously, a psycho-social support team comprising psychologists and counselors should be deployed to address the emotional impact of the situation. Regular check-ins, clear communication channels, and designated safe spaces within the tunnel can help maintain worker well-being. Family liaison officers should communicate with families, providing updates and support. Crisis counseling, group sessions, and on-going psycho- social support are essential, both during the incident and in the post-rescue phase.

4.6 Lessons Learned, Worker Training and Competency: Document and disseminate lessons learned from the incident to improve response knowledge and practices (9). Develop and conduct training programs based on the incident's findings, focusing on preventing similar incidents in the future. Reassessing and enhancing training programs for construction workers, supervisors, and operators engaged in tunnel construction is pivotal to cultivating a safety-

conscious culture and improving preparedness. The importance lies in empowering personnel to not only recognize and report potential risks but also to respond effectively to emergency situations. For instance, the training initiatives implemented during the construction of the Tokyo Bay Aqua-Line Tunnel in Japan serve as a noteworthy example. Workers and supervisors underwent rigorous training programs that encompassed risk identification, hazard reporting, and emergency response simulations. This included scenarios involving structural concerns, unexpected water ingress, or equipment malfunctions. Emphasis was placed on fostering a proactive mind-set, encouraging workers to actively participate in safety discussions and report any concerns promptly. Additionally, hands-on exercises equipped operators and supervisors with the skills needed to respond swiftly and effectively to emergency situations. By integrating practical scenarios into the training curriculum, the Aqua-Line project achieved a heightened level of preparedness among its workforce. Reassessing and enhancing training programs with a focus on risk recognition and emergency response not only ensures the safety of personnel but also contributes to the overall success and resilience of tunnel construction projects. This approach establishes a culture of vigilance, where every team member plays a crucial role in maintaining a secure and efficient work environment.

4.7 Comprehensive Maintenance and Safety Protocol for Tunnel Construction Equipment: To ensure the continuous operation and safety of tunnel construction equipment, a comprehensive maintenance and inspection schedule has been established. On a daily basis, operators will conduct visual checks at the beginning of each shift, inspecting face supports, shotcrete application equipment, divider wall reinforcement tools, and rock bolt grouting machinery for any visible damage or misalignment. Throughout the day, operational checks will be performed to monitor machinery during use, ensuring proper functionality, identifying any unusual noises or vibrations, and verifying the effectiveness of safety features (4).

Weekly inspections will involve a detailed examination of the equipment, focusing on high-stress components, hydraulic systems, and overall functionality. Safety checks will also be conducted to ensure that emergency stop mechanisms are operational, safety labels are visible, and personal protective equipment is in good condition. Monthly tasks will include preventive maintenance, lubrication of components, and a review of documentation, including updating maintenance logs and equipment manuals.

On a quarterly basis, an emergency evacuation drill will be conducted to test the efficiency of evacuation routes and emergency communication systems. This drill aims to ensure that all personnel are well-versed in evacuation procedures and that emergency exits are accessible.

Annually, a comprehensive equipment overhaul will take place, including a thorough inspection, replacement of worn- out parts, and testing of backup systems and safety features. Refresher training on emergency evacuation procedures and equipment operation will also be provided to all personnel.

Through comprehensive maintenance and safety protocol, in the event of a tunnel section collapse, emergency equipment for evacuation will be readily available. Evacuation routes will be clearly marked, and emergency lighting systems will be regularly tested to ensure functionality. Additionally, operators will be trained to respond swiftly to such situations, following established protocols for safe evacuation. This rigorous schedule not only ensures that all machinery remains in optimal working condition but also prioritizes the safety and preparedness of personnel in the face of potential emergencies

4.8 Investigation and Analysis: It is imperative to launch a comprehensive investigation into the root cause of the tunnel collapse. Engage experts in geotechnical engineering, tunnel construction, and safety regulations (10) to identify contributing factors. Analysis of the construction methodologies, geological conditions, and adherence to safety protocols leading up to the incident before resuming construction work.

