Specific blasting technique for tunnelling in hot zones

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Encountering hot zones while excavating tunnels for hydropower projects in the Himalaya, India, is a challenge for civil engineers. Blasting within the hot rock mass can pose serious threats due to possibility of temperature-induced unintended detonation of explosives. Moreover, the paucity of a suitable rock-blasting method for these hot zones sometimes compels engineers to realign the tunnel. Such a realignment is costly and time-consuming. A temperature of 50–98°C was encountered while excavating the rock mass for head race tunnel of Karchham–Wangtoo Hydro-Electric Project, Himachal Pradesh, India. The Directorate General of Mine Safety, India, suggests that blastholes with temperature greater than 80°C must not be charged and blasted. Similarly, the use of electric or non-electric detonators is discouraged above 70°C because of premature detonation. Hence excavation works were suspended for tunnel construction. A unique drill and blast method has been adopted for blasting the hot strata in the tunnel. The technique described in this study can be easily followed in similar situations for tunnel-rock excavation.

Keywords: Excavation sequence, geothermal energy, hot zone, quenching, tunnel blasting.

Background

GEOTHERMAL energy is a form of energy generated by the earth and accumulated within its strata. The geothermic domains are sometimes encountered during tunnelling and cause sudden increase of temperature on the blast face. Studies to determine geothermic zones are not conducted during the initial planning. The occurrence of high geothermic gradients and hot-water springs has been reported in the higher Himalaya, India. The geothermic gradient (90°C/km) of Tattapani, Himachal Pradesh, India, is capable of generating an energy potential of 1 MW (ref. 1). At Manikaran the maximum temperatures of right and left bank of Parvati river differ by around 60°C (ref. 2). A geothermic hot zone of 50°C was reported while excavating a tunnel under the Naptha–Jhakri Hydroelectric Project, located 6.3 km away from the Karchham–Wangtoo Hydro-Electric Project (KWHEP)[3]. The sudden emergence of a hot zone while tunnelling poses risk to blasting engineers and results in cost overrun. Tunnelling through hot zones is challenging because of high temperature, humidity and poor working conditions[4].

Drill and blast method (DBM) is commonly deployed for tunnel excavation in the Himalaya. The use of drilling and blasting to fire hot zones for tunnel excavation has never been reported in the literature. However, some researchers have studied the behaviour of explosives under high temperature and suggested a methodology to blast holes in fire zones of open-pit mines. Nabiullah *et al.*[5] studied the sensitivity of slurry, emulsion and nitroglycerine-based explosives exposed to high temperatures. They observed that slurry explosives lost their gel structure above 80°C and got ignited at a 160° ± 5°C. The emulsion explosives retained their properties up to 130°C and got ignited at 193° ± 10°C. Holiday and William[6] postulated minimum runaway time and recommended the use of emulsion explosives for blasting hot holes with temperature above 65.5°C in open-pit mines. Royal demolition explosive (RDX) or high melting explosive (HME) cords can be used for connecting emulsion explosives. They also suggested a drilling and blasting procedure for hot holes of open pit mines above 65.5°C (Table 1). On the contrary, Nabiullah *et al.*[7] reported that detonating fuse (DF) retains its stability up to a temperature of 110°C and can be used between 65.5°C and 110°C. However, the above-mentioned studies were limited to open-pit mines, where the working conditions differ from underground mines or tunnels. No relevant international research is available for blasting hot zones in tunnels and underground mines. The present work aims at addressing this paucity in the literature.

Project review

KWHEP is a 1000 MW run-of-the-river project built on River Sutlej at Karchham Wangtoo village of Kinnaur district, Himachal Pradesh. The project aims at harnessing hydel potential of the river by constructing a concrete gravity dam of 88 m height having six sluice spillway bays of size 9 m × 9 m, desilting chambers and a 17.2 km long and 11.28 m in diameter horse shoe-shaped head

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Table 1. Runaway time during charging of explosives and procedure prescribed for blasting hot holes in open-pit mines

