Linear Schedules for Tunnel Projects

Mun Wei Leong
Jacobs Associates
Seattle, WA

Daniel E. Kass, P.E.
Jacobs Associates
San Francisco, CA

ABSTRACT: Tunneling projects lend themselves to the use of linear schedules for planning, executing, and monitoring the progress of tunnel work. However, construction contracts generally require designers, construction managers, and contractors to use critical path scheduling (Critical Path Method) techniques. The techniques used in creating linear schedules and their benefits for planning, investigating alternatives, determining cost/time benefits of multiple heading, and evaluating actual performance will be presented.

INTRODUCTION

Most construction projects use the Critical Path Method (CPM) to plan and schedule the work. Construction contracts typically require the use of commercially available scheduling programs such as Primavera Project Planner because these programs calculate the critical path(s) for the project. CPM, however, is not the best tool to model linear projects or portions of projects. CPM schedule tasks for linear work usually lack sufficient detail to provide a useful management tool to evaluate progress on the linear tasks and in turn on the project’s critical path. This is because linear tasks are logically more spatially related than sequentially related. Moreover, updates and changes to CPM schedules can be complicated and time consuming when dealing with linear work, whose durations are controlled by production rates. CPM schedules also do not provide management with a simple graphic to visualize progress on linear projects or portions of projects. The linear scheduling method is not uncommon in the tunneling industry; however, this method of scheduling is typically not incorporated into project scheduling specifications. This paper discusses the advantages of using the linear scheduling method to plan, monitor, and measure progress during the various stages of a project—design through construction—on an exemplar tunnel project consisting of five shafts, various outfall structures, microtunneling, and an odor control building to be constructed. Examples of how to use the linear scheduling method for delay analysis will also be presented.

CPM SCHEDULING METHOD

CPM scheduling calculates the critical path through a network model of the work. This path of activities or tasks consists of those activities that control the overall duration of the project; changes to their durations change the overall duration of the project. Noncritical activities have “float,” which allows those activities to be delayed or postponed within the float values without delaying the overall project completion. Scheduling programs such as Primavera are commonly used to plan and monitor projects because of this ability to determine the critical path and the float for noncritical activities. Managers are able to use CPM scheduling programs to effectively plan and monitor complex projects, including cost and resource loading the schedule, and producing detailed graphs and reports on the status of the project. The CPM schedule provides information such as project duration, early and late start and finish dates, and float values for the project activities.

Figure 1 shows a simplified CPM schedule for a tunnel project using the Primavera P3 scheduling program. This example plan anticipates using one tunnel boring machine (TBM) to mine the entire reach of the tunnel, starting at Shaft 2, going to Shaft 5, remobilizing the TBM back to Shaft 2 to complete the remaining tunnel, and demobilizing the TBM at Shaft 1. The duration of the project is 67 months, with a Notice to Proceed (NTP) in mid-May 2008 and a Substantial Completion in mid-November 2013.

A CPM schedule for this type of project typically includes thousands of activities. Linear activities are usually modeled in CPM by breaking the operation(s) into a sequential series of tasks of shorter duration to account for variations in production rates for linear activities over significant distances (i.e., for variations in expected ground conditions). This complicates the CPM model, making the plan in the CPM schedule more difficult for project
personnel unfamiliar with its structure to fully understand. In addition, if actual production rates vary from the plan, periodic updates to the CPM schedule become a monumental task, and the calculated critical path becomes unreliable.

LINEAR SCHEDULING METHOD

The linear scheduling method uses a diagram to graphically show the location and time of each work activity. This scheduling method is well suited for linear-type projects such as tunnels, pipelines, and road construction, where repetitive tasks are performed over a distance. In linear schedules, continuous tasks performed over a distance are represented by lines composed of a continuous set of points. From this graphic depiction, the location of work in progress can be determined at any point in time. Nonlinear activities are best planned with a network schedule (CPM) and then graphically shown in the linear schedule as boxes or vertical bars.

A typical linear schedule identifies the length of the linear project on the x-axis and time of performance on the y-axis. The scheduler first places all known constraints (contractual, physical, and environmental) on the linear schedule, followed by key features at their physical locations. After which, the scheduler determines the duration of the major aspects of work such as mobilization, shaft construction, TBM setup and mining time, and other time-related activities. Once the duration for each major aspect of the work is determined, the scheduler can draw several drafts of the linear schedule, varying the starting shaft location, number of TBMs, number of shaft crews, production rates, etc., to determine the most optimum plan for the project. Finally, the controlling critical path in the linear schedule can be determined manually (Harmelink 1998), and the float (rates) can be determined for the noncontrolling linear activities.

