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Evaluating the sustainability of a hydropower project in the Himalayas: A case study for resolving legal disputes in tribunals

Aditya Rana *, Siddharth Singh , N.K. Bhagat , M.M. Singh , G.P. Jadaun , P.K. Singh

CSIR-Central Institute of Mining and Fuel Research, Dhanbad, Jharkhand, India

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ABSTRACT

Land use controversies often dog the construction of hydroelectric projects. Many important projects are battling in the tribunals because of Geo-environmental concerns. The paucity of scientific studies objectively investigating the litigations further aggravates the unsolvability of the disputes.

The Sawra-Kuddu Hydroelectric project, India, became a subject of litigation when project affected persons filed a suit in the National Green Tribunal questioning the sustainability of the built environment. The litigants petitioned that the additional adit's blasting vibrations can trigger the landslide of slip zone, and Thana village situated above it. The petitioners further claimed that vibrations had cracked the houses. They also asserted degradation in the apple cultivation due to tunnel construction. The tribunal took a stern note of the petition and banned the construction activities. The tribunal further ruled that a scientific investigation must be conducted to ascertain the cause of petitioners' claims.

The study results revealed that the vibrations originating from adit excavation are insignificant and cannot destabilize the slip zone. The high fluctuation of annual rainfall and tectonic strain were deemed responsible for the differential settlement of foundations and cracks in the houses. The horticulture study indicated that the physiological processes of apple crops were normal. The study's findings convinced the tribunal, and construction activities were resumed, resulting in the disputed 111 MW project's commissioning. Many run-of-the-river hydroelectric projects in the world are battling similar litigations addressed in the present study. A similar objective methodology is a need for the hour to resolve other hydroelectric projects' sustainability issues. The study findings will pave the path for the swift resolution of land disputes related to similar projects.

1. Introduction

In recent decades, world energy consumption has increased at an average yearly growth rate of 2.6%. Approximately 31% of the global energy requirement is fulfilled by oil. Coal and natural gas are responsible for meeting 29 and 21% of world energy demand. Non-conventional energy resources such as renewables (solar, wind, geothermal, biofuel, and waste, excluding hydro), nuclear, and hydropower share 11, 5, and 2% of global energy demand. Worldwide, 16.6% of electricity demand is fulfilled by hydropower [1]. In recent decades, the average annual growth rate of hydropower generation in the world has stagnated because of difficulty in locating new sites and land use controversies [2–4]. Presently, renewable energy shares 6% of the electricity demand in India. It is expected that renewable resources will fulfill 43–44% of the country's electricity demand in the future. Unlike other developed countries that have generated 80% of the estimated hydropower potential, India lags far behind at 25% [5]. India has constructed many hydroelectric projects (HEP) in the Himalayan range to tap the head difference of water for energy conversion. Recent studies claim that these projects' impact poses an unsustainable seismic threat to the young and fragile Himalayas. The Indian standard (2002) classifies the country into four seismic zones (Zone II, III, IV, and V). Indian Himalayan Range (IHR) is categorized in Zones IV and V, indicating high seismic activity in the region.

The Rio summit and Kyoto protocol have propelled the rapid

Abbreviations: AA, Additional Adit; DGMS, Director General of Mines Safety; EIA, Environmental Impact Assessment; HEP, Hydroelectric Projects; HRT, Head Race Tunnel; IHR, Indian Himalayan Range; NGT, National Green Tribunal; PAPs, Project Affected Persons; PAR, Photosynthetically Active Radiation; PPV, Peak Particle Velocity; SDG, Sustainable Development Goals; SKHEP, Sawra-Kuddu Hydroelectric Project.

* Corresponding author.
E-mail addresses: adityarana@cimfr.nic.in, adityarana.nitjaipur@gmail.com (A. Rana).

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development of hydropower projects in the Indian Himalayas. The shift towards hydel energy aims to mitigate climate change and environmental disputes associated with thermal energy. The majority of Himalayan hydropower projects are based on the 'run-of-the-river' scheme. This scheme is reckoned as an environment friendly substitute of thermal and conventional reservoir-based projects. The river water is impounded on large-scale in the construction of reservoir-based projects. This submerges vast forests and lands, inducing large displacement and greenhouse emissions.

Conversely, the river streams are channelized and diverted towards lofty mountains in run-of-the-river schemes. However, the phrase 'run-of-the-river' deceives from the associated environmental damages. These projects also comprise dams, diversion tunnels, and channels. Many run-of-the-river schemes have been constructed in a bumper-to-bumper manner on a single river basin in the Himalayas for efficient use of available energy potential. This recurrent diversion at many locations has led to the disappearance of the river from the bed. Hence, the false narration of 'clean energy' generation from Himalayas run-of-the-river schemes has withdrawn attention from disrupted environmental flows, landslides, deforestation, and other associated hazards. The GIS mapping of IHR has established the environmental impacts of hydropower

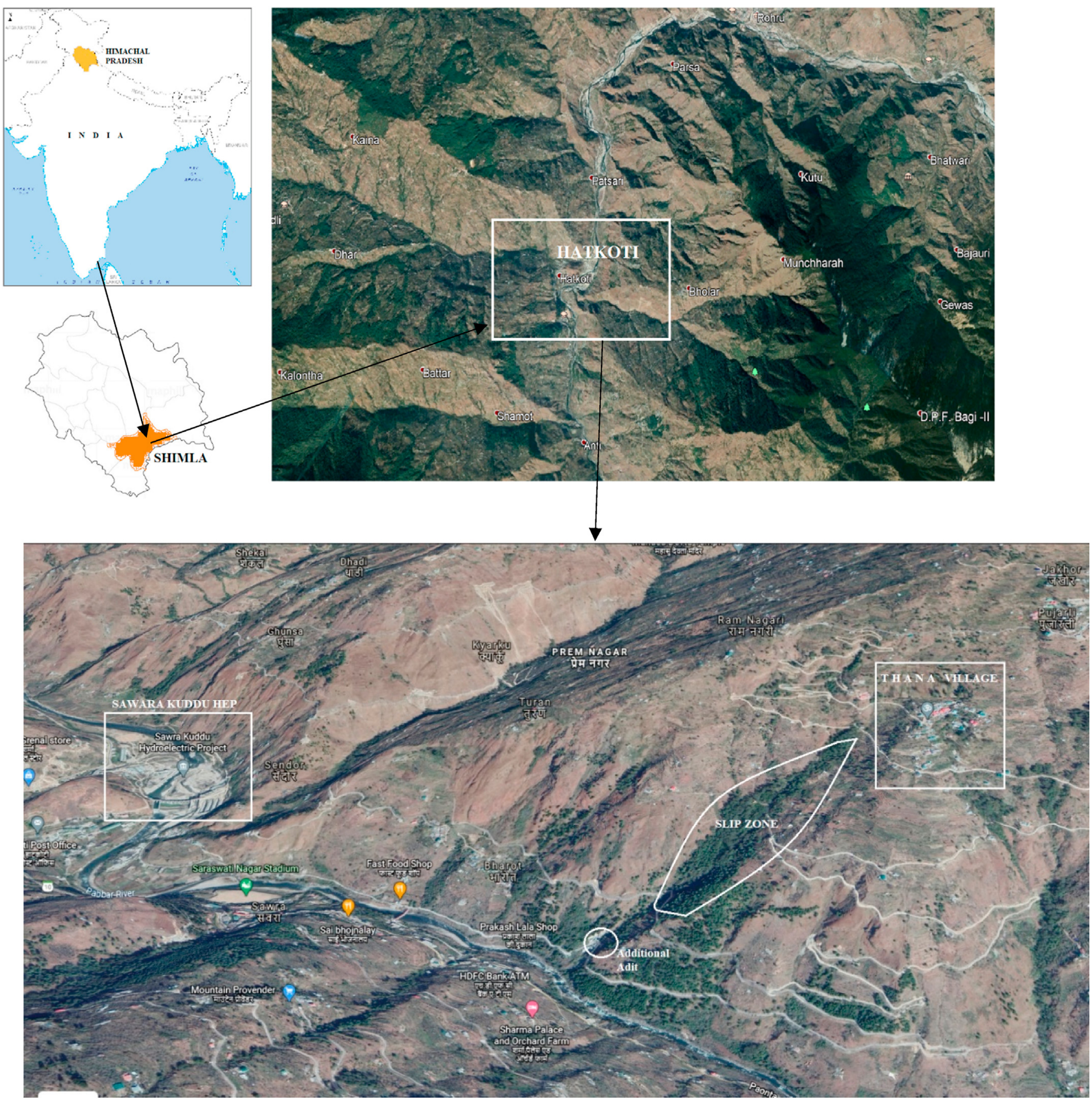


Fig. 1. Location and satellite view of SKHEP, slip zone, additional adit and Thana village on Indian map. (Source: Google Earth).

projects are not confined to fluvial ecology. A significant change in land use and land cover patterns has been reported in recent studies [6]. The 2016 Paris Agreement and high demand of renewable energy is anticipated to double the river fragmentation by 2030 [7]. Hence, riverine ecosystems are the 'biggest losers' of the 2016 Paris Agreement [8].