Highest temperature in borehole (°C)	Maximum total explosive time	Products to be used
37.7	NA	Pentolite primers, shock tube and detonators, bulk or cartridge blasting agent
37.7–65.5	NA	Pentolite primers, PETN cord products, no in-hole detonators, bulk or cartridge blasting agent
66.1–93.3	5 h	25/40 g RDX or HMX cord as down line
93.8–121.1	3 h	25/40 g RDX or HMX cord as down line and primer package emulsion blasting agent
121.6–148.8	1 h	25/40 g RDX or HMX cord as down line and primer package emulsion blasting agent
149.4–176.6	30 min	25/40 g RDX or HMX cord as down line and primer package emulsion blasting agent

Prescribed procedure

1. All holes for a particular blast must be drilled before actual loading begins on hot holes having temperature in excess of 66°C.
2. The temperature and depth of all holes must be checked and logged prior to loading any holes. A final temperature check will be made shortly before each hole is loaded.
3. Temperature checks will be made at several places in each hole (three minimum) to determine maximum temperature zone. The highest temperature will be measured using a digital temperature indicator (PT-100)-based sensor.
4. If the temperature of any hole in the shot is over 65.5°C, then the shot will be detonated within time frames as listed above.
5. In a large shot involving both hot and cool bore holes, the cooler ones ≤65.5°C will be loaded first and, as far as is safe and practical, all detonating cord and surface delays shall be completed in the cool area prior to loading any hot holes.

Sufficient non-combustible stemming materials such as sand, drill cutting or crushed stone will be available at the collar of each hole prior to the start of loading.

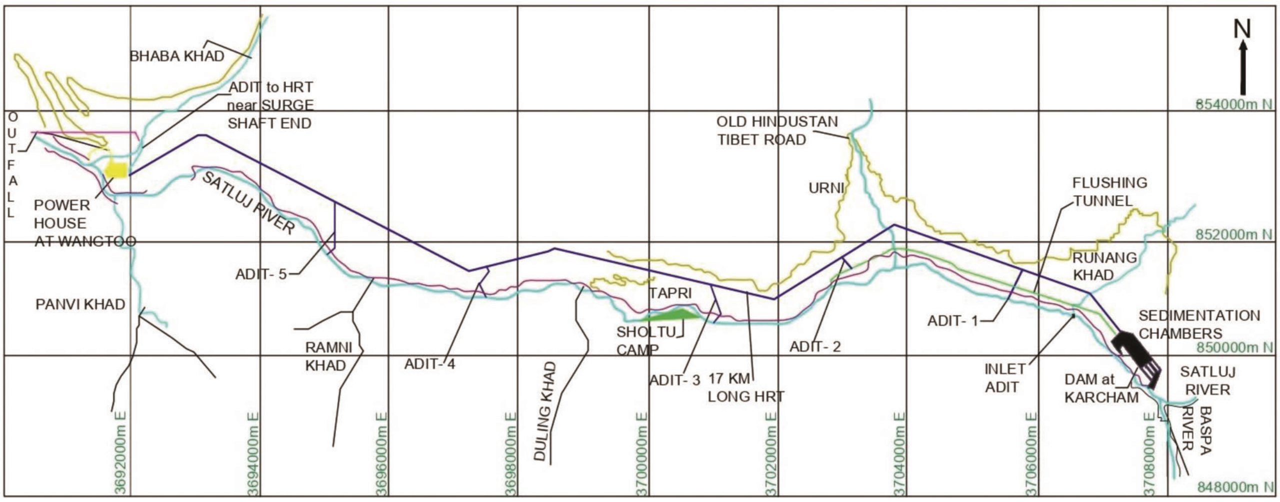

Figure 1. General layout of the project.

race tunnel (HRT). Figure 1 shows the general layout of the proposed project. A number of adits were constructed having 4.75 m diameter and 7.5 m height to join HRT. During the construction HRT, a hot zone with temperature variation up to 98°C was encountered between adits 3 and 4. The temperature within the drill holes varied between 72°C and 98°C and continued up to a distance of 400 m, which slowly reduced to normal assuming routine excavation practice.

The hot zone of a tunnel

The rock exposed within the hot zone of the tunnel was fine-grained granitic and quartzitic gneiss with mica schist bands. The strike of the bed varied between N10°W and S20°E with dip amount of 25°–30° in the northeast direction. The hot zone in the tunnel was devoid of any structural discontinuity such as shear or fault zone. The rock mass quality or *Q*-value in the hot zone of the tunnel varied between class III and class IV (Table 2). A 50 mm gouge-filled shear zone was observed between RD (running distance from benchmark) 1065 and 1070 m. One metre thick sheared schist and 35–40 cm thick shear zone were present between RD 1105 and 1135 m. A 50 cm thick shear zone was observed between RD 1160 and 1162 m. The high temperature posed a serious problem for excavating the rock mass in heading using drilling and blasting method. Hence the excavation works were suspended in the tunnel due to safety concerns.

