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A Computational Proposal For The Efficient Use Of The Rapid Tunnel Excavation Approach

D.M. Emiris
Lecturer, Department of Industrial Management & Technology, University of Piraeus

D.K. Paterakis
Civil Engineer

D.E. Koulouriotis
Lecturer, Department of Production Management Engineering, Democritus University of Thrace

Abstract
The situation of a tunnel excavation is frequently encountered in several construction projects. Tunnel excavation typically involves very specialized staff (engineers, foremen, operators and workers), as well as specific and expensive machinery, thus requiring efficient resource allocation and considerable capital investment. High-level project management techniques need to be employed, in order to efficiently tackle inherent problems in such projects [TURNER 1999]. This paper deals with the presentation of a novel algorithm to perform excavation bi-directionally, in order to optimize resource usage and to minimize execution time. A computational algorithm to automatically schedule activities has been implemented, which enables efficient use of resources and minimization of idle times.

Keywords: Rapid Tunnel Excavation, Optimization, Scheduling.

1. Introduction

The problem of *tunnel excavation* is frequently encountered in public road construction or railway transportation projects. The problem typically requires optimization of both the excavation time and the associated cost. The three most common methods for tunnel excavation are: (a) The Cut & Cover Method (C&C) (Figure 1), (b) The Full Face using a Tunnel Boring Machine (TBM) (Figure 2), and (c) The Sequential Excavation Method (SEM) usually NATM (Figures 3 and 4). The most popular of these, also used in most rail and road tunnel projects in Greece, is the SEM method. The SEM Method is also known as New Austrian Tunneling Method (NATM) or as OATM (Old American Tunneling Method). Extensive experimentation and the introduction of modern tools and techniques have dictated that for most cost and time efficient results, tunnel excavation should be performed bi-directionally, that is, starting in parallel from the two opposite directions.. In some cases, in order to minimize the project completion time, extra abroad shafts (vertical to the main tunnel) are used, to provide access to extra work fields. A 2.000m tunnel, for example, can be opened using this method from four positions with a maximum length of 250m for each part. The approach, called *rapid tunnel excavation*, leads to the minimization of the excavation time; however, it requires careful and intense project management in order to optimize resource allocation and to ensure qualitative results.

Figure 1: The Cut and Cover Method Figure 2: The Tunnel Boring Machine Method

Figures 3 and 4: The Sequential Excavation Method.

2. The Tunnel Excavation Problem

The typical SEM or NATM method, entails dividing the space to be excavated into segments (based on the rock quality) and mining the segments sequentially one at a time. It consists of the following general tasks, which are depicted schematically in Figures 5a and 5b below: (i) Entrance/Exit Cutting, (ii) Excavation – Supporting phase A, (iii) Excavation – Supporting phase B, (iv) Footings Placement, (v) Gaskets, (vi) Final Concrete Segment, and (vii) Final Sheeting.

