14.2—CONSTRUCTABILITY

The design for an underground project must be constructible. Too often road tunnels are designed by competent engineers who have never actually built anything. Their designs minimize the volume of excavation and concrete but are difficult to build. Underground construction is expensive due to the large proportion of labor used during the construction, the high wages paid to these workers, and the linear nature of the work. In order for tunnels to be less expensive to build, designers must also be schooled in how tunnels are built so they can recognize that their decisions on size, shape, location, and esthetics all have cost impacts.

A brief discussion of the labor portion of the cost of underground construction is in order so that designers can start to understand how their decisions impact these costs. Most underground civil construction is performed in a union environment. The union provides skilled labor that performs specific job functions. Typically there is a crew actually performing the work. This crew will consist of miners, miner foremen, operators to run and maintain the equipment, electricians to maintain the power that runs the equipment and provides the necessary lighting levels, as well as supervisory people. These folks actually performing the repetitive operations are called the heading or direct labor crews. These crews are supported by an entire separate group of people who supply the project with needed power, material, transportation, maintenance, and overall project management. These are called the service crews. The service crew can be as big as the direct labor crew. If approximately 25 direct laborers do the work, approximately 25 people support the work. These two or more crews are paid whether the work is going forward or not.

One typical example of where the design of a tunnel project can impact the cost is in a location where a tunnel must be widened to accommodate an exit or entrance or even an emergency pull-off. In most designs the cross section constantly changes from the road tunnel and widens to accommodate the exit, entrance, or emergency parking area. This looks nice, is visually pleasing, and minimizes both the excavated volume and the amount of concrete that is required in the lining, but is it easy to build and what does it add to the cost?

Most contractors will come back to the project's Owner and propose to accommodate the same structure in a stepped fashion instead of a smooth transition. Why? It is relatively easy to excavate the transition cross sections in a rock tunnel (more difficult in a soft ground tunnel operation) and certainly a smoothly transitioning excavation minimizes the volume of material that is taken out. However, the lining operation becomes complex and costly.

The smooth transition requires different custom-built forms for each foot of the structure. There is no, or limited, reuse of forms, and most importantly each of these custom forms must be built in place, used, and removed, thus slowing down the lining operation. Each use of a custom form requires both the direct crew and the service crew to be used for a longer duration, driving up the cost and increasing the schedule for the whole project.

But it is important to consider what the use of a larger cross section or a stepped transition can do for the cost and schedule. By going simply from the typical tunnel size to the full size required for the exit, entrance, or parking lane, the tunnel project pays for some extra excavation and concrete, but now only two forms (one extra) are need to be built, used, and removed. If using just two different cross sections is not possible, then a multistepped transition can help to minimize the time and money spent building, using, and removing all the specialized forms. An evaluation must be made whether it is faster and less costly to remove extra material and place extra concrete, or to install, use, and remove all the specialized forms.

So how can designs be made more constructible? One way is to include a construction expert on the Design Team. This construction expert would sit with the Designers reviewing what approach they want to utilize, make suggestions on how the design could be more easily built, make sure that all site constraints have been addressed, and provide insight into how a contractor would price the designs so that modifications of the design can be made to control cost and schedule.

14.3—CONSTRUCTION STAGING AND SEQUENCING

14.3.1—Construction Staging

Each underground project is unique; however, there are certain requirements and functions common to most or all tunnels. Each project requires one or several places from which the work can be prosecuted. All projects require large quantities of labor, material, and equipment to be brought underground to excavate and support the tunnel, and large quantities of muck and groundwater must be removed from the tunnel. All projects, therefore, require land area to set up Contractor's offices, shops, storage yards, muck storage piles, electrical substations, and many other space needs. It therefore is logical that the more space that can be made available to the Contractor to locate needed structures, store needed materials, and allow for the movement of materials and equipment into and out of the worksite, the more efficient and less costly the operation will be. On the other hand the smaller the available worksite, the more expensive and less efficient the operation will be (Figure 14.3.1-1).

