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Challenges and implications of deep tunnel construction in Uma Oya: a geo-engineering, environmental, and socio-political perspective

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Abstract

This paper examines the planning, design, and construction of the 15.3 km Headrace Tunnel (HRT) in Sri Lanka's Uma Oya Multipurpose Development Project (UOMDP). The project was approved under a USD 514 million EPC contract, with a benefit-cost ratio (BCR) of 1.328 and an expected internal rate of return (EIRR) of 13.06%, based on a 10% oil price increase. However, limited geological analysis and planning led to unanticipated socio-political challenges, resulting in a nine-year delay, and an additional USD 39 million in direct costs. Excavation, conducted using two Tunnel Boring Machines (TBM), encountered excessive groundwater ingress - highlighting the need for advanced geoengineering solutions and expertise to stabilize the HRT. This study explores the geoengineering, environmental, and financial challenges involved, and evaluates the risk management and decision-making processes used to address them. Technical interventions, including post excavation angled hole grouting and pre-excavation grouting were effective in controlling water ingress and securing tunnel integrity. The delay resulted in estimated revenue losses of USD 700 million from power generation, USD 110 million from irrigation, and USD 12.7 million from drinking water supply. The findings underscore the necessity of proactive on-site management and continuous monitoring to mitigate risks that could lead to social unrest and financial setbacks. The analysis highlights the integration of geo-engineering strategies, financial planning, and effective management as essential components for successful project delivery and long-term profitability. These insights serve as a valuable reference for future tunnelling projects to avoid delays and optimize outcomes.

Keywords Headrace tunnel, TBM, Geoengineering, Grouting, BCR, Uma Oya

1 Introduction

Tunneling has become increasingly prevalent in engineering projects of all scales [1–3]. Whether for highways, water conveyance systems, mining operations, or the creation of pedestrian and wildlife passages, the inherent complexities of tunneling often attract public scrutiny [4–7]. The practice of tunneling through soft materials dates back over

3,000 years. Early examples include mining and water conveyance tunnels, notably the qanat systems developed in arid regions of the Middle East [8–14].

The Industrial Revolution marked a turning point in tunneling techniques. While earlier methods relied primarily on manual labor for excavating soft rock, this era introduced more sophisticated, mechanized tools capable of tunneling through hard rocks. As societies sought improved connectivity, resource extraction, and infrastructure development the demand for robust, efficient tunneling processes became increasingly critical [5]. This period spurred major innovation in tunneling technologies, leading to significant achievements in transportation networks, mining operations, and large-scale water conveyance systems [15]. These developments, driven by rapid progress in engineering, facilitated the construction of tunnels on a previously unimaginable scale [16, 17].

As infrastructure development became a political priority, governments worldwide began initiating long-lasting projects to address the expanding needs of growing populations. These initiatives were not solely politically motivated but aimed at meeting genuine societal demands for better infrastructure and resource management [18]. Strategic planning, rigorous assessments, and sustainable development principles [15, 19, 20] characterized this shift toward future-oriented governance, focusing on long-term community well-being. Governments, collaborating with various stakeholders, undertook ambitious projects designed to address immediate infrastructure needs while laying the foundation for continued growth and prosperity. One such ambitious effort was the Uma Oya Multi-Purpose Development Project (UOMDP) in southeastern Sri Lanka (Fig. 1).

This study provides a comprehensive evaluation of the UOMDP, examining its planning, technical design, management challenges, and income generation potential. The primary focus, however, is on the challenges encountered during the planning, design, and construction phases of the headrace tunnel (HRT), which led to significant delays and financial losses. By identifying these shortcomings, the study aims to improve future large-scale projects by addressing deficiencies in geological and hydrological data. The objective is to enhance project preparedness, mitigate risks, and optimize decision-making processes. In doing so, the investigation seeks to establish a framework for more effective project planning and execution, promoting sustainable development and maximizing societal returns on major investments. Ultimately, the goal is to minimize damage, ensure timely project completion, and align project outcome with the expectations of donor-driven funding initiatives that often support such ambitious undertakings.

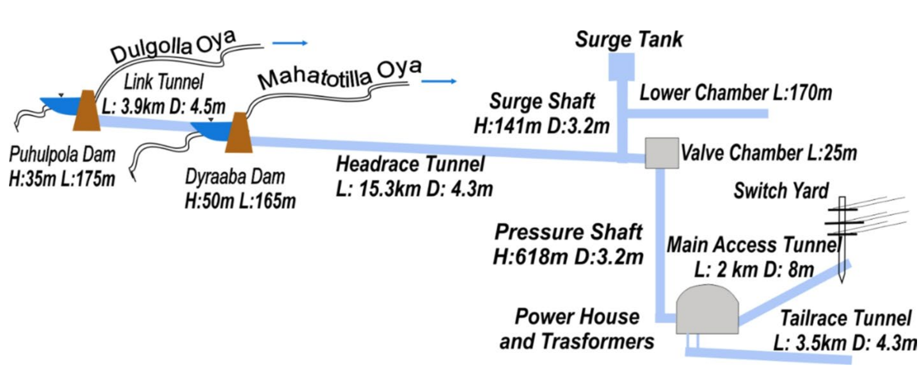

Fig. 1 Schematic diagram of project layout plan showing, two dams both constructed by roller-compacted concrete (RCC), tunnels, subsurface powerhouse and valve chambers including surge and pressure shafts

2 Metholdology

Construction of the UOMDP was a controversial endeavor from its inception, with government procedures initiated in 1989 by the Central Engineering Consultancy Bureau (CECB). Prefeasibility and feasibility studies were conducted and subsequently the EIA was performed with inadequate data acquisition. As a result, the available data was sensitive regarding its implementation, and public concerns about the construction emerged early on. Consequently, public access to data was limited. Construction formally began in 2008, and the HRT excavation commenced in 2014. However, the sudden ingresses of water into the tunnel, along with the drying up of wells and springs in the region, triggered a social uproar from the public, and civil society organizations. In response, the authorities shifted from a stance of limited disclosure to greater transparency, allowing an examination of the available data. The technical data covering, site preparation, drilling, dam design and construction, tunnel design and excavation, as well as the ongoing technical and social challenges encountered, were collected and made available. The data utilized in this study was either extracted from archived records or gathered from existing reports. During the construction phase, semi detailed engineering contributions, reports, and conference proceedings were produced, leveraging substantial data collection. Reports prepared on financial analysis and project justification were subsequently available to scrutiny. Additionally, numerical models were generated to simulate various scenarios, supported by this data to facilitate semi detailed ongoing analysis. Most of the primary data was obtained from government institutions, including the Meteorological Department, Irrigation Department, Agricultural Department, Geological Survey and Mines Bureau, Ceylon Electricity Board and National Water Supply and Drainage Board. For the present study, several field sessions were conducted in addition to routine field inspections of various project components. These field sessions took place from 2019 until the commissioning of the project in 2024. Geological data were collected on site using Brunton transit and plotted on 1:10,000 maps with the aid of Global Positioning System (GPS) and Digital Elevation Models (DEM). Fracture and lineament data were mapped on the DEM, and descriptive details were recorded in the field notebooks. Drilling data was gathered from previous records, and any modifications to angle hole representations were documented accordingly. Hydrological and geological data were used to develop numerical models and forecast hydrological outcomes under multiple scenarios [21]. Long term dug well water levels were also carried out to monitor temporal water availability in the region. Microseismic data which was available from the GSMB and Microseismic Research stations in Sri Lanka was also collected. This data was critical for assessing potential hazards or future disasters risks. All collected data was processed or synthesized to create relevant maps, descriptive diagrams, and narrative timeframes. The visual representations were developed using CorelDraw Home and Student Suite 2014. This study carefully analyzed and extracted data to identify the challenges and problems encountered throughout the project, with the aim of providing practical and adaptable solutions for similar future project in Sri Lanka and other regions.

3 The Uma Oya Multipurpose Development Project (UOMDP)

Uma Oya, located in the southeastern part of Sri Lanka, is a major tributary of the Mahaweli River. It originates in the central highlands at an elevation of 2,500 m above sea level (masl) and discharges into the Rantambe Reservoir at 152 masl, along the middle reaches of the Mahaweli River. The Uma Oya catchment spans an area of around 720 km² [22]. The UOMDP is a trans-basin water diversion initiative designed to transfer water from the Mahatotilla Oya Drainage basin to the Kirindi Oya Drainage basin (Fig. 2).

The Ministry of Irrigation and Water Management served as the project proponent, while the Central Environmental Authority (CEA) acted as the Project Approving Agency (PAA) [23]. The project aimed to support hydropower generation, water supply, and irrigation in the southeastern region of Sri Lanka. Initiated as an Engineering, Procurement, and Construction (EPC) contract, the project was developed as a turnkey initiative. Initially funded with economic assistance from the Islamic Republic of Iran, it secured an investment of $514 million, with the Export Development Bank of Iran (EDBI) contributing an initial $50 million until 2013 [24]. However, due to international banking restrictions on Iran, funding ceased, compelling the Sri Lankan government to continue the project using domestic funds. Despite these challenges, the original contractor, Farab Company of Iran, and their consultant, the Mahab Ghodss-POYRY Joint Venture, were retained [25, 26].

The project is designed to transfer an annual average of 145 million cubic meters (MCM) of water for irrigation purposes. It utilizes a substantial hydraulic head of over 700 m to generate electricity, with a power plant capacity rated at 120 MW. Additionally, the project supplies 39 MCM of water annually for industrial and drinking purposes in

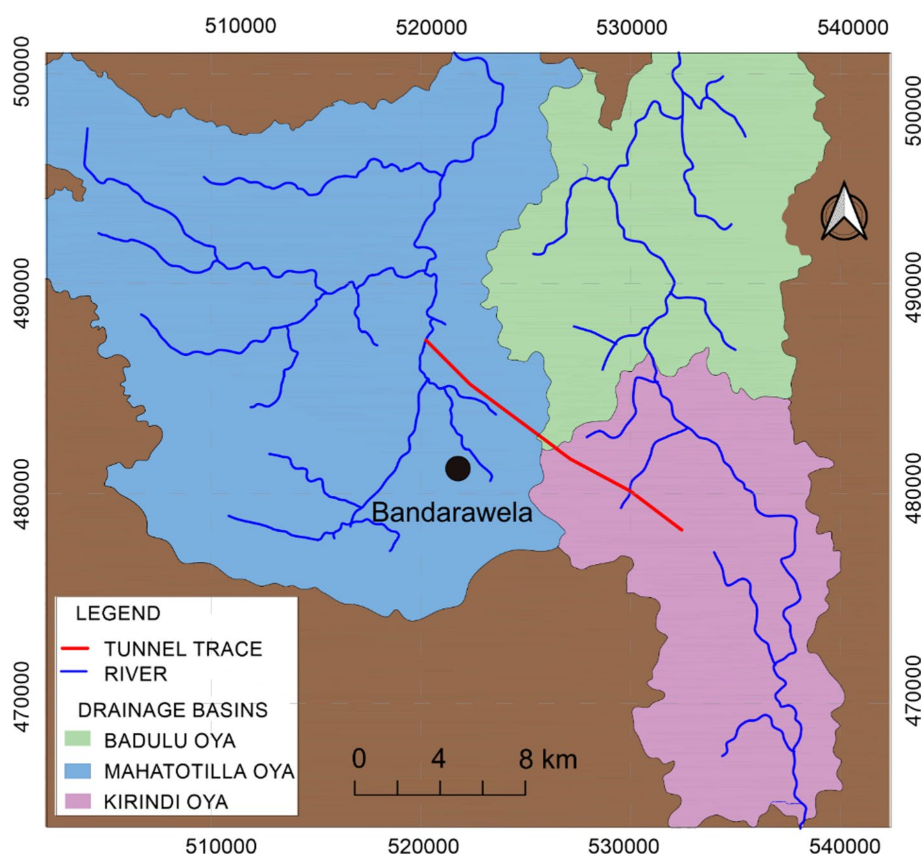

Fig. 2 The figure illustrates the trans-basin water diversion from Mahatotilla Oya Drainage basin to the Kirindi Oya Drainage basin through HRT (red line) of the UOMDP

the Badulla, Monaragala, and Hambantota districts through the National Water Supply and Drainage Board (NWS&DB) [24].

