Mechanical excavation of inclines and declines

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Tunnel boring excavation has come a long way in the last three decades, venturing into areas where the rock is hard, highly fractured, susceptible to water inflows or where mixed face conditions occur. Alongside this development, the excavation of inclines and declines by TBMs has also become possible. While the earliest such project was undertaken by a Jarva machine in 1967, it is Wirth's TBMs which are credited with having driven the greatest number of non-horizontal bored tunnels.

The technology developed for the boring of declines, first employed in coal mine applications, has been transferred to allow the boring of penstock declines for hydropower schemes. In recent years, the boring of inclined cable railway tunnels for all-weather access to ski slopes has become popular.

In North America the mechanical excavation of inclines and declines is still associated with coal mines. However, this is not the case in Europe, where inclines associated with hydropower-related tunnels, ventilation structures for trans-Alpine tunnels and, more recently, all-weather underground cable railways, are now being driven by TBMs.

Design considerations

The unique yet obvious consideration for excavating a tunnel having a substantial inclination from the horizontal is the action of gravity towards or away from the face. When boring an incline, muck, water and the machine will tend to slide away from the heading, these first two characteristics being advantageous, whereas the potential for the machine to slide away is nearly always a disadvantage.

In a decline excavation, muck, water and the machine will tend to slide towards the heading, and while the possibility of machine slippage is simpler to deal with, effective mucking becomes difficult, especially when water is present. In gentle gradient tunnelling, such as that required for water, sewer and transportation tunnels, contractors prefer to excavate upgrade so that water naturally drains away from the face. Consequently, total flooding is unlikely even when heavy inflows are encountered.

While the decision to tunnel downgrade is never taken lightly by the contractor, if no other alternatives exist, precautions can be taken that will ensure that the project is completed safely. One such precaution when water inflows are anticipated is to pre-grout along the alignment of the decline. However, this process may be cost-prohibitive, especially with longer declines, and even so, is not without its risks. Should the bottom of the decline be accessible, a pilot hole drilled through the invert of the intended decline can be used partially to pre-drain the rock along the alignment.

If the bottom of the decline is inaccessible, it is still possible to pre-drill a centred drain hole, with additional holes drilled along and outside the line of the decline to serve as dewatering holes. By blasting both the centre drain hole and the peripheral holes, hydraulic communication between them will permit the centre hole to act as a drain for the whole face area.

In addition to water considerations, the geometry of an incline will interact with geotechnical conditions, causing further stability and support challenges. For example, block fallout in horizontal tunnels generally occurs only when the support of the cutterhead is removed as the machine is advanced. In an inclined excavation, where the gravity component acts away from the face, blocks may become unstable even before they are completely daylighted by the cutterhead.

Fig 1. Start of incline at Tignes.

Excavation on an incline requires very specific design considerations in terms of the TBM's cutting and muck removal potential, the backup system, the muck handling as well as various ancillary subsystems. Considerations and conceptual design requirements for excavation of inclines and declines are summarised in Tables 5 and 6 respectively.

Mechanical v. conventional

The advantages of mechanically excavating inclines becomes apparent when this method is compared to conventional excavation. Drill+blast excavations can be dangerous as loose rock and ravelling material has the potential of falling to the bottom of the incline.

In addition to this, drilling equipment, scaffolding and supply lines must be removed before each round is blasted and stored away from the scatter zone, only to be reassembled to allow support and drilling to continue. While the Alimak-type of system does relieve this procedure, it is expensive to install and operate. When fine sandy and silty muck with larger fragments occur together in the invert, the mixture can, in the presence of adequate water, vibration or inclination, become unstable and lead to a mud flow.

Cost comparisons for inclined shaft drives by conventional and mechanically excavated means have established cost savings of 17% and 45% for 300m and 1000m drives respectively.

Coming of age

Excavating non-horizontal tunnels by TBMs has come of age: excavating upward drives is more easily achieved and is thus preferable to excavating declines. However, the disadvantages of excavating on an incline can be minimised or even effectively eliminated by proper engineering design, logistical planning, and suitable mechanical design.

The advantages of excavating on an incline include simpler, cheaper and more convenient mucking systems, while its greatest potential benefit lies in its safety and the operational costs when compared to conventional excavation methods. □

Table 1. Inclined mechanical excavation by Wirth machines.