The tunnel construction is the backbone for the development of hydropower projects. Rock blasting plays a pivotal role in the excavation of tunnels for hydropower projects. The decades of geological activities often deteriorate the geotechnical conditions posing a challenge to blasting engineers [9–12]. The construction of tunnels in weak, fragile, and sheared rocks can test engineering expertise, especially when the alignment passes through a terrain of the active tectonic zone. The vibrations originating from tunnel blasts can significantly disturb the nearby slope's stability and reliability [13]. The large-scale blasting for excavation can damage and disturb the rock mass beyond the excavation zone. This disturbed zone around an underground opening can significantly affect these constructions' lives and performances [14]. The rock blasting at the toe of slopes has resulted in unexpected landslides at Manwan and Longton Hydropower. The blast-induced nuisances and disturbances shall be effectively minimized for ensuring the stability of associated slopes [15]. Determining the dynamic stability of high rock slopes subjected to blast-induced vibrations is a complex phenomenon. It is a prevalent research gap requiring further research on specific hydropower, water resources, mining projects [16]. The blast-induced vibrations induce shear stresses in a structural plane. Further, the inertia forces can enhance the stresses responsible for inducing slides. The easiest way to control dynamic instability is to control the charge fired per delay. The charge per delay can be limited using millisecond delay detonators, reducing blast hole diameter, and decoupling the explosive charges [17]. The allowable charge weights per delay shall be calculated by trial blasting to minimize the impacts on slopes and other nearby structures' stability. The regular blasting shall be conducted after determining safe allowable charge weights per delay from trial blasting. Further, each blast shall be carefully monitored for preventing a slope movement. The blasting vibration propagating through rock mass can greatly damage the nearby rock mass. Hence, blast-induced vibration waves' propagation shall be studied

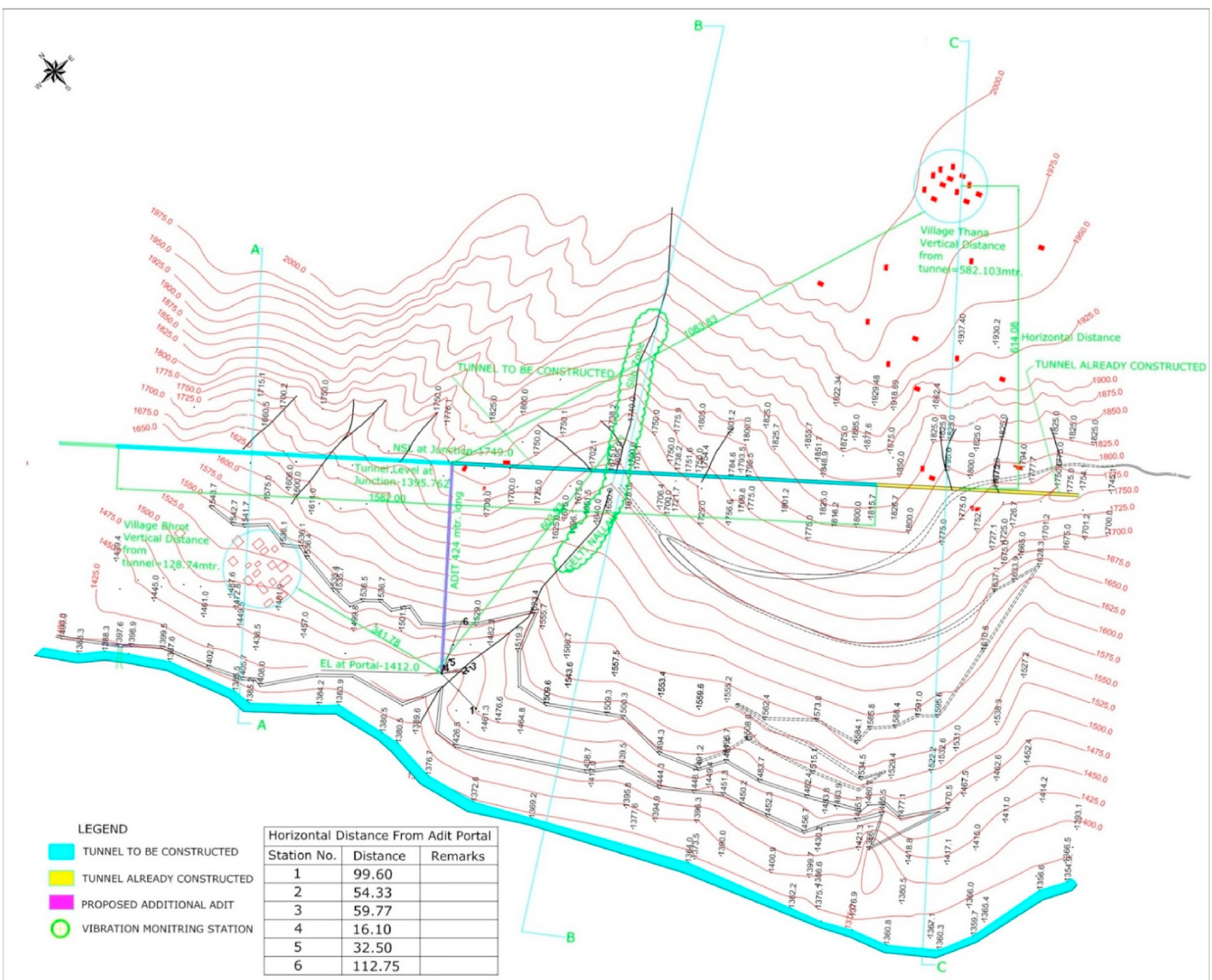


Fig. 2. A contour map showing the key features of the study area.

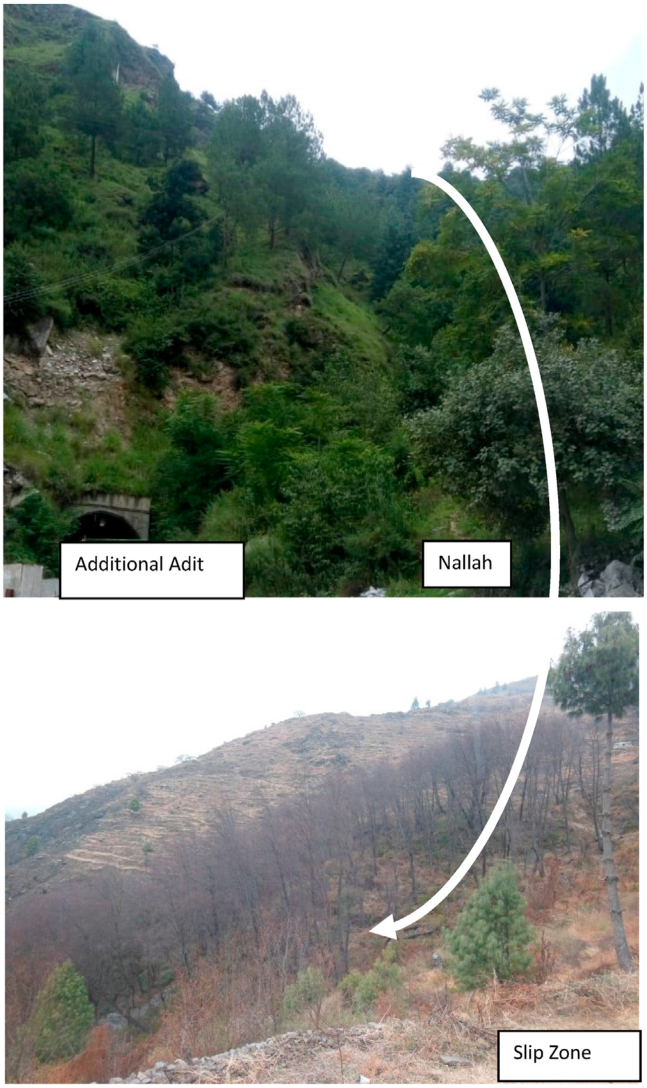


Fig. 3. Additional adit, nallah and slip zone.

