Mole Versus Conventional: A Comparison of Two Tunnel Driving Techniques

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In northwest New Mexico the U. S. Bureau of Reclamation is building the Navajo Indian Irrigation Project. As a part of the water conveyance system, two tunnels were built. Tunnel 1, 2 mi long, was driven with a Hughes tunneling machine. One-quarter mile away is Tunnel 2, which will eventually be 5 mi long (only 2 mi had been excavated at the time of this writing). The second tunnel is being driven by conventional methods. Both tunnels are in the San Jose formation consisting of sandstone, siltstone, and shale.

The author presents observations made while working in both tunnels. Comparisons are made of rock behavior, supports, techniques, personnel, and advantages and disadvantages of using a "mole."

A tunneling machine offers the following advantages: near-continuous operation; high daily footage; minimum overbreak resulting in a nearly 50 percent reduction in concrete; fewer personnel; safer operation; fewer supports required; minimum cleanup operations; and dynamite not required resulting in increased savings. Disadvantages include: long section needed to pay for itself; circular section only; specialized operator required; supports difficult to install; long wait for delivery; large initial investment; machine has to be designed for tunnel because of different diameters and geologic conditions; limited to softer materials; large ventilation system needed.

•IN THE San Juan Basin of New Mexico, the U.S. Bureau of Reclamation is building the Navajo Indian Irrigation Project, a 135-million dollar project to furnish water to the desert lands of the Navajo Reservation. Water from the Navajo Dam will be diverted through a system of tunnels, siphons, and canals. Because the surrounding country is so rugged, it was necessary to begin the diversion through a 2-mi tunnel, referred to as Tunnel 1. A second tunnel, which will be 5 mi long when completed, is located ¼ mi from Tunnel 1. At the time of this writing, 2 mi had been excavated. Both tunnels will be 20 ft in diameter.

Two entirely different techniques were used to excavate these tunnels: a boring machine in Tunnel 1 and conventional methods in Tunnel 2.

GENERAL OBSERVATIONS

In a comparison such as this, it is not accurate to state that a mole-driven tunnel is capable of progress x times as fast as a conventionally driven one, because of certain factors involved which may occasionally balance out or eliminate one another. For instance, a mole could not be used in tunnels of too short a length because the time to build one could conceivably consume 100 percent of the contract period.

It took practically a full year to build the mole for Tunnel 1. Therefore, the tunnel must be sufficiently long to allow the mole, once on the job, to catch up with where conventional methods would ordinarily be in the same amount of time. It was thought that the 2-mi Tunnel 1 was the minimum that the mole could handle and still pay for itself.

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Diameter is also an important factor, because it determines the size of the mole, influences the length of the construction period, and bears a direct relation to the capital cost. Therefore, the tunnel length would have to be proportionately longer in relation to the diameter for a mole to pay its way.

Too long a tunnel can also cause problems. The engineer on the mole stated that his machine could probably bore for 5 mi before an overhaul would be necessary. Overhauls of any sort are not done easily within the confines of a tunnel, nor is a mole moved to the outside easily or in a short time. Tunneling machines are presently designed for circular section tunnels only. A highway tunnel would require a horseshoe section. To design a mole for a horseshoe tunnel would require new concepts and would probably increase costs.

AREA GEOLOGY

The geology of the area is quite simple. Both tunnels are in the San Jose formation of Eocene Age. This is a typical continental deposit laid down in a deltaic environment. The rock types consist of sandstone alternating with lenticular layers of shale and siltstone. None of the shales or siltstones can be traced over long distances. The shales are commonly 3 to 4 ft thick, although they may reach 15 ft locally. Very few of the siltstones exceed 5 ft.

The sandstones range from fine to coarse and are sometimes conglomeritic although the majority are medium grained. A few are cemented by calcite, a few by iron cement, and some are clay cemented. Most are friable to moderately cemented. The sandstone is composed of about 70 percent siliceous materials. No compressive tests were run by the Bureau of Reclamation, but the designer of the mole did conduct a few and came up with a strength of 5,000 to 6,000 psi. Tests were not run on the shales or siltstones.

The shales are predominately the compaction type and are both silty and clayey, thinly bedded to laminated. They air slake rapidly to flaky particles. On steep slopes there is an almost constant rain of fine shale. Under natural conditions the shales assume stability on a slope of about $1\frac{1}{2}$:1.

The rocks dip 3 to 5 deg to the southeast. Folding or faulting was never observed any place within the San Jose formation. In several places the shales may dip as much as 45 deg; however, this is the result of initial deposition rather than any local or regional structure.