Manufacturer/ Model/ Date	Project/Location	Length m Diameter m	Slope degrees	Rock type
Wirth 3 TB II-300 E 1986–69	Grand Emosson Châtelard/Corbes Switzerland	1145 3.00	+29	vallorcine granite
5 TB 0–214 E 1969	Grand Emosson Châtelard/Barberine Switzerland	1019 2.50	–41	vallorcine granite
8 TB II–300 E 1970–71	Hornberg Reservoir Wehr/Schluchsee Power Station	1400 3.00	+24	granite
8.1 TBE 300/ 600 H 1971–72	Hornberg Reservoir Wehr/Schluchsee Power Station	1400 6.30	– 24	granite
15 TB II–300 E 1972–73	St. Gotthard Motto di Dentro Switzerland	800 3.00	+41	slate and gneiss
15.1 TBE 300/ 600 H 1973	St. Gotthard Motto di Dentro Switzerland	825 6.64	– 41	slate and gneiss
18 TB II–360 H 1972–73	Kaprun Austria	3200 3.60	+28	crystalline schist
19 TB I–253 H 1973	Hohtenn Lötschental Switzerland	1100 2.53	29	gneiss
23 TB II–300 E 1974	St. Gotthard Bäzberg Switzerland	475 3.00	+38	granite
23.1 TBE 300/ 664 H 1976	St. Gotthard Bäzberg Switzerland	476 6.64	– 38	granite
25 TB I–253 H 1975–76	Chiotas Süd Entracque Italy	1080 2.53	42	crystalline schist and gneiss
27 TB II–300 E 1975–76	Rovina Entracque Italy	1080 3.00	42	crystalline schist and gneiss
33 TB II–300 E 1976	Chiotas Nord Entracque Italy	1050 3.00	42	crystalline schist and gneiss
38 TB II–300 E 1977–78	Sellrain Silz Austria	1993 3.20	36	crystalline schist
39 TB IV–480 H 1977–78	Kühtai Austria	951 4.80	18	crystalline schist
42 TB II–300 H 1978	Fréjus I – Bardonecchia Italy	685 3.00	+45	schist and gneiss
42.1 TB 300/ 578 H 1978–79	Fréjus I – Bardonecchia Italy	685 5.78	– 45	schist and gneiss
43 TB II – 300 H 1978–79	Fréjus II – Bardonecchia Italy	690 3.00	+45	schist and gneiss
43.1 TB 300/ 578 H 1979	Fréjus II – Bardonecchia Italy	690 5.78	– 45	schist and gneiss
50 TB II 300/332H 1979	Shimogo I Japan	500 3.30	+45	sandstone
52 TB II – 360 H 1979–80	Grand Maison I France	1430 3.60	25	crystalline schist
55 TB II – 300/332H 1979–80	Shimogo II Japan	500 3.30	+45	sandstone
58 TBE II – 360/612H 1979–80	Shimogo I Japan	480 5.80	– 45	sandstone
59 TB II – 360 H 1980–81	Super Bissorte France	2750 3.60	20	gneiss
60 TB II – 360 E 1980–81	Grand Maison II France	1460 3.60	25	gneiss
62 TB I – 253 H 1980–81	Sildvik Norway	739 2.53	45	granite
63 TBE II – 330/612H 1980	Shimogo II Japan	480 5.80	– 45	sandstone
68 TB II – 360 H 1981	Grand Maison III France	1450 3.60	25	gneiss
71 TB II – 360 E 1981–82	Lautaret France	2855 3.60	+30	limestone and schist
75 TB II – 360 H 1982	Grand Maison IV France	1436 3.60	– 25	schist and gneiss
93 TB I – 262 E 1984	Vernayaz Switzerland	1170 2.62	32	granite
96 TB I – 300 E 1985	Syracus/Solarino I – Sizilien Switzerland	473 3.00	+44	limestone
112 TB I – 262/ 300 E 1985	Syracus/Solarino II – Sizilien Switzerland	472 3.00	+44	limestone

113 TBE 300/ 640 H 1985	Syracus/Solarino I – Sizilien Switzerland	473 6.40	– 44	limestone
114 TBE 300/ 640 H 1985–86	Syracus/Solarino II – Sizilien Switzerland	472 6.40	– 44	limestone
117 TB I -300E 1986	Ligerz Switzerland	417 3.00	+36	limestone
117.1 TBE 300/ 644 H 1986	Ligerz Switzerland	417 6.44	– 36	limestone
119 TBS III 390/480 E 1986	Val d'Isere France	570 4.20	16	limestone
119 TBS III 390/480 E 1986	Val d'Isere France	1689 4.20	24	limestone
124 TB I – 300 E 1986–87	Neuenburg I Switzerland	640 3.00	-20/8/17	limestone
126 TB II – 335 H 1986	Mörel Switzerland	250 3.35	30	schist
127 TB II – 335 H 1986–87	Mörel Switzerland	375 3.35	30	schist
129 TB I – 300 E 1986–87	Neuenburg II Switzerland	640 3.00	+20/8/17	limestone
140 TBE II – 545 H 1987	Neuenburg I Switzerland	640 5.45	-20/8/17	limestone
148 TBE II – 575 1988	Neuenburg II Switzerland	640 5.45	-20/8/17	limestone
161 TBS III – 420 E 1989 –	Funiculaire d'Tignes France	3100 4.30	+27	limestone
191 TB III – 450 E 1991	Campodolcino/ Spluga	1350 4.50	+26	
Murer TB 0 – 227 E 1987	Ilanz II Switzerland	336 2.27	32	schist

Table 2. Inclined mechanical excavation by Calweld and Jarva machines.