for controlling the damage beyond the desired excavation area. This technique was followed for the hard rock excavation for subway construction near a critical slip zone at Thsim Sha Tsui train station in Hong Kong [18,19]. The trial blasts shall be essentially conducted for demonstrating the safety of the technique. The trials also help ascertain and verify the attenuation characteristics and exhibit that the results of ground vibrations are within the safe acceptable limits [13]. Many methods (limit equilibrium, dynamic finite element, discrete element and response spectrum) have been proposed for analyzing the dynamic stability of high rock slopes subjected to blasting vibrations. These methods ascertain the safe threshold vibration levels of high rock slopes and relate them to Peak particle velocity (PPV) or peak acceleration. On these lines, the Chinese standard GB6722–201X recommends levels of allowable vibration velocity for different frequencies at the slope foot for ensuring the safety of civil engineering slopes [20]. Yang (1989) transformed dynamic blasting vibration loads into static equivalent static loads in conjunction with the limit equilibrium analysis [21]. Zhang (1996) and Li and Zhang (2007) converted particle acceleration to static loads and applied the limit equilibrium method for analysing the dynamic stability of rock slopes [22,23]. Ayhan et al. (2008) analyzed rock slopes' dynamic stability using the quasi-static method and rigid body limit equilibrium analysis [24]. Xu et al. (2006) investigated vibration waves' time histories using the Sarma method of the rigid body limit equilibrium analysis [25]. Wu et al. (2009) deployed a borehole camera to study the crack formation and quantify the excavation damage zone around a dam formation. They proposed a relationship '$\varepsilon = dT/dH$' between unloading strain 'ε,' crack depth 'H,' and crack displacement 'T.' for quantifying the damage nearby excavation zone [14].

The hydropower projects are often developed without adequate EIA (Environmental Impact Assessment) studies [26]. The hydropower projects of the Mekong basin, China, IHR, and the Amazon, Brazil, are under the scanner of eco-activists [27]. The changing land use pattern, notably, commissioning of hydel projects, has reduced the upland forest cover in the Amazon basin. Fifteen large hydro projects have already been commissioned in the Brazilian Amazon. Further, the Brazilian government has planned to commission 37 more such projects [28]. These projects will permanently flood 1, 00, 000 sq km of upland forests [29].

Nevertheless, these constructions will cause periodic flooding in the adjoining forest area. This periodic flooding will change soil organic content, acidic levels, and nutrient profiles of upland forests in the Amazon basin. Pereira et al. (2020) investigated the short- and long-term effects of flooding on the geochemistry of upland forests in the vicinity of Balbina Hydel Reservoir, Brazil. They concluded that artificial flooding's short-term effects are carbon loss, acidification, and increased availability of soil nutrients. However, the long-term flooding reduced soil acidity and caused carbon, nitrogen losses in the soil [30]. The Aswan Dam Hydroelectric project's construction resulted in a 90% flow reduction of the Nile river in the Mediterranean. The reduced flow culminated in substantial depletion of N, Si, and P in coastal waters. Nutrient exhaustion led to decreased diatom growth.

Consequently, the diatom reliant sardine and prawn populations subsided. The EIA studies generally performed for hydropower projects aim at evaluating water quality. However, the effects on nutrient availability are seldom evaluated in these studies. The reported studies are confined to studying hydrological connectivity,

Table 1
Parameters of trial blast design and measured values of PPV.

Blast no.	Date	No. of holes	Hole depths (m)	Charge/hole (kg)	Charge/delay (kg)	Total Charge (kg)	Pull achieved (m)	Distance (m)	Vibration PPV (mm/s)	Frequency (Hz)	Seismograph location
1	23.07.15	38	1.2–1.5	0.50–0.625	5	20.0	1.3	10	5.49	45.1	Above tunnel
								15	4.83	42.6	
								56	2.67	31.66	
2	25.07.15	45	1.5–2	0.5–0.875	7–10.5	32.5	1.0	15	7.26	56.8	Nallah
3	27.07.15	44	2–2.1	0.5–1	6–9.375	30.875	1.5	100	<0.51	–	On the slip zone
4	27.11.16	18	1	0.25–0.44	4.3	6.0	0.75	>300	<0.51	–	Petitioner's house
5	02.11.16	54	1.75	0.37–0.5	12.0	25.125	1	>300	<0.51	–	Petitioner's house
6	06.11.16	61	1.75	0.37–0.5	19.0	30.75	1	>300	<0.51	–	Petitioner's house
7	08.11.16	38	1.75	0.625	15.31	17.187	1	>300	<0.51	–	Petitioner's house

greenhouse emissions, and effects on fisheries. These investigations shall be essentially performed in EIA studies [31]. The soils of agricultural regions in the vicinity shall be examined as they contribute to food, clean water, and air. Soil science greatly attributes in attaining UN Sustainable Development Goals (SDGs). Soil characteristics considerably affect biodiversity, human health, water security, land restoration, climate change, and food security of a region. The UN General Assembly in September 2015 contemplated and incorporated land degradation in SDGs. All countries have to enforce the SDGs for accomplishing the prescribed objectives by 2030. The construction disputes of hydropower projects are land-related controversies having a paramount association with SDGs. The SDG 7 recommends "ensuring access to affordable, reliable, sustainable and modern energy for all". Nevertheless, hydropower development also interferes with the SDG 6 (ensure availability and sustainable management for water & sanitation for all) and SDG 13 (take urgent action to combat climate change and its impacts) [32]. Hence, the development of hydel projects and the associated land use pattern shall be investigated for achieving United Nations Sustainable Development Goals (UNSDGs) [30]. The participating countries at the Rio 12 sustainable development conference unanimously also resolved to free the world from land degradation to attain sustainable development [32].

The development of hydel projects has exerted an acute anthropogenic load on the montane forest ecosystem of IHR [33]. IHR is home to thousands of flora and fauna species, each adapting to its unique climatic conditions and other challenges. IHR houses about 50% of the total flowering plants in India. The cultivation of apple and other fruits plays a vital role in the economy of IHR [34]. Recent studies claim that the tunneling activities for construction of HEPs have adversely affected flora, fauna, biodiversity, agriculture, wildlife, and pasture lands in the IHR.