The UOMDP includes the construction of two roller-compacted concrete (RCC) dams. The first dam was built across the Dulgolla Oya River at 06°54′51″N 80°56′00″E in the Puhulpola region. Water from the Puhulpola dam is transferred via a 3.9 km long link tunnel to a reservoir at Dyraaba, where a second dam was built at 06°53′13″N 80°57′23″E across the Mahathotilla Oya River. From there, a 15.3 km long headrace tunnel (HRT) and a 618 m high vertical shaft convey water to the underground powerhouse [27]. The discharge from the powerhouse flows into the Alikota Ara reservoir via a 3.5 km long tailrace tunnel, which ultimately joins the Kirindi Oya River (Fig. 1).

Feasibility studies [28, 29] and subsequent detailed geological investigations [30] were conducted for the construction of the dams and tunnels. A Double Shield Tunnel Boring Machine (TBM), with a 4.3 m excavation diameter and semicircular probing capability, was selected for the first time in Sri Lanka (Fig. 3) [31]. Excavation of HRT began in March 2014 using a single TBM starting from the downstream end. To expedite progress, a second TBM was introduced from the upstream intake side in 2016.

4 Geology and physiography

Approximately 90% of Sri Lanka's geology consists of high-grade metamorphic rocks of Precambrian age, primarily ortho- and para-gneisses formed under amphibolite to granulite facies conditions. The remaining 10% is primarily composed of Miocene sedimentary rocks along with Jurassic and Quaternary deposits located in the northwestern part of the island [32]. Based on lithology, mineralogy, major and minor structures, field relationships, and crustal formation ages, the geological formations were classified into three prominent tectonic provinces [32]: the Highland, Wanni and Vijayan complexes, along with the centrally located Kadugannawa complex (KC) (Fig. 4). Highland Complex is the largest unit, extending in a NNE SSW and forming the central highlands of the

Fig. 3 The TBM showing the preparation to access through adit to drilled HRT while inverted segments laid beside the mountainous terrain of the highlands. Slopes were shotcreted while weep holes were placed to support heavy subsurface water discharge

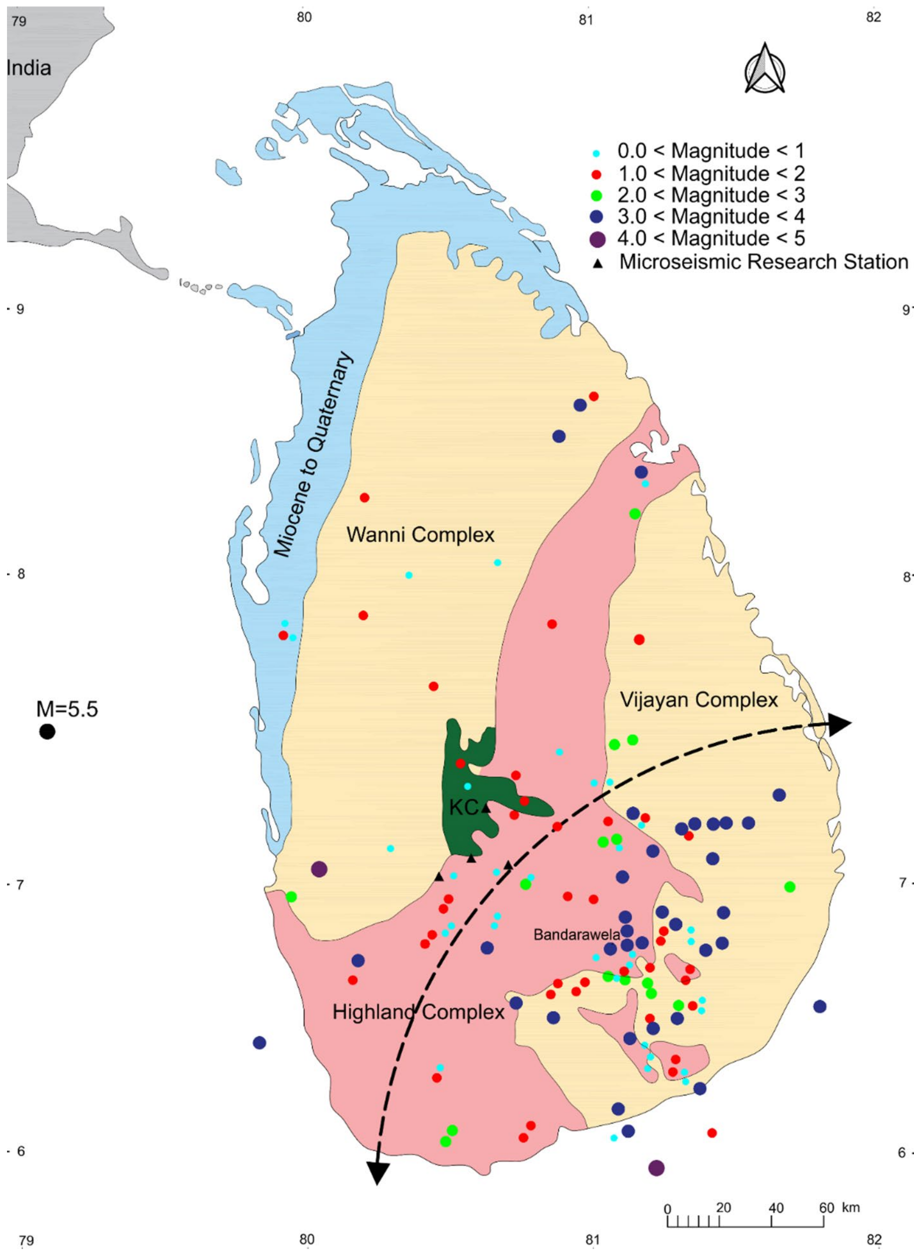

Fig. 4 The map shows the major geological formations in Sri Lanka (modified after Cooray [32]), the distribution of micro seismic activities (modified after Fernando and Kulasinghe [40]; GSMB [41]), and the arcuate axis of maximum uplift (modified after Vitanage [34]). Bandarawela is the major town located near the project area

Precambrian terrain. It comprises a Paleoproterozoic supracrustal assemblage and granitoid rocks that underwent granulite grade metamorphism and charnockitization during late Neoproterozoic/early Cambrian orogeny (540–550 Ma). The Wanni Complex situated in the northwest of the Highland Complex, consist of a suite of gneisses and granites along with a range of amphibolite to granulite facies rocks. The Kadugannawa Complex located in the island's central region, is predominantly composed of hornblende bearing gneisses. In contrast, the Vijayan Complex, situated in the eastern region, mainly consists of amphibolite facies gneisses and metasediments. The difference in rock types, metamorphic grades, deformation timelines, and tectonic contacts between the

Highland/Wanni and the Vijayan complexes indicate that they were juxtaposed during the final assembly of Gondwana [33].

Geomorphologically, Sri Lanka is divided into three erosional levels based on the elevation: lowlands, uplands, and highlands. The lowlands are characterized by flat and undulating terrain. The upland and highlands exhibit ridge and valley topography with hummocky mountain terrains dissected by fracture-controlled drainage courses forming diverse geomorphological features. The highest point of the country is Pidurutalagala, which stands at 2,524 m above mean sea level. The uplands and highlands receive significant rainfall and experience prolonged wet conditions. As a result, most of Sri Lanka's major rivers originate in this region, flowing downward in a radial pattern towards the Indian Ocean [34, 35].

Weathered overburden with lateritic soils is common in tropical regions [36]. In the Bandarawela region a thick regolith has developed from Fe rich lateritized soils. The subsurface rocks have undergone significant alteration due to geochemical process and variable climatic conditions, resulting in the formation of Red Yellow Podzolic soils [37–39]. Reports indicate that an unexpected weathering process affecting marble and dolomitic marble was accelerated by intense rainfall, high ambient temperatures, and excessive CO_2 levels typical of tropical soils (Eqs. 1 and 2) [39]. This intense weathering process often results in karst development, leading to high hydraulic conductivities that can destabilize tectonically active terrains.

$$CaCO_{3_{(s)}} + H_2O_{(l)} + CO_{2\,(g)} = Ca^{2+}_{(aq)} + 2HCO^-_{3\,(aq)} \tag{1}$$

$$CaMg(CO_3)_{2_{(s)}} + 2H_2O_{(l)} + 2CO_{2\,(g)} = Ca^{2+}_{(aq)} + Mg^{2+}_{(aq)} + 4HCO^-_{3\,(aq)} \tag{2}$$

Most tunneling activities are centered out through the hard rock terrains, and it is highly unlikely that such events have occurred in the soft rock formations of Sri Lanka. The HRT was constructed through high-grade Precambrian rocks [32], where engineers and planners anticipated minimal risks during drilling and boring (Fig. 4). The predominant rock types include quartzite, marble, charnockitic gneiss, khondalite, and quartzofeldspathic gneiss, along with undifferentiated charnockitic gneiss [30, 40] (Fig. 5). The anticlinal structure, along with the distribution of fractures and joints in different directions, is shown in Fig. 5. The inset diagram illustrates four possible scenarios for the development of weak zones extending deep in to the subsurface: (1) Weak zones developing along the foliation plane, (2) Discontinuities approximately following the dip direction but terminate before reaching the tunnel depth, (3) Discontinuities following

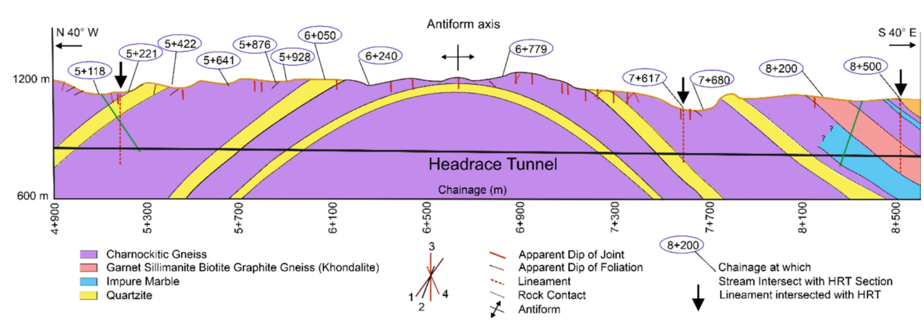

Fig. 5 The cross-section illustrates geological formations and structural details along the HRT (Modified after Gunatilake et al. [30])

an approximate vertical dip, (4) Discontinuities not following the dip direction of foliation or vertical joints, but instead forming in an entirely opposite orientation. These scenarios highlight the complex nature of weak zone development and their unpredictable alignment in relation to the tunnel path.

The tunnel's alignment cuts through a rugged hummocky mountain range, occasionally interrupted by scattered chasms and open valleys of varying elevations (Figs. 6 and 7). Figure 6 illustrates the complete trace of the HRT for the UOMDP on a 1:50,000 topographic map, including a 1,000 m buffer on either side. The tunnel passes through the Precambrian rocks (Fig. 5) beneath the upland peneplain [34], traversing in the northern and eastern regions of Bandarawela at elevations ranging from 1,510 to 980 masl (Fig. 7) The elevation of the HRT invert transitions from approximately 950 masl at the inlet portal to around 860 masl at the outlet, maintaining gradients of 0.01% and 0.002%, respectively [42].

The thickness of the overburden above the HRT varies between 30 and 660 m. The slope inclinations ranging from 35° to 61° on the right bank and 22° to 48° on the left bank [30]. Rainfall at Bandarawela Meteorological Station fluctuates with a positive trend (R^2 = 0.1076), ranging from 860 mm to 2200 mm annually, with an average of 1620 mm (Fig. 8a). The overall temperature variations exhibit a cyclical distribution pattern, with an increasing trend in recent years. The annual maximum average temperature ranges from 24.8 °C to 26.6 °C, showing a slight positive trend (R^2 = 0.0446). Similarly, the annual minimum temperature ranges from 16.5 °C to 17.9 °C, also indicating a slight positive trend (R^2 = 0.0567) (Fig. 8b) [43].

