Simulation of NATM Tunneling Construction in Gravel Formation
– Lessons Learned from Pakuashan Highway Tunnel Project in Taiwan

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ABSTRACT: Construction processes are complex operations that include the uses of equipment, materials, crews and geological conditions. Simulation can be used to study these processes in order to make competent decisions that will lower costs and shorten the duration of the project before it has started. Tunneling is a highly repetitive construction operation and simulation can be used to analyze the process. A model tunneling project is developed in this paper. This project is unique because of the soil conditions. A discrete event simulation methodology, CYCLONE, is used to build the operation model and simulate the tunneling processes. Statistical analysis indicates that duration of most tunneling operations can be modeled by Beta probability distribution. Results also show the model predicting the advancement rate of such tunneling project in accurate.

INTRODUCTION

Simulation can be used in the planning and scheduling of highly repetitive processes in construction projects. The tunneling process is a good example of construction projects that are highly repetitive. In tunneling projects the most important activity is the actual advancement rate of the tunnel. The total costs are directly related to the advancement rate. Simulation can be used to assess the advancement rate and find the problems of a project before it has started (AbouRizk et al. 1999; Nido et al. 1999). Though a few articles have been written concerning simulation and tunneling but most of these articles discuss the tunnel boring machine (TBM) method (Touran and Asai 1987; Sinfield and Einstein 1996; Touran 1997; Chung et al. 2006) used to build tunnel in soft rock.

However, the Pakuashan highway tunnel located in central part of Taiwan is unique in soil condition and therefore, the New Austrian Tunneling Method (NATM) is the chosen method of excavation at the Pakuashan Tunnel. It is worthy to have a model in predicting the advancement rate when similar tunnel is built. As a result, this paper aims at presenting a discrete event simulation model to be used to measure the production rate before a similar project can be started.

GEOLOGICAL CONDITIONS OF PAKUASHAN TUNNEL

The expressway tunnel is passing through the Pakuashan ridge, which is an anticline with the axis of the fold oriented in the north-south direction. The maximum height of the ridge or terrace is about 340m. The geological formations at the Pakuashan terrace consist of a thin layer of laterite, which is Quaternary deposit, near the ground surface and a thick layer of gravel formation underneath. The gravel formation belongs to the Toukoshan Formation of Pliocene Epoch, and it is composed of gravel, interlayers of soft sandstone, mudstone, and sand lenses. Thus, the gravel formation is very heterogeneous and is a composite stratum, which possesses the properties between soils and rocks.

The percentage of gravel content, the grain size distribution, the cementation of the matrix, and the groundwater situation control and affect the mechanical behavior of the gravel formation. The percentage of gravel content is as high as 86% and the rock size is as large as 2m for these gravel formations. The shear strength of the formation will be dominated by the fine content if the gravel content is less than 70%.

In general, the ground condition along the tunnel ranges in character from gravel and loose running sands to heavily compacted deposits of more cohesive material.

Groundwater can be found at two different sources. One is the perched groundwater, which is above the impermeable layer near the surface and the other one is the confined groundwater, which is between the folded belts of clayey layers inside the gravel formation. The progressing rate of the tunnel was slowed drastically in September 1998 as groundwater ingress was encountered. The ingress had a dramatic effect on the stability of the material. Therefore, gravity or vacuum wells were installed for dewatering around the tunneling face. Also a forepoling umbrella, was adopted when tunneling in faces with loose materials and groundwater seepage to prevent overbreaks and the flowing out of materials.

The conventional rock mass classifications, such as rock mass rating (RMR), Q-system, and rock structure rating (RSR), do not work well for the tunnels in gravel formation. Therefore, a different ground classification is adopted and used based on the encountered formations and in situ conditions in Taiwan. When the first subsoil exploration was conducted, there were five types of ground conditions encountered. However, once the construction was started, only three types of ground classifications were used: C2, D1, and D2. Table 1 shows cross sections of the three types of ground classifications.
TUNNELING PROCESSES

The tunneling processes are similar in each ground. However, there is no forepoling process in C2 and D1 grounds. Hence, only tunneling process for D2 ground is described as follows in this paper.

