Tunnel Boring Machine Excavation of the Beverly Sewer Tunnel

A refitted tunnel boring machine can operate effectively in hard, high-strength igneous rock, offering cost and time savings and reduced potential for vibration damage and complaints.

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While tunnel boring machines (TBMs) have been used world-wide for decades, the first successful use of a tunnel boring machine in hard rock in Massachusetts occurred in 1990 at the Beverly Sewer Tunnel in Beverly. Many factors were involved in the selection of mechanical excavation over conventional drill-and-blast tunneling. The performance of a reconditioned TBM that completed the tunnel had a beneficial impact on the cost, scheduling, ground support requirements and environmental issues that were involved with the Beverly Sewer Tunnel project.

Project Description

The Danvers-Beverly Relief Interceptor Project. The South Essex Sewerage District (SESD), servicing the communities of Danvers, Beverly and Salem, began conceptual planning of the relief interceptor in the mid-1970s in order to create a regional wastewater system that combined functional existing interceptors, some of which are a century old, with new relief interceptors. The additional sewer capacity would thereby provide for future development and population increases. Increased capacity would also eliminate overflows that degrade the Beverly Harbor and Danvers River Estuary and jeopardize the local commercial fishing industry.

As shown in Figure 1, the Danvers-Beverly Relief Interceptor connects the Danvers Pump Station to the proposed Beverly Pump Station, which in turn transports the sewage to the SESD Treatment Plant. The project involved a number of phases:

- Cut-and-cover construction from the Danvers Pump Station to the Bass River;
- Extending the interceptor beneath the river (Bass River Siphon) to a junction chamber at the Bass River Shaft;
- Tunneling beneath the Goat Hill area of Beverly (Beverly Sewer Tunnel) to the Water Street Shaft;
- Cut-and-cover construction from the Water Street Shaft to the Beverly Pump Station; and,

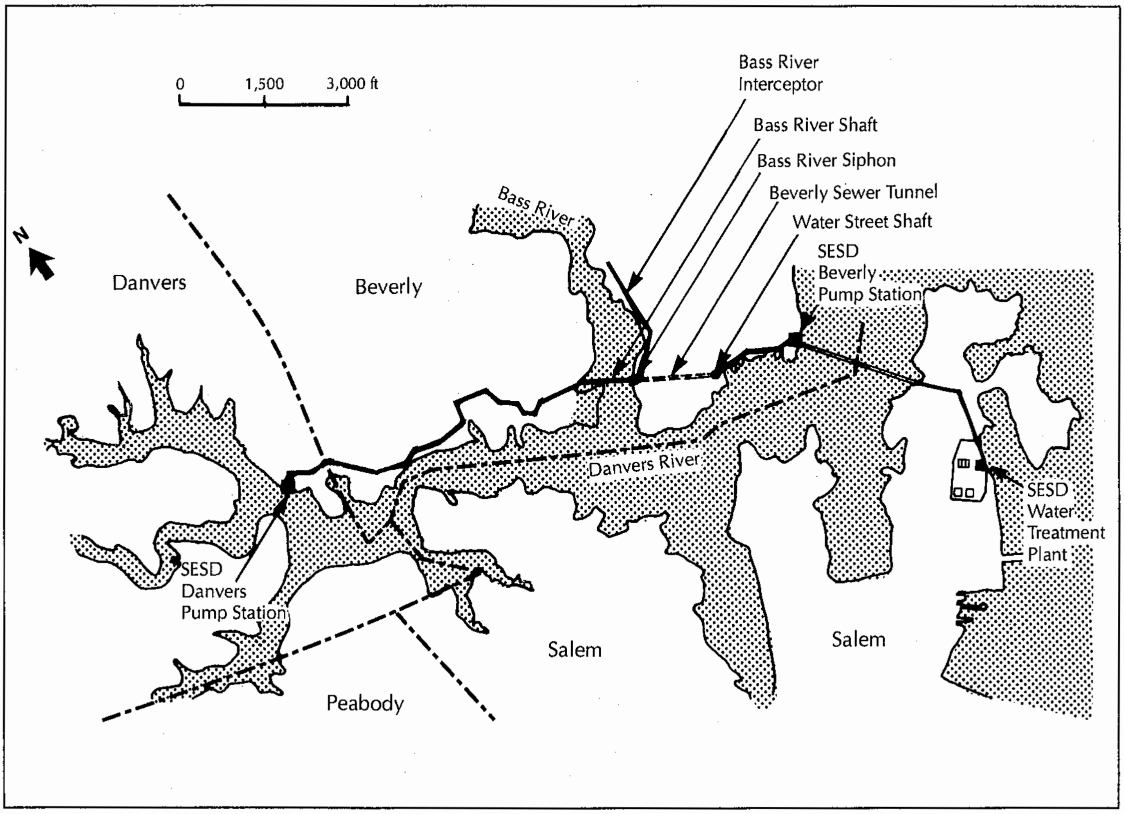

FIGURE 1. A schematic plan of the Danvers-Beverly Relief Interceptor location.

- Extending the interceptor beneath Beverly Harbor to the SESD Treatment Plant in Salem.

The tunneled portion of the project in Beverly, from the Bass River Shaft under Goat Hill to the Water Street Shaft, called the Beverly Sewer Tunnel, is under discussion here.

The Beverly Sewer Tunnel. The Beverly Sewer Tunnel was designed to combine incoming flows from the Bass River Siphon and the Bass River Interceptor and convey them to the Beverly Pump Station (see Figure 1).

Construction of the Beverly Sewer Tunnel required the excavation and support of two shafts through soil overburden and rock to a depth of approximately 60 feet, and approximately 1,570 feet of 8.5-foot diameter hard rock tunnel. The location of the shafts and the tunnel alignment are shown in Figure 2.

From a hydraulics standpoint, the tunnel and shafts were designed as an "inverted siphon." A junction chamber at the top of the Bass River Shaft combines the inflows, which then pass through a weir system and into one or more of three ductile iron sewer pipes with outside diameters of 25.8 inches, 32 inches and 44.5 inches. The pipes, flowing full, carry the flow down the shaft, through the tunnel, and up the Water Street Shaft. An outlet chamber at the Water Street Shaft diverts the flow into a 54-inch diameter sewer pipe that leads to the pump station. The tunnel and shafts were backfilled with lean concrete in order to avoid having to install permanent rock support and to provide some additional corrosion protection for the ductile iron pipes.