The temperature of the rock mass was determined with a digital thermometer using probe holes drilled on the left, right, centre, crown and bottom of the tunnel. The length of probe holes was kept equal to the tunnel

Table 2. Rock mass classification of hot zones

Ranking distance (RD) (m)				
Initial distance	Final distance	*Q*-value	Group	Rock mass class
950	1040	4.6–5.3	III	Fair
1040	1050	4	IV	Poor
1050	1065	4.6	III	Fair
1065	1070	2.8	IV	Poor
1070	1105	6.3–7.9	III	Fair
1105	1135	1.9–3.4	IV	Poor
1135	1360	4.1–8.5	III	Fair
1360	1370	3.9	IV	Poor
1370	1389	4.1–4.5	III	Fair

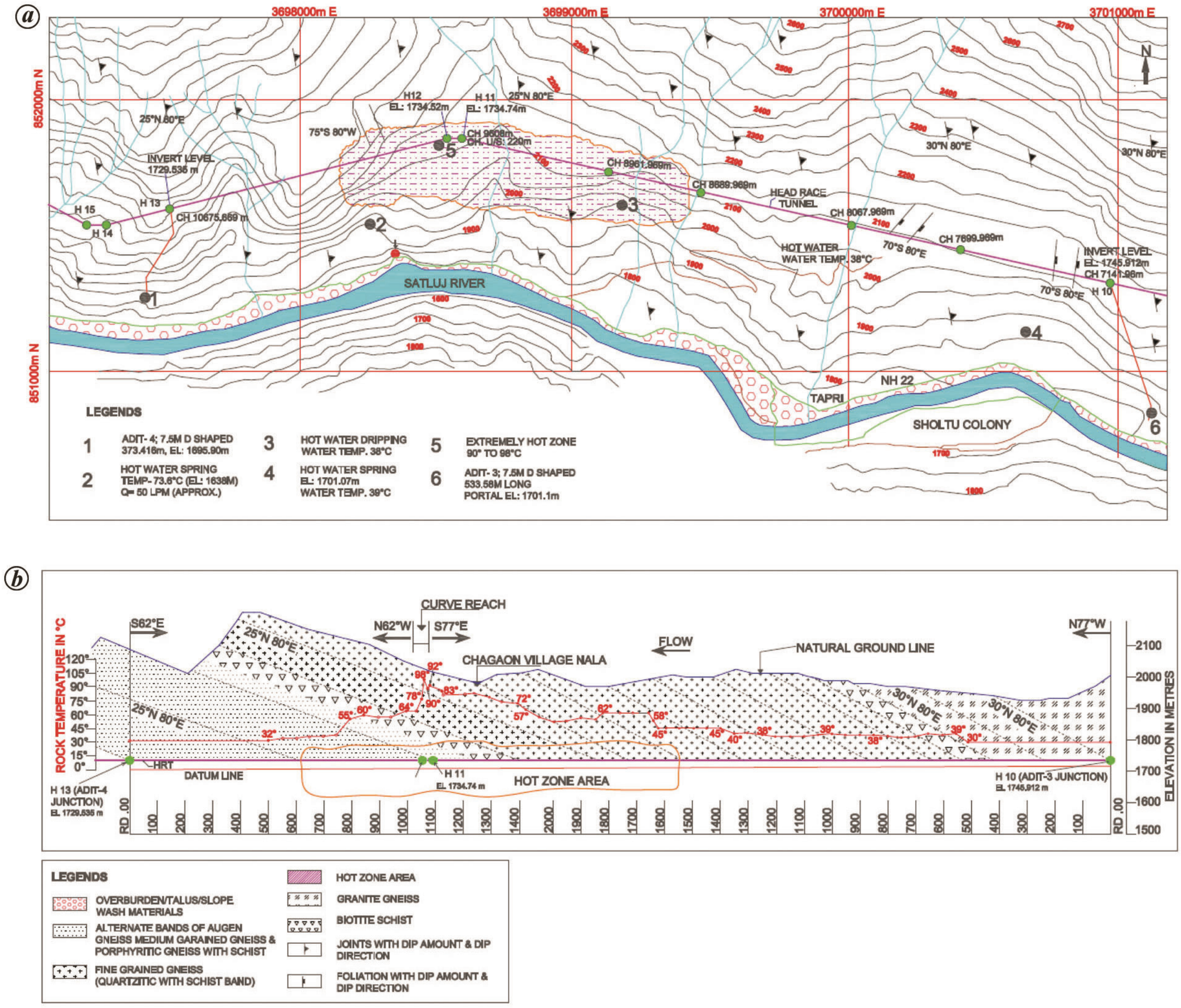

Figure 2. ***a***, Topographical layout of the hot zone and its surrounding area. ***b***, Geological cross-section of head race tunnel.

advance round on each face and the same holes were used for drill and blast. The hot zone in the tunnel was first encountered at 770 m upstream of adit 4 with temperature variation between 50°C and 65°C. The same temperature range