Moreover, the blasting in weak rock mass for the construction of HEPs may trigger landslides and is an immediate matter of concern [35]. The Geo-environmental assertions are postulated in the aforesaid investigations (pertaining to IHR) by surveying the

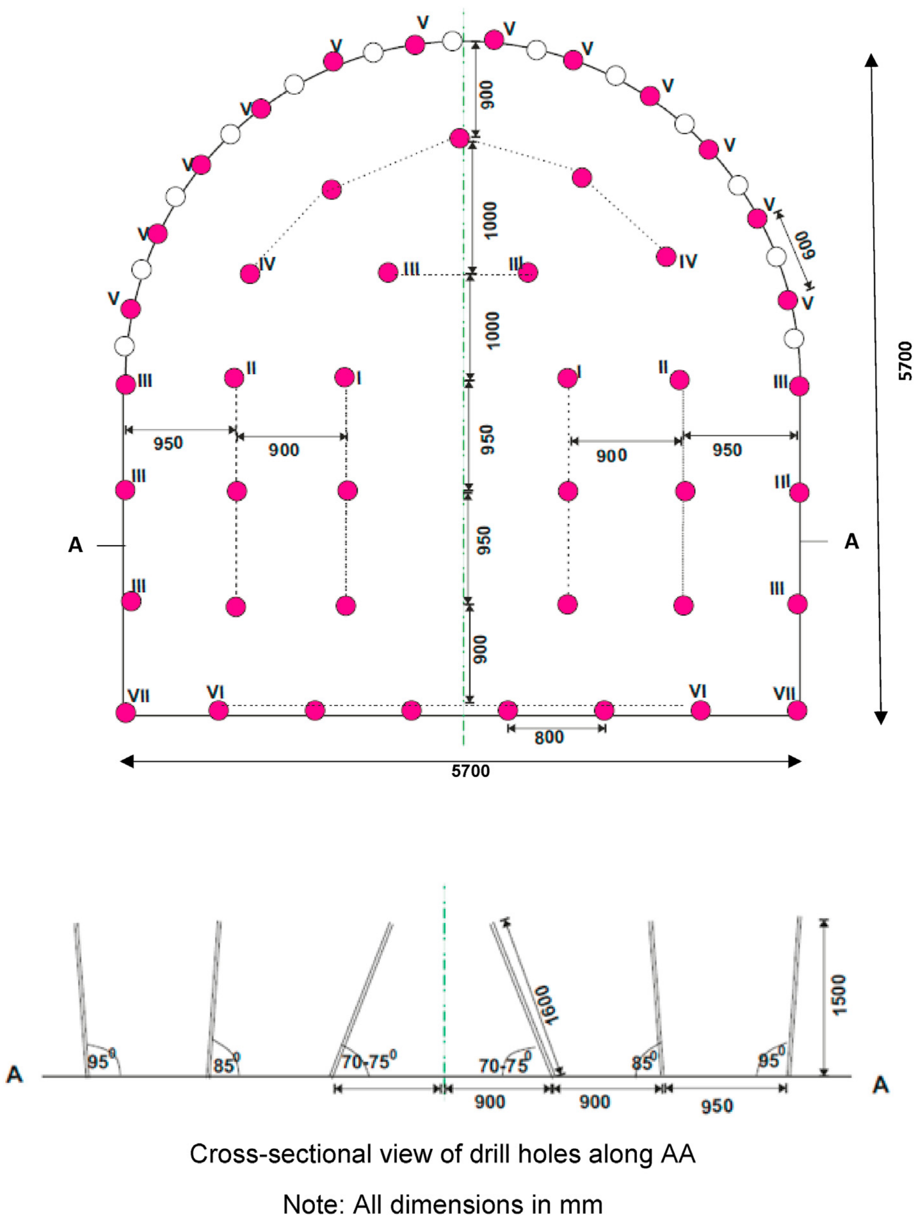


Fig. 4. Drilling and firing pattern for Q-value less than 1.

perceptions of project affected persons (PAPs); hence, these opinions cannot be considered scientific. The uncertain impacts of HEP on surroundings have resulted in continual disputes between PAPs and project builders [36]. The lack of research investigations studying the Geo-environmental influences of HEP has aggravated these land use disputes [37].

1.1. Research significance

Hydropower development is synonymous with environmental and land-use disputes. Disorganized, rapid, and extensive development in the fragile and diverse IHR has damaged the ecosystem. In IHR, the mountain rivers have been cascaded to reservoirs and diversion tunnels of hydropower projects. The recurrent channelization of the river for different hydro-projects has virtually dried it at many parts. Consequently, the region has been plagued by devastating floods, landslides, deforestation, soil erosion, biodiversity loss, and forest fires. This impairment in the Himalayan ecosystem is attributed to the rapid increase in hydropower development [38].

In 2013, the country faced a catastrophic disaster consisting of floods and landslides in the Uttarakhand Himalayas. The experts opined that the incessant disruption in Ganges' natural flow and its tributaries was a prime reason behind this disaster. PAPs have launched many protests to dissent against the socio-economic and ecological impacts of Indian HEPs. The Tehri Dam and Save Narmada protests lasted for several years, with much opposition from the masses [39]. Notwithstanding, the Indian government is keen on utilizing the untapped hydropotential of the country [39].

There is a dearth of objective research investigating and addressing the concerns raised by the PAPs of SKHEP. The available literature on the subject either survey the opinions of PAPs or analyze satellite imageries near HEP. The consequences of hydropower construction on the regional soil and apple cultivation (an

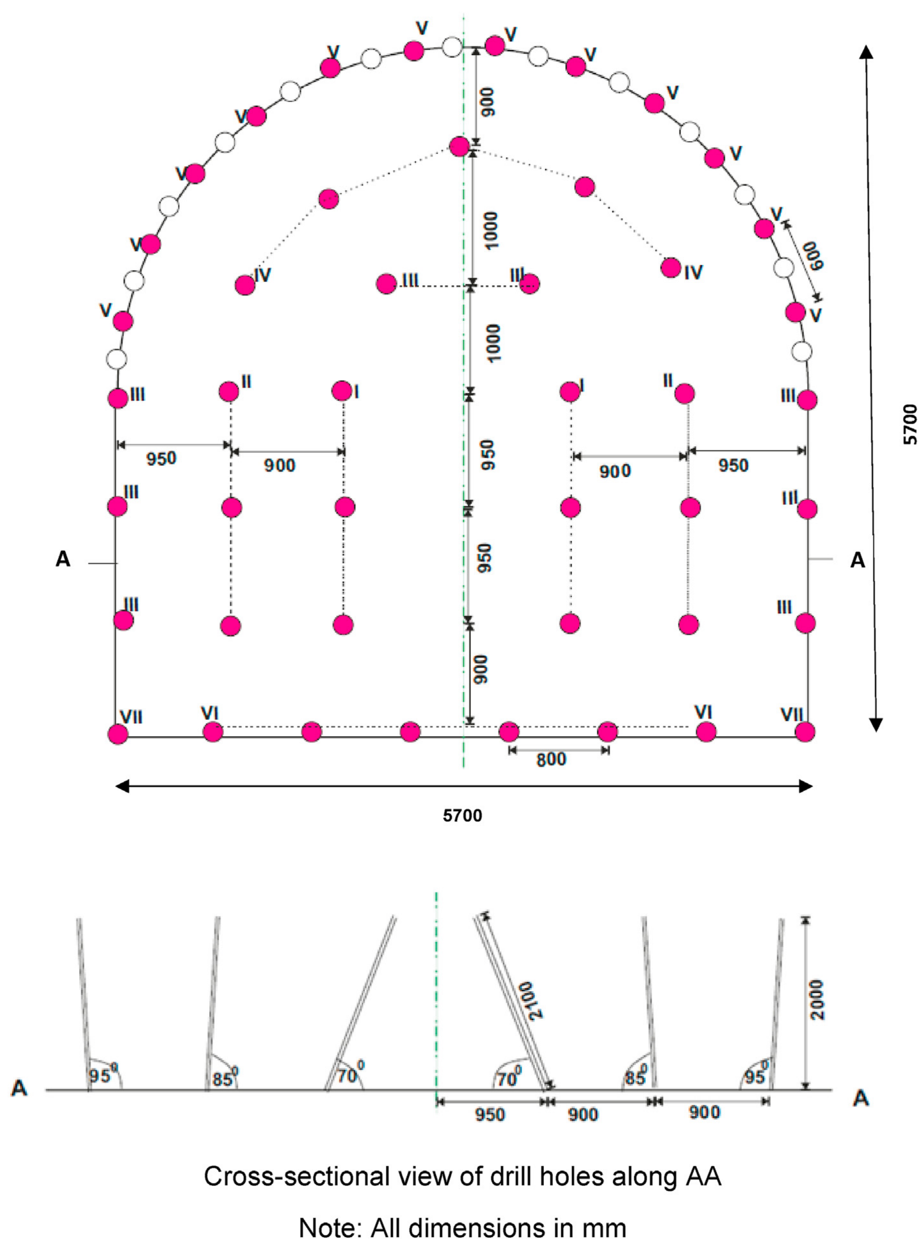


Fig. 5. Drilling and firing pattern for Q-value more than 1.

important and high-value cash crop of the IHR) have never been investigated experimentally. The effects of tunnel blasting and the controlled blasting for safe excavation near a slip zone susceptible to landslide have not been reported previously.