4.9 De-watering: Given the critical necessity of de-watering the tunnel due to machinery being trapped behind a collapsed section, it is strongly recommended to prioritize the resolution of this issue once construction work resumes. The project site manager's insights indicate that water ingress is causing damage to construction- related machinery, underscoring the urgency of addressing this concern. A systematic approach, including initial assessments to identify the water source and strategic implementation of de-watering methods such as sump pumps, well point systems, and submersible pumps, is crucial. Establishing drainage systems within the tunnel and continuous monitoring will facilitate the safe removal of water, allowing for the efficient recommencement of construction activities. Implementing preventative measures, such as improving tunnel lining and waterproofing, is essential to control water ingress in the future.

4.10 Safety Measures and Protocols: Review and strengthen safety measures and protocols for tunnel construction. Implement immediate corrective actions based on the findings of the investigation. Conduct a comprehensive risk assessment for on-going and future tunnel construction projects, considering geological conditions, construction methodologies, and equipment reliability (9). As per the standard operating procedures, any tunnel of proposed length of three km or more is required to have an escape tunnel for evacuation in case of any calamity strikes. There should be an escape tunnel in case of

collapse or emergency. There should not any negligence of standard operating procedures which are meant for the safety of worker and people engaged in the construction work. In the case of Silkyara tunnel section collapse there was no escape Passage.

4.11 Enhancing Emergency Preparedness: In the event of a tunnel collapse, a meticulously crafted emergency response plan is imperative, with a specialized emphasis on prompt communication, coordinated rescue operations, and effective leadership strategies. Swift and efficient communication forms the bedrock of the plan, necessitating the establishment of clear protocols and designated channels. Integrated communication systems, including two-way radios, satellite phones, and digital platforms, will be deployed to ensure redundancy and reliability. Regular drills will be conducted to familiarize all stakeholders with these protocols and technologies, enhancing the speed and efficacy of communication during a crisis.

4.12 Leveraging the Disaster Management Act for Silkyara Tunnel Collapse: The Silkyara tunnel collapse caused due a landslide, it is strongly recommended to promptly and effectively utilize the provisions outlined in the Disaster Management Act of 2005. This legislation offers a robust legal framework, enabling authorities to swiftly declare such incidents as disasters and activate necessary response mechanisms. The establishment of the National Disaster Response Fund (NDRF) and State Disaster Response Fund (SDRF) within the Act provides a vital resource for allocating funds towards immediate relief and rehabilitation efforts. We recommend issuing notifications in accordance with the Act to empower both local and national authorities, allowing for the seamless coordination of rescue operations, emergency measures, and efficient resource mobilization.

The roles delineated for District Disaster Management Authorities (DDMAs) and State Disaster Management Authorities (SDMAs) in the legislation should be adhered to, ensuring a well-managed crisis response. Additionally, the Act's provisions extending to post-disaster recovery provide a framework for allocating funds to reconstruct critical infrastructure, including the Silkyara tunnel, and restoring normalcy in the affected region.

4.13. Harmonizing Human Expertise and Technological Innovation: The rescue mission underscores the critical significance of a remarkable combination of technological interventions and human resources. Amidst crises such as tunnel collapses or disasters, the collaboration between advanced technology and skilled human intervention becomes paramount. In instances like the mentioned rescue mission, the work carried out by "rat hole miners" played a pivotal role. These individuals often equipped with traditional knowledge and expertise, exemplified the indispensable value of human resources in such situations. While modern technology

undoubtedly provides essential tools and methods for rescue operations, the involvement of human capabilities, particularly those rooted in traditional practices, brings invaluable insights and adaptability to the rescue efforts. The scenario sheds light on the complementary relationship between technological advancements and the wealth of knowledge and experience possessed by human resources. It underscores the need for a harmonious fusion of both elements to effectively address challenges and navigate through emergencies, ultimately leading to successful outcomes in rescue missions.