Once the plan is completed, the scheduler can use the information from the baseline linear schedule (Figure 2) to create the CPM schedule (Figure 1). Among its many advantages, the linear schedule allows the scheduler to have an overview of the entire project in a single graphic. This is not the case with the CPM schedule. For the nonlinear portions of the project, however, the CPM schedule provides a network for the work and can be used to determine the performance time for those tasks included in the linear schedule.

Some of the advantages of the linear scheduling method are:

- It is easy to understand and present graphically,
- It provides the scheduler with a simple overview of the project by identifying the location for each activity,
- Relationships between different construction activities, such as shaft and microtunnel construction, are easily identified,
- Required resources for the linear tasks can be identified at any time,
- Contractual, weather, environmental, and other constraints can be easily identified,
- Changes to the schedule are easy to make, and
- It is easier to measure progress and identify and evaluate performance-improving opportunities with the schedule.

The disadvantages of the linear scheduling method are:

- It cannot use computer programs to determine the critical path,
- Nonlinear portions of the project are not sufficiently detailed,
- Tasks cannot be cost loaded or the total project costs easily determined,
- Activities may not represent the true complexity of the work, and
- Features included in CPM scheduling program, such as resource leveling or the determining of float values, cannot be used.

Despite these disadvantages, the linear scheduling method is a superior tool for planning, scheduling, and monitoring linear projects such as tunnels. In the following three examples from one project, we will demonstrate how the linear scheduling method can be used during design and construction, and to evaluate the impact of a change on the time of performance.
Figure 1. Simplified CPM schedule for a tunnel project using Primavera P3
Figure 2. Baseline linear schedule example
EXAMPLE 1: USING THE LINEAR SCHEDULING METHOD FOR THE DESIGN OR BIDDING PHASE

The linear scheduling method can be used effectively during the design phase. A planner can provide the owner with various options such as using multiple TBMs or varying the shaft location. The planner can evaluate the effect of a late permit or other restrictions such as real estate negotiations or environmental restrictions. Once the planner identifies the impact of these potential issues, the owner can make informed decisions to address the various concerns by either revising the specifications and design drawings, or addressing the potential issues as a contingency in the budget. In the following two examples, we will evaluate three scenarios for the project:

- Scenario 1: Plan the project using one TBM, performing the mining from Shaft Number 2
- Scenario 2: Plan the project using two TBMs
- Scenario 3: Plan the project using one TBM, performing the mining from Shaft Number 1

The results of the three schedules are summarized in Table 1.

### Table 1: Comparison of the three construction options

<table>
<thead>
<tr>
<th>Item</th>
<th>Scenario 1: 1 TBM from Shaft 2 (Fig. 2)</th>
<th>Scenario 2: 2 TBMs (Fig. 3)</th>
<th>Scenario 3: 1 TBM from Shaft 1 (Fig. 4)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1. Project Duration</td>
<td>67 months</td>
<td>56.5 months</td>
<td>68 months</td>
</tr>
<tr>
<td>2. Number of TBMs</td>
<td>1</td>
<td>2</td>
<td>1</td>
</tr>
<tr>
<td>3. Site Prep and Earthwork</td>
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<td>1 crew</td>
<td>1 crew</td>
</tr>
<tr>
<td>4. Shaft Construction</td>
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<td>1 crew</td>
<td>1 crew</td>
</tr>
<tr>
<td>5. Micro Tunnel</td>
<td>1 crew</td>
<td>1 crew</td>
<td>1 crew</td>
</tr>
<tr>
<td>6. Finishing</td>
<td>1 crew</td>
<td>2 crew</td>
<td>2 crew</td>
</tr>
<tr>
<td>7. Building</td>
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<td>1 crew</td>
<td>1 crew</td>
</tr>
<tr>
<td>8. Other and Risk</td>
<td>Medium</td>
<td>Low</td>
<td>High</td>
</tr>
</tbody>
</table>

**Scenario 1: Using One TBM on the Project, Mining from Shaft 2**

The linear schedule in Figure 2 shows the plan for using one TBM on the project, mining from Shaft 2. This plan involves the contractor mobilizing and mining Tunnel 2 from Shaft 2. Once the TBM breaks through at Shaft 5, the contractor would remobilize the TBM at Shaft 2 to mine Tunnel 1. After Tunnel 1 is complete, the contractor would demolize the TBM and complete the odor control building, remaining shaft lining at Shafts 1 and 2, and the system tie-in.