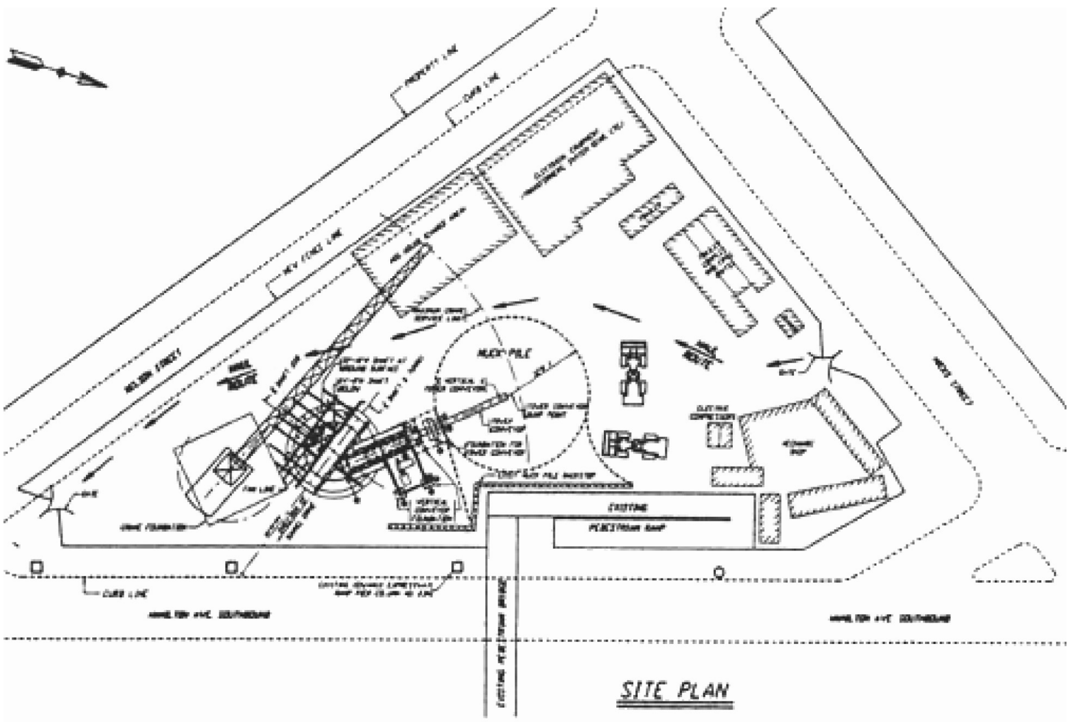

Figure 14.3.1-1—Confined Worksite and Staging Area

Underground projects serviced by shaft(s) require room to excavate the shaft. There should be room to allow equipment access and easy flow of the work all around the shaft location. Typically, Owners, who must acquire property to locate the shaft, will minimize the size of the property and thereby minimize their expenditure for property acquisition. This strategy can be shortsighted. Paying more for more room can actually provide for a more efficient operation, lowering the overall cost for the work and providing the Owner the opportunity to sell off the extra property after the project is completed at a higher price, thereby further lowering the total cost of construction.

Portal projects benefit from not having the expense and schedule impact of excavating and supporting the shaft(s), but also require property on one or both sides of the project to enable the Contractor to efficiently prosecute the work (Figure 14.3.1-2). Portal areas for a road tunnel may be limited by existing geotechnical hazards.

Figure 14.3.1-2—Tunnel Portal

14.3.2—Construction Sequencing

Underground construction is a series of individual activities that must be completed before subsequent activities can start. This series of unique activities is then repeated and repeated until the operation is complete. For tunnels that employ drilling and blasting to create the tunnel opening, the series is "drill, load, shoot, muck, and support." Each round is drilled a certain length or depth using a pre-engineered drill pattern. Once the drilling is done the explosives are loaded into the drill holes and "wired up." Equipment and crews are then pulled back a safe distance from the loaded face and the blast is "shot." Exhaust gases produced by the explosives are removed from the face and fresh air is sent to the heading area. After around 30 minutes the crew is brought back into the area to scale or knock down any loose rock and remove the excavated material, or muck. Once the muck is removed, the initial tunnel support is installed to make the excavated opening stable and safe for the crew to work under. The cycle is complete and the tunnel has been advanced some distance. The next round can be started when all of these activities have been completed.