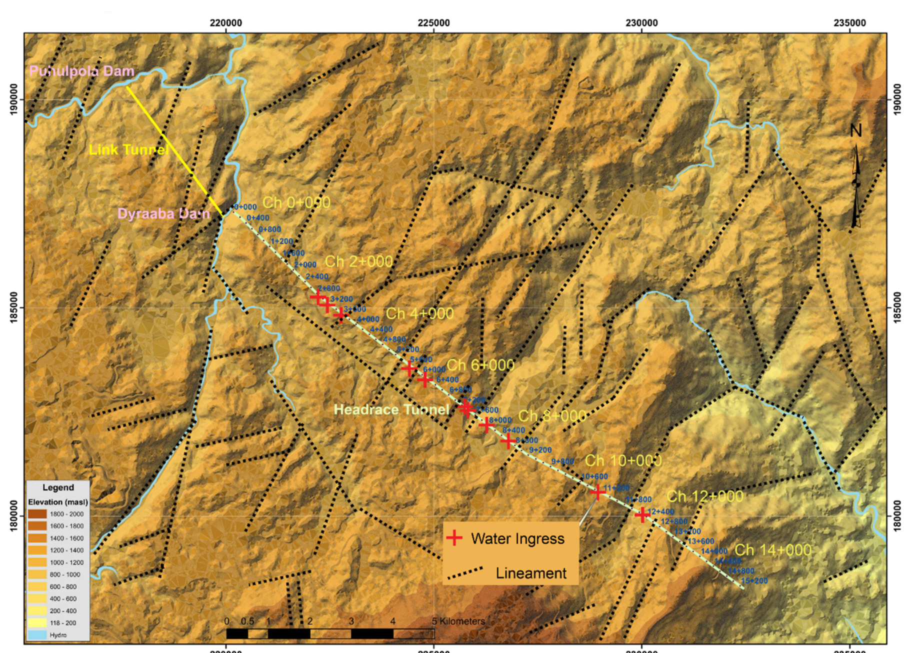

Fig. 6 Digital Elevation Model (DEM) of the area covering the UOMDP. Clearly showing the rugged mountainous regions with clear cut lineaments/deep fractures/shear zones in NW-SE, NNE-SSW and NE-SW. Chainage along HRT including major water ingress points are shown (Modified after Gunatilake et al. [30])

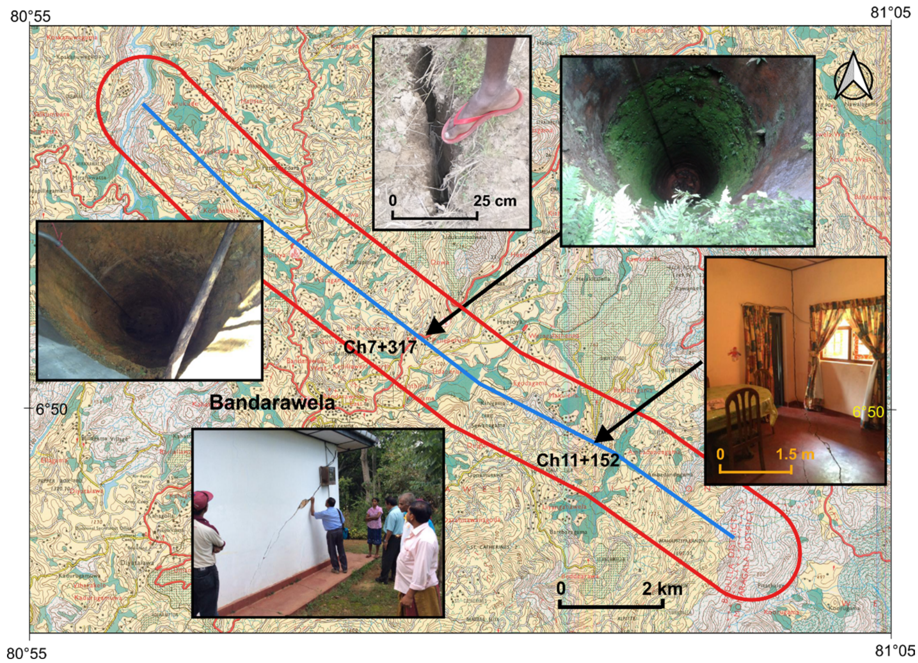

Fig. 7 Topographic map of the study area indicating HRT trace (Blue) and the surrounding 1 km buffer zone (Red) (Modified after Survey Department1:50,000 map). The inset photos clockwise show major disastrous issues encountered at Ch 7 + 317 and Ch 11 + 152 causing severe social unrest. (1) Cracks propagated in the overburden, (2) Dried up dug well, (3) Cracks found in households, (4) Cracks found in households, (5) Dried up dug well

5 Challenges in technical, social, financial and disaster sectors

The Uma Oya Multi-Purpose Development Project (UOMDP) has faced numerous challenges in the technical, social, financial, and disaster related sectors. These challenges range from geological complexities in the region, adverse water ingress into the tunnel, inadequate environmental and social assessments, to financial constraints, all of which have contributed to significant delays in project completion.

5.1 Technical challenges

During the feasibility study, 13 boreholes were drilled along the tunnel trace (Table 1), revealing the presence of highly weathered (HW) rock segments below the surface [28]. Geologists, project planners, and design engineers analyzed these data before proceeding with the project design. The frequent occurrence of HW segments in the subsurface indicated potential problems, particularly in terms of water ingress, given the region's tropical climate with moderate to high rainfall. Though infiltration is typically around 8% for most regolith's developed on hard rocks [42, 44], the estimated recharge potential in the study area is significantly higher, ranging from 10 to 20% of rainfall in forested areas [21]. These results indicate a highly dissected and karstified subsurface, which increases the potential for water ingress. Additionally, several perennial streams cross the projection of the tunnel trace on the ground, posing an obvious threat of substantial water ingress (Fig. 5). The area's steep slopes also posed challenges for surface preparation, erosion control, and access road construction.

Accurately predicting weak geological zones ahead of the tunnel excavation is difficult without advanced techniques such as ground-penetrating radar (GPR), tunnel seismic prediction (TSP), and exploratory drilling [45]. Dharmagunawardane and Gunetilake

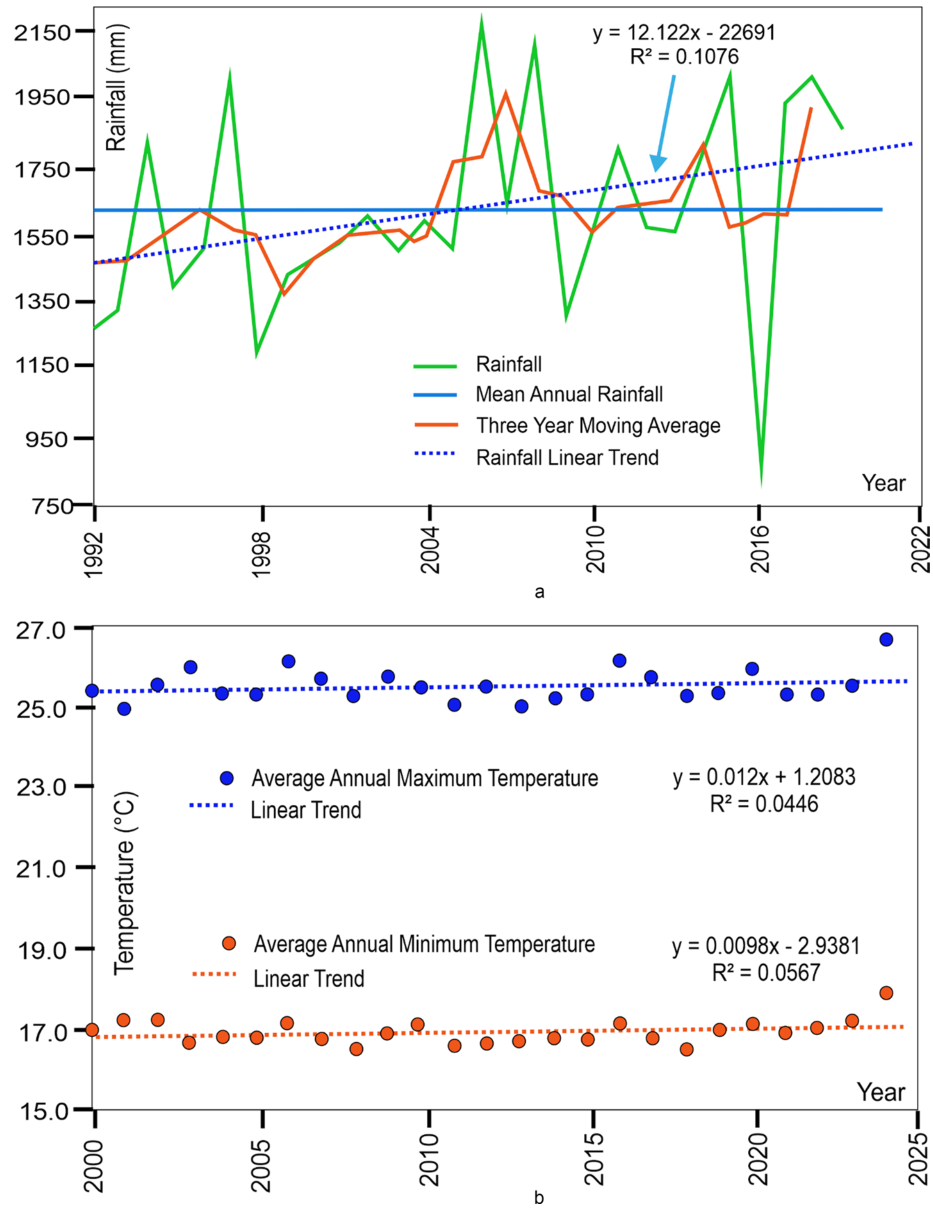

Fig. 8 **a** Mean annual rainfall variations at Bandarawela meteorological station [43]. **b** Average annual maximum and minimum temperature variations at Bandarawela meteorological station [43]

[46] conducted an investigation using two-dimensional resistivity imaging along the HRT to identify such weak zones. Figures 5, 6 and 9 illustrate possible scenarios for weak zone development, highlighting the complex and unpredictable alignment of these zones in relation to geological and hydrogeological features. Figure 9C reveals dormant reverse faults associated with structural discontinuities in the charnockitic gneiss, which are prone to rapid weathering under groundwater circulation. Micro joints are aligned as conjugate pairs with steep dips (80–85-degrees). Incipient weathering is evident even at this depth, indicating susceptibility to further weathering when groundwater is encountered. Mobilized marble in the area has generated subsurface voids that cannot be easily detected through surface observations alone (Fig. 9A, B and E). Moreover, employing

Table 1 Borehole details along the tunnel trace from the feasibility study (POYRY 2012)

Borehole name	Borehole depth (m)	Groundwater level (m)	Weak/Highly Weathered (HW)/Water bearing segments (m)	Tunnel level from surface (m)
DT 01	80	08		56
DT 02	245	86	228–232 HW segments	225
DT 03	245	84		261
DT 04	280	102	201–205 HW segments	293
DT 05	295	82		335
DT 05 A	250	08	125–126 HW segments	209
DT 06	220	02	185–201 HW segments	255
DT 06 A	400	46	202–210, 295–309 HW segments	306
DT 07	305	47	Dug wells around the bore hole dried up during drilling	305
DT 08	241	18		161
DT 09	242	30	79–83 HW segments	292
DT 10	243	62		455

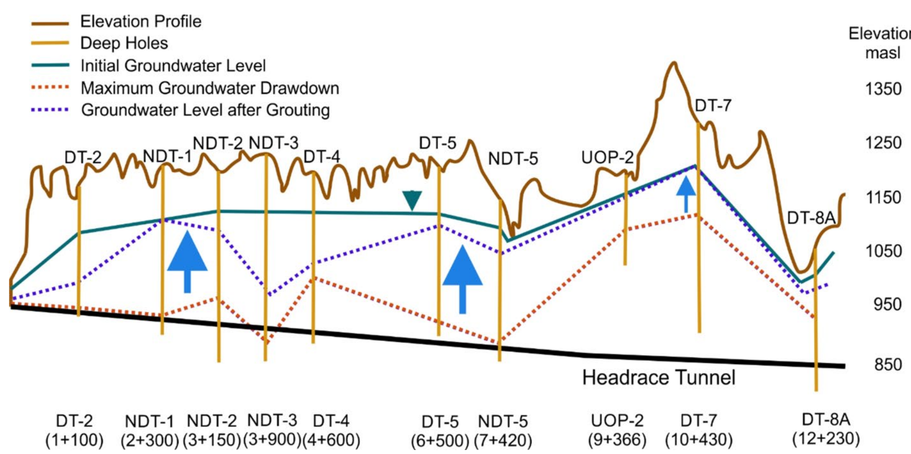

Fig. 10 Spatial and temporal variation of groundwater table recorded at borehole sites. Arrows indicate the recovery of the water table after grouting operation implemented

extensive scanning techniques or exploration drilling is often unfeasible due to high costs.