5.0 CONCLUSION

The Silkyara Tunnel rescue mission exemplifies the success achievable through innovative and collaborative crisis response. Employing unconventional solutions such as underwater cables and parallel rescue approaches, the mission demonstrated adaptability and determination in ensuring the safety of trapped workers. Collaboration among diverse teams underscored the importance of joint efforts in complex rescue operations. The involvement of both advanced technology and skilled human intervention, particularly from "rat hole miners" with traditional expertise, highlights the complementary nature of modern tools and human capabilities. Moving forward, the lessons learned will enhance construction methods, ensuring heightened preparedness and resilience for future projects.

Annexure-1
Silkyara tunnel site &Rescue operation photographs

Silkyara Tunnel before the incident

Section experienced the collapse and debris accumulated on the passage

Debris removal was initially attempted to clear the tunnel passage.

Use of horizontal Drilling in initial phase of Evacuation

Mild Steel MS Pipe for Evacuation

American Auger Machine reached Uttarkashi to speed up the drilling

Connecting of Steel MS Pipe for inserting to initiate the safe evacuation.

Iron Rib Protection work near the collapsed area for safety

Hydra Crane for removal of Debris

Construction of Approach road by BRO and selection of point for vertical drilling

Water seepage seen near the mouth of tunnel

Mild Steel MS Pipe for Evacuation and showing respect to local deities for safe evacuation

Hindrance in horizontal drilling due to some metallic object, NDRF/SDRF using gas cutter

Due to metallic hindrance auger machine got stuck, strategies to speed up the evacuation

Fortification of the mouth of collapsed section for safety and gas cutter to remove auger machine

Ambulance and doctors & medical staff deployed for the on-site health observations

Process of transferring the food packed in bottles

Site Visit for geology and Parallel rescue plans

On-site medical facility and man-power

Vertical Drilling on the roof of tunnel for alternative rescue of workers


Site visit and monitoring of progress on evacuation process of trapped workers

Medical check-up and observation of rescued workers at CHC, Chinyalisaur


Site visit and discussion with project manager and District Magistrate, Uttarkashi



Annexure-II: List of Instruments/Resources mobilized & Trapped workers

So N.	Name of the agency	Machinery deployed	Man power
1	NHIDCL	1nos American Auger Machine air lift from **Delhi** by C-17 (three Flight) on emergent basis	**MD NHIDCL, Camped at site and headed the rescue opertation Director (A&F), Director T, ED (P) are supervising the operation at site since 12th Nov 2023 the day of the incident. Three ED (T)s are also present. 2 Managers & 4 engineers present at site. 350 techinical work force & 450 supporting force are working in the operation 24*7 on behalf of EPC contractor M/s NECL. Total = 825**
2		1nos Auger Machine air lift from **Indore** by C-17 (two Flight) on emergent basis	
3		Shotcrte machine 2nos from Devprayag (PKG III)	
4		1nos Shotcrete machine from Devprayag (PKG III)	
5		1nos Boomer from Devprayag (PKG III)	
6		1nos Grouting machine from Devprayag	
7		1nos HDD machine from Devprayag	
8		1nos Vertical Drilling machine from Devprayag	
9		1nos Hydraulic jack from Devprayag	
10		1nos Plate binding machine from Devprayag	
		Plasma Cutting Machine from Hyderabad	
		Lesar Cutting Mashin from Chandigarh	
		GPR d	
11		1nos ROC machine from Vikasnagar	
12	THDC	1nos Boring machine from THDC Tehri	**6 technical officers**
13	SJVNL	1nos Pile Rig machine from Devprayag	**Sr. Level officer 5, Technical Engg. 7 & 3 skilled labour Total = 15**
14		1nos Plie Rin machine from VALSAD Gujrat	
15		1nos Pile Rig machine from HIRA KUND ORISSA	
16		2nos MIG wellding machine from Saharanpur UP	
17	RVNL	1nos Excavator (Hitachi Ex-200) from Max infra/ RVNL-PK-1	**4 seinor officers, 2manager, 6 engg, 4 supervisous, 14 labour Total = 30**
18		1nos JCB from L&T/ RVNL PK-2	
19		Dumper from Silkyara site	
20		1nos Hydra-15 T from Max Infra/ RVNL-PK-1	
21		1nos Crane-35 T from Max Infra/ RVNL-PK-1	
22		Drilling Rig 8" bore from sardar tubwell store, 11Civil lines Rookee	
23		AVN 1200 TB (with components) from DELHI	
24		TBM component by flight from Mumbai & Nasik on emergent basis	