Geologically one could not ask for better conditions with which to make comparisons of such radically different tunnel driving techniques.

GEOLOGIC COMPARISONS

No attempt is made to make comparisons on a station-to-station basis. Rather, comparisons are made of the behavior of similar rock types during and after excavation.

In a tunnel driven in shaley conditions, the question is how did the shale react. The shales in both tunnels were of the compaction type and air slaked rapidly after exposure to air. Whether the shale is above or below the surface, the process of air slaking is an attempt on the part of the shale to assume stability. When a shale in a tunnel starts lying on a 1:$1\frac{1}{2}$-slope, the overlying rock will no longer be stable. When a sandstone is undercut by a rapidly retreating shale, it will fall. It is the large sandstone blocks which cause damage when they fall, but their falling is generally the fault of the shale.

The shales reacted the same in both tunnels in that they tried to reach stability. The difference appears in the amount of time it takes the shale to begin air slaking. In either tunnel it would generally take 1 to 2 days to begin falling, even after its initial exposure. However, once exposed, differences occurred. In Tunnel 1 the shale would begin dropping immediately after a new reach was exposed. It was believed that this was due to the compressive effects of the cutterhead. After the mole passed, the shale would almost spring into the tunnel and, unless immediately supported, would continue falling.

In Tunnel 2 the shale always took 1 to 2 days to begin falling, even after its initial occurrence. The difference in time was probably due to the arch and sides being scaled right away and the dangerous rock removed. Also, the effect of the blasting undoubtedly removed much of the loose material.

The shape the arch took as the shale fell was an interesting observation. In Tunnel 1 the arch took the shape of an inverted V.

In Tunnel 2, because of the flat-lying attitude of the rock, the arch was flat. Here the shale would simply fall away from a poorly bonded bedding plane and leave a flat sandstone. Had the arch in Tunnel 1 been left unsupported, this flat-type back would surely have developed also.

In Tunnel 1, because of the arching effect of an almost perfectly circular section, the sandstones could stand quite a bit of undercutting. The sandstone was strong enough to cantilever itself. Often only a thin wedge of sandstone would remain, and it remained stable.

Even relatively thin shales would undercut the sandstone in Tunnel 2, but few attempts were made to stabilize any of them. Because perched water seeped from the top of practically every shale, any protective material such as asphalt or gunnite would soon come off.

Water caused minor problems in both tunnels. In Tunnel 2 the main problem was one of constant seeps which would weaken the bond in the bedding planes and cause the shale to fall in large pieces.

In Tunnel 1 the same problem occurred with one addition. Because the water was associated with the shales and leaked from the top of them, they became lubricated and quite slick. For one stretch, shale formed the entire side of the tunnel. With the shale slick, it was impossible for the mole to maintain a bearing while pressure was exerted at the cutterhead. The whole machine would slide backward. It became necessary to drill shallow holes behind the bearing pads and insert 3-in. steel pins so that the mole would slide against them and come to rest. Needless to say, progress was quite slow through this reach. If this condition had been expected to extend for a long distance, then permanent teeth would have been welded to the pads.

Bedding and jointing played an important role in the stability of Tunnel 2. It was, of course, the flat-lying bedding plane of a sandstone which formed the flat back so commonly found. As the shale or sandstone broke off, it fell in the shape of cubical pieces, the result of intersecting bedding and jointing.

These geologic features went practically unnoticed in Tunnel 1 for two reasons. First, as the mole performed its excavation, it very neatly plastered a thin layer of silt, clay, sand, and dust over the entire section. In most cases it was difficult just to pick out rock types. To distinguish the degree of bedding or jointing was practically impossible. Second, a true circular section tunnel theoretically offers the strongest available geometric figure. Rock fall under the given geologic conditions depends on the relationship between bedding and jointing. By creating a self-supporting circular section, the chances for rock fall are reduced and the beds and joints are rarely seen.

SUPPORTS

Supports in Tunnel 2 were of the usual type, either I-beams or rock bolts. Four-inch I-beams were used almost exclusively where thick shales formed the arch. The use of bolts was limited more to pinning rather than support. Bolts ranging in length from 6 to 12 ft were used. These were torqued to about 180 ft-lb.

In Tunnel 1, because of space limitations, 4-in. I-beam half-rings were the main means of support. When bad rock was first encountered, an attempt was made to use rock bolts. As the working room on top of the mole was less than standing room, bolts of adequate length could not be installed. Only short bolts could be used, and this usually resulted in the anchor being in shale. These bolts would rapidly fail.