In tropical climates, differential weathering further complicates tunneling efforts. When impure marble is present, intense weathering generally resulted in karst development, which could cause high hydraulic conductivities that render unstable terrains. The water table in all boreholes was within the first 100 m from the surface, implying a 200 m water column above the proposed tunnel [47, 48] (Fig. 10). Borehole data revealed highly weathered zones along nearly vertical joints with low core recovery and rock quality designation (RQD) values [21, 49, 50]. Borehole DT-7 recorded significant water loss, and nearby dug wells subsequently dried up.

Excavation of the 15.3 km HRT commenced in March 2014, with the TBM advancing from the downstream end (Ch 14 + 939) [27]. For the first 3.8 km, water ingress through open joint planes in the unweathered crystalline rock was minimal. However, on December 24, 2014, at Ch 11 + 152, significant water ingress occurred, with peak flows estimated at 450 l per second (l/s) (Table 2). This water flowed freely through the HRT under gravity without flooding the tunnel interior [51]. Although the flow decreased to 250 l/s

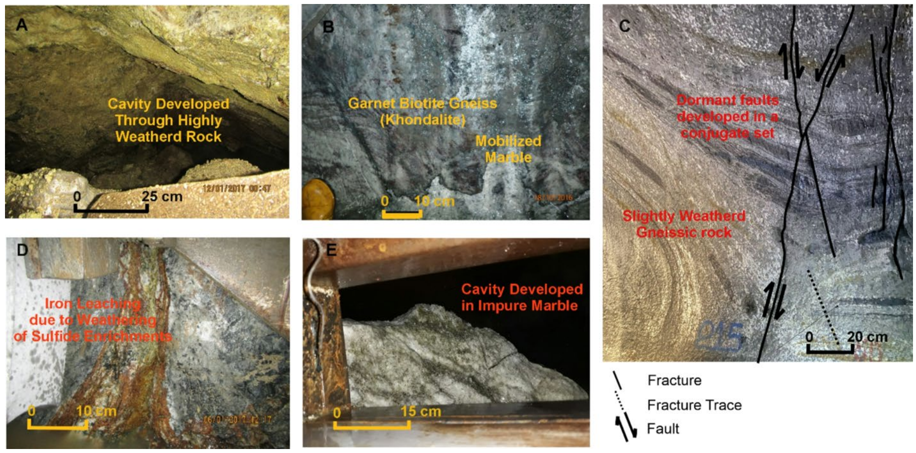

Fig. 9 Photographs showing weathering effects and structural weak zones encountered during tunnelling. **(A)** Photograph taken on January 12, 2017, showing a cavity formed in highly weathered rock at the HRT outlet tunnel, chainage 8 + 095, left wall, at a depth of 268 m. **(B)** Photograph taken on October 18, 2016, showing mobilized marble within the Khondalite or Garnet Biotite Gneiss at the HRT outlet tunnel, chainage 8 + 645, left invert area, at a depth of approximately 255 m. **(C)** Photograph from October 2023 showing the access to the HRT outlet adit tunnel, left wall, and displaying dormant reverse faults at chainage 0 + 215, right wall, depth ~ 150 m; **(D)** Photograph taken on January 06, 2017, showing leaching stains caused by sulphide minerals, likely formed through hydrothermal alterations and subsequent groundwater circulation, at HRT outlet tunnel, chainage 8 + 134, right wall, depth 268 m. **(E)** Photograph showing a cavity formed by the dissolution of impure marble within charnockitic gneiss at the HRT outlet tunnel, chainage 5 + 712, right wall, at a depth of 300 m

over the next month, the issue persisted, with multiple water-bearing zones encountered at different chainages. Significant water ingress of up to 1,363 l/s was encountered during tunnel excavation, disrupting progress (Fig. 6; Table 2). As depicted in Figs. 5 and 6, most of these incidents are directly linked to the discontinuities encountered in the region, which are predominantly associated with perennial streams. Grouting attempts with the original probe design proved ineffective in stopping the water flow [52, 53]. The inadequacy of pre-excavation grouting was recognized as a potential cause of long-term operational challenges. The TBM had limitations in pre-grouting efforts, which led to delays and interruptions in the tunneling process. In addition, manpower mobilization, project management challenges, and technical inadequacies in geological and hydrogeological understanding and planning further complicated the construction.

5.2 Social challenges

In modern times, projects are evaluated not only for their positive contributions but also for potential negative impacts on the environment and local communities. Community reactions, whether positive or negative, often emerge over time and can be influenced by political and social factors. In some cases, projects proceed without adequate community engagement, resulting in a politically charged atmosphere with public criticism, both locally and internationally.

It is customary to carry out the Environmental Impact Assessment (EIA) and Social Impact Assessment (SIA) to understand the impacts resulted from the construction and operation of a new project [54]. The EIA for the Uma Oya project completed by the University of Sri Jayewardenepura [22] was criticized for being conducted hastily, serving the vested interests of the Sri Lankan government at the time [23]. Social challenges are common in construction projects, but the unexpected subsurface water ingress had particularly severe consequences, leading to public backlash [55]. As Premadasa and

Table 2 Zones with excessive water ingress in the HRT while excavation was on going

Location ID #	Date/	Start Chainage (m)	Date	End Chainage (m)	Length of the Zone (m)	Water Ingress (l/s)	Nature
1 (DS)	18-Sep-2014	12 + 295	18-Sep-2014	12 + 243	52	200	Yellowish to reddish brown completely weathered brecciated/soft material. Discolored hard rock with water bearing joints
2 (DS)	24-Dec-2014	11 + 152	19-Apr-2015	10 + 650	516	450	Charnockitic gneiss- Fresh rock- Water bearing open joints
3 (DS)	10-Sep-2016	8 + 710	15-Oct-2016	8 + 658	52	377	Impure Crystalline limestone - sheared weak rock - easily erodible material
4 (DS)	30-Dec-2016	8 + 185	13-Jan-2017	8 + 083	102	450	Impure crystalline limestone and garnet-quartz-feldspar gneiss -sheared, weathered, and weak -comprise easily erodible material.
5 (DS)	7-Mar-2017	7 + 425	12-Mar-2017	7 + 404	16	420	Charnockitic gneiss-Fresh Rock-Two water bearing jointed zones with openings
6 (DS)	12-Apr-2017	7 + 321	20-Jun-2017	7 + 264	57	1363	Charnockitic gneiss- Fresh rock- Fractured Zone-Water bearing open joints
7 (DS)	24-oct-2018	6 + 226	31-Oct-2018	6 + 199	27	550	Charnockitic gneiss- Fresh rock- Fractured zone- Water bearing
8 (DS)	11-Jan-2019	5 + 712	19-Jan-2019	5 + 706	6	1200	Calc silicate gneiss-water bearing cavity
9 (DS)	12-Jul-2019	3 + 540	19-Jul-2019	3 + 542	2	40	Charnockitic gneiss- Fresh rock- Water bearing open joints
10 (US)	11-May-2019	3 + 385	17-May-2019	3 + 390	5	80	Charnockitic gneiss- Fresh rock- Water bearing open joints
11(US)	04-Oct-2018	2 + 892	17-Jan-2019	2 + 902	10	110	Charnockitic gneiss- Fresh rock- Water bearing open joints

(DS-Downstream, US-Upstream)

Waterman [56] has pointed out, dewatering related environmental impacts have potential negative impacts when constructing underground facilities. The excessive water ingress caused the groundwater table to drop, resulting in cracks in the walls and floors of houses in several villages, including Makulella, Weheragalathenna, Udaperuwa, and Egodagama in the Bandarawela Divisional Secretary (DS) Division, and Heeloya and Palleperuwa in the Ella DS Division [57, 58] (Fig. 11). Throughout the tunnelling process, eleven notable incidents of significant water ingress were encountered (Fig. 6), which resulted in groundwater table dropping below the tunnel level (Table). Following the drop in groundwater levels (Fig. 10a), over 2,600 traditional irrigation wells and springs partially or completely dried up (Fig. 11). As Fig. 11 shows, many dried wells are located near the central parts of the HRT, indicating subsurface water movement toward deep fractures along the Heel Oya lineament (Fig. 6). Additionally, 8,300 homeowners reported cracked houses, and sinkholes formed in the affected areas [44, 54, 56]. Cracks as wide as 10 cm and 1–2 m deep extended across several meters in some locations

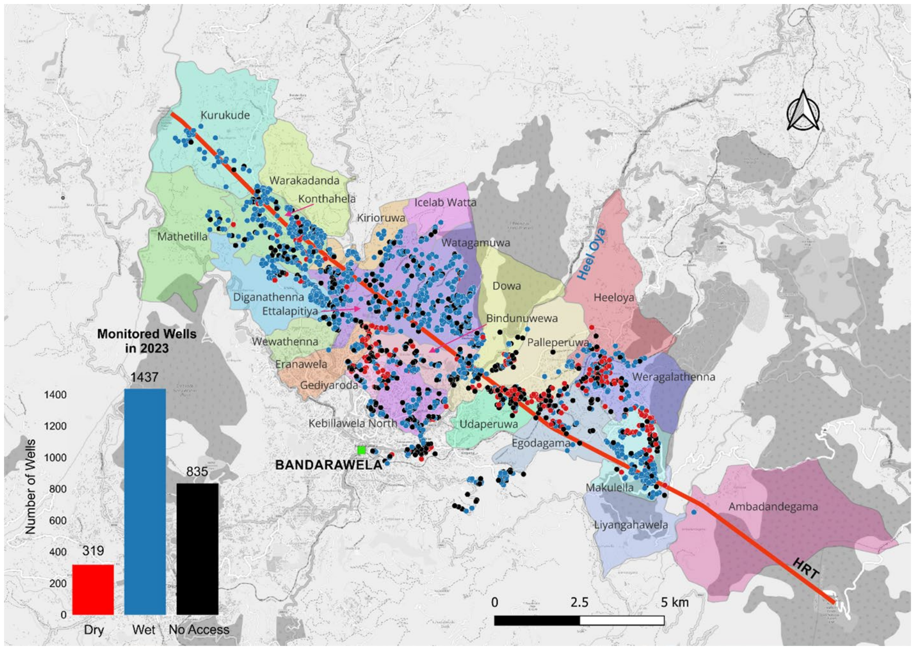

Fig. 11 Continuously monitored observation wells indicate the distribution of dry and wet wells in 2023. The DS divisions around the HRT (represented by the red line) depicted using different shades of color

(Fig. 7). The drying of wells and springs further exacerbated the situation, leading to public unrest and widespread social upheaval [58, 59]. This sudden unexpected event caused a heavy socio-political upheaval with long marches and huge protests.