Site and Subsurface Conditions. Located approximately 25 miles northeast of Boston, the city of Beverly is in the Seaboard Lowland Section of the New England Physiographic Province. Rock in the region is typically classified as igneous or metamorphic, from the Paleozoic Era. It has been subjected to several episodes of tectonic activity during which large-scale regional folding and faulting have developed ac-

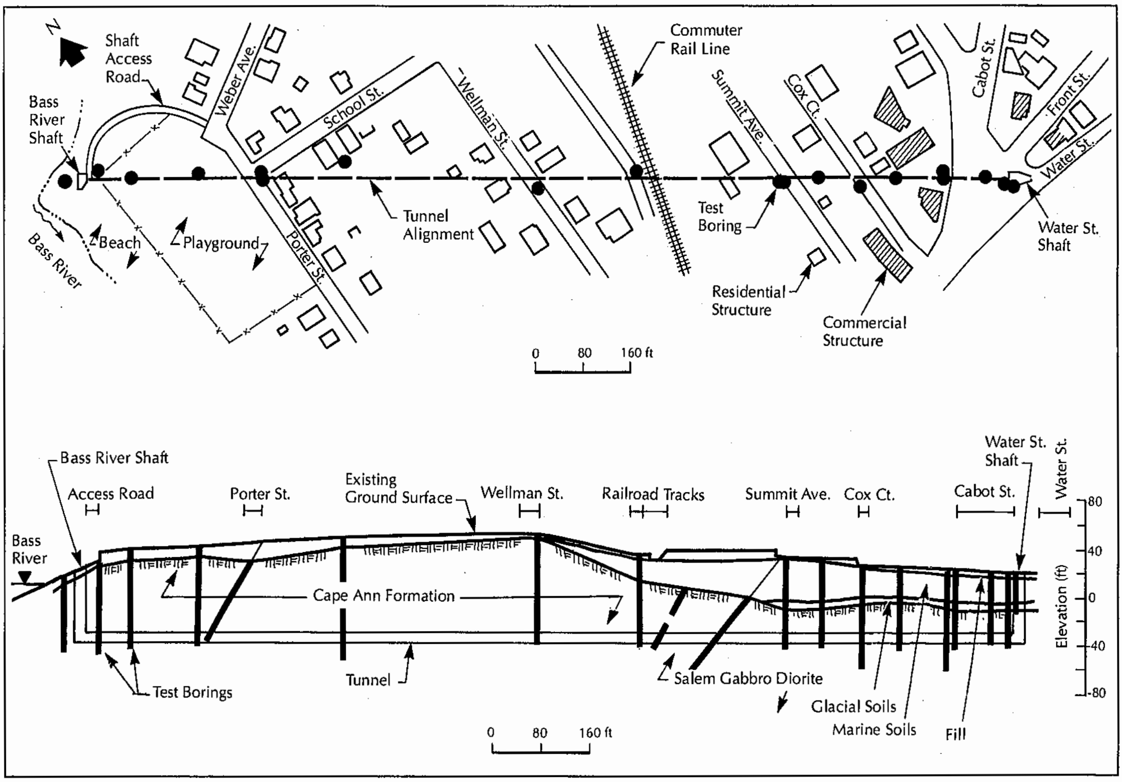

FIGURE 2. Plan and general geologic section of the Beverly Sewer Tunnel location.

companied by granitic intrusions.[1]

A detailed subsurface exploration program consisting of test borings, field permeability testing, seismic refraction surveys and geologic field mapping was conducted in 1983 to determine stratigraphy, lithology and rock mass properties along the tunnel alignment.[2,3] Laboratory tests and analyses were performed on soil and rock samples to aid in classification and to define significant engineering properties.

Figure 2 shows a simplified geologic profile along the tunnel alignment. Overburden soils ranged in thickness from about two to 42 feet. The overburden typically consisted of marine deposits of fine sands and clayey silts overlying glaciofluvial and glacial till deposits.

Two major bedrock units were encountered along the tunnel alignment: Cape Ann Granite and Salem Gabbro-Diorite. The granite is described as hard to very hard, very slightly weathered, coarse to medium grained. The gabbro-diorite is described as hard to very hard, slightly weathered, medium to fine grained. Table 1 illustrates the average mineralogical composition of the two rock types. Based on the exploration program, it was anticipated that about 60 to 65 percent of the tunnel excavation would be in the Cape Ann Granite formation, about 30 to 35 percent in the Salem Gabbro-Diorite, and the remaining in mafic igneous dike rock.

Table 2 lists some average engineering properties of the intact rock derived from laboratory testing of core samples. Based on Deere and Miller, the intact Cape Ann Granite would be classified as high-strength, average modulus rock; while the Salem Gabbro-Diorite would be classified as high-strength, high modulus rock.[4]

During geologic field mapping four major joint sets were identified in the granite, as summarized in Table 3. No outcrops of gabbro-dioritic rock were exposed to allow mapping. However, based on analyses of rock core from test borings, including an angled boring in the gabbro-diorite, it was assumed that the primary joint sets were similar throughout the alignment.

TABLE 1
Mineralogical Composition From Petrographic Analyses

Cape Ann Granite

Mineral	Estimated Percentage
Microperthite	60-70
Quartz	20-30
Hornblende	0-5
Pyroxene	0-5
Opaques & accessories	0-5

Salem Gabbro-Diorite

Mineral	Estimated Percentage
Plagioclase	50
Quartz	15-20
Hornblende	15-20
Sericite	10
Biotite	5
Augite	5
Opaques & accessories	0-5

From Refs. 2 & 3

Several shears (naturally occurring rock discontinuities along which displacement of limited extent has occurred) were observed during the geologic mapping program. These shear features were generally continuous, but were not considered to be shear zones (*i.e.*, the shearing was confined to a plane and did not significantly affect the rock on either side of the plane). The exploration program did not identify any discontinuities that could be classified as faults.

Rock mass quality along the proposed tunnel alignment was determined using the Rock Quality Designation (RQD) technique.[5] RQD is defined as the summation of intact, unweathered pieces of rock four inches in length or greater within a core run, divided by the total length of the core run, expressed as a percentage. Within the tunnel's zone of influence (invert to one tunnel diameter above crown), approximately 93 percent of rock cores obtained during the subsurface exploration program had RQD values exceeding 50 percent, with a mean of about 73 percent. This rock would be classified as fair to good quality according to Deere *et al.*[5] RQD in the gabbro-diorite was typically slightly higher than in the granite.

Groundwater levels were typically about 47 to 75 feet above the tunnel invert and were consistent with variations in topography and ground surface. Based on water pressure tests in borings along the tunnel alignment, the rock mass generally exhibited low equivalent permeability (less than 10^{-5} cm/sec) with some isolated areas of potentially higher water inflows. Total inflow within the tunnel was estimated to be less than 300 gallons per minute (gpm), with each shaft adding an estimated additional 20 gpm.

Design Requirements

The vertical alignment of the Beverly Sewer Tunnel was established to provide a minimum of one tunnel diameter of rock cover above the crown of the tunnel. The minimum cover occurred near the Water Street Shaft (east) end of the tunnel (see the profile in Figure 2). The tunnel sloped up at a slope of about one foot in 100 feet from the designated Bass River work

TABLE 2
Summary of Engineering Properties of Intact Rock

Property/Parameter	Average Value: Cape Ann Granite	Average Value: Salem Gabbro-Diorite
Unit Weight (pcf)	164	179
Total Hardness	183	107
Compressive Strength (psi)	20,200	18,200
Tangent Modulus (psi)	9.8×10^6	11.3×10^6

From Refs. 2 & 3

TABLE 3
Summary of Cape Ann Granite Joint Sets

Joint Set No.	Strike Range	Dip Range	Typical Spacing (ft)
1	N38°E - N90°E	46° - 90° SE	1-3
2	N40°W - N10°E	49° - 90° NE 77° - 90° SW	1-3
3	N40°W - N90°E	71° - 90° NE 71° - 90° SW	> 10
4	N73°E - N20°W	17° - 34° NE	> 10

From Ref. 3

shaft towards the Water Street Shaft in order to allow drainage away from the heading as tunneling advanced. Tunneling was only allowed from the Bass River Shaft, which was separated from the residential community by a playground (see Figure 2), in order to reduce construction impacts on the community and to minimize traffic disruption in the congested streets around the Water Street Shaft.