The contractor had some success with 4-in. channel irons, which were for the most part 12 ft long and anchored in sandstone at each end with rock bolts. The bolts were installed after the mole had passed and working room became available. As the shale spread across the tunnel, the channel irons were useless because they would then be entirely in shale. At this stage, the contractor began installing 4-in. I-beam half-ring supports (Fig. 1). Because the top was a near perfect circle, these rolled supports could be used. They were placed by pinning each end at springline with two 18 by 1-in. rebars. This was adequate until the shale began another downward plunge. Five-foot dutchmen were added at the crown so the springline pins would drop below the shale.

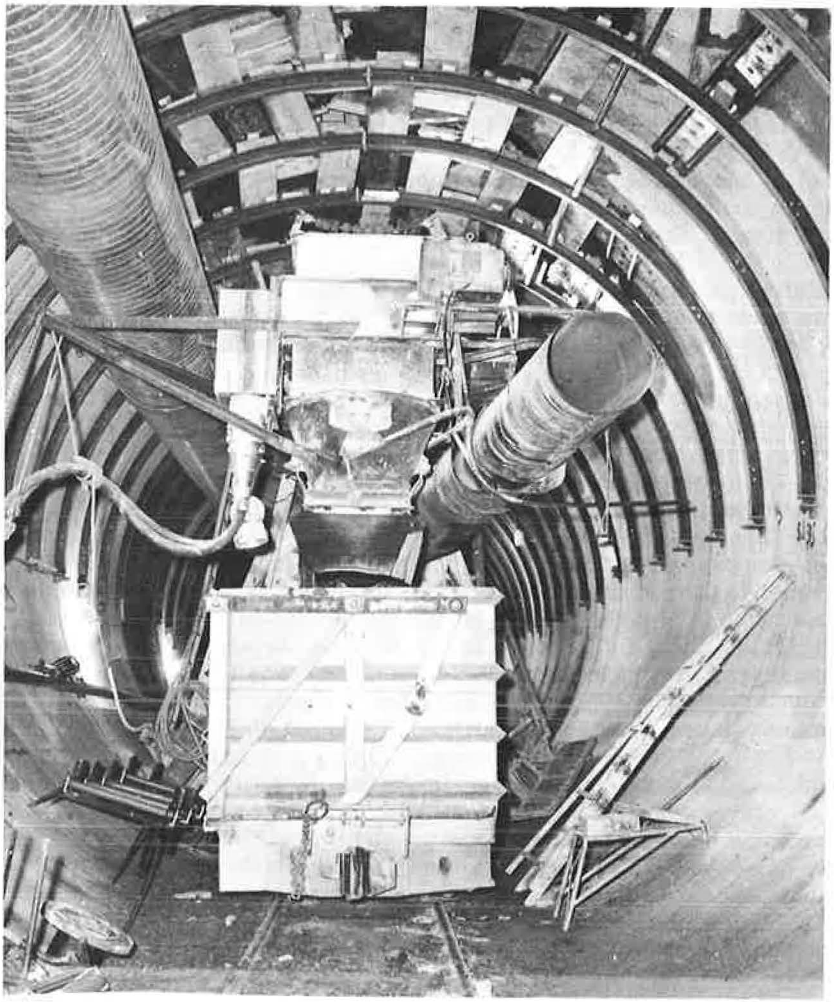

Figure 1. Half-ring supports used in Tunnel 1; conveyor belt in center dumps muck in car at lower center.

By this time the shale was out of the crown, but the slaking and overbreak actually became more severe on the sides than it ever was on the arch.

In Tunnel 1 the supported reaches totaled 44 percent of the entire length of mechanically driven tunnel. These supports were used exclusively in sections where shale was a problem.

Possibly one of the greatest advantages in using a mole is the savings on concrete due to less overbreak. Practically 50 percent less concrete is used for lining a nearly perfect circular tunnel when compared with a conventionally driven tunnel. The specification quantity for concrete in Tunnel 1 was 36,350 cu yd. If conventional methods had been used, it is estimated that 54,000 yd would have been required. Overbreak concrete is at the contractor's expense, although its costs will be hidden in his specification amounts.

Tunnel 2 required 72 percent support for an almost similar length. Seven percent was supported by 4-in. wide-flange steel supports whereas the remaining 65 percent used rock bolts. This does not include sections where bolts were used as pins or where it was felt that the bolts were improperly installed. In addition, supports were required in both sandstone and shale sections.