The social unrest significantly disrupted construction activities, resulting in delays and logistical challenges. Residents struggled to access drinking water, and inadequate government responses only intensified tensions. Rival political factions supported protests, demanding immediate action. Eventually, public pressure forced the President of Sri Lanka to order a temporary halt to tunnel excavation until a solution could be found. Despite criticisms of the Uma Oya project, especially regarding government decisions made without thorough investigation, political pressure continued to influence the project's trajectory [58].

5.3 Financial challenges

The project faced considerable financial strain due to construction delays, operational stoppages, and public backlash. The delays led to substantial financial losses, with the Sri Lankan government shouldering the burden. Mismanagement across different sectors of the project further exacerbated the situation. Technical shortcomings, particularly in understanding the geological and hydrological conditions and accurately identifying water-bearing fractures, contributed to additional setbacks. Moreover, compensation payments to affected residents added to the government's financial responsibilities. Originally scheduled to begin in 2010 and be commissioned by 2015, the project's completion has been pushed to early 2024. This nine-year delay has resulted in major revenue losses, including reduced power generation, diminished irrigation capacity, and limited drinking water supplies, along with increased costs due to the extended project timelines.

5.4 Challenges due to disasters

The project is situated in the moderately rainfed highlands of Sri Lanka, a region characterized by vulnerable, rugged mountains and steep slopes, which pose significant risks of mass movements (Fig. 6). Additionally, the area experiences a relatively high frequency of micro tremors, with recorded magnitudes exceeding 3.0 on the Richter scale (Fig. 4). In particular, the Bandarawela region has experienced numerous micro tremor incidents, which may exacerbate landslides or destabilize soil mass, particularly during heavy rainfall. A recent study on seismic activity near the Victoria Dam, constructed across Mahaweli River, provided insights into these anticipated challenges [59]. Using interferometric synthetic aperture radar (InSAR) techniques, time-series displacements caused by low-magnitude earthquakes ($5.5 \geq M$) were detected. The study highlighted that the highlands are prone to "collapsed earthquakes," a phenomenon supported by geological evidence of dynamic topography and prolonged vertical movements (Fig. 4) [34]. Gravity anomaly measurements revealed correlation between these anomalies and changes in the terrestrial water storage (TWS) encompassing atmospheric water, groundwater storage (GWS), and surface water. Seismic events were found to impact groundwater levels through oscillations and permanent offsets [60, 61, 62]. Based on data from the Global Land Data Assimilation System (GLDAS), the time-series of GWS levels showed that the collapse earthquakes positively responded to the changes in the soil moisture. Furthermore, increasing rainfall trends and rising annual temperatures indicate the effects of global warming, necessitating close monitoring and adaptation strategies (Fig. 8a and b). The variations in TWS, coupled with the region's seismic history, suggest that tremors could significantly impact the long-term stability and operational viability of the project.

6 Addressing technical, social, financial and disaster challenges

Overcoming the technical, social, and financial challenges faced by the UOMDP requires a comprehensive approach. This includes implementing technical solutions, effective project management strategies, and proactive measures to mitigate social and logistical disruptions.

6.1 Technical solutions

The project encountered significant technical difficulties, particularly with excessive water ingress during tunneling [63]. Ideally, geologists and engineers should have conducted a thorough analysis of the available technical data before advancing the project design. Key technical solutions were implemented to address these issues. These included pre-excavation grouting and defining an acceptable residual water ingress value. Selecting a suitable TBM with full-circular grouting capabilities was critical. Water-sealing gaskets and angled hole drilling were also used. In addition, steel lining tunnel supports were incorporated for added safety.

6.1.1 Selecting an appropriate TBM with Full-Circular grouting capability

The initial selection of a TBM with only semi-circular probing capabilities was unsuitable for the geological and hydrogeological conditions of the project, which included fractured charnockitic gneiss, khondalite, and mobilized marble creating large cavities. For deep tunnels with such geological complexities, a TBM with full-circular probing and grouting capability would have been more suitable. After tunneling nearly half a kilometer at chainage 7 + 063, the manufacturer had to retrofit the TBM by adding additional probe drilling holes to achieve full-circle probing capability [64] (Fig. 12). Moreover, this modification incurred extra time and costs, and excavation progress had to be halted for three months, leaving the TBM idle during this period.

The lack of pre-excavation grouting was identified as a potential cause of long-term tunneling issues. Despite recognising the risk of encountering uncontrollable water-bearing zones, excavation proceeded without adequate preparation. Subsequent studies revealed that temporary measures were ineffective at controlling water ingress, prompting the introduction of pre-excavation grouting. This method involves drilling quasi-horizontal, fan-shaped holes ahead of the excavation face and injecting grout until the water ingress or weak zones are sealed off (Fig. 7).

Excavating without properly sealing heavy water ingress or stabilizing weak, collapsing areas presented ongoing challenges for engineers and managers. The cumulative water ingress was monitored using a fixed Parshall flume to measure total water flow at the HRT outlet on a daily basis. The time series graph illustrates flow rate variations recorded at various chainages as tunnelling progressed through the rock (Fig. 13). Significant water ingress events, marked by a sequence of numbers corresponding to different excavation times, are highlighted in the graph. The maximum recorded water flow rate – 1,363 l/s at chainage 7 + 317 (Fig. 13) on April 12, 2017– marked a critical point, forcing the design engineers to adopt a firm decision regarding pre-grouting. However,

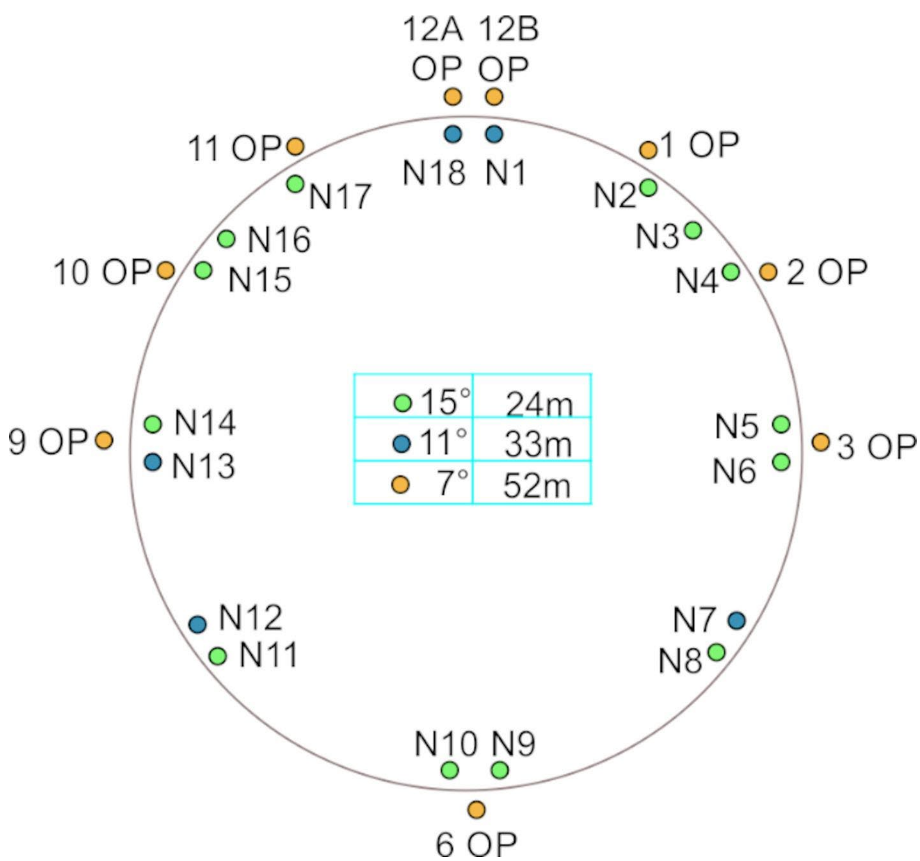

Fig. 12 TBM shield modification with drilling quasi horizontal additional probe ports distributed in a fan shape ahead of the excavation face. The probe hole configuration before and after TBM modification; OP– Old probe holes with 7° inclination (9 holes), N– newly added holes with 15° and 11° inclinations spreading in a fan shaped through the entire TBM tail-shield (18 holes) [41]

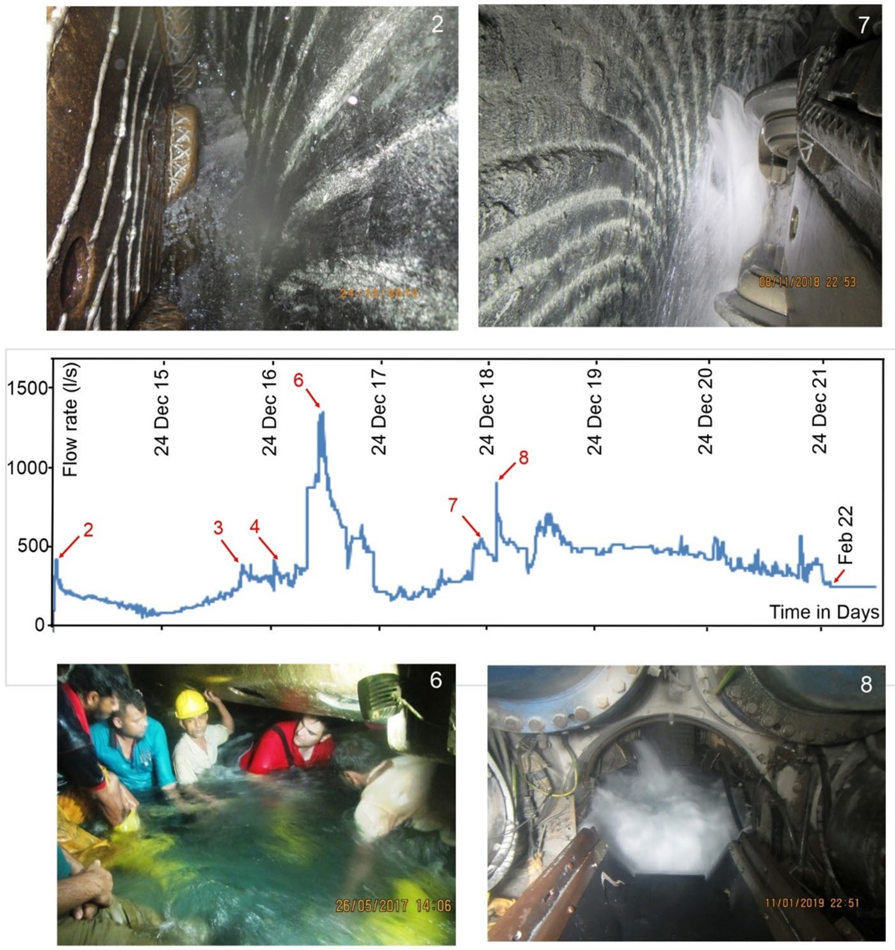

Fig. 13 Time series graph indicating significant cumulative water ingress events accompanied by photographic evidence: **2**. A face photograph showing sudden ingress of 450 l/s from fresh water bearing open joints. Water ingress from a horizontal joint at the bottom left of the face was measured on December 24, 2014 at Ch 11 + 152, **6.** A photo showing TBM tail shield area after water ingress of 1363 l/s on April 12, 2017 at Ch 7 + 231, **7.** An excavation face photo after water ingress of 550 l/s on October 24, 2018 at Ch 6 + 226, and **8.** A photo showing TBM gripper shield area after water ingress of 1200 l/s on January 11, 2019, at Ch 5 + 712 (as detailed in Table 2*)*

pre-excavation grouting could not be immediately implemented, which delayed excavation by seven months while post-grouting measures were carried out to mitigate water ingress. Following this significant event, the contractor decided to introduce pre-excavation grouting alongside the originally planned post-grouting. To facilitate this, the TBM was modified to include 18 additional probe holes. Based on full circle pre-grouting methods, the multi-dimensional evaluation by Mousavi [53], which considered long-term costs and environmental impacts, the decision to implement pre-excavation grouting was deemed essential. Grouting was initiated ahead of this chainage. A comparison of pre-excavation grouting (Ch 11 + 152 to 10 + 650) and post-excavation grouting (Ch 7 + 063 to 6 + 550) showed that pre-excavation grouting was more cost efficient, time efficient, and had fewer social impacts (Table 3).