It was assumed during the design phase work, which was completed in 1983, that the tunnel would be driven using drill-and-blast techniques due to economic considerations, although provisions were included in the contract documents to allow TBM excavation as an alternative. The contractor was given flexibility to choose the tunnel cross section geometry within the minimum and maximum limits indicated in Figure 3.

Tunnel Support. Fully grouted rock dowels were required as minimum initial support at the tunnel portals at the Bass River and Water Street shafts. These dowels were approximately 15 feet long and were installed as pre-reinforcement — *i.e.*, they were installed prior to commencing tunnel excavation from the Bass River Shaft and prior to holing through at the Water Street Shaft. Portal pre-reinforcement consisted of a single row of four or five dowels (No. 8, upset threaded bar, grade 60 steel, about 15 feet long) located two feet above the crown of the tunnel, angled upward at 30 degrees from horizontal and parallel to the tunnel centerline.

Based on the relatively good quality of the rock mass and the favorable orientation of the primary joint set (striking nearly perpendicular to the tunnel alignment), there was no minimum initial rock support specified for the tunnel. Instead, the contract documents required

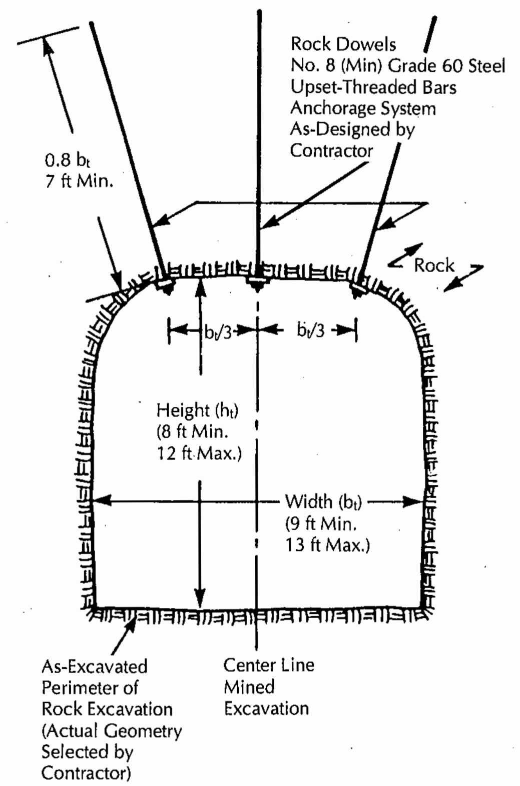

FIGURE 3. Schematic section showing minimum/maximum specified tunnel size and suggested initial support.

FIGURE 4. Looking southeast along the tunnel alignment from the playground at the Bass River Shaft.

the installation of rock support on the basis of observed rock conditions in the tunnel. Figure 3 shows suggested initial rock support where required, consisting of untensioned, fully grouted rock dowels, three per row, spaced at five-foot intervals along the tunnel axis. Based on the available geotechnical information for the site, it was estimated that up to 20 percent of the tunnel drive would require pattern rock dowels for initial rock support, assuming smooth blasting techniques were used at the tunnel crown.[3] It was anticipated that spot dowels would be required to support isolated unstable rock blocks at random locations throughout the tunnel.

Schedule. It was estimated that tunnel excavation, assuming drill-and-blast methods, would advance at the rate of about six feet (or one tunnel round) per day, for a total duration of about 262 work days, or about 45 weeks (at six days per week, 12 hours per day). The contractor was to complete all work within 540 calendar days (77 weeks) after formal execution of the contract agreement.

Construction Impact Mitigation. The distance from the crown of the tunnel to ground surface ranged between 45 and 79 feet. Above the tunnel was a residential and light commercial neighborhood that contained a number of historical buildings, some dating back to the seventeenth century. Figure 4 shows some of the houses over the tunnel alignment. It was taken from the playground adjacent to the Bass River Shaft, looking southeast towards a drill rig installing geotechnical instrumentation over the crown of the tunnel. Figure 5 presents a view looking northeast at the Water Street Shaft, and depicts some of the commercial and residential structures near the shaft.

As noted previously, it was assumed during

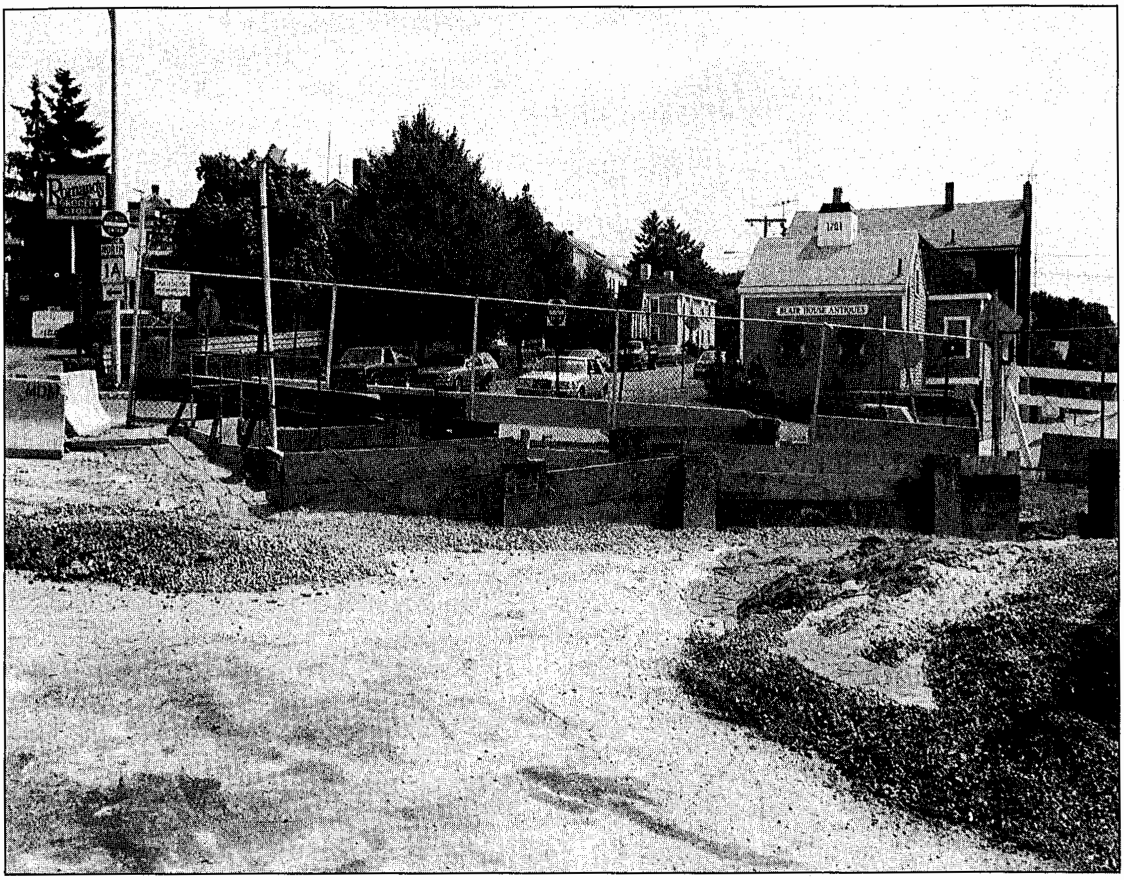

FIGURE 5. Looking northeast at the Water Street Shaft and nearby historic structures.

the design phase work that the tunnel would be driven using drill-and-blast techniques. Because of the proximity of the residences to the shaft and tunnel construction, in particular to blasting operations, the impacts of ground vibrations and air blast were sensitive issues within the community. A number of provisions were incorporated into the contract documents to minimize these and other construction related impacts on people living and working in the area.