In tunnel boring machine (TBM) excavated tunnels, there is also a defined sequence of activities needed to advance the heading. The TBM usually completes this series much faster than in drill-and-blast tunnels but the elements remain similar. The TBM cuts into the rock or earth a certain distance at the same time the muck is removed by conveyor to either waiting muck cars or to a continuous horizontal conveyor, so the TBM is able to combine these two operations, thereby saving time and speeding up the tunnel progress. After the end of the TBM's stroke (the hydraulic pistons used to push the TBM cutting head into the rock have a defined length), the excavation is stopped and the TBM readied to start the next excavation cycle. While this is happening the length of tunnel that has just been exposed must be supported to provide a stable and safe opening. The TBM can sometimes be configured to perform this support function concurrently with the excavation sequence, depending on the size of the tunnel opening, type of ground being excavated, and design of the machine. This can be another advantage of using a TBM but does not change the fact that this operation must be done before the next excavation cycle can begin.

Tunnels are usually stabilized for long-term use by placing an internal final concrete liner. The concrete lining operation also contains a series of individual steps that must be completed in sequence before the next length of tunnel can be lined.

14.4—MUCKING AND DISPOSAL

Muck is the industry term for excavated material produced during the advancement of the tunnel. All tunnel mining produces muck. This excavated material must be removed from the working face of the tunnel so that the next advance can be made. Tunneling is a series of individual steps, each of which must be completed before the next can start. Once the muck is produced it must be removed from the tunnel and finally disposed of in a legal manner or used as fill for some portion of the tunnel project or other project where it could have a beneficial use.

Muck is actually a broken-down state of the in situ material through which the tunnel is driven. Because the natural material is disturbed by blasting, cut with a TBM or roadheader, or cut out with a bucket excavator, the volume of muck removed is actually larger than the natural bank material. This swell is usually approximated as 70 to 100 percent more in rock and 25 to 40 percent in soil.

The material that is excavated must be removed from the tunnel. The method chosen to remove this material depends on many factors such as the diameter or size of the excavation, length of the tunnel excavated from any given heading, material being moved, grade of the tunnel being driven, and whether the material is going to a shaft for removal or a portal. Horizontal conveyor belts are commonly used for large excavated tunnels that are longer than a few thousand feet (a few hundred meters) and are excavated by a TBM (Figure 14.4-1). Conveyors can move a large quantity of material quickly. Conveyors require that the excavated material be of relatively uniform small size so that it will sit in the belt during the transfer to the shaft or portal. Conveyors can sometimes be used with a drill-and-blast excavation method if the contractor employs a crusher to make the drill-and-blast rock a more even and smaller consistency. This crushing is necessary to ensure that the material sits nicely on the belt and is small enough so that when it is loaded onto the belt it does not damage or rip the belt material. Conveyors are usually limited to a grade (or slope) less than 18° to successfully transport muck, but this is never an issue in road tunnels. Conveyors can transport rock or soil. The soil must not be too wet or it will not transport well. Conveyors can also be used in tunnels where there are curves in the alignment but this requires some special care and equipment.

Figure 14.4-1—Horizontal Muck Conveyor

Material that is too wet to carry on a conveyor belt can sometimes be pumped out of the tunnel through a pipeline from the TBM to the shaft or portal. This method is successfully used on soft ground tunnels where the material is clay-like or where sufficient water (and often conditioners) is mixed with the excavated material to make it slurry-like.

For smaller tunnels excavated by a TBM, contractors often choose to load the excavated muck into rail cars and haul it out of the tunnel using locomotives. Rail haulage also has some limitations such as the grades are usually limited to less than 4 percent; a great amount of rolling stock is required; and great care must be paid to maintaining the track.