from upstream was recorded up to RD 1060 m. However, between RD 1063 and 1068 m from the upstream end, rock temperature varied from 78°C to 98°C. Figure 2 depicts the average rock temperature recorded along the tunnel alignment at different RDs along with the geology. Figure 3 shows the temperature log of blast face at RD 1068 m. The temperatures on blast faces were also monitored using a thermal imaging camera. The camera assigns pixel values in accordance with temperature. Figure 4 shows the pixel values assigned for temperatures at the rise side of RD 1361 m. Figure 5 is a sample image captured at RD 1350 m showing a maximum temperature of 96.6°C. No dripping or water discharge, i.e. dry excavation was noticed throughout the length of the hot zone of the tunnel.

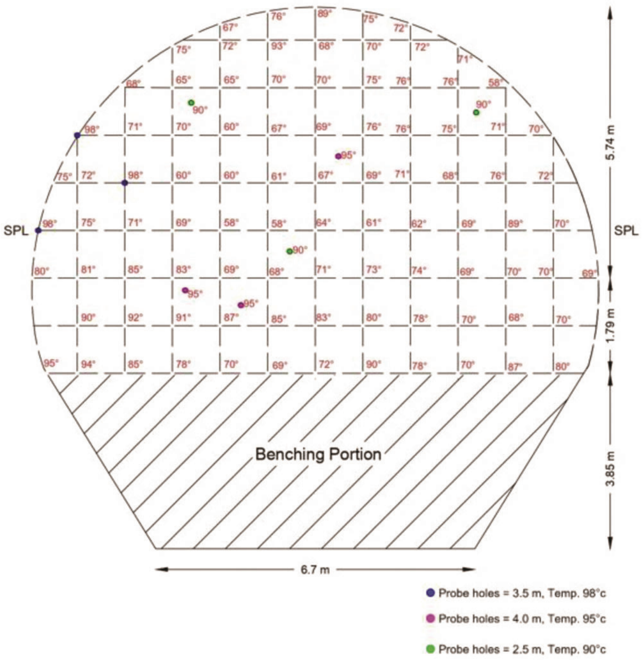

Figure 3. Temperature mapped at RD 1068 m.

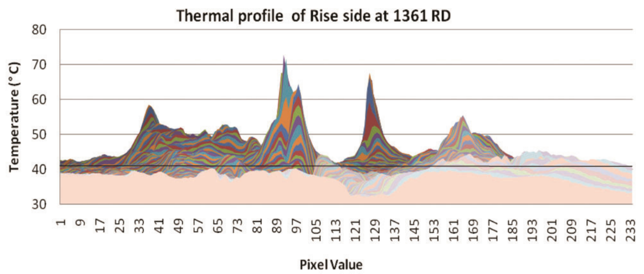

Figure 4. Pixel values assigned for temperatures measured at the rise side of RD 1361 m.