Blasting Impact Mitigation. Some of the blasting related mitigation provisions included:

- Restrictions on blasting hours to the period between 8:00 a.m. and 7:00 p.m., Monday through Saturday.
- Limits on the maximum peak particle velocity of ground vibration and maximum peak air blast overpressure at the nearest residential structure, based on United States Bureau of Mines research on blasting near residential structures (see "Close-In Construction Blasting: Impacts & Mitigation Measures," on pages 73–92 for a more complete discussion of these limits).[6,7]
- Vibration monitoring and reporting for each blast by an independent professional engineer or seismologist under contract to the contractor.
- Pre-Blast Condition Surveys of all above ground structures in the area of blasting, by an independent professional engineer or seismologist under contract to the owner.
- Pre-Blast Radon Surveys of all residential structures in the area of blasting, by an independent engineering consultant specializing in such work, under contract to the owner. This provision was added as a result of citizen concerns about tunnel

TABLE 4
Comparison of TBM *vs.* Drill-&-Blast Tunneling

TBM Tunneling	Drill-&-Blast Tunneling
Continuous Operation	Cyclic Operation
High Initial Capital Cost	Relatively Low Initial Capital Cost
Potentially Long Delivery Time	Relatively Short Delivery Time
Circular Profile Only	Variable Shape & Size Openings
Excavation Rate: Relatively High in Favorable Geology; Poor in Unfavorable Geology	Excavation Rate: Relatively Low; Adaptable to Adverse Geology
Relatively Low Induced Ground Vibrations	Ground Vibrations & Overpressures
Little Rock Disturbance; Minimal Overbreak; Rock Support Requirements Potentially Reduced	Rock Disturbance; Greater Rock Support Requirements
Uniform, Small Muck Chips	Bulky Blast Rock

From Ref. 8

excavation increasing the migration of radon into basements of houses above the alignment.

- Submittal of detailed blasting plan by the contractor, for review by the design engineer, prior to blasting at either shaft.

Citizen Mandated Mitigative Measures. In addition to the blasting related controls, there were also provisions to minimize noise impacts and disruption and danger from truck traffic through the residential neighborhood. As a result of meetings between the owner, engineer, city officials and a citizens' group, the following provisions were added to the contract documents:

- Overall operations only permitted between 7:00 a.m. and 8:00 p.m., Monday through Saturday. In addition, the contractor was *required* to work six days a week (Monday through Saturday) in order to reduce the total duration of construction and so reduce the total duration of related impacts on residents.
- Prohibition of hauling of muck from the Bass River work shaft through adjacent residential streets. All muck was loaded onto a barge in the adjacent Bass River using a conveyor system and barged to an offloading site away from the residential neighborhood.
- Prohibition of any truck traffic through residential streets on week days during the school year between the hours of 7:30 a.m. to 8:15 a.m., and between 2:15 p.m. to 3:00 p.m.
- Prohibition of contractor employee parking on streets near the Bass River work shaft. Only a limited staging area was provided at the Bass River work shaft, so the contractor was required to provide off-site office facilities and staging area for workers and materials.

In addition to the above provisions, presentations were made to residents prior to construction to address their concerns and to inform them of the work to be undertaken and the controls in place to minimize impacts on them. During tunnel construction, informational meetings were held with residents on a monthly basis to keep them informed of progress and to answer questions or respond to complaints.

Geotechnical Instrumentation & Monitoring

A program of geotechnical instrumentation and monitoring was undertaken by the owner's geotechnical consultant during construction and included:

- Observation wells and piezometers to monitor and document the effect of construction on the groundwater table, as related to water well yields and long-term effects of groundwater drawdown on adjacent structures.
- Settlement pins on structures to monitor and document the effects of construction

on adjacent structures.

- Borros settlement points to monitor surface settlements that could have resulted from drawdown within marine deposits.
- Multiple Position Borehole Extensometers (MPBXs) installed from ground surface to monitor rock movements above the crown of the tunnel, in order to evaluate the performance of the initial rock support system, especially in areas of minimal rock cover.
- Blast monitoring to observe compliance with submitted procedures and supplement and confirm the contractor's vibration measurements.

Shaft & Tunnel Construction

Due to a lack of funding, the project, which was designed in 1983, did not go to bid until 1989. The construction contract was awarded to the low bidder in the fall of 1989. The contractor proposed using a reconditioned TBM to excavate the tunnel instead of employing drilling and blasting. However, drill-and-blast excavation was still required for the excavation of the shafts and a starter tunnel.

TBM vs. *Drill-and-Blast Tunneling*. The advantages and disadvantages of TBM *vs.* drill-and-blast tunneling are compared and summarized in Table 4. When construction of the Beverly Sewer Tunnel was released for bid, it was anticipated that because of the relatively short length of the tunnel (slightly less than 1,600 feet), it would most economically be excavated by conventional drill-and-blast tunneling. It was felt that the cost of mobilizing a TBM would be difficult to amortize on such a small project. In addition, it was felt that the relatively high compressive strength, high hardness and high quartz content in the granitic and gabbrodioritic rock would result in relatively low penetration rates and require the frequent maintenance and replacement of cutters.

The contractor judged that a properly configured TBM could advance at significantly higher rates than with drill-and-blast tunneling. The contractor estimated that even with the time to mobilize, assemble, demobilize and disassemble the machine, there would be savings in construction time and, therefore, in construction costs over drill and blast. The contractor also expected to see reduced costs (over drill and blast) from:

- Reducing rock support requirements as a result of the minimal rock disturbance by the TBM.
- Reducing the amount of muck to remove and concrete backfill to place as a result of a reduction in overbreak.
- Reducing the time and fees for the blast monitoring consultant, whose presence would only be required during the shaft and starter tunnel blasting.
- Reducing the potential for damage claims as a result of blasting vibrations.
- Reducing potential work stoppages or restrictions as a result of community complaints or actions.

The contractor planned to lease a used TBM that would be available after a short reconditioning period, so two of the biggest disadvantages of TBM tunneling were immediately offset (*i.e.*, high initial capital cost and long delivery time). Thus, the combination of TBM leasing, along with the potential cost savings noted above, was responsible for the low bid for the project. The total bid price was well below the design engineer's estimate, and below the eight other bidders that based their costs on drill-and-blast construction.