टनल के अन्दर फंसे श्रमिकों का एवं सम्बन्धित राज्यों के तैनात नोडल अधिकारी विविरण

(झारखण्ड–15, उत्तरप्रदेश–08, बिहार–05, उडीसा–05, पं0 बंगाल–03, उत्तराखण्ड–02, असम–02, हिमाचल–01)

क्र.स.	नाम	पिता का नाम	पता	राज्य का नाम	सम्बन्धित राज्यों के नोडल अधिकारी	मोबाईल नं0
1	विशाल कुमार	धर्म सिंह	मण्डी हिमाचल प्रदेश	हिमाचल प्रदेश		7876019267
2	विश्वजीत कुमार	हेमलाल महतो	ग्राम सिमराधाब झारखण्ड	झारखण्ड	श्री भूवनेशव प्रसाद– मो0– 7762843006	8789689146
3	सुबोध कुमार	बुधन कुमार	ग्राम सिमराधाब झारखण्ड	झारखण्ड		7633974639
4	अनिल बेदिया	चकरू बेदिया	खिराबेरा रांची झारखण्ड	झारखण्ड		9835919157
5	राजेन्द्र बेदिया	श्रवण बेदिया	खिराबेरा रांची झारखण्ड	झारखण्ड		8950454307
6	सुकराम	बढन बेदिया	खिराबेरा रांची झारखण्ड	झारखण्ड		9835546012
7	टिंकू सरदार	बोनू सरदार	दुमरिया झारखण्ड	झारखण्ड		9905807977
8	गुनोधर	चन्द्रमोहन	मणिकपुर बाराबोतला झारखण्ड	झारखण्ड		6202379367
9	रंनजीत सिंह	रिसपाल लौहार	मणिकपुर बाराबोतला झारखण्ड	झारखण्ड		6379498972
10	रविन्द्र	धनंजय नायक	मणिकपुर दुमरिया झारखण्ड	झारखण्ड		7294165808
11	समीर	सन्तोष नायक	बन्कीसौल दुमरिया झारखण्ड	झारखण्ड		7667490415
12	महादेव	घासीराम नायक	चेलाबेडा पश्चिमी सिंहभूम झारखण्ड	झारखण्ड		6352539912
13	भुक्तू मुर्मु	बसेत मुर्मु	कुंडालुका बांकीसोल झारखण्ड	झारखण्ड		9324684079
14	चमरा उराव	भगतु उरॉव	ग्राम लरता कुर्रा झारखण्ड	झारखण्ड		9508507189
15	विजय होरो	अर्जुन होरो	ग्राम गुमड लरता झारखण्ड	झारखण्ड		7763005674
16	गणपति	खिदुवा	ग्राम मदुगामा कुर्रा झारखण्ड	झारखण्ड		7505554716
17	सबाह अहमद	मिसवाह अहमद	ग्राम पेउर पो0 पेउर भोजपुर बिहार	बिहार	श्री प्रत्य अमृत मो0–9431815833	9693629604
18	सोनू साह	स्वालिया शाह	ग्राम साहनी बिहार	बिहार		7668755170
19	विरेन्द्र किसकू	मुनी लाल किसकू	तेतरिया कटोरिया बिहार	बिहार		7983141686
20	सुशील कुमार	राजदेव विश्वाकर्मा	ग्राम चंदनपुर बिहार	बिहार		7909020292
21	श्री दीपक कुमार	श्री शत्रुघन, बिहार	मुज्जफरनगर, बिहार	विहार		6209020080
22	सेविक पखेरा	असिथ पखेरा	हरीनाखली पश्चित बंगाल	पश्चिम बंगाल	श्री अश्विन कुमार– मो0– 8637065545	7047393809
23	मानिर तालुकदार	केतालुकदार	कुछ बिहार वेस्ट बंगाल	पश्चिम बंगाल		9476273821
24	जयेदव परमानिक	तापश परमानिक	निमडांगी हुगली वेस्ट बंगाल	पश्चिम बंगाल		9477890395