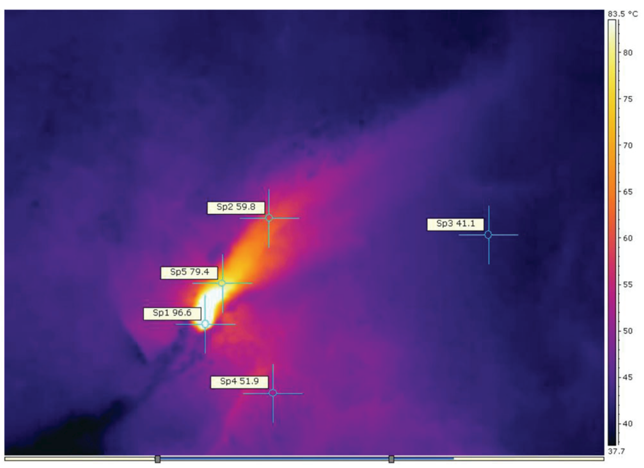

Figure 5. Thermographic image of the tunnel face at RD 1350 m.

Methodology

The excavation was divided in two stages as shown in Figure 6, i.e. 7.5 m high heading and 3.85 m deep benching for ease of operations and manoeuvrability of the machines. The face area of the tunnel heading was about 72.14 m^2. A hydraulic boomer with twin boom drill jumbos was used for drilling. The average drilling rate for a single boom varied between 130 and 160 m/h for 45 mm single-pass drilling[8]. In the routine excavation schedule the drilling and blasting cycle time used was 4–5 h for drilling 78–85 holes of 45 mm diameter for drivage of heading (Table 3).

After sudden emergence of high temperature zone, it became imperative to redesign the sequence of excavation. Under the prevailing temperature conditions within the tunnel, the methodology was largely governed by the time span within which an engineer and workmen can work safely and comfortably. The adopted methodology was broadly divided into two categories: (i) cooling the drilled holes and blast faces for availing a transit time equivalent to the working time for explosives placement, and (ii) placing the explosives in the transit time. The blast face was quenched by sprinkling cold water on the face and pumping water within each hole for one minute

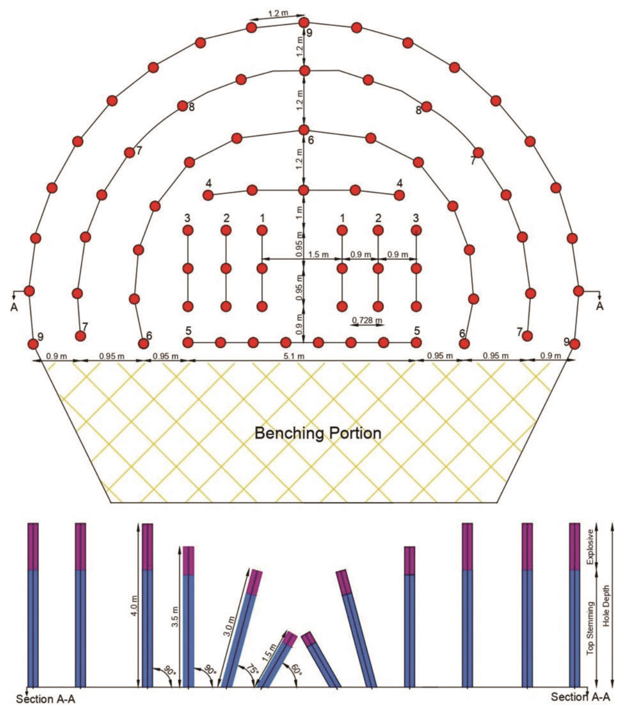

Figure 6. Initial excavation sequence.

Table 3. Time calculations for full-face blasting cycle of 4 m hole depth

Approximate number of holes	78–85
Total length of holes (m)	312–340
Approximate penetration rate of one boom (m/h)	95
Time taken to drill 78–85 holes with two boomers (min)	100–110
Approximate time taken for charging, stemming and connection of holes with long delay detonators (min)	160
Total time for full-face blasting cycle of 4 m hole depth	260–270 min or 4–5 h

Table 4. Temperature drop after quenching of holes between RD 1068 and 1384 m

RD of blast (m)		Hole temperature (drilled; °C)										Temperature after quenching (°C)	Temperature after 45 min of quenching (°C)
		Centre		Left		Right		Crown		Bottom			
From	To	Maximum	Minimum	Maximum	Minimum	Maximum	Minimum	Maximum	Minimum	Maximum	Minimum		
1068	1072	95	63	98	90	90	69	90	75	95	92	39.4	65.88
1155	1184.5	85	68	89	49	80	60.9	81	69	81	28	30	46.36
1243	1263	89	67	82	69	86	68	85	68	86	78	31.83	48.38
1265	1295	83	69	84	68.3	85	59	84	68	85	72	28.23	47.739
1298	1327	81	40	89	72	81	62	90	61	81	26	27.24	51.21
1328	1348	80	72	82	69	84	65	89	74	84	25	29.25	50
1354	1384	76	65.3	89	65	78	65.3	77	68	78	68	27.85	50.759