Once the muck arrives at the shaft or portal, it must be off loaded and then disposed of. Figure 14.4-2 shows a muck train dumping at a tunnel portal. A shaft is a vertical hole through which all excavated material must be lifted and removed and through which all material required for the tunneling operations must be lowered to the tunnel level. In addition all personnel working on or inspecting the tunnel must come in and out of this shaft. In other words it is a busy place. There are many ways to transport muck up the shaft. Muck cars can be lifted one by one up the shaft, dumped in a pile on the surface, and lowered back down to the tunnel. Muck cars can be dumped into a hopper at the bottom of the shaft and then loaded into a bucket that is hoisted to the top and dumped, or the muck from the hopper could be loaded onto a vertical conveyor and conveyed to the top of the shaft and dumped onto a pile or hopper. Similarly, muck can be pumped to the surface and deposited on a horizontal conveyor or a stockpile, or run through a processing plant to remove the water and the residual dumped on a pile or into hoppers.

Figure 14.4-2—Muck Train Dumping at Portal

Portals provide easier access to a tunnel since they eliminate the bottleneck that the shaft imposes. Muck is easier to remove at a portal since track can be paced on the ground or on an elevated trestle so that muck cars can be pulled outside to dump their loads onto a muck pile.

The critically important thing to remember is that tunneling is a series of sequential steps, each of which must be completed before the cycle can start again. This means that any disruption in the muck-removal operation will delay the start of the next round or the next advance. If the workers cannot dispose of the muck, they cannot produce more! This is also true once the muck reaches the surface. There should be a place to store the muck that is brought out of the tunnel until it can be loaded into trucks or rail cars and hauled away. Without this storage capability on the surface (Figure 14.4-3), all muck brought out of the tunnel must immediately be loaded into surface trucks or rail cars for disposal. If there is a hold-up in the surface trucking or rail cars, then no more muck can be brought out and the tunnel advance must stop. This situation is called being muck bound and must be avoided at all costs. The more muck storage that is available, the more unlikely it will be for a project to become muck bound. Worksites must be large enough to provide this storage cushion: the larger a worksite, the bigger the cushion. It is increasingly more difficult to find available land in and around cities to provide a suitably large worksite. Typically, urban sites are small and therefore special care must be taken to ensure a steady stream of vehicles to remove the muck as it is produced and to deliver workers and materials as needed. Thought must also be given to the hours of operation allowed in urban tunnel projects. If the hours of operation for surface work are restricted, that is, surface work is not allowed after 10 p.m., then in order to operate the tunnel 24 hours per day, there must be someplace to store muck underground that is produced on the shift where no surface work is allowed, and construction noises must be kept below a threshold based on local ordinances, certain realistic decibel levels, or both.

Figure 14.4-3—Surface Muck Storage Area

14.5—HEALTH AND SAFETY

Construction engineering and safety go hand in hand. Underground construction is inherently a dangerous undertaking. Work goes on in a noisy environment, in close quarters, often with moving heavy machinery. Careful attention must be paid to the layout of worksites; workers must be protected at all times. The overriding philosophy must be that "everyone goes home safely at the end of their shift."

Every step of the operation should be planned with safety in mind. Normal surface safety concerns are also appropriate for underground construction. Workers must be safeguarded from falling off the work platforms used in the mining process. Workers must be protected from being struck by the moving equipment used throughout the mining process. Workers most be protected from being electrocuted. However, there are also many additional hazards that workers must be protected from and guarded against.

Work underground involves mining through rock or soil or a combination of both. In order to excavate the opening required for the tunnel, the natural properties of the ground are disturbed. The ground is usually not a homogeneous mass but has been subjected to massive forces of nature and has been altered. Once the opening has been excavated it must be supported in order for workers to be protected from falling material, collapse, or other deterioration of the tunnel roof or crown. So it is the job of the construction Engineer to plan on making the tunnel opening stable to allow workers to move freely and without concern for falling material.