25	तपन मंडल	मन्तु लाल मंडल	सनकरसनापुर उडिसा	उडिसा	श्री सत्यनारायण आचार्य, मो0 7008053648	8984405190
26	भगवान बत्रा	मंतू बत्रा	ग्राम नवरंग पुर उडिसा	उडिसा		7000018542
27	विशेषर नायक	महेश्वर नायक	जोगीबन्द मयूरबंज उडीसा	उडिसा		6300436870
28	राजू नायक	मुचीसम नायक	कुल्दिया बडकेदम मयूरबंज उडिसा	उडिसा		7853008180
29	धीरेन	मयूर भंजउडीसा	बडाकुदर उडिसा	उडिसा		9548049454
30	अखिलेश कुमार	रमेश कुमार	कोलाना मिर्जापुर उत्तर प्रदेश	उत्तरप्रदेश	श्री अरूण कुमार मिश्रा– मो0– 9721939303	7307227193
31	अंकित	सीताराम	ग्राम मोतीपुर कला उत्तरप्रदेश	उत्तरप्रदेश		6345382923
32	राम मिलन	सुख सागर	मोतीपुर उत्तरप्रेदेश	उत्तरप्रदेश		6386722475
33	सत्यदेव	रामसागर	मोतीपुर उत्तरप्रेदेश	उत्तरप्रदेश		6306401120
34	सन्तोष	विसेश्रर	मोतीपुर उत्तरप्रेदेश	उत्तरप्रदेश		8174895656
35	जयप्रकाश	गनू	मोतीपुर उत्तरप्रेदेश	उत्तरप्रदेश		8810939673
36	राम सुन्दर	मनीराम	मोतीपुर उत्तरप्रेदेश	उत्तरप्रदेश		6386753905
37	मंजीत	चौधरी	भेरमपुर मंघा खीरी उत्तरप्रेदेश	उत्तरप्रदेश		7668745039
38	पुष्कर		पिथौरागढ, उत्तराखण्ड	उत्तराखण्ड	श्री देवेन्द्र सिंह पटवाल,	7819845509
39	गब्बर सिंह नेगी	श्री उदय सिंह	ग्राम विशनपुर कुम्भीचौड कोटद्वार, उत्तराखण्ड	उत्तरखण्ड		9548379914
40	संजय	बीरेन	रामफलबिल कोकराजहर असम	असम	श्री कृपाल जोति मो0–9435592762	9389314661
41	रामप्रसाद	रूपेन नरजरी	रामफलबिल कोकराजहर असम	असम		6900885642

Annexure-III: Field visit schedule

04/01/2024	Nainital to Barkot Travel
05/01/2024	1. Interview and visited SDM Barkot Sh. Mukesh Chand Ramola 2. Barkot Portal of Tunnel visit and Interview with site Manager 3. Silkyara Portal of tunnel visit (site of tunnel collapse incident) and interview with site Manager 4. Transit walk in the tunnel surrounding and visited the vertical drilling points 5. Interview with SDM Dunda as the tunnel site in Silkyara is under the administration area of Dunda Tehsil
06/01/2024	1. Visited DDMO office in Uttarkashi to collect secondary information and interview about the incident 2. Visited the DM Uttarkashi, Shri Abhishek Ruhela,IAS
07/01/204	Journey from Uttarkashi to Nainital

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