COMPARISON OF TECHNIQUES

Tunnel 1

The mole, properly called a tunneling machine, was developed for the prime contractor on Tunnel 1 (Fig. 2). Approximately 1 yr was spent building this tunneling titan. Exact costs were never revealed, but they have been estimated to be in excess of $750,000. When completely assembled, the machine was 64 ft long and weighed 280 tons. Three major components made up the machine: the head assembly, the outer frame, and the inner frame. Connected to each frame were hydraulic jacks which served a dual purpose: (a) bearing against the tunnel sides while drilling, and (b) locomotion. The cutterhead was actually connected to the outer frame so that jacks from the inner frame maintained the bearing while drilling. When moving forward, the outer jacks were extended, the inner ones withdrawn and the inner frame moved ahead 5 ft. The inner jacks were then extended, the outer withdrawn, and drilling began again and the cycle repeated.

The machine was capable of drilling 5 ft at a time before moving became necessary. Under ideal conditions, the mole could advance up to 10 ft per hr. Geologic conditions, of course, made the difference between poor or good advances. Using actual maximum advance figures, the machine could excavate up to 100 ft per day in supported ground, although this was considerably higher than the average. Excavating in unsupported sections, the maximum advance was 166 ft in 1 day. Generally, the average footage per day was 60.45 or 6.07 ft/hr.

The main cause of delay when going through supported ground was the placing of supports. It was necessary to hand carry the half-ring supports, in two pieces, to the mole and install them by manpower.

Other reasons for delay or complete shutdown included changing the diameter of the cuttinghead, repairs on the mole (mostly minor), muck cars jumping the tracks, and power changes or troubles.

Figure 2. Tunneling machine used in Tunnel 1; lower bearing pads are part of outer frame; shoes are attached for walking to tunnel.

The tunneling machine was equipped with a cuttinghead capable of cutting three different diameters: 19 ft 10 in., 20 ft 10 in., and 21 ft 2 in. For an unsupported section, the 19-ft 10-in. diameter was used, but for supported reaches, to accommodate the steel, the bore was increased to 20 ft 10 in. Either decreasing or increasing the diameter could be done in about 2 hr.

Control for line and grade was accomplished by a laser beam. The source of the beam was set on a platform about 12 ft off the invert and offset 5 ft from centerline. The beam was then projected to a grid screen on the mole which showed the operator his position with regard to line and grade. Any deflection of the mole would immediately be detected and corrected by use of the hydraulic jacks. Highly accurate survey control by the engineers was necessary to locate the laser beam source box properly and keep it located. The source box was moved ahead approximately every 200 ft. Correction for grade was also made at 200-ft intervals.

To achieve an almost constantly running operation, which is not divided into separate cycles, a different method of removing muck was used in Tunnel 1. Fastened directly to the rear of the mole was a 150-ft conveyor belt mounted on a frame. The front of the frame was supported by legs and wheels which rode on the tracks. The rear of the frame rode on legs and wheels which angled out and rode against the tunnel sides. The conveyor was high enough to allow a string of muck cars to drive under the entire length of the belt. The car next to the motor was filled, the train backed one car length and the next car filled. When the train was full, it backed several hundred feet to a passing track. An empty train then pulled ahead to the belt and the cycle repeated.

Tunnel 2

The major equipment used in Tunnel 2 consisted of a railroad, three passing tracks, one flying carpet (sliding floor), drill jumbo, six rotary drills, and two Goodman-Conway mucking machines.

All tunneling equipment traveled on a single 36-in. gage railroad track. Three movable passing tracks were installed at various intervals in the tunnel and were used for storage of muck cars, both full and empty.

The sliding floor was located at the heading. Sliding a section of track to within a few feet of the heading allowed the mucker to move in quickly and begin work without the need of men installing track.

The six rotary drills worked off three levels of the drill jumbo. The jumbo itself was 64 ft long and weighed over 110,000 lb.

The mucking machine could load about 1½ cu yd at a time. It took about 2 min 40 sec to fill a 15-cu yd muck car. About 45 sec was required to switch cars.

A complete cycle of drilling, blasting, and mucking could be accomplished under ideal conditions in 3 hr 20 min. This would advance the tunnel about 11 ft. Breaking the cycle down into its component parts, the following average times were required: drilling (63±, 12-ft deep holes), 45 min; loading (18 lb of dynamite and 50 lb of ammonium nitrate), 40 min; ventilation time, 10 to 30 min; and mucking, 1 hr 15 min.