6.1.2 Establishing residual ingress value

TBM excavation ended with breakthrough at chainage 4 + 178 on October 3, 2019. However, groundwater continued to enter the tunnel at several locations, totaling 520 l/s.

Table 3 Analysis of pre-excavation grouting from Ch 11 + 152 to 10 + 650 and post-excavation grouting from Ch 7 + 063 to 6 + 550 along the HRT

Uma Oya	Chainage (Tunnel length)	Initial Water ingress	Water reduction after grouting	Environmental/social damage	Cement (Tons)	Time taken for excavation (Months)	Technique used for grouting	Time taken for grouting	Total time taken (Months)	Total cost
Pre-excavation grouting	7 + 063–6 + 550 (513 m)	No huge water ingresses into the tunnel	Up to 60 bar effective grouting pressure reach in each probe hole reaching 2 l/s/m	No damage	993	8	No need for special grouting machines and additional team as required for post excavation grouting	Grouting and excavation were done in parallel	8	Cement + excavation cost
Post-excavation grouting	11 + 152–10 + 650 (516 m)	450 l/s	Up to 50 l/s	Huge water ingress, significant environmental issues; dried dug wells, cracked houses, and cost escalation due to delayed excavation and compensation	887.5	4	Hired specialized grouting team & machines while employing special grouting technique	7 months and excavation stopped for grouting	11	Cement + grouting team + equipment + excavation cost

To reduce residual flow, post-excavation grouting was employed. An initial target of residual water ingress at 50 l/s had been arbitrarily established without any scientific and technical justification. Maintaining this target proved challenging. To address this issue, the new project management team decided to conduct a fresh seepage analysis. This analysis considered key factors such as grout material (Ordinary Portland Cement - OPC) and grout hole spacing (1.2 m). The study carried out by Mahab Ghodss - POYRY Joint Venture [65], concluded that 300 l/s was a more realistic final residual water ingress value. Following this analysis, grouting efforts were intensified to match the revised target. Ultimately, the water ingress was reduced to approximately 300 l/s, aligning with the revised target.

6.1.3 Incorporating Water-Sealing gaskets in segmental linings

Four types of tunnel support were introduced in different sections of the HRT such as full-ring concrete segments, shotcrete, rock bolts, and invert-only support [45] (Figs. 14 and 15a). The segmental linings were installed without water-sealing gaskets [66]. Once the segmental lining was in place, the space between the rock and the segment lining was filled with pea gravel, followed by the injection of thick grout (Fig. 9a). However, the invert part of the segment could not be fully sealed because the flowing groundwater washed away the grout. This made it difficult to accurately observe locations of seepage through weak zones and weathered rocks. Water seeping into the segmental space would often reappear at other points where the grout barrier was weak, complicating efforts to map and pinpoint seepage locations. Engineers expected that applying water-sealing gaskets (Bull Flex bulkhead) to the segments would have mitigated these issues. Moreover, a full segment lining has been introduced and some of these water ingress problems have been curtailed (Fig. 14).

6.1.4 Incorporating angle holes in segmental linings

Absence of openings for drilling angled holes in the segments (Fig. 15a), a significant shortcoming in the design which created challenges for grouting vertical joint sets, particularly at 85/340 and 80/270 orientations (Fig. 15b and c). The available radial grout holes in the segments could not intersect all the joints, preventing effective grouting to seal off water ingress (Fig. 15c). Allowing more efficient post grouting, a new angled-hole drilling method has been incorporated only at invert only sections (unlined sections) [53, 67].

6.1.5 Incorporating a steel lining tunnel support

During the excavation of the HRT from the outlet side, a weak zone was encountered near chainage 12 + 295 in September 2014 (Fig. 6b; Table 2, Location ID #1). This section initially showed water ingress in sound rock mass, which later transitioned into crushed and completely weathered material, including a fault gauge with clay. The area was supported by full segmental lining during excavation. However, structural issues soon became apparent: segment cracking, chipping, and spalling at corners and edges, along with joint defects like stepping (open gaps between segments). Longitudinal subsidence of the inverted segment was also observed in the muddy and faulted zone. To mitigate these issues, short-term rehabilitation measures were implemented to stabilize the area and prevent further deterioration during construction. Despite these efforts, geological

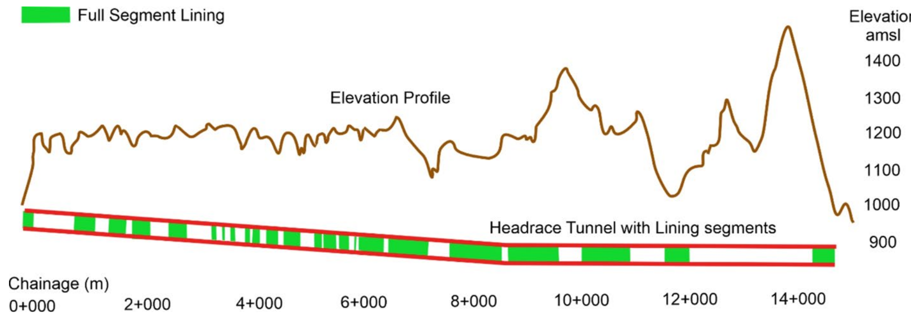

Fig. 14 Sectional drawing of the HRT showing segments with full lining along the entire 15.3 km long tunnel

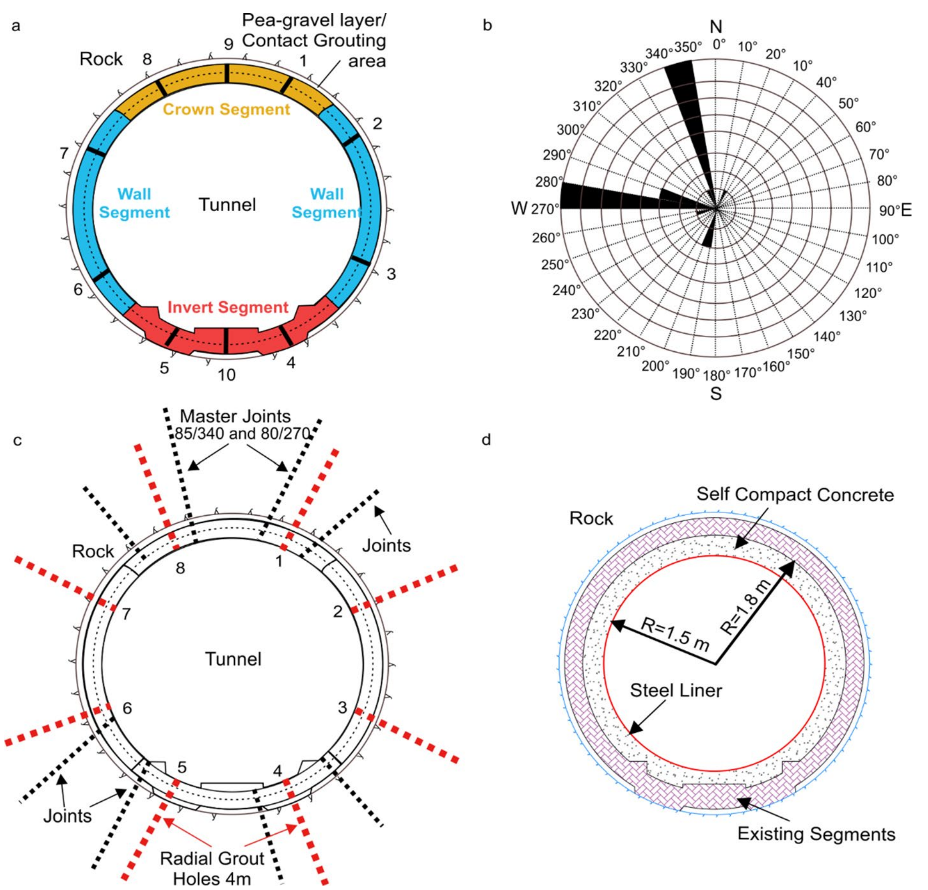

Fig. 15 **a** Diagram illustrating segment distribution, including the pea gravel layer surrounding the tunnel opening.
(adapted from Amberg Engineering [42]). **b.** Rosette diagram displaying the bearings of major joint sets at 270° and 340°. **c.** Schematic section depicting major joint distributions and the original radial grout holes around the tunnel, highlighting inadequacies in intersecting joints to improve grouting effectiveness. **d.** Schematic section showing a continuous steel lining with a self-compacting concrete membrane applied over the existing segments (adapted after Mahab Ghodss-POYRY JV [68]).

surveys revealed that the rock mass condition between chainage 12 + 228 and 12 + 286 was extremely weak, raising concerns about the long-term stability of the segmental lining. A common approach to this problem is the application of secondary concrete lining on the inner surface of the segments. However, this method required substantial reinforcement, nearly equivalent to the strength provided by a steel lining embedded in concrete. Given the poor durability of the surrounding rock, strict crack width restrictions were essential to minimize the reinforcement required. Additionally, the weak rock mass behind the segments posed a risk of washout due to water seepage [69]. Considering the risks and excessive reinforcement needs, a continuous steel lining was proposed as a safer and more practical alternative. This solution offered superior safety compared to secondary concrete lining and proved to be more cost-effective in practice (Fig. 15d).

6.2 Social solutions: engaging with affected communities, providing compensation, and ensuring transparent communication

This project marked several significant milestones for Sri Lanka: it was the first time a Tunnel Boring Machine (TBM) was used and the first long tunnel with underground power plant was built. However, it also resulted in unprecedented environmental damage due to tunneling activities, which caused considerable hardship for affected communities. The public, particularly those impacted by the project, remained skeptical and critical of its outcomes. Recognizing this sentiment, the new management team prioritized maintaining transparency in their operations. Their approach aimed to balance public concerns with the continuation of project activities, ensuring accountability without disrupting progress.

Addressing social challenges requires direct engagement with affected communities and providing compensation for damage. As a constructive measure, the contractor allocated 6 million USD for water distribution to approximately 4,200 affected families, which included the provision of plastic tanks. As groundwater levels increased due to positive technical measures - such as post-grouting and proper sealing of the HRT - the community wells gradually began to recover. Over time, water tables returned to their original levels. Figure 16 based on the monitoring of wells in the region represents dry to total monitored wells as a percentage. The severity of the impact on the affected community following the major water ingress into the HRT in 2014 continued to escalate until 2017, when authorities implemented pre-grouting operations to resume HRT excavation. These measures significantly improved the recovery of wells in the region, thereby alleviating social pressure. Additionally, compensation totaling Rs 1,500 million

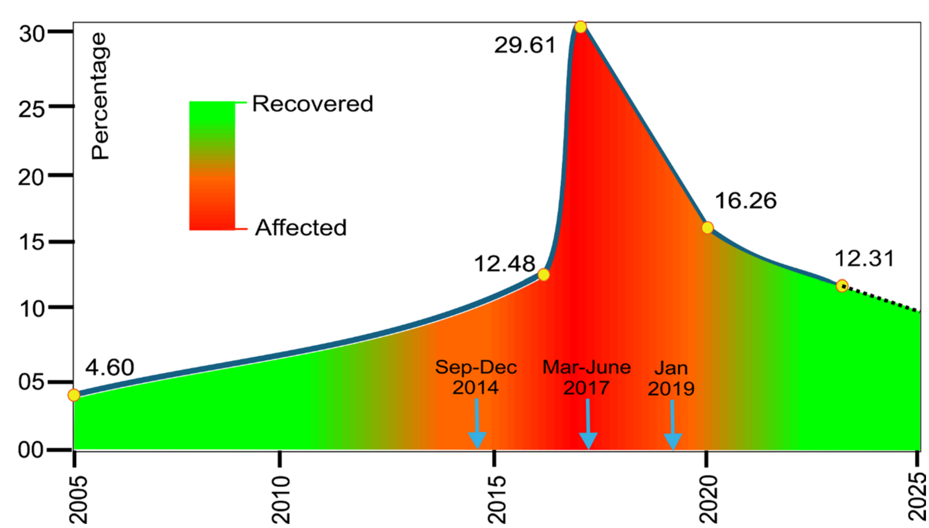

Fig. 16 The diagram illustrates the temporal variations in monitoring well behavior, considering the percentage of dry wells relative to the total wells monitored within the affected communities in the region. Major water ingress events from 2014 to 2019 are indicated on the time axis with blue arrows

(Approximately 5 million USD) was paid for damages to about 8,000 houses, along with Rs 500 million (Approximately 1.6 million USD) (1USD = Rs.300) for damages to around 3,600 agricultural plots.