Table 5. Calculated time for drill–blast sub-cycles of 4 m hole depth

Parameters	Sub-cycle I (piloting)	Sub-cycle II	Sub-cycle III	Sub-cycle IV	Sub-cycle V
Approximate number of holes	31	13	20	10	22
Total length of holes (m)	93.5	52	80	40	88
Approximate penetration rate of one boom (m/h)	95	95	95	95	95
Time taken to drill 96 holes with two boomers (min)	30	17	26	13	28
Approximate time taken for charging, stemming and connection of holes with long delay detonators (min)	40	25	30	20	35
Total time for each blasting sub-cycle of 4 m hole depth	70	42	56	33	63

Table 6. Time calculations for full-face blasting cycle of 1.5 m hole depth

Approximate number of holes	78–85
Total length of holes (m)	117–127.5
Approximate penetration rate of one boom (m/h)	95
Time taken to drill 78 holes with two boomers (min)	37–42
Approximate time taken for quenching, charging, stemming and connecting holes with cord relays (min)	60–70
Total time for drill–blast cycle (min)	90–100

using a hydro-boomer. No coolant was mixed with water for quenching. The process resulted in a significant temperature drop, for conducting blasting activities (Table 4). Hydro-boomer which was readily available on site was only required for quenching. The readily available resources made the quenching process easy to get sufficient transit time to work with reduced cycle time. However, it was noted that the blast faces with initial temperature greater than 90°C retained a temperature greater than 50°C after 45 min of quenching. Thus, it was decided to complete the drilling–blasting activities within sub-cycles of 35 min. A blasting team comprising one engineer, one certified shot-firer and eight trained blasting crew members was deployed for blasting the hot strata.

If a conventional full-face blast cycle was divided in five sub-cycles, some sub-cycles could still not be completed within 35 min (Table 5). Furthermore, 45 min time was observed to be the highest limit which a person could sustain near the tunnel face. Symptoms of heat oedema, heat cramps, heat rashes, heat syncope, heat exhaustion and heat stroke were frequently reported by workers because of prolonged exposure, i.e. beyond 45 min to high temperature and humidity.

Alternatively, the practice of a full-face drill–blast cycle of 1.5 m hole depth could have undesirably consumed 90–100 min (Table 6). Nevertheless, if a 1.5 m deep full-face blast was divided in five sub-cycles, then each sub-cycle was completed within 35 min. The heading

Table 7. Drilling, charging and blasting time for sub-cycles of 1.5 m hole depth blast

Parameters	Sub-cycle I (piloting)	Sub-cycle II	Sub-cycle III	Sub-cycle IV	Sub-cycle V
Approximate number of holes	31–35	13	20	10	22
Total length of holes (m)	46.5	19.5	30	15	33
Approximate penetration rate of one boom (m/h)	95	95	95	95	95
Time taken to drill 96 holes with two boomers (min)	15	7	10	5	11
Approximate time taken for quenching, charging, stemming and connecting holes with cord relays (min)	20	15	20	10	20
Total time for drill–blast sub-cycle (min)	35	22	30	15	31

Table 8. Blast design parameters adopted for blasting in the hot zone between RD 1068 and 1072 m

RD of blast (m)	Maximum temperature (°C)	Minimum temperature (°C)	Temperature drop after quenching (°C)	Type of blast	Number of holes	Hole depth (m)	Charge per hole (kg)	Explosive used (kg)
1068	98	90	48	Pilot	38	1.5	0.77	29.26
1068				Widening	9	1.5	0.77	6.93
1068				Widening	9	1.5	0.77	6.93
1068				Widening	9	1.5	0.77	6.93
1068				Widening	13	1.5	0.77	10.01
1069	94	69	33	Pilot	33	1.5	0.77	25.41
1069				Widening	9	1.5	0.77	6.93
1069				Widening	9	1.5	0.77	6.93
1069				Widening	9	1.5	0.77	6.93
1069				Widening	9	1.5	0.77	6.93
1070	93	80	48	Pilot	35	1.5	0.77	26.95
1070				Widening	9	1.5	0.77	6.93
1070				Widening	9	1.5	0.77	6.93
1070				Widening	9	1.5	0.77	6.93
1070				Widening	13	1.5	0.77	10.01
1071	94	63	32	Pilot	29	1.5	0.77	22.33
1071				Widening	9	1.5	0.77	6.93
1071				Widening	9	1.5	0.77	6.93
1071				Widening	9	1.5	0.77	6.93
1071				Widening	13	1.5	0.77	10.01
1072	95	69	36	Pilot	33	1.5	0.77	25.41
1072				Widening	9	1.5	0.77	6.93
1072				Widening	9	1.5	0.77	6.93
1072				Widening	9	1.5	0.77	6.93
1072				Widening	9	1.5	0.77	6.93