In the same amount of time the mole could excavate slightly more than 20 ft. The average daily footage in Tunnel 2 was 51 ft, using 4.6 cycles.

Causes of delay or shutdown in Tunnel 2 were of the types ordinarily found in conventional tunneling techniques (i.e., mechanical breakdowns, derailments, installation of supports, scaling of loose rock, and removal of misfires). Control for line and grade in Tunnel 2 was accomplished by standard survey methods.

Personnel

The number of personnel on any job depends on the management and can vary considerably. In making a comparison between the two tunnels, similar jobs have been eliminated (such as superintendents, warehousemen, and cat operators). Use of a mole automatically eliminates positions commonly found in conventional methods, such as miners, drillers, and nippers. Under typical operating conditions the personnel working in Tunnel 1 in a 24-hr period was 30. When supports were installed, the number increased to 42. Tunnel 2, under different contract, required an average of 32 people

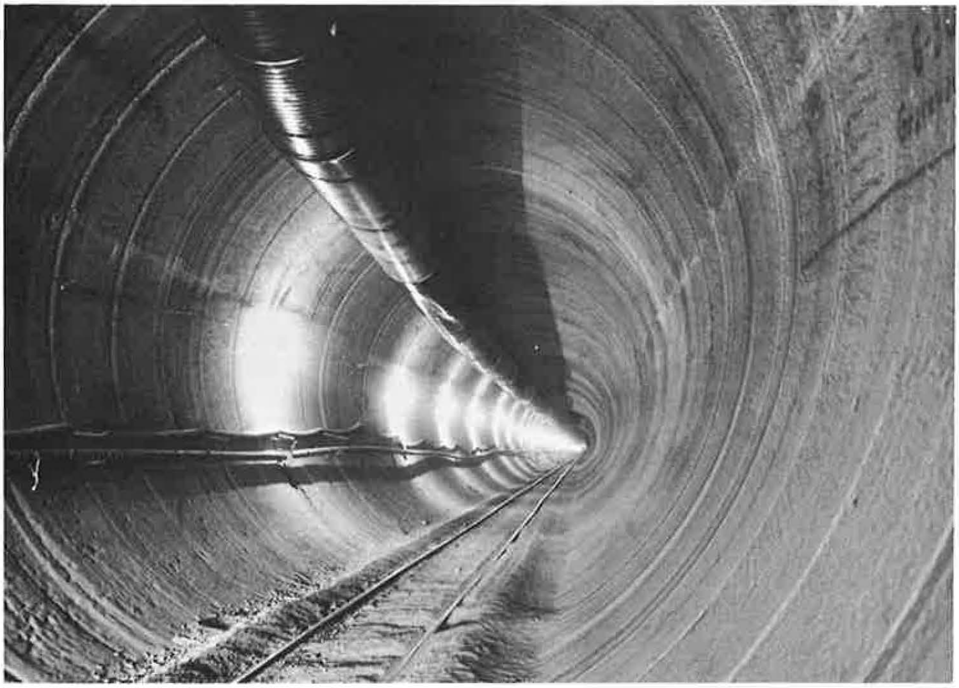

Figure 3. Tunnel 1 showing typical unsupported section.

Figure 4. Tunnel 2 showing typical supported and unsupported sections.

per 24 hours. Under different management personnel requirements might have varied considerably.

SUMMARY

In summarizing, it might be advantageous at this time to compare the pros and cons of using a mechanical boring machine.

Advantages

1. Near continuous operation.
2. Greater daily footage.
3. Minimum overbreak resulting in about a 50% reduction in concrete when compared with a conventionally driven tunnel.
4. Fewer personnel required under proper management.
5. No drilling or blasting required resulting in a safer operation.
6. Surrounding rock remains undistrubed and minimum of new stresses are introduced.
7. Excavates a near self-supporting section.
8. Very good bit footage.
9. Practically no cleanup time required.
10. A substantial savings realized since dynamite is not required.

Disadvantages

1. Long section needed to pay for itself.
2. Circular section only.
3. Specialized operator required.
4. Supports difficult to install.
5. Long wait for delivery.
6. Large initial investment.
7. Still in developmental stage.
8. Machine has to be designed for each tunnel because of different diameters and geologic conditions.
9. Presently limited to softer materials.
10. Ventilation system must be larger to provide for dust control.

In the comparison, it appears that the advantages far outweigh the disadvantages, and Figures 3 and 4 offer the final proof.