The apex court of India has imposed a ban on the construction of twenty-four HEPs in IHR due to PAPs' environmental concerns. The government of India urged the Supreme Court to uplift the ban partially. However, the apex court declined, citing that the Geo-environmental impacts of mining, tunneling, and blasting on the Himalayan ecosystem have never been investigated scientifically. The present study is significant as it addresses some notable points raised by PAPs during the construction of a hydropower project in the IHR.

1.2. Background of the study: concerns raised by PAPs

PAPs of Sawra-Kuddu HEP lodged their grievances in the National Green Tribunal (NGT), New Delhi, to cease Sawra-Kuddu HEP's construction. The concerns raised by PAPs are as follows:

(i) The villagers apprehended that the seismic vibrations induced during the tunnel blasting for excavation of additional adit to head race tunnel (HRT) can destabilize 300 m high unstable slip zone. The village Thana is located 600 m above the slip zone, and the villagers were anxious that the failure of slip zone would devastate the village.
(ii) The villagers claimed that the blast-induced vibrations for the tunnel construction are damaging their houses.
(iii) The villagers petitioned that tunneling activities are degrading the apple cultivation.

The tribunal took a serious note of the petition and imposed a ban on the construction activities of the HEP [40–42]. At the time of the court's order, all tunnels excluding additional adit to HRT were excavated. Further, the NGT constituted a committee consisting of authors to (i) ascertain the causative parameters behind the claims of PAPs and (ii) investigate the feasibility of sustainable construction of the additional adit to HRT.

2. Site

Sawra-Kuddu HEP is a 111 MW run-off-the-river scheme on the Pabbar River near Hatkoti (Tehsil - Jubbal, District - Shimla, State - Himachal Pradesh, India). The location of SKHEP, slip zone, additional adit, and Thana village on the Indian map and satellite image is shown in Fig. 1. The project's main components are barrage, power intake, desilting chambers, HRT, surge shaft, pressure shaft, underground powerhouse, transformer hall, pothead yard, and tail race tunnel. These structures have been constructed using the 'Drill and Blast" method of excavation. A 424 m long D-shape additional adit (AA) was under excavation to expedite the tunneling work of HRT.

The main hurdle for the excavation of AA was its proximity to the Thana Slip zone. The slip zone lies at about 220 m away from AA axis and 500 m from the AA-HRT junction. Thana is situated atop of the slip zone and around 1083 m away from the junction, as shown in Fig. 2. Villagers apprehended that the tunnel blasting during the excavation of AA can reactivate the slip zone, resulting in a landslide, devastating the Thana village (Fig. 3). A nullah adjacent to AA that drained the water during the seasonal rainfall formed the slip zone base.

The adit was excavated up to 29 m before the tribunal imposed the stay. Exposed rock at the adit face and within the adit was mainly Quartz-phyllite Schist. The rock was moderately to highly jointed, thinly foliated and sheared. The joints were smooth and rough planar. The discontinuities were filled with clay. At a few locations, the joint planes were also stained, indicating the weathering effect. The orientations of major discontinuities were N15°-30°E (15°–20° Dip), S60°-80°W (75°–80° Dip), and S30°-40°E (60°–80° Dip). Water seepage within the tunnel was not

Fig. 6. Satellite image showing the location of additional adit, slip zone, Thana village and main monitoring points. (Source: Google Earth).

observed. Q value of rock mass varied between 0.02 and 4.

3. Methodology

The investigation was designed in such a manner that each concern postulated by the PAPs is scientifically addressed. The methodology was divided into four below-mentioned sub-points:

(i) Designing and blasting trial rounds in additional adit of the hydropower project.
(ii) Measuring the intensity of the blast-induced ground vibration at the slip zone and near the petitioners' structures.
(iii) Studying the extent of structural damages in Thana village and ascertaining the causative parameters.
(iv) Horticulture study (soil fertility and photosynthesis in apple orchards)

3.1. Trial blasts

For the trial study, seven blasts were fired within Additional Adit. The design parameters of different blasts for the trial study are given in Table 1. The vibrations originating from the blasts were measured near petitioners' structures and slip zone. The blasts were conducted using emulsion explosives (Superpower 90) and long delay detonators. The depth of blast holes was varied between 1 and 2 m with a drill hole diameter of 45 mm. The number of blast holes in trial rounds was varied between 18 and 61. The quantity of explosives charged within a blast-hole varied between 0.25 and 1 kg. The maximum charge fired within a delay ranged between 4.30 and 19 kg for different trials. Total explosives fired in a round ranged between 6 and 32.50 kg. The rock mass was excavated using two drilling and firing patterns. The pattern represented in Fig. 4 was used when the rock mass quality (Q-value) was less than one. In contrast, the pattern shown in Fig. 5 was used when the Q-value was more than 1.

3.2. Vibration measurement

The seismic parameters (particle displacement, PPV, particle acceleration, and their associated frequencies) of a blast can be co-related to any structure's destructive potential. The seismic

a: Vertical and horizontal cracks in a house of Thana Village

b: Horizontal cracks in a house of Thana village

c: Horizontal, vertical and oblique cracks a house of Thana village

d: Horizontal and vertical cracks in a house of Thana village

Fig. 7. Cracks in the village houses
Fig. 7a: Vertical and horizontal cracks in a house of Thana Village
Fig. 7b: Horizontal cracks in a house of Thana village
Fig. 7c: Horizontal, vertical and oblique cracks a house of Thana village
Fig. 7d: Horizontal and vertical cracks in a house of Thana village.

measurements were conducted at structures located in the Thana and other villages in the slip zone's vicinity and an additional adit (Fig. 6).

The blast-induced dynamic response can be easily monitored using PPV [43]. It is a universally accepted vital parameter for evaluating the blast-induced damage to surface structures. The blast-induced ground vibration in PPV (mm/s) was recorded using digital seismographs with an inbuilt microprocessor and external triaxial transducer. The transducer records PPV in three orthogonal directions (Longitudinal, Vertical, and Transverse). These PPVs can be summed to obtain a peak vector sum. The seismograph also recorded frequencies in each direction. The triggering level of the seismograph was 0.51 mm/s. It analyzed the frequencies using Fast Fourier Transform analysis. It also depicted the dominant frequency (the band with the highest energy/amplitude) for a blasting event.

3.3. Studying structural damages

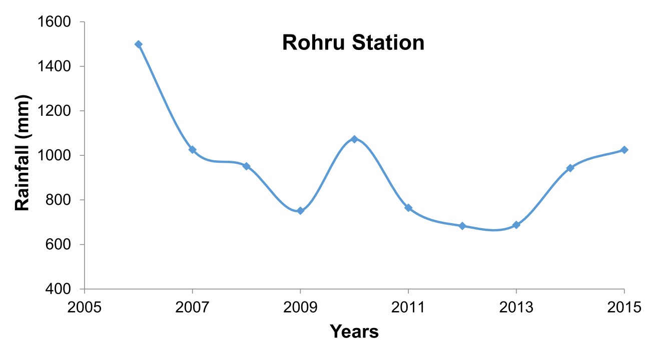
A detailed survey concerning the nature, pattern, and extent of structural damages in the Thana village was conducted. The inspection revealed the following facts:

(i) The general construction quality of the houses consisted of dry-stone rubble masonry with clay or cement plaster. Few houses were also noted to be constructed over RCC columns and beam.
(ii) Single and double-story houses were typical in the village, with their age varying between 1 and 25 years.
(iii) Wide horizontal, vertical, and oblique cracks were noticed in the majority of houses (Fig. 7), except the houses constructed over columns and beams (Fig. 8). The width of the cracks ranged from 1 mm to an inch. Similar cracks were also observed on the floor and along the junction of the walls and ceiling.
(iii) Cracks' natures were similar in almost all the houses; however, they were more prominent and frequent in double-storied buildings.