Because tunnels are by definition below the surface, lighting of the workspace is an important part of underground safety. The Occupational Safety and Health Administration (OSHA) has regulations governing all elements of working underground, and the construction Engineer must be familiar with them all. There are required levels of lighting for actual work locations as well as previously excavated openings. It is important to remember that tunnels are long, linear work places. As the tunnels are advanced, more and more safety plant must be added along with productive support elements.

One of the more challenging aspects of tunnel safety is the fact that workers must be constantly supplied with high quality breathable air. Again, OSHA is very specific in its requirements. Each person underground must be supplied with 200 ft^3/minute (cfm) of air. In addition, much of the equipment underground is powered by internal combustion engines. Diesel fuel is the only fuel allowed underground. OSHA has specific requirements for the equipment and for the amount of air that must be delivered to the underground work area for each and every piece of diesel equipment working underground. This diesel air requirement is in addition to the requirement for each and every person underground. The quality of the tunnel atmosphere must be tested on a regular schedule to ensure that sufficient quantities of oxygen are present and that concentrations of undesirable gases and byproducts of internal combustion engines are controlled to acceptable levels.

Also, tests must be performed on a regular basis to ensure that air movement across the excavated cross section is no less than 30 ft/minute.

If this were not enough, as discussed in Chapter 8, Mother Nature can often provide challenges to the safety of workers underground. There can be gases underground that can seep into the tunnel opening after the excavation operation. These gases can be poisonous, such as hydrogen sulfide, or explosive, such as methane. Whenever these gases are present or suspected to be present, the construction Engineer has additional OSHA requirements to be aware of and to follow. Extra ventilation will be required, in addition to the air needed for both people and diesel equipment, and the required quantity can be substantial. Whenever these gases are suspected, there are extra requirements for continuous monitoring of the atmosphere, with automatic shutdown of equipment should the gases be detected in concentrations higher than allowed.

Water entering the tunnel opening is also a safety issue in tunnels. Most tunnels are excavated below the water table. The tunnel opening acts as a big drain, and any water running through the rock or contained in the soil tends to collect in the tunnel. Water running through the tunnel bottom, or invert, can cause several potential safety issues. Tunnels can be accessed by one or more shafts, by a combination of shafts and portal, or from a portal alone. It is desirable to drive tunnels uphill so that any water that seeps into the excavated opening flows away from the working face by gravity. This water is usually allowed to run in a ditch located at the side of the tunnel invert. Care must be taken that workers do not step into or fall into this ditch. The higher the inflow of water into the tunnel, the greater the problem of safely conveying it back along the tunnel and finally out the shaft or portal.

Tunnels that are driven downhill have the problem that water flows to and accumulates at the working face. This collected water must be removed from the work area by pumping. The water is pumped through a pipe at the side of the excavation. This pipe must extend all the way to the shaft or portal, where it can be removed from the tunnel. Water can also enter the tunnel in sudden large flows. These can be very dangerous occurrences, and for any tunnel where this is a possibility, extra care must be taken in planning for worker safety. Tunnels under bodies of water are of particular concern for this risk of sudden large inflows of water.

Fires in tunnels are especially dangerous and can lead to extensive damage and risk to workers' safety and life. The tunnel construction Engineer must be aware of this potential danger and plan to mitigate the risk at every stage of the project. Most tunnels are driven from one point to another from a single point of entry. This single point of entry is what makes tunnel fires so dangerous and concerning, as shown in (Figure 14.5-1). The tunnel environment contains numerous potential sources of fire. Equipment can malfunction and catch fire. Workers using welding or burning torches can set off a fire. Leaking hydraulic fluid or fuel from equipment can be ignited by a stray spark or discarded cigarette. Conveyor belts used to transport muck can build up heat from rubbing on or over something and ignite. All these possible fire risks, and more, must be addressed by the construction Engineer to minimize the possibility of a fire or to minimize potential damage and injuries resulting from a fire. Only retardant material and hydraulic fluid should be allowed on any underground equipment or material. Fire suppression systems should be required for all underground equipment, conveyor belt motors, and storage magazines. Vertical muck removal belts should be equipped with deluge water systems to dump large quantities of water on any belt-fire event. Fire and life safety issues during operation and maintenance of road tunnels are not included in the scope of this Manual.