1. The forepoling machine is placed in position and the holes are marked. The holes are then drilled and cleaned and the steel rods are inserted.
2. In the forepoling process, there will be 28-49 holes drilled into the tunnel face. The forepoling process will advance 8-10 sections. Each forepoling section is 0.8-1.2m long.
3. Once the steel rods are placed, holes can be grouted and the tunnel face can be dug.
4. Shotcrete is always applied to the tunnel face (see Shotcrete Sealing on the flow chart). However, depending on the geological condition, shotcrete is added to the sidewall only 70% of the time. The application of shotcrete is 5cm thick.
5. After the shotcrete is applied, the wire mesh is placed.
6. The steel rib cage is assembled and placed. There are different kinds of steel rib cages used depending on the soil type.
7. After the steel rib is placed, the second application of shotcrete is applied. The second application of shotcrete is 10-15cm thick.
8. Wire mesh is placed for the second time.
9. A final application of shotcrete is applied in order to finish the surface of the face.
10. Repeat Steps 2-9 for 4-5 sections before bolting is started.
11. After Steps 2-9 have been repeated for 4-5 sections, a temporary heading invert is needed. The next step is to dig the heading invert.
12. The bolts are placed and grouted.
13. Wire mesh is placed at the heading invert. Then an application of shotcrete, which is 5cm thick, is applied. The wiremesh is placed a second time and the second application of shotcrete is applied which is 10-15cm thick.
15. Restart a new section.

MODEL AND DATA ANALYSIS

The CYCLONE (CYCLic Operation NEtwork) discrete event simulation methodology is used in developing the simulation model (Halpin 1977). The model used for the sake of estimating tunneling advancement rate based on aforementioned tunneling processes is presented in Fig. 1. The name and duration for each activity used in the model are provided in Table 2. Pakuashan tunnel is a twin tunnel. The data collected in one tunnel was used to build to simulate the tunneling advancement rate. Data collected from the other then was used to verify the accuracy of the model. At least 30 cycles of tunneling operations for most activities were observed from March to August in year 2000.

### Table 1. Ground Classifications.

<table>
<thead>
<tr>
<th>Classification</th>
<th>Description</th>
<th>Cross Section</th>
</tr>
</thead>
<tbody>
<tr>
<td>C2</td>
<td>Mudstone containing layers of soft sandstone,</td>
<td></td>
</tr>
<tr>
<td></td>
<td>siltstone, or gravel</td>
<td>Mudstone</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>D1</td>
<td>Mainly gravel with pockets of sand lenses. Mostly coarse and grainy material with better cementation and interlocking strength.</td>
<td>Gravel</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>D2</td>
<td>Loosely packed gravel with layers of silty sand, sand, or clay in between.</td>
<td>Loosely Packed Gravel</td>
</tr>
</tbody>
</table>
Table 2. Activity name and duration for D2 ground.