Manufacturer/ Model/ Date	Project/Location	Length m Diameter m	Slope degrees	Rock type
Calweld				
1971	Coal Shaft Wabash Coal Southern Illinois	853 5.18	– 17	limestone sandstone shale
Jarva 7 Mark 11 1967	Adirondack Mine Republic Steel Corp., Mineville, New York	234 3.05	– 27	magnetite ore, lead ore, hornblende biotite gneiss and granite gneiss
18 Mark 14 1970	Oak Park Mine Hannah Coal Div., Consolidated Coal, Cadiz, Ohio	549 4.27	– 16	sandstone and shale
46 Mark 12 1975–76	Urling 2 #3 Coal Mine, Shelocta, Pennsylvania	745 4.27	3.2	shale, coal, sandstone, limestone and fireclay
57 Mark 12 1976	Emile #4 Coal Mine Shelocta, Pennsylvania	227 4.27	4.5	shale, coal sandstone, limestone and fireclay
68 Mark 8 1978	Westmoreland Coal Mine Eccles, W. Virginia	319 3.05	– 17	shale, coal, sandstone, limestone and fireclay
72 Mark 8 1979	Pocahontas Coal Co. Thurman, W Virginia	945 3.05	+11	shale, sandstone and limestone
96 Mark 12 1983–84	Tjodan +45 Incline Lysebotn, Norway	1250 3.20	+41	granite and gneiss
104 Mark 12 1985–86	Naddvik Nyset-Steggje Norway	1370 3.50	+44	granite
Mark 12 1988	Gerlos II Austria	800 3.65	+ 38	quartz and phyllite

Table 3. Inclined mechanical excavation by Voest-Alpine machines.

Manufacturer/ Model/ Date	Project/Location	Length m Diameter m	Slope degrees	Rock type
Voest-Alpine TVM 34 – 38/42 1973	Headrace Tunnel, Mapragg Project Switzerland	1400 4.20	+32	limestone
TVM 34– 38/42 1973	Headrace Tunnel, Mapragg Project Switzerland	4.20	+16	
TVM 24 – 27 H	Headrace Tunnel, Böchstein Project Austria	930 2.15	+36	gneiss

Table 4. Inclined mechanical excavation by Komatsu and Robbins machines.

Manufacturer/ Model/ Date	Project/Location	Length m / Diameter m	Slope degrees	Rock type
Komatsu				
1985–86	Bilston Tunnel Perisher Skitube New South Wales Australia	3300 5.00	6	granite
Robbins				
111–117 1972–73	Pipeline Tunnel Obergestein Switzerland	1328 3.70	6	schist
111–117 1977	Inclined Shaft, Sunnega, Zermatt Switzerland	1799 3.50	14–32	schist
181–122 1968–72	White Pine Mine, Michigan	2591 5.48	8	hard shale
112–124–6 1975	Inclined Tunnel Sarelli, Switzerland	488 3.30	32	limestone
122–126 1970–71	Tajo-Segura Water Project, Spain	476 3.81	–11	limestone with clay pockets
122–126–1 1980–81	Sotiel Mine Huelua, Spain	1775 3.81	–16	black shale with quartz pockets and pyrites
182–129–3 1977–78	Llauset Moralets Spain	1421 5.50	4	limestone
123–133 1973	Ferden Tunnel Ferden Hohtenn Switzerland	600 3.65	32	soft gneiss
145–168 1975–76	Hydro Penstock, Grimsel Oberaar, Switzerland	789 4.30	46	alaskite and gneiss
61–176 1977	Blyvoor Mine, South Africa	900 1.84	17	quartzite
61–177 1977	East Driefontein Mine, South Africa	1500 1.84	17	quartzite
129–182–1 1982–83	Hydro Shaft Beninar, Spain	1200 4.20	47	granite, shale gneiss
1210–187 –1 1982–83	Rail Tunnel Pitztal, Austria	3150 4.10	17	schist, granitic gneiss
136–204 1979	Hausling Incline Zillertal, Austria	1314 4.20	29–41	dolomite, phylite
136–204 1982–83	Rail Shaft Felskinn, Switzerland	1570 4.20	+28	schist, amphibolite gabbro
136–204 1986	Inclined Shaft Reutte, Germany	1500 4.20	35	
186–207– 1A 1982–84	Water Supply Makkah Saudi Arabia	6402 5.60	2	granite, diorite basalt, syenite aplite dykes
94–218–1 1985	Amlach V Hydro Incline, Austria	338 3.20	9–23	dolomite
252–226– 1A 1989–91	Svartisen Hydro Norway	5975 8.50	4	micaschist, gneiss granite
1212–228 1985–86	Amlach V Hydro Austria	674 3.89	29	dolomite, amphibolite mica schist
1013–249 1989–90	Hintermuhr Hydro Austria	6000 3.2		limestone, phyllite
120–3001 1984–86	Conveyor Tunnel Mt. Isa, Australia	1150 3.71 × 6.50	–8	greenstone quartzite