The Beverly Sewer Tunnel TBM. A reconditioned 8.5-foot diameter TBM was chosen to excavate the Beverly Sewer Tunnel. Figures 6 and 7 show generic TBM components for a similar TBM. The principal components are the cutterhead, the main body and the muck removal system. The cutterhead of this full-face, hard rock TBM consists of a number of disc cutters mounted on a circular, flat or convex head (see Figure 7). The cutterhead is rotated by electric motors through a main bearing attached to the main body. The Beverly TBM cutterhead rotated at a speed of 12.5 revolutions per minute. As the cutterhead rotates, thrust cylinders press the disc cutters into the rock mass. The disc cutters (see Figure 8) cut grooves, or kerfs, into the rock mass and rock chips (muck) are formed through shear and tensile failure of the rock (see Figure 9).

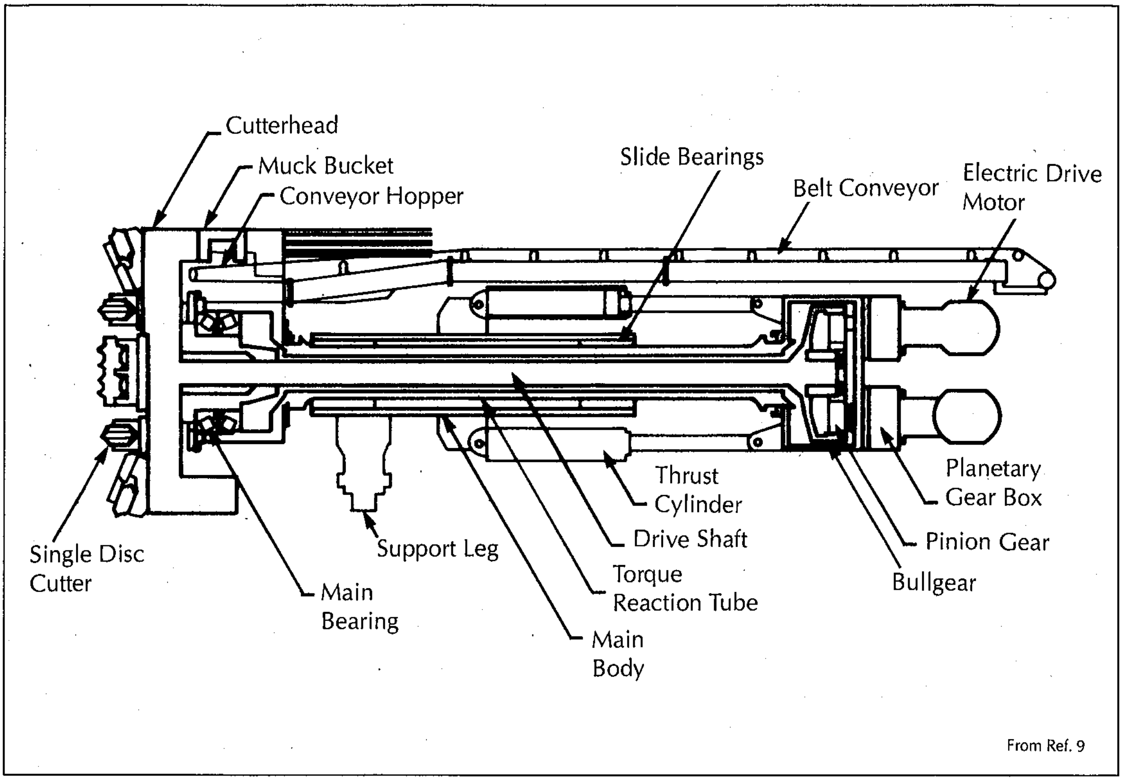

FIGURE 6. Schematic sketch of the TBM components.

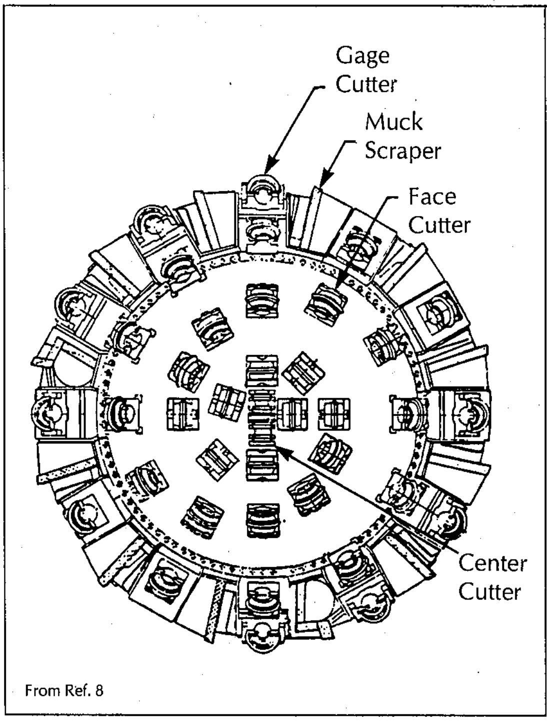

FIGURE 7. Schematic sketch of a TBM cutterhead.

Figure 10 shows the cutterhead of the TBM holing through at the Water Street Shaft. A total of 18 disc cutters, 15.5-inches in diameter, were mounted on this TBM, one more than the normal complement for this type of TBM.

Muck scrapers, the conveyor hopper and the conveyor system constitute the muck removal system. The muck is captured by muck scrapers (see Figure 7) or buckets that pick up muck as the cutterhead turns and deposit the debris onto a conveyor system (see Figure 6) that transports the muck to the rear of the TBM. Once there, the muck falls into rail cars that deliver the debris to the tunnel shaft for final disposition.

The main body structurally supports the cutterhead and mucking systems and houses the torque, steering, stabilizing and thrusting systems that operate the TBM. The torque system on this machine consists of three electric motors that drive the cutterhead. The thrusting system consists of hydraulic cylinders that extend and retract the cutterhead. A number of gripper pads (four on this machine) stabilize