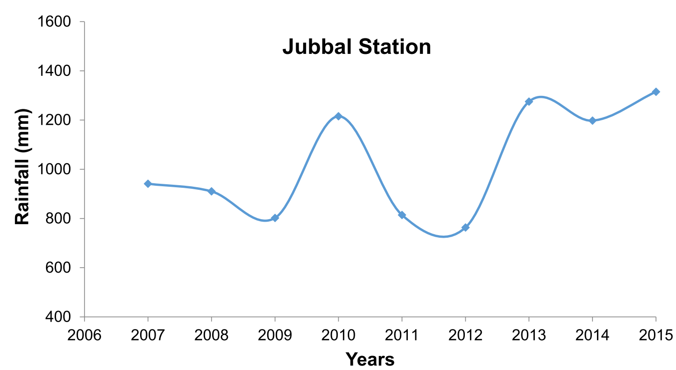
Fig. 8. A building over columns and beams without any cracks.

Rainfall data were collected from the rain gauges installed at Jubal and Rohru, situated 12.5 and 13 km, respectively, from the site. Annual rainfall data at the two stations are depicted in Fig. 9.

The structural elements, such as walls and ceilings, can crack due to many reasons. The variation in moisture and temperature, elastic deformation, creep movement, reinforcement corrosion, chemical reactions (alkali-silica reaction, sulphate, carbonation, acidic reactivity, etc.), subsurface settlement due to unequal bearing pressure, vegetation growth, poor quality construction material, building house on a hill, etc. Are some of the major causes responsible for cracking the building elements [44,45]. The shearing and settling actions can crack the house walls in a varying manner (horizontal, vertical, and transverse). The seismic motions generate X-cracks because the relative motion of foundations induces tensile stresses along the house walls' diagonals [46].



a: Annual rainfall recorded at Rohru station



b: Annual rainfall recorded at Jubbal station

Fig. 9. Annual rainfall recorded at the stations adjacent to SKHEP
Fig. 9a: Annual rainfall recorded at Rohru station
Fig. 9b: Annual rainfall recorded at Jubbal station.

Table 2
DGMS standard for permissible limit of ground vibration (Technical Circular Number 7 of 1997).

Type of structure	PPV in mm/s at foundation level of structure at Dominant excitation frequency, Hz		
	<8 Hz	8–25 Hz	>25 Hz
(A) Buildings/structures not belong to the Owner			
1. Domestic houses/structures (Kuchcha, brick & cement)	5	10	15
2. Industrial buildings	10	20	25
3. Objects of historical importance and sensitive structures	2	5	10
(B) Buildings belonging to Owner with a limited span of life			
1. Domestic houses/structures	10	15	25
2. Industrial buildings	15	25	50

Fig. 10. Monitoring of blast vibrations near structures in Thana village.

3.4. Horticulture study

Soil samples were collected at four locations; three samples were collected from petitioners' apple gardens (Jhobta, Chatranta, Baliram Thakur), and one sample from the apple garden belonging to the hydropower project. The investigated sites were located at a distance greater than 300 m from the additional adit. The soil samples were collected from 15 to 30 cm depth by auger digging. The collected samples were tested for soil fertility and minerals/nutrient concentration.

As mentioned earlier, photosynthetic investigations were also conducted in ambient climatic conditions on intact plants at the locations. A portable photosynthetic system was used to assess the Photosynthetic rate (Ps), Stomatal conductance (Gs), Transpiration rate (E), Soil respiration (SR), and Intracellular CO2 concentration (Ci) in the field. The measurements were made on cloud-free days between 09:00 and 10:00 h. During the measurements, the Photosynthetically Active Radiation (PAR) ranged between 1100 and 1200 μmol m^{-2} s^{-1}. Only healthy and mature leaves devoid of any injury were considered in the analysis of physiological parameters.

4. Results and discussion

4.1. Structural damage in Thana village

The structural response to blast-induced vibration is influenced by many factors such as age, height, weight, stiffness, type, quality of construction material, state of foundation, repair, etc. Directorate General of Mines Safety (DGMS), India, has specified the PPV limits for different structures (Table 2). The FFT analysis (>25 Hz) indicated that a PPV up to 15 mm/s is safe for the structures. However, the scientific team considered 5 mm/s as a safe vibration limit for Thana village structures, considering extreme safety to PAPs' structures. The PPV measurements near the PAPs' structures for trial blasts no. 4, 5, 6, and 7 (Table 1) indicate that the blast-induced vibrations cannot trigger a seismograph in the Thana village (Fig. 10). The magnitude of vibration was imperceptible (<0.51 mm/s) and cannot damage structures as per DGMS.

The wide horizontal cracks in the buildings indicate vertical tensile forces oriented towards the foundation. The settlement or downward movement of foundation can be held responsible for vertical tensile forces. Similarly, the occurrence of vertical cracks indicates the movement of the foundation in the horizontal direction. The oblique cracks are the result of the interaction between vertical and horizontal tensile forces.

As the magnitude of vibration recorded in the village was insignificant, it cannot instigate such damage or crack in the houses. The leading cause of such cracking as per the crack morphology appears to be a substantial foundation settlement or movement possibly due to the following reasons:

1. High fluctuation in annual rainfall causing swelling and shrinking of the foundation,
2. Storage of high magnitude strain imparted due to plate tectonics.

Rainfall gauges installed at Rohru and Jubbal monitoring stations were taken into consideration in the assessment of rain precipitation occurring in and around the Thana village, as this area lies midway between the above two stations. The rainfall plots shown in Fig. 9 indicate a high fluctuation of annual rainfall in and around the project area. The rainfall fluctuation may have imparted swelling and shrinkage pressures within the ground, causing foundation movement. This movement generated tensile forces, created cracks in the houses, and contributed to the foundations' resettlement.

It is a fact that the Indian plate is moving below the Chinese plate (Fig. 11). In this tectonism, the Indian plate reflects the tremendous stress and strain, which will ultimately be released in a

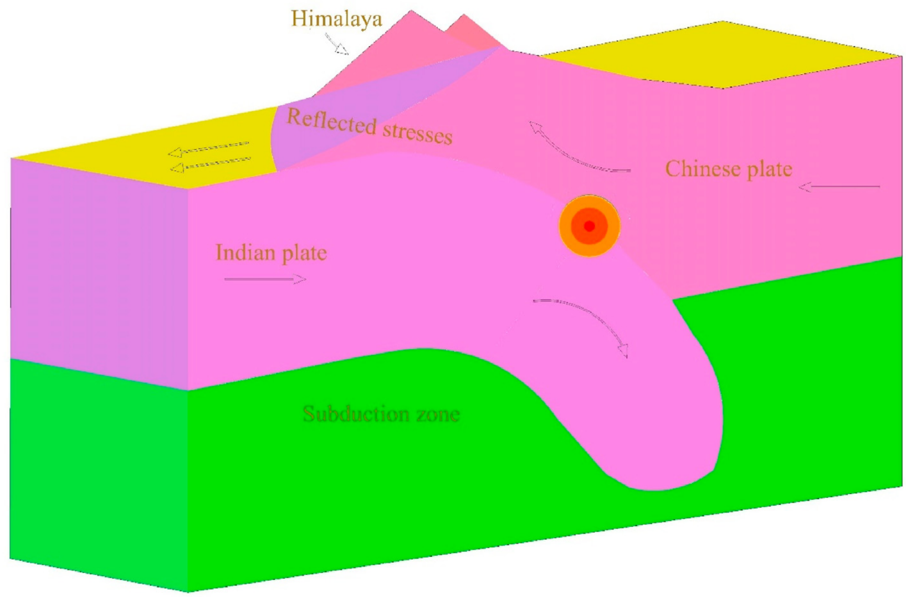


Fig. 11. Tectonism between Indian and Chinese plates.

direction where the rock-air interface exists. It can be seen from Fig. 12 that high rise slopes have fair possibilities to release the strain stored in the rock mass due to the existence of the rock-air interface. In such a condition, it is quite likely that the foundation may resettle in the process of strain release. Consequently, depending upon the direction of release of strain, horizontal, vertical, and oblique cracks would appear in the buildings and may widen in due time. On the other hand, the houses constructed on the almost horizontal/flat ground surface may not suffer such severe damages as there is no free space to release strain. The construction of the foundation and superstructure using heavy drystone rubble masonry with clay or cement plaster will generate high relative movement and cracks in such circumstances.