The advantage of this plan is that the contractor is able to save costs by using one TBM to complete the project. The use of Shaft 2 allows the contractor to minimize the risk by having the mining site close to the middle of the project, which reduces the requirements of the support mining equipment. This method of construction also allows the contractor to perform the cleanup work for Tunnels 2, 3, and 4 after completion of the mining. This step moves a significant amount of work off the critical path. Another advantage of this plan is that the contractor would be able to service the TBM after it is removed from Shaft 5 and before it is reassembled at Shaft 2. This allows for greater success with the TBM in completing Tunnel 1.

The disadvantage of this plan is it would take 67 months to complete the project with one TBM. Additionally, it may be more expensive to set up the TBM from Shaft 2 because of the proximity of the Shaft 2 location to the middle of the project. This plan also requires the contractor to remobilize the TBM from Shaft 5 to Shaft 2, which would take 5 months to complete.

**Scenario 2: Using Two TBMs on the Project**

The linear schedule in Figure 3 shows the advantages of using two TBMs on the project. Essentially, the planner assumes that the contractor would begin mobilizing and mining Tunnel 2 from Shaft 2. Once the TBM breaks through at Shaft 3, the contractor would begin mobilizing the second TBM at Shaft 2 to mine Tunnel 1. The mining of both tunnels would be performed from Shaft 2.

This construction method allows for much quicker project completion, with a total project duration of 56.5 months. Initially, it looks as if the project could save 14 months, with 11 months on mining Tunnel 1 and another 3 months on remobilizing the TBM from Shaft 5 to Shaft 2. However, the critical path of the tunnel also changes from
completing removal of the TBM at Shaft 1 and completing the odor control building and tie-ins, to removing the TBM at Shaft 5 and completing the cleanup and tie-ins and drop structure at Shaft 5. Therefore, the net savings using two TBMs is 10.5 months because of the additional time needed to complete the cleanup for Tunnels 2 through 4 and time to complete the drop structure at Shaft 5.

The disadvantages of using two TBMs are cost and space: the additional cost for a second TBM and whether the Shaft 2 location has sufficient space to allow for the mining of two TBMs. These are considerations the owner must take into account. Additionally, the plan must account for the increased capacity to handle the additional spoils, increased use of precast segments, as well as logistics such as traffic control, handling water treatment, and even the availability of skilled labor to run the two TBMs.

Scenario 3: Using One TBM on the Project, Mining from Shaft Number 1
In the third scenario, a different mining shaft site is considered because of space or site condition concerns. The linear schedule in Figure 4 shows the projected schedule using Shaft 1 instead of Shaft 2 as the mining shaft. In this scenario, the contractor can continuously mine the TBM and eliminate the need to remobilize the TBM from Shaft 5 to complete Tunnel 1. This step saves three months on the schedule. However, Shaft 1 has a final lining that only can be placed after the TBM is removed. This adds an additional four months to the schedule. The net effect of mining from Shaft 1 is one additional month to the schedule (Table 1).

The advantage of this construction sequence is that it would allow the contractor to complete the work from one mining shaft without the need to remobilize the TBM. The disadvantages could include the technical difficulty of moving material from Tunnel 4 to Shaft 1. Additionally, it could delay the work to complete the lining at Shaft 1, the odor control building, and the start of cleaning up and tie-ins for the tunnel until after the TBM is removed.

The linear schedule allows the project team to discuss the advantages and disadvantages of these construction schemes. The owner can use the linear schedule to evaluate the risk of each option and determine the reasonable completion time for the project. The contractor can use the linear schedule during bid to determine the best means and methods of construction, identify potential risk to the work, and adjust its bid accordingly.
Figure 3. Linear schedule example with two-TBM option
Figure 4. Linear schedule example with Shaft No. 1 as starting shaft location
The owner decided to go with Scenario 2—constructing the tunnel with one TBM, mining from Shaft 2. This is due to many factors, among them the additional cost of a second TBM, the reduced length of time for maintenance because of mining from Shaft 2, and the reduced risk of completing a majority of the shaft concrete and cleanup work off the critical path. However, even with the best option, as we all know, changes will occur during construction. The ability to adapt to changing conditions greatly reduces the risk and increases the success of a project. The linear scheduling method provides a good tool for the planner to evaluate the effect of a change and appropriately plan the proper response.