face was sequenced to be excavated into four sub-cycles when temperature varied between 50°C and 70°C (piloting as sub-cycle I and widening sub-cycles II, III and IV). For temperatures higher than 70°C, five-stage excavation with four widenings was done considering safety measures (Figure 7). Figure 8 shows the loading of explosives in sub-cycle I, i.e. pilot stage. Each blasting sub-cycle could be completed in 35 min when the drill depth was restricted to 1.5 m and the number of holes was restricted to 40 for piloting and 15 for widening (Table 7).

Technical datasheet of non-electric detonator shock tube combination specifies that it must not be used above 70°C (ref. 9). The literature review for open-pit mines indicates that DF and emulsion explosives cartridge are capable of withstanding the encountered temperature. Further, the industry does not manufacture any special explosives for hot zones. Hence initiation within the hole was planned using 10 g DF and emulsion explosives were used as blasting agent. Cartridges of 40 mm diameter and 390 g weight were used. The detonation velocity and density of explosives was 4000 ± 200 mm/s and 1.07–1.25 g/cm^3 respectively. Moreover, it was noted that by replacing non-electric detonator shock tube combination with a system of DF and cord relays, a further margin of 10 min can be obtained. Cord relays are delay detonators covered within a plastic coating; hence they are safe for providing delays in the row. The cord relays were covered with a moist cloth to shield them from the hot surface. The initial cut area for pilot tunnel was kept at 5.1 × 3.8 m^2. Table 8 provides details of charged quantity and its distribution for tunnel faces with temperatures greater than 90°C. Alternate periphery holes for widening were also pumped with normal groundwater to obtain a high transit time and good profile. Finally, the end of DF was taken 20–30 m away from the hot face and initiated with electric detonator while placing it over a wooden block. Tunnelling progress in the hot zone significantly reduced because of repetitive blasting and venting cycles. When the two tunnel faces joined together, a comfortable atmospheric condition was encountered within the tunnel along with sufficient lowering of hole temperature due to heat convection within the excavated tunnel. The benching operation was then comfortably and safely performed using 4 m hole depth.

Safety procedures

It is recommended that the hot zones must be fired in tunnel excavation using explosives and accessories with sensitivity more than the encountered temperature. Cord relays can be used for inter-row delays and must be covered with a moist cotton cloth to protect them from the hot surface. A wooden block must be placed between the initiating detonator and ground surface for preventing unintended detonation. Blasted muck must be quenched again before handling. A substitute team must be kept ready to replace unwell crew members. Oxygen cylinders and a medical team must be available at the site to attend any emergency. Crew members must be frequently served glucose water to prevent dehydration. Figure 9 depicts the methodology to be followed for safe excavation of hot zones while tunnelling.