4.2. Vibration measurement at slip zone

The PPV measured on Nallah (foot of slip zone) at 15 m from the blast face was 7.26 mm/s (frequency-56.8 Hz). However, the seismograph did not trigger at a distance of 100 m on the slip zone. The Chinese standard GB 6722−201X (Table 3) was used for ascertaining the effects of blasting on the slip zone due to the unavailability of an Indian standard correlating PPV to slope stability. The frequency of blasting vibrations can significantly affect the stability of slopes [47]. The frequency of recorded vibration was more than 50 Hz, and the permissible PPV (Table 3) at this frequency is 10 cm/s. The recorded vibration was around 13 times less than the minimum permissible value. Similar studies on the subject also indicated that the blast-induced PPV is significantly less to cause damage at the investigated sites. Cai et al. [48] and Zhang [49] measured the sonic wave velocities pre- and post-blasts and conducted vibration monitoring at the Three Gorges project. They concluded that a PPV between 13.8 and 16.6 cm/s generated a 0.20−0.70 m deep fracture zone having a radius of 1.4−2.0 m. Furthermore, Huang and Song [50] concluded that at a PPV of 3.5 cm/s, negligible damage is induced in the rock mass. Haibo et al. (2011) [51] manifested a safety threshold level of 5 cm/s for preventing damage to parent rock mass located 30 m away from the charge hole in bed rock blasting for a nuclear power plant.

Hence, it was concluded that the slope of the slip zone would withstand the blasting vibrations of the additional adit.

The Jutogh nappe has been formed due to plate tectonic movement along a low-angle thrust fault. It has caused crushing of rock along the plane of movement, as evident from Figs. 13 and 14. In such a zone, natural weathering and erosive forces would obviously remove the crushed or clay material down the stream and widen the slip zone dimension.

4.3. Horticulture study

Spatial variations in photosynthesis rate, transpiration rate, stomatal conductance and intracellular CO_2 of different apple plots are shown in Fig. 15. Photosynthesis rate, stomatal conductance and intracellular CO_2 were highest in the Baliram plot, followed by Chatranta, SKHEP Guest House and Jhobta plots. The highest transpiration rate in apple plants was noted at Chatranta, and the lowest in Jhobta plots (Fig. 15). The maximum spatial variation was observed for stomatal conductance and minimum for photosynthesis rate.

Stomatal conductance estimates the gas exchange rate (carbon dioxide uptake) and transpiration (water loss) through the leaf stomata as determined by the degree of stomatal aperture. In simple words, it measures the physical resistance to the movement of gases between the air and the leaf's interior. It is a function of the density, size, and degree of opening of the stomata. Higher values of open stomata will permit greater conductance and enhance photosynthesis, transpiration rates. The results indicate that the apple species in Baliram and Chatranta perform better plant physiological processes than the SKHEP Guest House and Jhobta plots. For this reason, the apples of Baliram and Chatranta plots were larger than the SKHEP Guest House and Jhobta plots.

The values of soil temperature, moisture, and respiration (CO_2 efflux) were almost similar in all the plots (Fig. 16). Nutrient uptake by plants is essential for their development and passage of minerals into the food chain. Soil fertility is one of the crucial factors controlling crop yields. Soil physicochemical characteristics such as macronutrients (N, Ca, Mg) and micronutrients (B, Zn, Fe, Cu, Mn) are important elements controlling fertility. The soil analysis suggested that the major nutrients (Nitrogen, Ca and Mg) were in low

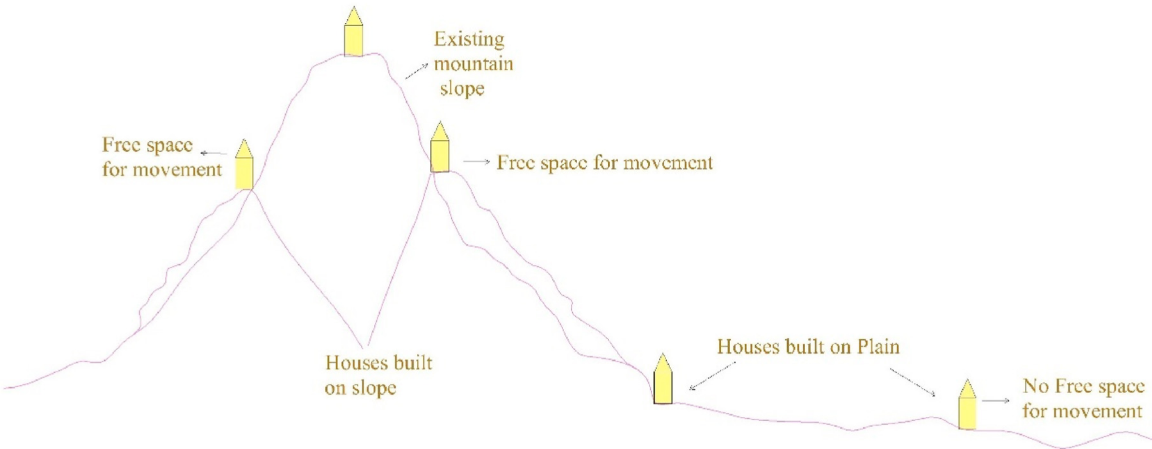


Fig. 12. Strain release causing cracks in the houses located above the hills.

Table 3
Safe values of PPV at slope foot (cm/s) as per GB6722–201X.

S. no.	Vibration frequency (Hz)	Safety PPV at slope foot (cm/s)
1	Below 10	5–9
2	Between 10 and 50	8–12
3	Above 50	10–15

Fig. 13. Strata showing normal dip with mild effect of thrusting of the nappe.

to medium concentration and secondary nutrients (Boron, Zinc, Copper and Manganese) were in desired concentration (Table 4).

Significant findings of the horticultural investigation are as follows:

1. Physiological processes (Photosynthesis, Transpiration and plant respiration) were observed to be normal, indicating that the soil's required moisture exists.
2. The tested values of major nutrients like Nitrogen, Calcium, and Magnesium were within the low to the medium range due to flowering and fruit development. The plant absorbs a drastically high quantity of nutrients and moisture in these stages.
3. The deficiencies can be overcome by adding suitable organic fertilizers in the initial stage of flowering and fruit development from time to time.
4. Mild variations in physiological processes may occur depending upon the quantity of naturally occurring nutrients and moisture at concerned sites.

5. Conclusion

The present study fills the research gap by objectively addressing and resolving the litigations related to run-of-the-river hydel projects. PAPs' assertions to halt the construction activities of the hydel project were found inaccurate and trivial. The vibrations originating from the adit excavation were imperceptible and incapable of inducing structural damages. The observed structural cracks can be attributed to differential foundation settlement/ movement due to variation in annual rainfall and tectonic strain. The intensity of blast-induced ground vibrations was insufficient to trigger the landslide of the slip zone. Normal physiological processes in apple crops indicated the presence of adequate moisture in the soil. The deficiency of significant nutrients during the flowering or fruit development stage can be effectively mitigated using organic fertilizers.

Upon submitting the investigation report, the National Green Tribunal uplifted the ban on additional adit construction and other

Fig. 14. Vertical joint plane with nappe indicating high tectonic forces near Thana village.