Figure 5 shows that the mining rate for the TBM is 30% faster than was anticipated during the bid. As a result, the contractor is concerned that the receiving shaft may not be sufficiently completed to receive the TBM. In this instance, the planner adjusts the rate of production for mining by 30%, using the baseline linear schedule in Figure 2. The linear schedule in Figure 5 shows that the increase in production rate would possibly result in the TBM arriving at Shaft 4 during a nonwork period. The analyses show that Shaft 3 and Shaft 4 would be sufficiently completed prior to the arrival of the TBM. The overall project would be completed 9.5 months ahead of schedule. Using this information, the project team can evaluate the need to increase the capacity of the segment plant to accommodate the increase in production rate. The project team can begin investigating the need to apply for a special permit to work during the nonworking period at Shaft 4 or even consider slowing down the production of the TBM.

In the second instance, the contractor discovered issues concerning late permits at Shaft 3. This delay impacted the start of the construction on this shaft. The planner can insert the delay due to the permit in the linear schedule and determine if the delay would impact the critical path. The linear schedule in Figure 6 shows that the start of Shaft 3 would be delayed by four months. However, there was sufficient float in the schedule to not impact the critical path, although the permit delay did impact the sequence of shaft construction. In an effort to mitigate the delay, the contractor could mobilize to Shaft 5 after completing the slurry walls at Shaft 2. Additionally, the slurry wall work at Shaft 4 could also extend into the three-month nonworking period between the months of October and December. The permit delays also caused the float available between completing Shaft 2 and the arrival of the TBM to be reduced from six months to two months. The last issue regarding float may not be a problem if the production rate of the TBM remains the same and there are no further delays to shaft construction. The planner would be able to present the information to the project team to discuss the impact of the permit delay and any further mitigation efforts to implement on the project.

In both of these examples, the planner could use the CPM schedule to evaluate the impacts. However, making these changes to the CPM schedule can be complex and takes time to complete. The use of the linear schedule allows the project team to make sound and informed decisions in a timely manner.
Figure 5. Linear schedule example with mining production increased 30%
Figure 6. Linear schedule example with permit delays at Shaft 3
EXAMPLE 3: USING THE LINEAR SCHEDULING METHOD FOR CLAIMS AND DISPUTES

Changes and unforeseen delaying events do occur during construction. Events that impact time are typically a point of contention between the owner and the contractor. The use of the linear schedule can be used to evaluate the impact of the change to the overall project schedule and help determine who was responsible for the impact to the critical path.

In this example, the contractor on the project encounters several delays related to late permits to Shaft 3 and design changes to the odor control building. These are owner-caused delay. Additionally, the contractor also encountered problems while excavating Shaft 4. This issue is attributable to the contractor and delayed the completion of excavation by 1.5 months. The linear schedule can be used to evaluate the impact of the delays on the overall project schedule and determine if a delay is a critical path delay or a concurrent delay.

Figure 7 shows the linear schedules with the delays mentioned above incorporated into the schedule. The overall impact of all the delays impacted the project by 2.5 months. The linear schedule in Figure 7 shows that the contractor delay while excavating the shaft caused a 1.5-month delay to the critical path. The design changes to the odor control building delayed the critical path by one month. The delay due to the late permits at Shaft 3 and the delay in completing the slurry wall at Shaft 4 did not cause delays to the critical path.

An analysis determines that the owner should compensate the contractor for one month of time extension and delay damages to the overall project. The owner should also compensate the contractor for the actual cost due to the permit at Shaft 3 but should not compensate the contractor for time or time-related cost for the Shaft 3 delays.
Figure 7. Linear schedule example to evaluate project delays
CONCLUSION

The linear scheduling method is a much better tool for planning a tunnel project than the CPM schedule. Both owners and contractors can use the linear schedule to evaluate the project from the design and bid phase, through construction, to evaluating disputes. The linear scheduling method is easy to use and understand. However, it should be used in conjunction with the CPM schedule because of the CPM schedule’s ability to record details and provide the many different tools not available with a linear schedule.

REFERENCE