silt was mixed with water and ejected by compressed air. Between the shafts the length of the proposed tunnel is 1 mile, and about one-eighth of the distance had been accomplished when the works were stopped for financial reasons.

Small subaqueous tunnels have been driven through clay without difficulty under Lakes Michigan and Erie, and elsewhere in America. In England a heading was driven nearly across the Thames in 1807, and eighty years later two 10 feet 6 inch iron-lined tunnels were constructed under the river close to the foundation of London Bridge by Mr Greathead, with the aid of a simple annular shield advanced by six hydraulic presses. Where open gravel or water has to be tunnelled through a diaphragm must be fitted to the shield. Mallet proposed in 1858 to carry in this way a tubular tunnel across the English Channel. Various plans have been suggested for the removal of the soil in advance of the shield. Mr Greathead would effect it by the circulation of a closed current of water, carrying the stuff through the shield from front to back ; and an American plan provides for forcing it bodily out of the way by a plough-shaped shield, aided by jets of water at a very high pressure.

*Tunnelling through Mountains. —*Where a great thickness of rock overlies a tunnel, it is necessary to do the work wholly from the two ends, without intermediate shafts. The problem resolves itself into devising the most expeditious way of excavating and removing the rock, and there are none of the uncertainties and difficulties which make subaqueous tunnelling of so high an interest. Ex­perience has led to great advances in speed and economy, as will be seen from the following particulars of the three tunnels through the Alps, the longest yet constructed.

|  |  |  |  |
| --- | --- | --- | --- |
| Tunnel. | Length. | Progress per Day. | Cost. |
|  | Miles. | Lineal Yards. | Per Lineal Yard. |
| Mont Cenis | 7½ | 2∙57 | £226 |
| St Gotthard | 9⅓ | 6∙01 | 143 |
| Arlberg | 61/5 | 9∙07 | 108 |

In 1857 the first blast was fired in connexion with the Mont Cenis works ; in 1861 machine drilling was introduced ; and in 1871 the tunnel was opened for traffic. With the exception of about 300 yards the tunnel is lined throughout with brick or stone. Little interest now attaches to the method of tunnelling adopted at Mont Cenis, as it is in several respects obsolete. During the first four years of hand labour the average progress was not more than 9 inches per day on each side of the Alps ; but with compressed- air rock-drills the rate towards the end was five times greater.

In 1872 the St Gotthard tunnel was commenced and in 1881 the first locomotive ran through it. Mechanical drills were used from the commencement. Tunnelling was carried on by driving in advance a top heading about 8 feet square, then enlarging this sideways, and finally sinking the excavation to invert level (see figs. 3 and 4). Air for working the rock-drills was compressed to seven atmospheres by turbines of about 2000 horse-power. Six to to eight Ferroux drills, making about 180 blows a minute, were mounted on a carriage and pushed up to the point of attack. From thirteen to eighteen holes were drilled by the machine and its sixteen attendants to depths of from 2' 7" to 4' 3" in three to five hours, and the work of charging with dynamite, firing, and clearing away was then done by twenty-two men in three to four hours. The charge per hole averaged 1¾ lb, and after firing a strong current of compressed air was directed over the face of the excavation. Four sets of holes were under favourable circumstances drilled in twenty-four hours, which rendered a progress of 13 feet per day in such rock as gneiss attainable in each heading.

The driving of the Arlberg tunnel was commenced in 1880 and the work was completed in little more than three years. The main heading was driven along the bottom of the tunnel and shafts were opened up 25 to 70 yards apart, from which smaller headings were driven right and left. The tunnel was enlarged to its full section at different points simultaneously in lengths of 8 yards, the excava­tion of each occupying about twenty days, and the masonry 14 days. Ferroux percussion air drills and Brandt rotary hydraulic drills were used, and the performance of the latter was especially satisfactory. After each blast a fine spray of water was injected, which assisted the ventilation materially. In the St Gotthard tunnel the discharge of the air drills was relied on for ventilation. In the Arlberg tunnel over 8000 cubic feet of air per minute were thrown in by ventilators. In a long tunnel the quick transport of materials is of equal importance with rapid drilling and blasting. In the Arlberg, to keep pace with the miners, 900 tons of excavated material had to be removed, and 350 tons of masonry to be in­troduced, daily at each end of the tunnel, which necessitated the transit of 450 wagons. This traffic was carried on over a length of 3⅜ miles on a single track of 27-inch gauge with two sidings. When the locomotives ran into the tunnel the fires were damped down, and, as the pressure in the boiler was fifteen atmospheres, the stored- up heat in the water furnished the necessary power. The cost per lineal yard varied according to the thickness of masonry lining and the distance from the mouth of the tunnel. For the first 1000 yards from the entrance the prices per lineal yard were £11, 8s. for the lower heading; £7, 12s. for the upper one; £30, 10s. for the unlined tunnel ; £45 for the tunnel with a thin lining of masonry; and £124, 5s. with a lining 3 feet thick at the arch, 4 feet at the sides, and 2 feet 8 inches at the invert.

*Long Tunnels.—*The new Croton aqueduct tunnel from Croton dam to the reservoir in New York is worthy of note both for its great length and the rapid progress made with it. The distance is 33¼ miles and practically the whole is tunnelled through rock. Shafts were sunk about 1½ miles apart and headings driven each way. Ingersoll drills were chiefly used, and the rate of advance with the headings was in 1886 1¼ miles per month. The old Croton aqueduct was 7 feet 8 inches wide by 8 feet 5 inches high ; the new one is 13 feet 7 inches in width and height.

*Tunnelling in Towns.—*Where tunnels have to be carried through soft soil and in proximity to valuable buildings special precautions have to be taken to avoid settlement. The important Metropolitan tunnels constructed by Sir John Fowler have already been de­scribed under Railway (vol. xx. p. 239). Another successful ex-