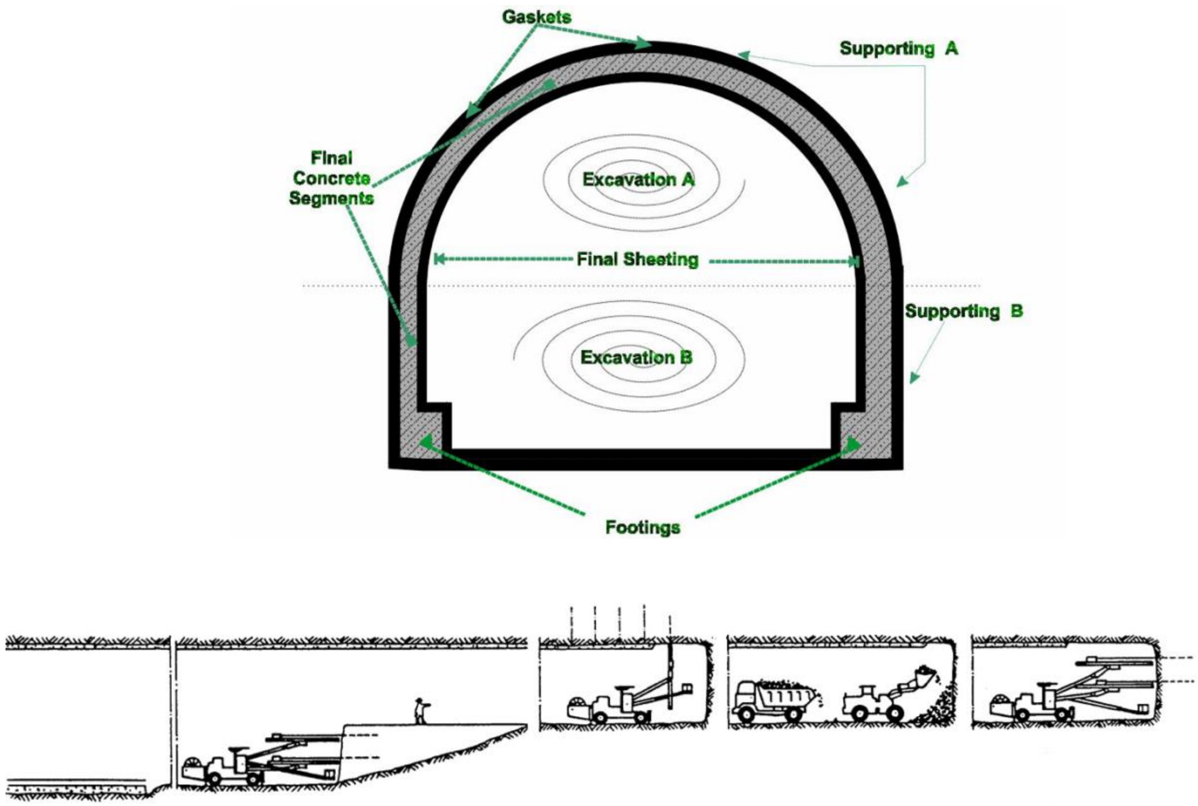

Figure 5: **Schematic Description of Tunnel Excavation Tasks (a) front view, (b) side view.**

Typical views of a tunnel entrance and concreting task are shown in Figures 6 and 7, respectively.

Figure 6: Tunnel Entrance.

Figure 7: Concreting Task.

A project contract may also contain, apart of the above, the road construction (ground topology, blacktop etc.) for the approaching and the inner parts of the tunnel; however, focus remains in the excavation procedure. For each task there is a specialized workshop, with the appropriate machinery and skilled personnel [GRAHAM 1998, McCARTHY 1998]. The above tasks are described below:

(a) In the *Entrance/Exit Cutting*, high explosives are normally used in order to shape a satisfactory opening (entrance), typically extending in the upper half part of the construction. Special machinery then takes over in order to contour the entrance and to allow the other workshop start working.

(b) In the *Excavation-Supporting* of the tunnel 's *A* part, excavation is again achieved mainly by high explosives. Excavators, bulldozers and dumpers come in to weed out the muck, and to make enough space for the supporting machinery. Supporting is made by long grapnels, which are inserted into well cleaned holes. Special jackhammers not only drill the right holes radially but also clean the holes by high-pressure air. The last stage of the supporting, is the ejaculation of express-coagulation concrete.

(c) The *Excavation-Supporting B* task deals with the lower part of the tunnel. Excavation is performed using excavators, underground Jumbo-gimlets, loaders and trucks only, rather than explosives. The supporting procedure is the same as it in the *Supporting A* phase. The lower walls are supported, but with less denseness of grapnels, as the roof and the arch are estimated to be the most critical.

(d) The aim of the *Footings Placement* task is to achieve stability of the entire construction. Footings are made by concrete and create the base of the construction, which is contoured so as to allow the following workshops to go on. Cement mixers and wooden patterns are used mostly at this stage.
(e) Erosion and water tightness are two basic problems for the engineers to deal with. The next task thus deals with the *Gaskets*. Immediately after the first concrete coating, put at stage of *Supporting A*, a coat of gaskets follows. These gaskets consist of a waterproof film and geotextile and are applied by the hot air welding method. They are applied all over the walls of the tunnel, except the floor.

(f) By this time, tunnel is ready for *Final Concrete Segment*. The use of a steel mold, a rather complicated machine, makes this possible. The machine has the shape of the tunnel, moves only forward on railways and its height is adjustable, while its length usually is between 5-12 meters.

(g) The task of the *Final Sheeting* concerns the complete excavation of the tunnel. It involves the final workout of the concrete segment, the contact groutings and the dyeing of the whole surface, usually at light colors to help the lighting of the inner tunnel.