Figure 14.5-1—Fire in Work Shaft

Of equal importance in dealing with tunnel fires is how best to provide for the safety of the workers underground. This can be accomplished in several ways. Rescue chambers, where workers can take refuge in a fire, are fully equipped and supplied with independent air supplies, and insulation can be deployed along the tunnel as the tunnel is advanced. Equally important, the tunnel can be planned with intermediate access points that can be fully equipped to be able to remove workers from the tunnel when the tunnel has been excavated past these locations.

The tunnel construction Engineer must also be certain to make sure that the job specifications require strict compliance with all safety measures and local, state, and national regulations. The Engineer must stress to the Designer and the Owner that money spent on worker and job-site safety is money well spent since the cost of accidents and replacing structures damaged or destroyed by a fire event is so high.

14.6—COST DRIVERS AND ELEMENTS

There are numerous cost drivers associated with underground construction. These can be grouped into physical, economic, and political cost drivers.

14.6.1—Physical Costs

The single most important driver of project cost is the ground through which the tunnel will be driven. The ground controls the methods and equipment used to drive the tunnel, the support elements that will be needed to ensure that the excavated cross section remains stable and safe for the personnel constructing the tunnel, and the final lining needed for long-term stability of the structure. In addition the ground through which the tunnel is driven will contain varying amounts of groundwater that will dictate the pumping requirements, waterproofing needs, and lining quality that will ensure a dry tunnel environment.

The use that the tunnel will serve also has a significant impact on the costs. Tunnels for roads and rail must be dry to safeguard the traveling public, so a watertight structure is imperative. Road and rail tunnels are also grade restrictive and curvature restricted, which also impact project cost. Tunnels that will serve as road and rail infrastructure must be able to deliver large quantities of fresh air throughout the length of the tunnel and be able to remove smoke and heat developed during a fire incident anywhere in the tunnel. Large ventilation structures or in-line fan systems are needed to supply this air and remove smoke.

In rail or road tunnels refuge areas or rest areas are often needed, along with on and off ramps or connections to outside rail or road systems.

14.6.2—Economic Costs

All tunnels require personnel, equipment, materials incorporated into the physical structure, and materials that are consumed during the construction of the tunnel, along with insurance, bonds, offices, shops, and other indirect elements. These all impact the cost of the project. The largest portion of these costs is the actual cost of labor. Labor is broken down into the labor actually driving the tunnel, or the direct or heading crews; the support crews that provide all the needed supplies of the tunnel, maintain the equipment used during the tunnel driving operations, and provide access to and from the tunneling operation; and the supervision needed to ensure that all the components work together in the required sequence.

Material is another major cost component of tunnel operations. Prices for materials such as cement, steel, and copper wiring may fluctuate erratically due to strong worldwide demand. Currently, the price escalation of key materials is a significant cost driver and one that is often not addressed in the Contract Specifications as a separate cost. Tunnels require large quantities of both permanent and consumable materials in a constant stream.

The continual cost of disposing of the muck or excavated material that is produced during tunnel operations represents another economic cost. Muck can sometimes be sold off by the Contractor or Owner to help reduce the cost of tunnel construction. However, the market for this material is not guaranteed, and often the Contractor must pay to haul this muck away and also pay to dispose of it at approved dump locations. More and more regulations governing the disposition of materials are driving up the cost of tunnel construction.

Bonds and insurance are smaller components of tunnel costs that are becoming cost drivers due to the increased scrutiny being imposed by the insurance and surety industry. Since most Owners require both bonds and insurance on their projects by law and as risk management tools, any Contractor that cannot qualify for bonds and insurance cannot bid the project. After the terrorists attacks of September 11 and some high profile corporate failures, the marketplace for both bonds and insurance has tightened up, and many providers have stopped writing bonds and certain types of insurance.