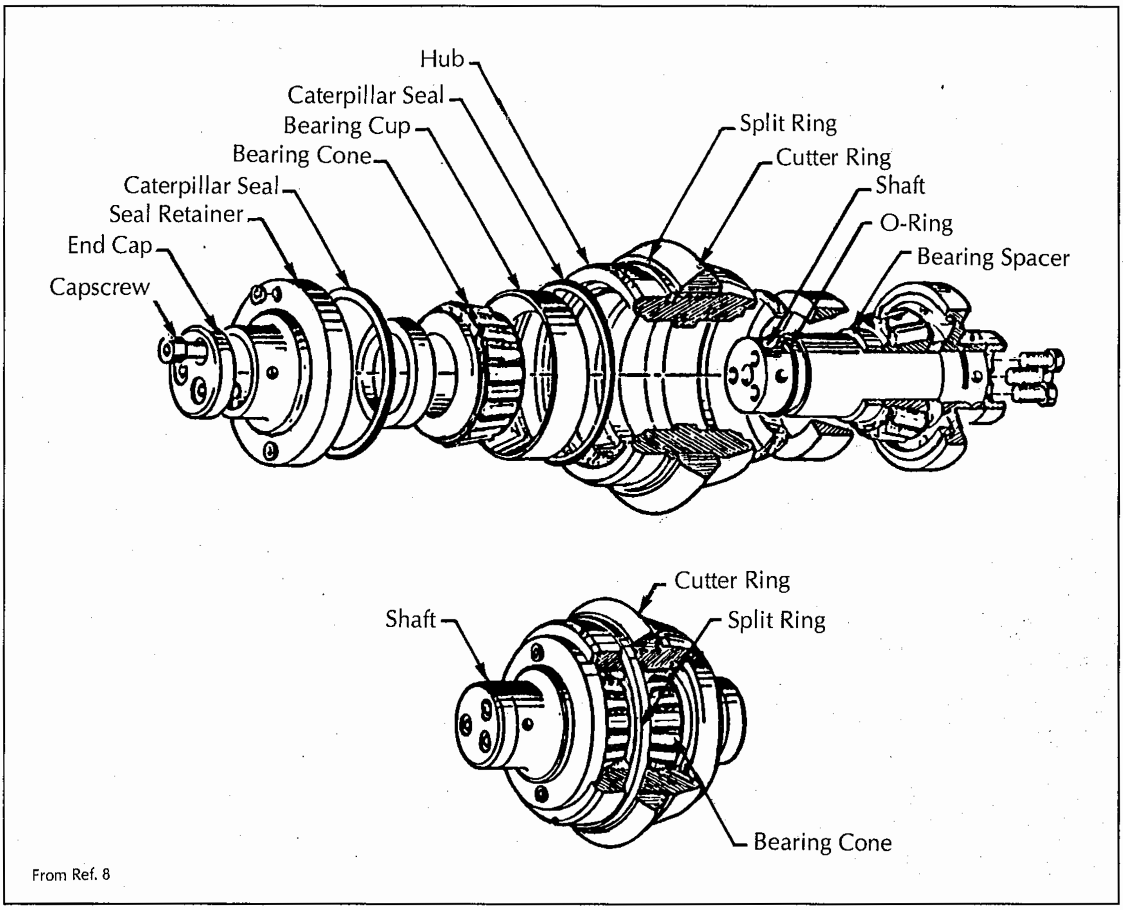

FIGURE 8. Schematic sketch of the disc cutter.

and support the cutterhead, and permit adjustments to the orientation of the TBM so that the appropriate alignment can be maintained. Support legs are used in conjunction with gripper pads to advance and reposition the TBM after each stroke cycle.

This TBM had most recently been operating in less abrasive, softer sedimentary rock, so a number of modifications were made, in addition to installing the extra disc cutter, in order to allow the machine to operate effectively in the hard, igneous rocks in Beverly. The electric drive motors and hydraulic system were upgraded to provide for the greater cutterwheel torque and thrust force needed to negotiate the hard rock environment. Typically, this type of TBM has a total drive horsepower of 375 horsepower (hp), a maximum thrust force of 280 tons and a maximum anchor force of 840 tons.[9] The Beverly TBM was upgraded to

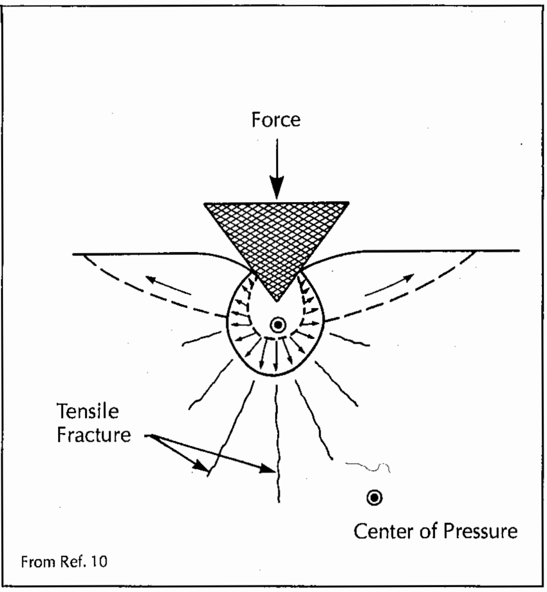

FIGURE 9. Schematic sketch of the failure mechanism for fragmented rock with a TBM.

FIGURE 10. The cutterhead holing through the Water Street Shaft.

a total drive horsepower of 450 (three motors at 150 hp each, 460 volts AC, three-phase, 60 Hertz), a maximum thrust force of 300 tons (33,000 lbs per cutter) and a maximum anchor force of 900 tons.

TBM Performance at the Beverly Sewer Tunnel

The reconditioned TBM commenced mining on April 30, 1990, and "holed through" at the Water Street Shaft on August 4, 1990 (see Figure 10), for an average advance rate of approximately two feet per hour (ft/hr) or about 19.3 feet per day (for an average 9.6-hour day). The highest daily advance was 40 feet in a 10.25-hour day (or 3.9 ft/hr). The average penetration rate (rate of advance when the TBM is cutting rock at the face) was approximately five ft/hr, while the highest penetration rate was about 6.9 ft/hr.

One means of evaluating the performance of a TBM is through machine utilization, expressed as a percentage of the total construction time during which the TBM is in operation mining and mucking rock. Utilization herein includes all operational mining time, including the time required to restroke and realign the TBM before commencing another stroke, or push. Restroking time for this project was estimated to be about eight percent of the machine operating time.

TBM Utilization at the Beverly Sewer Tunnel. Utilization records at the Beverly Sewer Tunnel were maintained by the geotechnical engineer that was present daily during the operation of the TBM. Construction involved a single shift typically of seven to 13 hours duration, six days a week. Operational and non-operational times were recorded in 15-minute increments along with the reason or cause of delay. Average utilization of the TBM at the Beverly Sewer Tunnel project was approximately 42 percent of total

TABLE 5
Summary of the Ten Most Significant Causes for TBM Delays on the Beverly Sewer Tunnel

Description of Delay	Delay Category	Percent of Construction Time
Inspect, Repair & Replace Disc Cutters	TBM Maintenance & Repair	10.0
Awaiting Muck Train*	Back-Up System Maintenance & Repair	8.0
Electrical Problems	TBM Maintenance & Repair	6.1
Repair & Replace Conveyor	TBM Maintenance & Repair	5.6
General Maintenance	TBM Maintenance & Repair	5.0
Dust Guard Repairs	TBM Maintenance & Repairs	4.6
Groundwater Delays	Geology	4.6
Install Trailing	Back-Up System Maintenance & Repair	4.1
Installing Track & Utility Lines	Back-Up System Maintenance & Repair	3.0
Clearing Conveyor Jams	Geology	2.4

* A single track was utilized without switching capability. Locomotive delays started at about 700 feet from the shaft when the TBM could be restroked and reset prior to the locomotive transporting two muck cars to the shaft and then returning with two empty cars.

construction time.

Utilization depends on the ability of the tunneling equipment to operate in a geological environment supported by ancillary and associated back-up systems. Consequently, the factors that result in delays, and consequently influence utilization and performance, are attributable to three primary factors:

- Geological conditions
- Back-up systems
- The TBM itself

Geological conditions "represent the major uncertainty with respect to the prediction of utilization,"[10] since pre-construction subsurface explorations rarely provide complete insight into the geological problems that will be encountered during construction. Typical delays attributable to geological conditions encountered during this project include those resulting from groundwater inflow, supporting or reinforcing the rock mass with steel sets or rock bolts, and those associated with conveyor jams or hand excavating muck from the tunnel invert. Delays resulting from geological factors accounted for eight percent of the construction time.