The above tasks can be further separated to more analytical subtasks [GRIFFIS & FARR 2000]. For example, Task II (Excavation – Supporting phase A) can be further analyzed as follows: Drilling – Blasting - Muck "earth" moving - Temporary support installation (Anchors - Steel reinforcements – Shotcrete). The above tasks follow a specific pattern and sequence.

3. The Rapid Tunnel Excavation Method

The possibility to perform some, but not all, tasks at the same time has lead to an approach of tunnel construction, named *The Rapid Tunnel Excavation*. The first change was made by having two (or more in case of use abroad shafts) different workshops working simultaneously. Keeping a logical distance, considering time and ground, the workshops proceed avoiding conflicts or interactions. The total time for completing both tasks is not equal to the sum of duration for the two tasks' duration, but the duration of the first one plus the time distance. A second change is to prohibit workshops start working from one side to another until they get out of the tunnel. Some of the workshops may start from the first entrance and proceed until they complete slightly more than the half of the total tunnel's length; then, they may move out of the tunnel, be translocated to the other entrance and start working to the opposite direction [BOWLES 1996]. It has been noticed that, in this way, more workshops could work at the same time, achieving finally even shorter completion time.

There exists such a combination of tasks, which permits maximum activity at a certain time period. When *Excavation-Supporting A* has finished the first part, the workshop moves to the other entrance but also starts the *Excavation-Supporting B* from the first entrance. Similarly, the workshops of the *Excavation-Supporting B* and the *Footings* work. Almost together with the *Footings* starts the task of the *Gaskets*. After the specified time distance, the workshops of the Final Concrete Segment and the Final Sheeting begin working inside the tunnel. It is obvious that, some conflicts among workshops may exist, in point of dynamic output, and must be taken under serious consideration by the project manager or the civil engineer. Figure 8 depicts task sequencing in rapid tunnel excavation, where it can be noticed that the three first major tasks may be executed in parallel, so as to optimize resource usage and time execution, in contrast to the excavation methods from only one entrance.

Nevertheless, it should be stressed that, it is crucial to identify as much accurately as possible the point in time were concrete-related tasks (i.e., gaskets, concrete segments, etc.) should start. The reason is that concreting is carried out from only one direction both for practical (concreting equipment cannot be removed backwards once entered in the tunnel), as well as for safety purposes (usually when excavation takes place in a tunnel segment, no other tasks can be executed at the same time in that segment). The advantage of the proposed method is that concreting from Entrance I starts when excavation from Entrance II is already running (and is executed in parallel to this), thus minimizing execution time compared to both the unidirectional tunnel excavation method, as well as any other bi-directional tunnel excavation method that waits until all excavation works are finished before concreting.

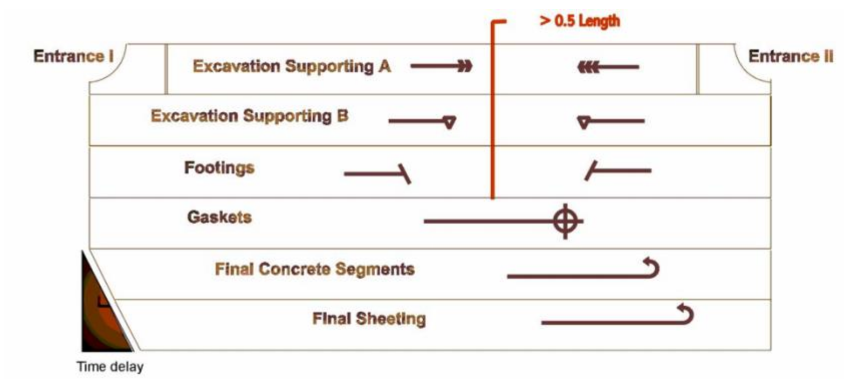

Figure 8: **Task Sequencing during Rapid Tunnel Excavation.**

A successful implementation of this approach would result in minimization of the time between the end of excavation in Segment II and the end of concreting in Segment I. The net time advantage for the project is almost equal to the time needed for concreting of Segment I. Depending on the speed of excavation (which depends mostly on the ground composition), one main obtain a gain between 5% to 20% of the total project time. The net amount in days is however fixed. The critical step for the engineer, as well as for the project manager, is thus to estimate where exactly this break should be made in order to ensure optimal resource allocation, minimal construction time and conformance to the quality of the result, without increasing planned cost (but rather reducing it). The present article presents a software package developed in order to facilitate this decision [LEWIS 1998, REMENYI 1999]. For scheduling purposes, one must take into account that the concrete lining for the entire tunnel is executed at a uniform rate from the one entrance to the other [KERZNER 1998].