14.6.3—Political Costs

Significant costs are placed on projects by either the communities through which the tunnels will be mined, or by Owner agencies by the requirements and restrictions incorporated into the Contract Specifications. Tunnels are expensive undertakings, even without these restrictions, but when concessions to various groups are added to the requirements, costs can skyrocket. Tunnels built in rural areas experience few of these political costs, but those driven through urban settings can experience significant costs due to these restrictions. Typical restrictions are mandating certain types of construction to minimize community disruptions, that is, mining an underground cavern instead of digging down from the surface, or not having a work shaft at a certain location because it is too close to neighbors. Restrictions on the hours worked is commonly employed when the tunnel is in an urban location. Tunnels are a sequential series of operations, each of which cannot proceed until the preceding task is complete. With restrictions on hours of operation, fewer steps can be completed in reduced time so the job takes longer. In one case an Owner agency allowed 24-hour tunneling (recognizing that this is a typical mode of operation), but limited the hours that could be worked at the surface where the muck is brought out to be trucked away. In order to compensate for this reduced time, the underground opening had to be made larger, so that the muck produced during the time when no surface work could be done could be stored underground awaiting the time of day when it could be brought to the surface and trucked away—the political cost of being a good neighbor.

Owners might drive up the cost of doing underground work by restricting the costs that are recoverable by the Contractor in a change order or claim situation and by preventing the Contractor from recovering delay costs if the delay is caused by the acts or inaction of the Owner. "No damage for delay" clauses might suggest to Contractors that they incorporate into their bids these potential costs and a provision that the Owner pays for them whether they occur or not.

14.7—SCHEDULE

The importance of the development and use of a realistic schedule and cost estimate for all phases of a project cannot be overemphasized. It is critical to understand the relationships among all the activities and costs that go into a project, as well as the needs and interests of all those who are affected by the planning, design, construction, testing, and commissioning of the work. With this understanding, projects can go forth in an orderly, predictable manner, which in the end benefits everyone.

The schedule is the roadmap of how the project progresses through all the necessary steps. It is advised that a comprehensive schedule be developed during the early stages of the conception of a project. During this early stage the project may be too immature to support realistic time durations, but some time must be assigned to each and every component; such as planning, siting, environmental process, permitting, right-of-way acquisition, preliminary and final design, bidding, contract award, construction, testing, commissioning start-up, and any activity or phase that is important to or has a cost for the project Owner. As the project develops and more of the actual scope and restrictions are known, the schedule must be reevaluated and updated to reflect this new knowledge. Schedule development should be a living process that is used and revised constantly to be of maximum benefit to the project.

The realistic time needed to accomplish all aspects of the project must finally be reflected in the schedule. It makes no sense to handicap the tool (schedule) or the process by introducing artificial or incorrect restrictions or by putting unrealistic expectations into the schedule. In fact, these restrictions and incorrect assumptions always create problems later on in the project, usually in the form of delays, claims, and higher costs. There can be a positive case made for an Owner to actually build some float time into the schedule, if possible, so that there is some way to cushion the effects of unknown occurrences that could impact the project schedule.

Unrealistic schedules sometimes might result from external forces, such as the desire to have a project completed in time for an upcoming event or election. These external forces always need to be acknowledged and addressed on a case-by-case basis. They can wreak havoc on a schedule, but they must be taken seriously. It should be noted that throughout a project's life, its schedule will be at the mercy of these external forces. Having said this, the best (and only) way to begin a project is with a realistic, well-thought-out schedule and cost estimate. This will reduce the risk that the Owner agency will be called on to defend a low-ball cost assumption and an inaccurate timeline necessary to complete the project. It is important to remember that the cost and schedule numbers that are initially released to the public are ones the project must maintain and defend throughout the project's life. It is much easier if these costs and schedules are reasonable and defendable, backed by professional experience and industry standards.

Numerous examples can be found where projects suffered from low cost and schedule pronouncements that were never achieved. In contrast, where realistic cost and schedules were developed, the Owner agency managed the projects and was not constantly defending the numbers or the timeline. Having realistic schedules and budgets produces a win-win situation for both the Owner agency and the contractors by eliminating or at least minimizing the conflicts and finger pointing that can occur on a project that is squeezed for time or cash—or both!