The maintenance, repair and operation of back-up equipment and systems affect utilization indirectly. Back-up systems delays include those stemming from the installation of utilities (*i.e.*, water, electric, ventilation and compressed air) and/or railroad tracks, the power supply, muck train delays and shaft operations. Also included in this category were delays associated with adding additional segments of the trailing gear once mechanical tunneling had begun. Back-up sys-

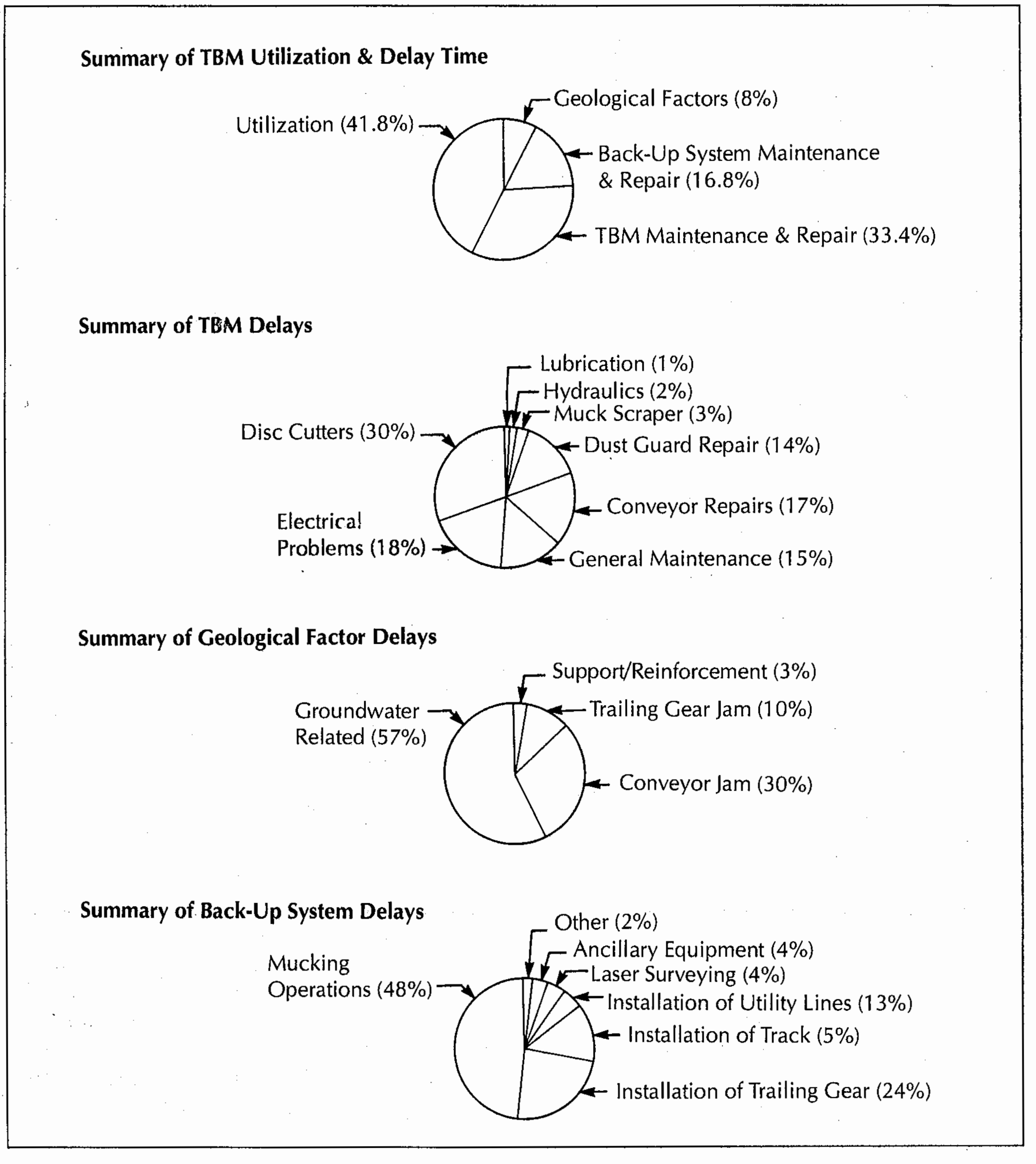

FIGURE 11. Utilization summary for the TBM at the Beverly Sewer Tunnel.

tem delays accounted for 16.8 percent of the total construction time.

The maintenance and repair of the TBM directly affect utilization. For this project, TBM maintenance and repair delays include those associated with general maintenance and inspections, with inspecting and replacing disc cutters, with hydraulic and lubricating systems, with motor and/or electrical problems, and problems associated with muck conveyors. Maintenance and repair of the reconditioned TBM accounted for 33.4 percent of the available construction time.

Table 5 summarizes the ten most time-consuming causes for delays on the Beverly project. Figure 11 illustrates the percentages of utilization and non-utilization time with a breakdown by delay category of the latter.

Benefits of TBM Use on the Project

The use of a TBM on the Beverly Sewer Tunnel Project produced many benefits, specifically those dealing with tunnel support requirements, schedule and disturbance to the community.

Tunnel Support Requirements. A total of 120 rock dowels and six steel sets were installed in order to reinforce and support the rock mass within the tunnel. For the most part, rock wedges in the crown and at the springlines were stable. Rock falls did not occur and those discrete rock wedges that were potentially unstable were reinforced with rock dowels by the contractor.

Steel sets with timber lagging were installed where a series of relatively flat lying, gouge-filled joint sets were encountered and where slaking or raveling of the clayey gouge material was feared. Based on the anticipated support requirements (up to 20 percent of the tunnel drive with pattern bolts) for carefully executed smooth blasting, the estimated number of dowels, including spot dowels, that would have been required would have been over 200. Thus, the non-destructive tunneling process afforded by the TBM reduced anticipated tunnel support requirements by about 40 percent, thereby reducing tunnel support costs, as well as reducing potential rock fall hazards to workers.

Construction Project Schedule. Contract documents required that construction be completed within 540 days subsequent to the formal execution of the contract agreement that occurred on October 18, 1989. Tunneling was completed on August 4, 1990, only 97 days after the start of boring work and 165 days ahead of the design engineer's estimated tunnel completion date, which had been based on conventional drill-and-blast tunneling. Thus, the use of a TBM reduced the duration of tunneling work by over 60 percent compared to the anticipated drill-and-blast duration.

Construction Vibrations. From the early stages of the project, the impact of construction blasting at the shafts and in the tunnel in close proximity to residential housing was a major concern of the SESD. Blasting operations at the Bass River and Water Street shafts were monitored to ensure compliance with the specified ground vibration and air overpressure limits, which were aimed at preventing damage to nearby structures and minimizing human discomfort. Twelve shaft rounds and five tunnel rounds (for the TBM starter tunnel) were detonated at the Bass River Shaft; and eight shaft rounds and one tunnel round were detonated at the Water Street Shaft. Blast vibrations were in all cases within specified peak particle velocity limits.