Ensuring transparent communication, a specialized team of environmental and social impact monitors were appointed to assess measures taken on groundwater recovery and how to relieve social unrest. Tunnel stability and groundwater recovery has been restored with the newly designed mitigatory measures of applied rock supports and grouting. Continuous rising of water table after grouting and water filling of the tunnel was evidenced by recent measurements (Fig. 10a). Compared with previous data represented by Golian et al. [21], significant changes can be seen as many former dry wells showing slow recovery. Politicians in the region exhibited mixed reactions; however, with the distribution of supplies to the affected individuals, public unrest seemed to be effectively managed.

6.3 Financial solutions: securing reliable funding and improving project management

While controlling water ingress at the HRT, the contractor faced financial difficulties and requested the release of retention money. However, the project management team initially did not agree to this request. Subsequently, the government appointed a new project management team, which made critical decisions to address both financial and technical challenges. As a financial solution, the project's retention money was released in a controlled manner to support the contractor and sub-contractors, ensuring that funds were disbursed prudently to maintain project stability and progress.

Mobilizing manpower and resources efficiently has been a persistent challenge, underscoring the need for better coordination and project management. Properly addressing technical shortcomings, particularly in understanding the geological and hydrological conditions and accurately identifying water-bearing fractures, could have prevented the excessive water ingress and work stoppage. These interruptions, along with the associated claims, could have been avoided. The contractor claimed 39 million USD during work stoppages, which the client had to pay, and an additional 6 million USD was spent on water distribution to affected communities.

Despite these financial challenges, the Sri Lankan government played a critical role in ensuring the project's completion. Strategic political maneuvering helped create a favorable environment to mitigate further disruptions. After considerable delays and criticism, the project was finally commissioned on April 24, 2024, with total costs reaching 553 million USD.

6.4 Solutions for anticipated disasters

To mitigate anticipated disaster risks, the project requires proactive monitoring and timely remedial measures. Given the increasing trend in rainfall, appropriate erosion control measures must be implemented to reduce the risk of slope instability and runoff related damage. The effects of global warming should be addressed through modeling studies aimed at identifying necessary interventions to adapt to changing climatic conditions. Fortunately, micro tremors are being continuously recorded across the Mahaweli region's dam sites and irrigation network, providing critical data. Authorities must prioritize the analysis and application of this data to anticipate and prevent potential disasters, thereby avoiding additional financial burdens. For the project's long-term success and uninterrupted operation, continuous monitoring of key parameters is essential. These include dug wells, tube wells, piezometers, water tables, erosion and mass movements including support data acquisition for collapsed earthquakes and deformations. Allocating emergency funds promptly following any damaging incident will enable the efficient execution of mitigation and repair measures. This approach will help address potential issues before they escalate, reducing the need for time-intensive and costly interventions in the future.

7 Cost benefit analysis

The projects longevity and profitability, overcoming the challenges with due solutions are the key ingredients for a successful project output and efficient operational outcome. The cost benefit analysis, which incorporated environmental values into the basic economic framework, was conducted to evaluate the project's environmental and investment efficiency within the context of Sri Lanka's national economy. The project's economic life is considered to be 50 years [70]. It was assumed that hydro-mechanical equipment would require an overhaul after 25 years, and electromechanical equipment after 30 years from the project's commissioning (Director, Broadlands Hydropower Project 2010 pers. comm.). The economic costs for these replacements were estimated Rs 1,610,000,000 (Approximately 5.3 million USD) for hydro-mechanical equipment and Rs 20,160,885,175 (Approximately 67.2 million USD) for electromechanical equipment (anticipating USD 1 = Rs. 300) (Fig. 17).

The Internal Rate of Return (IRR) is a key metric for assessing the profitability of future projects. It is the discount rate at which the investment cost would break even in terms of its present value, making the Net Present Value (NPV) of all cash flow equal to zero in a discounted cash flow analysis [71]. A higher IRR is generally more desirable, indicating greater profitability. For the Uma Oya project, NPV (Eq. (3)) was calculated using

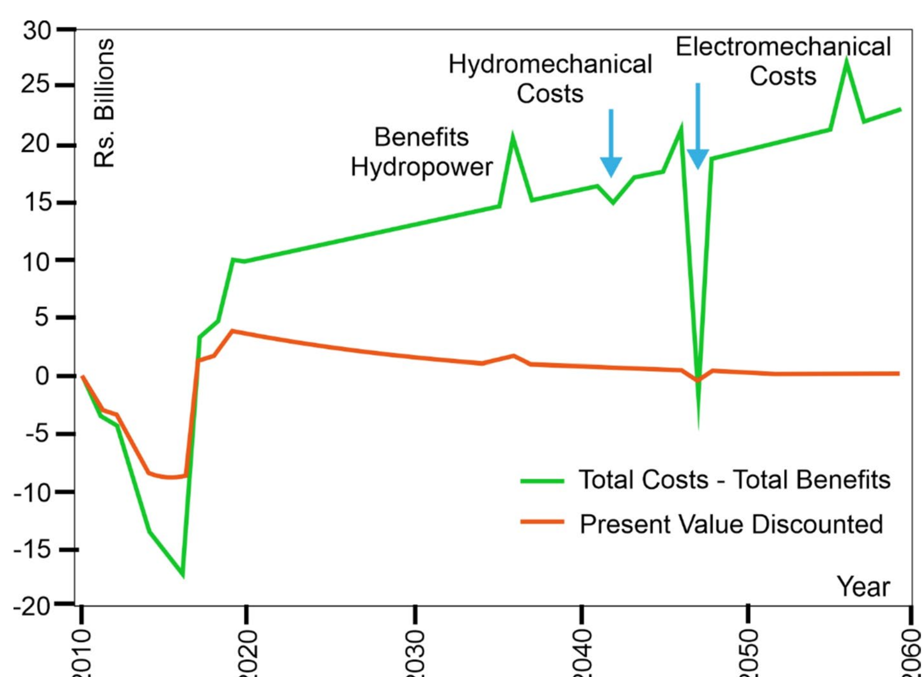

Fig. 17 The graph showing total costs (TC), total benefits (TB) and discounted present value calculated until projected 50-year period ending in 2059 [70]

discount rates at 5%, 10% and 12%. Since the IRR exceeded the discount rate according to the parameters in the economic analysis, the project was deemed favorable. Considering two scenarios– one with a 10% increase or the other with the 10% decrease in fuel costs - the IRR stood at 13.06% and 11.84% respectively [70]. In both cases, barring technical or socio-political issues, the project could have achieved annual benefits exceeding the costs as early as 2017.

The benefit-cost ratio (BCR), a profitability indicator in cost-benefit analysis, was also calculated. For the two fuel cost scenarios, with an NPV of 0.1, the BCR ranged from 1.328 to 1.191, respectively. Despite various omissions, biases and uncertainties that could affect the project's execution, the decision was made to proceed, anticipating smooth progress [70].

$$NPV = \sum_{i=1}^{i=n} \frac{S_i}{(1+r)^i} - C \tag{3}$$

where,

i = the actual year

S = annual savings

$\frac{1}{(1+r)^i}$ = the discount factor

r = the discount interest rate

C = the initial investment

Though originally slated for commissioning in 2015, the project took an additional nine years, with irrigation water supply and power production finally initiated on 24th April 2024. The project was executed under an Engineering, Procurement, and Construction (EPC) contract, with an estimated cost of 529 million USD including 15 million to cover contingency. Initially 85% of the funding was to be provided by the Export Development Bank of IRAN. However, due sanctions imposed on the Iranian government in 2013, 90% of the funding burden shifted to the Sri Lankan government. This shift caused significant delays and became a major political and social issues for the Sri Lankan authorities.

Additional costs were incurred due to work delays, further geological analysis, engineering planning, compensation payments, and social costs which escalate the project costs to 553 million USD. For the contractor, this type of project, with its many uncertainties and the constraints of an EPC contract, proved to be disadvantageous. Under the EPC contract, the client was only required to pay for progress made on the HRT excavation, not for additional grouting or compensation for affected communities. As a result, the contractor experienced financial losses, and the client had to release retention funds as a good will gesture to keep the project moving forward.

While the project is ultimately valuable in addressing the country's power and irrigation needs, the energy and irrigation losses, along with interest payments and other delay-related costs, have significantly impacted its financial outlook. The current projection suggests that the project may only reach a break-even point by 2030 (Fig. 18; Table 4). The opportunity costs resulting from the delay– such as the loss of power generation, reduced agricultural production from irrigated land, decreased domestic and industrial water supply, and other indirect benefits– have been separately calculated (Fig. 18).

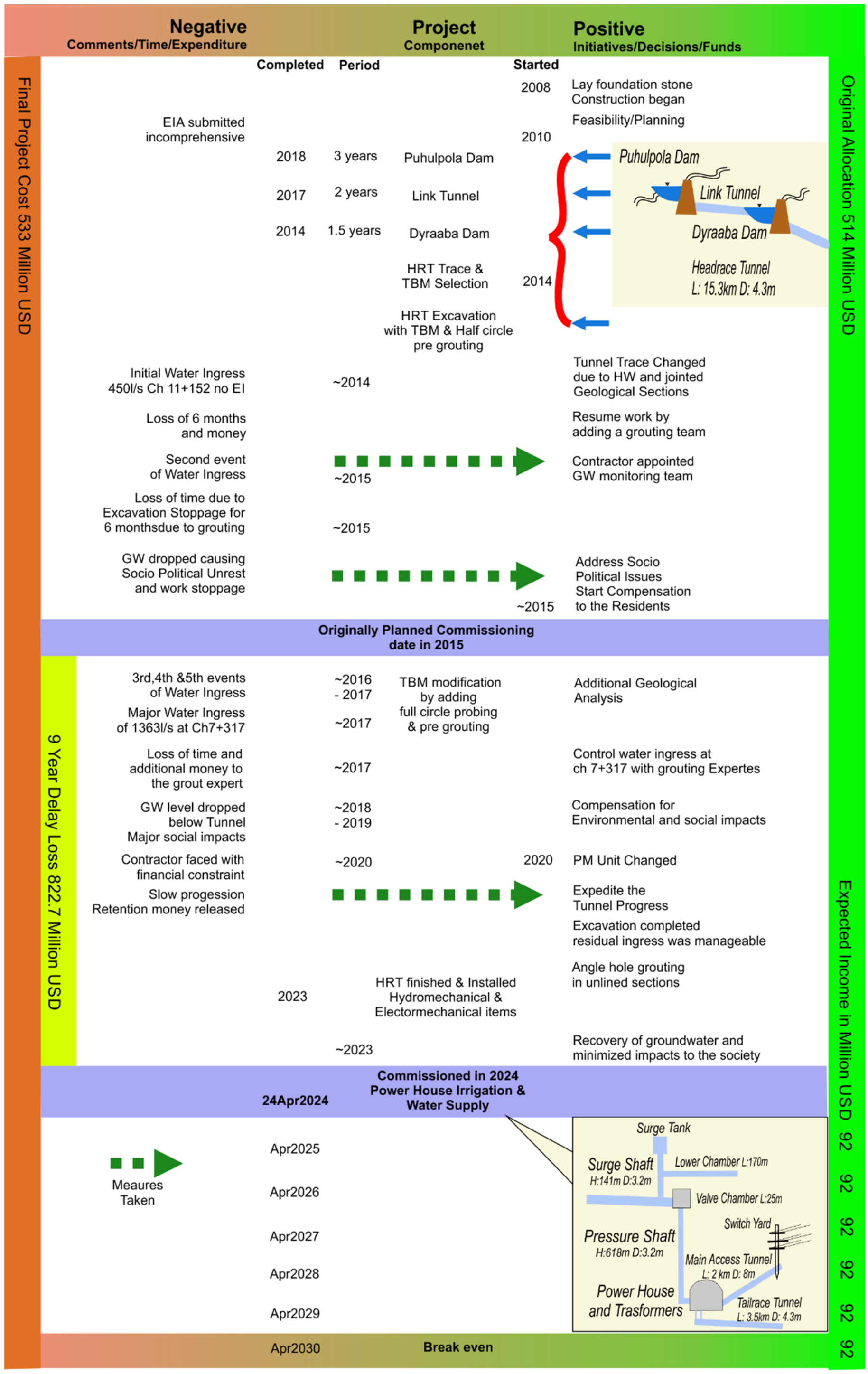

Fig. 18 The project timeline, including the problems encountered as negative points, and solutions adapted as positive outcome with a breakdown on expenditure and income till the breakeven