Table 5. TBMs working in inclined excavations.

Thrust pressure. To counteract the effect of gravity, it is necessary to increase thrust pressure in proportion to the angle of the incline.

Slip-back prevention. Mechanism required to prohibit machine slippage, especially when advancing the TBM or when the hydraulic system is shut down. Alternatively, it is possible to brace the machine against the lining.

Muck handling. When excavating inclinations of less than 20°, one would normally utilise a conventional mucking system whereby the muck is picked up by cutterhead buckets, loaded on to a conveyor, and removed from the heading. With inclines steeper than 20°, cutterhead buckets may or may not be used, with the muck being channelled into invert muck chutes with the assistance of running water. However, in blocky ground the danger of large blocks falling from the crown is increased. Muck handling is generally easier with steeper slopes, when it can be passed through a rock crusher and out along the invert. By raising the muck with cutterhead buckets which discharge on to a chute located in the upper portion of the machine, a clean invert is left behind the cutterhead.

Fluids. Hydraulic and lubrication fluids will tend to pool in the lower portions of their respective systems, not in the bearings and gears where they are most needed. This problem can be eliminated by providing a circulating lubrication scheme with porting that ensures the necessary movement of fluids. Additional lubrication of the main bearing seals may also be required as there is a real danger that muck may build up in the invert and chute area.

Serviceability. Specific design considerations which account for the inclination of the drive include angled walkways/ emergency access. It is wise to get assurances from the component manufacturers that no damage or loss of performance will result from operating equipment at a tilt.

Lining/support. Excavations for inclined cable railways generally utilise pre-cast invert segments to anchor the final rail. In ski tubes, the predominant support system consists of invert segments with rock bolts, miners' straps, mesh and shotcrete.

Effect of water. While water will always drain away from the face in an incline, there is always the possibility that fines and muck may be washed around the invert segments, which can antagonise slippage problems or make the setting of invert segments difficult.

Table 6. TBMs working in declined excavations.

Thrust pressure. Due to the effect of gravity upon the machine, it is possible to decrease the thrust pressure in proportion to the angle of the incline. However, in blocky ground there is always the possibility that the dead weight of the TBM may rest on only a few cutters, thus causing their bearing capacity to be exceeded.

Slip-back prevention. A mechanism is required to prevent forward slippage during work at the heading or when changing cutters. A mechanism similar to that employed in incline machines may be used. Access to the heading can be minimised by providing cutters that can be changed from the rear.

Muck handling. While excavating a decline it is possible to raise the pickup point and lower the discharge point of the primary conveyor to counteract the decline angle. When this measure is inadequate, fluted belts or chain conveyors may be employed; however, the working angle and the capacity limitations for such equipment should be carefully checked. The design of the system should take account of probable water inflows as this will add to the difficulty of picking up muck, to prevent it being washed back off the conveyor.

Fluids. Hydraulic and lubrication fluids will tend to pool in the lower portions of their respective systems rather than in the areas where it is most required. With the greater potential for even minor flooding, components should be raised as high as possible from the invert.

Serviceability. While facilities should be provided to prevent the occurrence of runaway equipment, tools or supplies down the decline towards the work area and face, the need to gain access to the heading can be minimised by providing cutters that can be changed from the rear of the machine. A review of declined emergency egress and/or stairways is recommended.

Lining/support. Most decline excavations have been in relatively competent ground that could be stabilised using rock bolts, shotcrete and mesh.

Effect of water. In a decline water will always drain towards the face and work areas, and even in a dry drive additional pumping capacity may need to be installed. Water may also wash fines and muck to the cutterhead and its bearings, and thus a review of the lubrication system and seals is recommended.

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