4. Software Description

A user-friendly and computationally efficient algorithm to calculate the optimum tunnel's "cutting" percentage has been developed, given the morphological elements and the dynamics of the specific workshops. The software runs under Windows OS and has limited needs for memory and disk space. The algorithm's inputs are the total length, the length of the two openings of the tunnel (morphological elements) and the average output of each workshop for the specific project (dynamic elements). The time distance between each pair of phases, the average translocation time of the workshops and the precision of the results may also be determined additionally. The results are the optimum "cutting" length, as well as the duration of each stage and the total duration.

The software starts with the main screen, where the user may create a *New* project profile, *Open* an existing one, or to read the *Help* files. The software uses Excel spreadsheets and the user may use an already set sheet by filling all the required elements; furthermore, the user may choose between the *Simple* and the *Detailed Mode*. In the former mode, the space-time, the translocation time and the precision of the results are set by default to be 5 days, 10 days and 50 meters, respectively. The results are printed in a cell form. The results are the optimum "cutting" length of the tunnel, the duration of each task (also the starting and the stopping days of workshops) and the final total duration of the whole construction. Results may also be shown in *Graphical mode*, where there is a simple tunnel's along cut drawing and the starting and ending point and time for each workshop. The user may *Save* the results as an Excel sheet or as a Text document. The characteristics of this software enable the user (typically the project manager) not only to make the first time scheduling of the project, but also to adjust the schedule while the project is running [LEWIS 1995, HARRIS &McCAFFER 1995, KWAKYE 1997]. Revisions are easy, given new more realistic data and so is the close guidance of the workshops. The stored results allow the final assessment to be made and to have some references for future similar projects' planning. An updated and advanced version is currently under development.

5. Results and Discussion

Experimental results using realistic data (Table 1) for a tunnel along the national road Tripoli-Kalamata in Peloponnisos have been used to corroborate the significance of the development and are presented. Two major construction companies to help plan tunnel excavation are presently using the software.

Total Length	1300 m	*Dynamic of Gaskets Workshop*	12 m/day
Length of Entrances	20 m	*Dynamic of Final Concrete Segment Workshop*	12 m/day
Dynamic of Entrance Workshop	2 m/day	*Dynamic of Final Sheeting Workshop*	12 m/day
Dynamic of Excavation A' Workshop	5 m/day	*Translocation Time*	10 days
Dynamic of Excavation B' Workshop	12 m/day	*Distance Time between Workshops*	5 days
Dynamic of Footings Workshop	15 m/day	*Precision of results*	20 m

Table 1: **Tunnel Excavation Project Realistic Data.**

The optimum "cut" is at the length of **730m** from the starting point. The total duration of the tunnel project is **430 days**. The following time schedule indicates the finish time of each task.

Excavation-Supporting A (part 1st) (**143**) ● Excavation-Supporting A (part 2nd) (**264**) ● Excavation-Supporting B (part 1st) (**265**) ● Excavation-Supporting B (part 2nd) (**322**) ● Footings (part 1st) (**323**) ● Footings (part 2nd) (**371**) ● Gaskets (**420**) ● Final Concrete Segment (**425**) ● Final Sheeting (**430**)

The experimental results have shown the feasibility of the proposed approach and show little difference compared to the actual progress.

A new, improved version of the software is under preparation which adapts results based on updated measurements of the project progress and the ground conditions, which result from more dense or more frequent sampling. The new software is planned to exhibit the following functionalities: (a) Detailed tunnel segmentation based on the rock quality and the production rate; guiding tables such as the ones presented in [HOEK & BROWN 1982, HOEK & KAISER 2000, US ARMY CORPS 1997, MARAGOS 1997] may be used for that purpose, (b) Analysis based on the usage of approach shafts for more excavation fields, (c) Cost analysis, and (d) Sensitivity analysis, that is, execution of different hypothetical scenarios during planning to produce safe estimations of time and cost.

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