7.1 Loss of opportunity in power generation revenue

The powerhouse, with a capacity of 120 MW, provides peak energy production (4.5 h per day) of 147 GWh/year and off-peak energy of 143 GWh/year, totaling the energy production of 290 GWh/year. When comparing unit generation costs, hydropower is significantly more economical, with a cost of approximately Rs. 20 per unit compared to

Table 4 Breakeven calculation

Final Project Cost in USD	**553million**
Total estimated net annual income in USD	92 million
Breakeven point	6 years

Rs. 130 per unit for diesel and Rs. 70 per unit for coal. This means a loss of Rs. 110 per unit when using diesel and Rs. 50 per unit when using coal, if hydropower were available. This was based on whether hydropower is available, as replacing the peak hour periods by diesel power consumption and off-peak hours by coal power. Not to mention the many environmental and economic benefits which the country loses due to delay. In addition to these financial losses, the country has also missed out on substantial environmental and economic benefits due to the delay in project completion.

The total profit per year from Uma Oya's power generation, considering both peak and off-peak demands, is estimated at Rs 23.3 billion per year (approximately 77.66 million USD). Since the project was delayed for 9 years, the total loss accrued due to this delay amounts to approximately 700 million USD.

7.2 Loss of opportunity in irrigated agriculture production revenue

The expected annual diversion of irrigation water is 145 million cubic meters (MCM), including 100 MCM during the Maha Season (associated with the northeast monsoon, typically runs from September to March) and 45 MCM during the Yala Season (associated with the southwest monsoon, runs from May to end of August) [69] (Table 5). Farmers primarily cultivate paddy during the Maha Season and other field crops such as ground nuts, sesame, green grams, onions and maize during the Yala season. Considering irrigation water requirements – 1.32 m (4 feet) for paddy and 0.762 m (2.5 feet) for other field crops - in addition to the rainfall [72], approximately 7,575 hectares could be irrigated during the Maha season, and 5,910 hectares during the Yala season.

The annual income from cultivation in the downstream area was estimated using the information in AgStat [73], as detailed in Table 5. Given the 9-year delay in irrigated agriculture production, the total annual income loss is estimated to be Rs. 3,675 million (approximately USD 12.25 million). Over the course of the 9-year delay, this would result in a total loss of approximately USD 110.25 million.

7.3 Loss of opportunity in domestic and industrial water supply revenue

The Uma Oya Multipurpose Development Project has allocated 39 million cubic meters (MCM) annually for the water supply project. Based on the National Water Supply and Drainage Board (NWS&DB) tariff system from 2012, the minimum annual income from this water supply can be approximated at Rs 390 million. Over the course of the 9-year delay, the total loss in water supply revenue is estimated at Rs 3,510 million (approximately USD 12.7 million).

7.4 Loss of opportunity in indirect benefit revenue

The supply of electricity, irrigation water and domestic and industrial water provides substantial indirect benefits to the community. These benefits include improved health conditions, time and cost savings from alternative supply sources, increased income through eco-tourism and livestock production, employment opportunities, and enhance recreational activities. As a result of delayed project commissioning, the nation lost

Table 5 Annual income of cultivation in the downstream area

Maha Season (north-east monsoon from September to March in the following year)				
Crop	**% cultivation***	**Extent (Ha)**	**Net Profit/Ha (Rs)**	**Income (Rs.)**
Paddy	90%	6,817.5	150,000	1,022,625,000
Other field crops	10%	757.5	450,000	340,875,000
Total	100%	7,575.0		1,363,500,000
				USD 4,545,000
Yala Season (effective during the period from May to end of August)				
Crop	**% cultivation***	**Extent (Ha)**	**Net Profit/Ha**	**Income (Rs)**
Paddy	10%	591.0	150,000	88,650,000
Ground Nut	15%	886.5	380,000	336,870,000
Maize	10%	591.0	145,000	85,695,000
Kurakkan	10%	591.0	350,000	206,850,000
Gingerly	10%	591.0	135,000	79,785,000
Vegetable	10%	591.0	800,000	472,800,000
Onion	5%	295.5	1,300,000	384,150,000
Green gram	10%	591.0	400,000	236,400,000
Cowpea	10%	591.0	115,000	67,965,000
Fruits	10%	591.0	600,000	354,600,000
Total	100%	5,910.0		2,313,765,000
				USD 7,712,550

*General practice in the area

**1 USD = Rs. 300

significant opportunities, leading to an estimated total revenue loss of USD 823 million over a 9-year period with an annual income loss of USD 92 million. Had the project been commissioned on time, the total investment of USD 514 million could have been recovered within 6 years. However, due to delay, it will take 15 years to fully recover the project costs.

8 Summary and conclusion

Planning, designing and constructing deep underground tunnels - such as the Uma Oya HRT - pose significant challenges [74]. Meticulous pre-feasibility and feasibility studies are therefore essential to minimize the risk of costly funding reallocations for future corrective measures. Engineers and geologists must evaluate potential risks using the best available resources and conduct thorough investigations during construction, along with vigilant post completion monitoring. These steps are critical for promptly identifying and addressing tunnel related issues, ensuring long term structural integrity and project success.

Unpredictable weathering often led to unforeseen complications and additional costs. Weak, sheared, mobilized rock masses and deeply weathered zones could have been identified earlier through comprehensive geological mapping. In a study on deep drilling for groundwater extraction in Precambrian terrains, Jayasena et al. [75] observed that perched water bodies can drain from upper to lower sections through interconnected deep fractures. Building on this insight, Jayanath and Jayasena [67] confirmed the presence of perched water bodies in a 200 m water-bearing zone above the HRT, which could drain suddenly, causing severe water ingress. Implementing pre-excavation grouting beyond the tunnel face would have mitigated these risks. Although such grouting may have incurred additional upfront costs, it would likely have saved significant amount of time and money in the long term.

Despite an average rainfall of 1620 mm and an estimated recharge potential of up to 20% [21], construction proceeded without adequately addressing the risk of water ingress. Later hydrogeological models likewise predicted substantial water ingress [76–80]. Moreover, excavation proceeded without sealing heavy water ingress or stabilizing weak and collapsing ground, leaving engineers and managers to contend with persistent water management problems. This study systematically examined water ingress within the HRT and evaluated the effectiveness of subsequent remedial measures. Although the tunnel ultimately received segmental lining, our analysis show that pre-excavation grouting would have been significantly more effective than the post excavation grouting that was applied. Comprehensive geological and structural mapping identified two dominant fracture sets with near vertical dips (85/340 and 80/270). Inadequate treatment of these features allowed water ingress rates as high as 1363 l/s, prompting criticism from both the client and local communities.

From the outset, the Uma Oya project was politically, and environmentally sensitive and rushed with limited feasibility studies [23]. Though the government initiated the project, the social and political complications stemming from tunnel excavation eventually required additional leadership intervention. Further, environmental challenges from excessive water ingress also caused severe social and political disruptions. In certain areas around the tunnel path, groundwater levels fell below the tunnel invert resulting in severe water shortages for communities living approximately 1150 masl [45] (Fig. 10a). Residents reported incidents of partially or completely dewatered traditional irrigation wells and perennial springs, cracked houses, crop damage, and sinkhole formations. To compensate the affected community, the contractor incurred approximately 18 million USD in costs. An additional 6 million USD was spent on post excavation grouting to mitigate further damage. Despite environmental damage that could not be entirely prevented, the grouting methods employed here effectively addressed water ingress. While not all remedial measures were feasible, groundwater decline, and tunnel water ingress were substantially mitigated (Fig. 10a).

The project timeline, challenges, and solutions provide a roadmap for avoiding future project delays by critically analyzing data and addressing anticipated technical issues early on (Fig. 17). Strategic foresight could have prevented public unrest and work stoppages. For example, thorough geological and hydrological assessments and pre-grouting before TBM operation would have reduced compensation needs and time delays, ensuring smoother project execution. Moreover, the original project costs of 514 million USD subsequently escalated to 553 million USD due to additional claims. The 9-year delay led to substantial revenue losses: approximately 700 million USD in delayed power production, 110 million USD in irrigation losses, and 12.7 million USD in drinking water supply losses (Fig. 17).

The region is highly susceptible to natural disasters, including mass movements on steep slopes and erosion caused by heavy rainfall. These risks are further exacerbated by rising temperatures associated with global warming and frequent micro tremors. These conditions pose risks for landslides, erosion, and seismic activity that could disrupt project operations and infrastructure. Establishing comprehensive monitoring of rainfall, groundwater levels, and tremor activity, along with an early warning system, would allow for the detection of potential landslides and erosion threats. Authorities can implement erosion control measures to manage increasing rainfall and associated runoffs that can weaken slopes. The network of micro seismic stations distributed across central Sri Lanka can effectively monitor seismic activity (Fig. 4), while modeling studies should be undertaken to predict impacts and enhance resilience against extreme weather. An emergency fund should also be allocated for immediate response and repairs in case of disaster-related damage, helping to prevent long-term operational downtime.

This study highlights the importance of proper geological assessments and thorough Environmental Impact Assessments (EIA) as prerequisites for the efficient execution of tunnel projects without significant delays. Many unexpected local delays could have been avoided through clear professional judgments and effective management decisions. Lessons learned from the Uma Oya project provide valuable insights for similar future endeavors. This case underscores, that development projects, whether publicly or donor-funded, are highly sensitive to economic, sociopolitical, and environmental variables. With rigorous engineering and geological assessments, such projects can achieve their desired outcomes while minimizing environmental impacts.

In conclusion, while the use of Tunnel Boring Machines (TBMs) was justifiable, comprehensive geological analysis and groundwater management from the outset are essential for ensuring timely project completion and maintaining profitability. Unanticipated geological and hydrological challenges contributed to construction delays, management strain, socio-political pressure, and a loss of public trust. Although extensive investigations have been conducted, continuous monitoring and pragmatic decision-making remain crucial to safeguarding the economic viability and overall success of UOMDP and similar infrastructure projects.

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Author contributions
M.G.S. Jayanath was responsible for the conceptual design, field implementation, and initial drafting of the paper; H.A.H. Jayasena contributed to the manuscript design, supervised the work, and provided detailed writing. M.G.S. Jayanath and B. Gunaratna conducted the economic analysis. All authors reviewed and approved the final manuscript.

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Data availability
Most of the data analyzed during this study are included in this article, while the remaining are available from the authors on reasonable request.

Declarations

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Not applicable.

Consent for publication
Authors give full consent for the publication of this work.

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