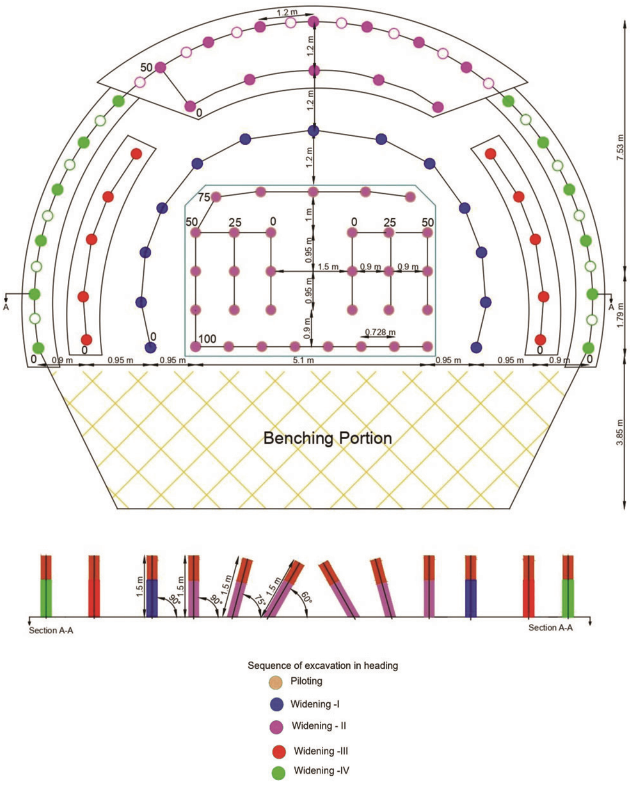

Figure 7. Sequence of excavation and blast design for temperatures greater than 70°C.

Figure 8. Loading of explosives in the sub-cycle I (pilot).

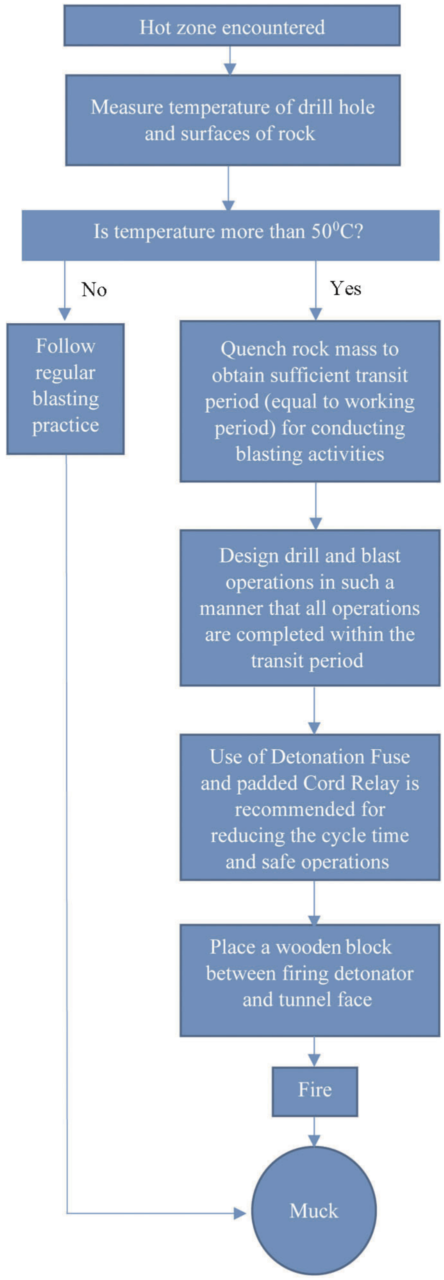

Figure 9. Methodology for blasting hot zone in tunnels.

Conclusion

The occurrence of geothermic hot zones while tunnelling has been reported in the literature. However, there is a paucity of research on drilling and blasting for excavating hot zones in tunnels and underground mines. The Directorate General of Mine Safety, India, discourages blasting in hot holes having temperatures greater than 80°C. Hence tunnelling through hot zones is difficult and risky. The lack of a suitable drilling–blasting technique for the hot zone of a tunnel sometimes impels engineer to realign it. This is costly and time-consuming. A hot zone was encountered while excavating HRT of 1000 MW KWHEP. The temperature of the hot zone varied between 50°C and 98°C. The tunnelling works were suspended in the absence of a suitable excavation technique. An innovative drilling and blasting technique was designed to tunnel through the hot strata. This technique can be replicated for similar situations. The salient features of this drill and blast tunnelling technique are as follows:

(i) The temperature of the blast face in the hot zone must be lowered to obtain a transit time by quenching the face and holes.
(ii) The transit time must be equal to or greater than the time for which workmen can sustain hot conditions near the blast face.
(iii) The drill and blast cycles must be designed such that the cycle is completed in the transit time.
(iv) Piloting and widening method is recommended for reducing the cycle time.
(v) Drill depth and number of widening operations must be customized in accordance with the transit time.
(vi) A combination of DF and cord relay must be used for safe and swift operations due to their high temperature resistance.

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