<table>
<thead>
<tr>
<th>Activity</th>
<th>Name</th>
<th>Duration (min)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1 (COMBI)</td>
<td>Positioning of Forepuling Machine</td>
<td>Constant (30)</td>
</tr>
<tr>
<td>4, 14, 24, 34, 44 (COMBI)</td>
<td>Mark Holes</td>
<td>Beta (5, 19, 10.2, 3.9)</td>
</tr>
<tr>
<td>5, 15, 25, 35, 45 (COMBI)</td>
<td>Drill Holes</td>
<td>Triangular (11, 13, 23)</td>
</tr>
<tr>
<td>6, 16, 26, 36, 46, (COMBI)</td>
<td>Clean Holes</td>
<td>Beta (4, 25, 9.3, 4.3)</td>
</tr>
<tr>
<td>7, 17, 27, 37, 47 (COMBI)</td>
<td>Insert Steel Rods</td>
<td>Triangular (5, 8, 15)</td>
</tr>
<tr>
<td>8, 18, 28, 38, 48 (COMBI)</td>
<td>Grout Holes</td>
<td>Beta (2, 19, 6.7, 4.7)</td>
</tr>
<tr>
<td>9 (NORMAL)</td>
<td>Wait For Solidification</td>
<td>Constant (480)</td>
</tr>
<tr>
<td>10, 11 (COMBI)</td>
<td>Excavate Tunnel Face</td>
<td>Triangular (110, 120, 190)</td>
</tr>
<tr>
<td>41 (COMBI)</td>
<td>Shotcrete Sealing</td>
<td>Beta (20, 50, 36.1, 9.4)</td>
</tr>
<tr>
<td>52 (COMBI)</td>
<td>Shotcrete Sidewall (5cm)</td>
<td>Triangular (25, 30, 45)</td>
</tr>
<tr>
<td>53 (COMBI)</td>
<td>Install Wire Mesh</td>
<td>Beta (20, 45, 28.9, 6.6)</td>
</tr>
<tr>
<td>54 (COMBI)</td>
<td>Steel Rib Gathering</td>
<td>Constant (10)</td>
</tr>
<tr>
<td>55 (NORMAL)</td>
<td>Assembly</td>
<td>Triangular (15, 20, 25)</td>
</tr>
<tr>
<td>56 (NORMAL)</td>
<td>Installation</td>
<td>Beta (30, 50, 38.6, 6.8)</td>
</tr>
<tr>
<td>57 (NORMAL)</td>
<td>Correction and Fix</td>
<td>Beta (15, 35, 29.2, 4.5)</td>
</tr>
<tr>
<td>58 (COMBI)</td>
<td>Reapply Shotcrete (15cm)</td>
<td>Beta (45, 85, 58.1, 12.0)</td>
</tr>
<tr>
<td>59 (COMBI)</td>
<td>2nd Wire Mesh</td>
<td>Beta (20, 45, 28.9, 6.6)</td>
</tr>
<tr>
<td>60 (COMBI)</td>
<td>2nd Shotcrete Application (15cm)</td>
<td>Beta (45, 85, 58.1, 12.0)</td>
</tr>
<tr>
<td>63 (NORMAL)</td>
<td>Wait for Solidification</td>
<td>Constant (60)</td>
</tr>
<tr>
<td>65 (COMBI)</td>
<td>Bolting</td>
<td>Triangular (200, 320, 510)</td>
</tr>
<tr>
<td>66 (COMBI)</td>
<td>Grouting</td>
<td>Triangular (100, 160, 235)</td>
</tr>
<tr>
<td>71 (COMBI)</td>
<td>Temporary Heading Invert Excavation</td>
<td>Beta (110, 195, 146.2, 25.5)</td>
</tr>
<tr>
<td>72 (COMBI)</td>
<td>Install Wire Mesh</td>
<td>Triangular (30, 35, 55)</td>
</tr>
<tr>
<td>73 (COMBI)</td>
<td>Reapply Shotcrete</td>
<td>Beta (55, 100, 78.6, 13.8)</td>
</tr>
<tr>
<td>74 (NORMAL)</td>
<td>Cure Shotcrete</td>
<td>Constant (120)</td>
</tr>
<tr>
<td>75 (COMBI)</td>
<td>Dirt Refill</td>
<td>Beta (30, 100, 67.3, 14.8)</td>
</tr>
</tbody>
</table>

FIG. 1. Tunnel advancing operations for D2 ground.
The collected data were first used as the resources for duration fitting in 95% confidence level. Beta and triangular probability distributions are suitable in modeling the duration required in completing those activities listed in Table 2. For example, the duration of activity-mark hole, can be modeled by Beta probability density function whose minimum, maximum, mean, and standard deviation values are 5, 19, 10.2, and 3.9 minutes, respectively. In addition, the duration of activity-insert steel rods, is suitable to be presented by triangular probability density function whose minimum, mode, and maximum values are 5, 8, and 15 minutes, respectively. On the other hand, the activity's duration marked with constant value was acquired based on superintendent's notes rather than field observations.

The simulation results (see Fig. 2) show the variation of advancement rate in C2, D1, and D2 grounds. The average advancement rates for these grounds are 14.34, 12.02, and 18.21 hours per meter, respectively. The least advancement rate is found in D2 ground because forepoling and temporary heading invert were required when tunnel was constructed. However, only temporary invert was needed and hence, a better advancement is found in C2 ground. The best simulated advancement rate is found in D1 ground and is in great fluctuation because there was 50% probability that the temporary heading invert is needed when D1 ground is encountered. Figure 3 shows the comparison of advancement rates obtained by simulation and actual observations. Simulation was run for 10 cycles. The simulated accumulative times for 10 cycles are compared to actual data. The estimated time required to complete 10 cycles of tunneling operations is around 1,630 hours and about 1,661 hours were observed in finishing these cycles. The accuracy of the prediction is 98.8% (1,630/1,661*100%).

SUMMARY

This paper presents a discrete event simulation model used to estimate the advancement rate when NATM tunneling method is adopted in building tunnel penetrating the gravel formation. The duration of most tunneling activities can be modeled by Beta or triangular probability density functions in 95% confidence level using historical data. The simulation illustrates the developed simulation model that is reliable to be used to measure the production rate before a similar project can be started.

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