Although the vibration levels from blasting were below safe levels for cosmetic damage to residential structures, there were still complaints about noise and vibration after many of the blasts. These complaints resulted because the level of perception of humans to ground vibrations is about two orders of magnitude below the safe level for damage to structures. Hendron and Oriard have shown how the level of perception of humans compares to actual damage levels (see Figure 12).[11] Although ground vibration levels from the project were well below "safe" limits, they were in the range of "disturbing" to people. Combined with the air blast overpressures, which would tend to rattle windows, these levels were high enough to result in complaints, especially by people who did not hear the warning whistle and were startled by the noise and vibration. Most of the complaints were for disturbance only, although there were several complaints of alleged damage resulting from the blast vibrations. Subsequent review of these damage complaints indicated that they were not blasting related.

The vibrations from TBM excavation, on the other hand, were less than 0.01 in/sec at the ground surface above the tunnel, which is below the level of perceptibility of humans as shown in Figure 12. Complaints about construction activity ceased once mechanized tunneling began. This abatement highlights one of the advantages to TBM usage — reduced ground vibration and air overpressure levels — and demonstrates the reduced environmental impact of TBM usage on the local community.

Measured Deformations Above Tunnel. Measured ground surface settlements above the tunnel were in all locations less than 0.1 inch, and in most cases were less than 0.05 inch. These small settlements were attributed to:

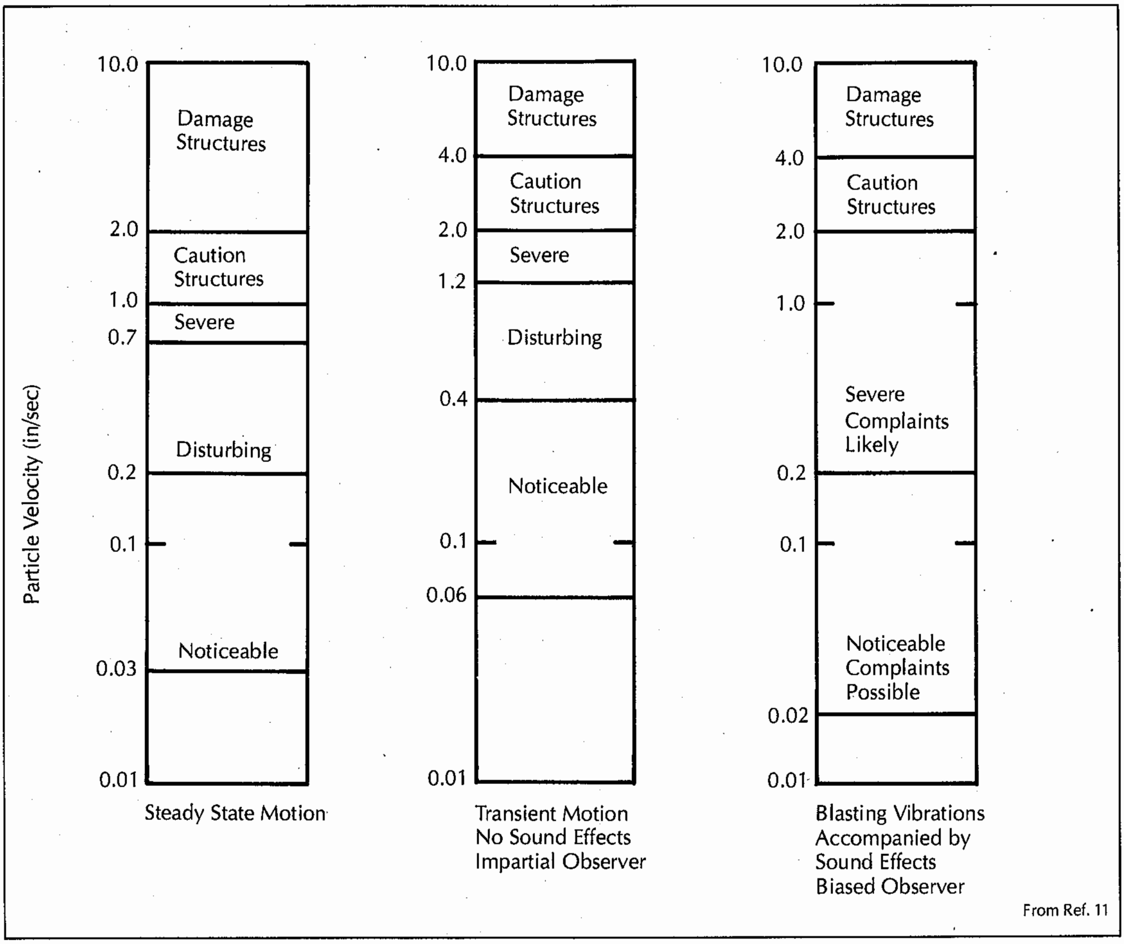

FIGURE 12. Human response to blasting.

- Small deformations in the rock mass above the tunnel (less than 0.05 inch as measured by MPBXs).
- Very small consolidation related settlements in marine and glacial soils above the tunnel that resulted from groundwater drawdown.

Deformations above the tunnel would also have been anticipated to be small with drill-and-blast construction. The major concern for deformations was for possible loss of ground into the tunnel in areas near the Bass River Shaft where there was minimum rock cover over the tunnel crown. With drill-and-blast construction, the potential for such loss of ground would have been greater due to the possibility of explosive gasses opening joints or causing overbreak above the crown.

Summary & Conclusions

A reconditioned TBM successfully completed approximately 1,600 feet of a 8.5-foot diameter tunnel in a hard, high-strength igneous bedrock in Beverly, Massachusetts, with an average advance rate of 2 ft/hr, or 19.3 ft/day, for an average 9.6-hour day. The average penetration rate was about 5 ft/hr.

Comparing the TBM method to drill-and-blast tunneling for this project, the TBM excavation method resulted in:

- A 40 percent reduction in tunnel support requirements over those which were estimated for careful smoothwall blasting.
- A 60 percent reduction in tunneling time over that which was estimated for drill-and-blast tunneling.

- The elimination of complaints from residents about noise and vibration.

The utilization rate (including restroking) of the TBM was approximately 42 percent of total construction time. Delays due to geological conditions accounted for eight percent of construction time. Delays for maintenance and repair of the TBM accounted for about 33 percent of construction time. Delays for maintenance and repair of back-up systems accounted for about 17 percent of construction time.

The performance and utilization of the reconditioned TBM on the Beverly Sewer Tunnel confirm that TBMs can operate effectively in hard, high-strength igneous rocks native to Massachusetts. Furthermore, short tunnels, which historically have been bid as conventional drill-and-blast tunneling operations, can be mined with reconditioned TBMs that are available at substantially less cost than a new TBM and that can be mobilized more rapidly.

While public response to the mechanical excavation was not measured directly, it should be noted that during shafting and starter tunnel operations involving drill-and-blast techniques, public complaints were directed to the contractor, the police department and/or the fire department after every blast round. Complaints were generally about disturbance, although several complaints were made regarding damage (which were not substantiated). By contrast, no complaints were raised during the TBM tunneling operations. Therefore, the use of a TBM in tunneling in the vicinity of residential or commercial neighborhoods has significant advantages over drill-and-blast tunneling from an occupant disturbance and public relations standpoint, as well as in limiting the potential for vibration damage or damage claims.

In consideration of these points, tunnel designers should make provisions in contract documents for the use of TBMs (even in short, hard rock tunnels), if the tunnel has a commonly used diameter or if there is any flexibility in tunnel size.

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