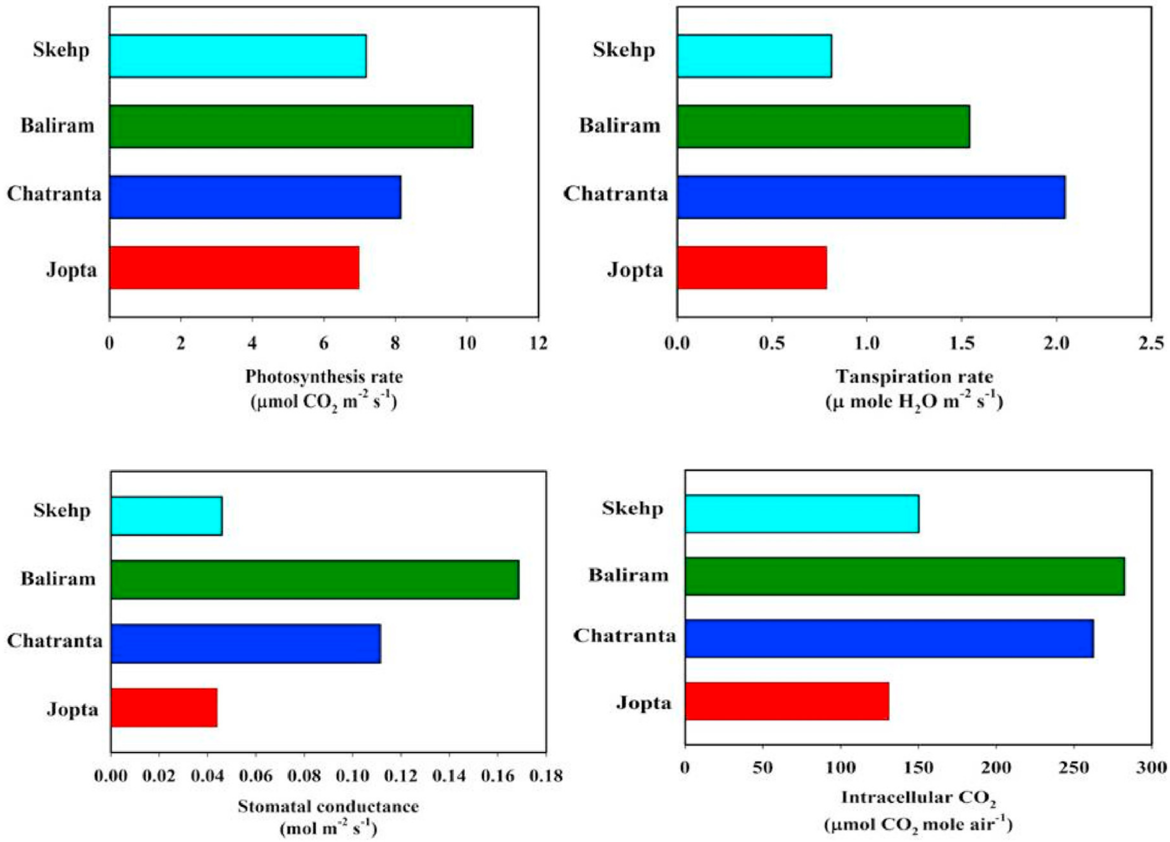


Fig. 15. Variation in rate of photosynthesis, transpiration, stomatal conductance and intracellular CO_2 at different plots.

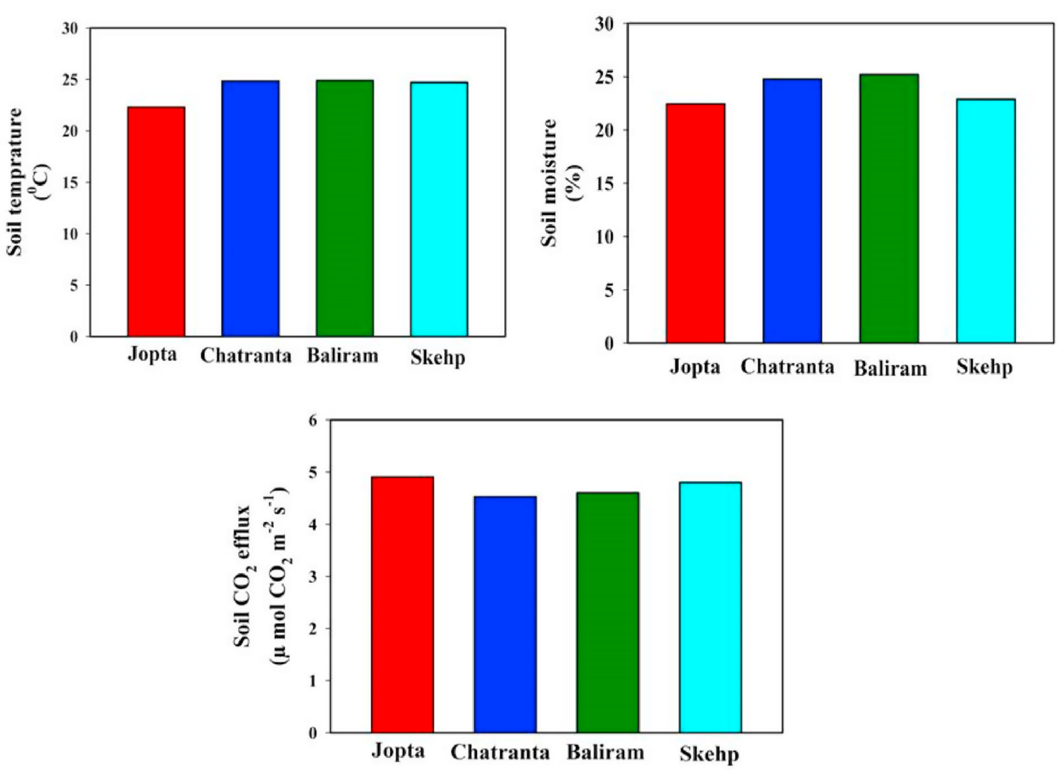


Fig. 16. Spatial variations in soil temperature, moisture and CO_2 efflux.

Table 4
Nutrients present in the soil.

S.no.	Sample	pH (1:2)	EC (ds/m) (1:2)	N (kg/Ha)	Ca (mg/kg)	Mg (mg/kg)	B (mg/kg)	Zn (mg/kg)	Fe (mg/kg)	Cu (mg/kg)	Mn (mg/kg)
1	Jhobta	6.44	0.46	314	1448	201	1.90	11.40	32.50	10.50	16.90
2	Chatranta	5.82	0.14	230	718	103	0.97	2.64	38.80	2.06	10.80
3	Baliram	5.92	0.22	209	761	62.80	0.56	3.36	35.10	0.88	3.78
4	Guest house	6.22	1.60	273	1639	58.80	1.82	7.70	35.10	7.94	9.39

remaining structures. However, the tribunal further ruled that all blasts shall be designed as suggested, and the authors shall monitor the resulting vibrations during the construction. The vibrations originating from all the blasts were well within the limit (Annexure 1). The scientific investigation resulted in the timely construction of the 111 MW project.

PAPs of integrated Kashang valley hydroelectric project (243 MW) have claimed that the tunnel and underground blasting has distressed local geology, flora, fauna, commercial horticulture, eroded soil and triggered slope failures/landslides in the endangered area [52–54]. Similarly, three tunnel-based run-of-the-river projects (480 MW Pala Maneri, 381 MW Bhairon Ghati, and 600 MW Loharinag Pala HEPs) have been suspended by the Indian Government in Bhagirathi valley due to similar concerns [55]. The Loharinag Pala HEP has been shelved as the PAPs have claimed that the tunnel blasting has cracked and damaged Pala village and Bhatwari town's roads. PAPs of Singoli Bhatwari HEP are perturbed on similar lines because of landslides, vegetation loss, and cracks in houses. The study's findings can be applied to Kashang valley, Pala Maneri, Bhairon Ghati, Singoli Bhatwari, Nyamjang Chu, Pala Maneri, Loharinag Pala, Punatsangchhu, and many such run-of-the-river HEPs battling in the tribunals. The investigation results will help in tapping the litigated hydropower potential around the world. Further, the replication of similar methodology will aid in settlements of justified claims of PAPs.

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CRediT authorship contribution statement

Aditya Rana: Writing – original draft, Visualization, Formal analysis, Investigation, Validation. **Siddharth Singh:** Formal analysis, Investigation, Resources. **N.K. Bhagat:** Writing – review & editing, Resources, Investigation. **M.M. Singh:** Conceptualization, Methodology, Funding acquisition, Supervision. **G.P. Jadaun:** Data curation. **P.K. Singh:** Project administration.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supplementary data

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