Modeling Uncertainty in Operations with Nonstationary Cycle Times

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Abstract: This paper describes an approach for probabilistic analysis of construction operations in which nonstationary cycle times have a major impact on production. A nonstationary cycle time is defined as a cycle time that varies with the passage of time and project progress. Examples of projects in which nonstationary cycle times affect production include linear operations such as highway construction and tunneling operations. As the project progresses the haul time of the earth-moving equipment increases. Although the proposed approach is sufficiently general to be used with various types of construction operations, the specific model presented was developed for tunneling operations. The model predicts the muck-handling requirements of the tunneling operation at the desired level of confidence. Application of the model is shown through a numerical example, and the results are compared with the results of a conventional deterministic analysis.

Introduction

In a number of heavy-construction projects the travel times of earth-moving equipment increase as the project progresses. For example, in a highway project the distance between the embankment construction area and the borrow pit increases as the contruction of the embankment proceeds. Tunneling and pipe-laying projects show the same characteristic. As the haul distance increases, the equipment travel time and hence cycle time increases. Cycle times that increase or decrease with the passage of time (given that the project is progressing) are called nonstationary cycle times (Halpin 1990). The increase in cycle times results in a progress slowdown unless some remedial action is taken by the management. In many cases, activities affected by nonstationary cycle times are on the critical path, and their slowdown or delay can alter project duration. The remedial action undertaken by management is usually in the form of changing the work configuration or assigning more equipment to the job. In the highway case, for example, the possibility of a closer borrow pit may be investigated, or the number of trucks or scrapers may be increased to offset the effect of increasing haul distance.

In this paper, a model is developed to quantify the impact of nonstationary cycle times on the capacity of the haulers under certain conditions. The model predicts needed hauling capacity for a sustained project progress rate as the time advances, at various confidence levels. Although the model is described in relation to a typical tunneling operation, it can be generalized for any project involving nonstationary cycle times.

Tunneling Operation

In tunneling projects, nonstationary cycle times of the muck trains (material handling system in most tunneling operations) may slow down con-

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siderably the tunnel advance rate. This is especially true where the tunnel length is more than 1 mi (1,609 m), and where the excavated material should be hauled to the portal or a shaft. Haul distance increases as the tunnel advances. In this paper the assumptions are that the TBM (tunnel boring machine) is used for constructing the tunnel and the train is used for muck handling. Tunnel advance rate is a function of various parameters. These parameters include but are not limited to ground and groundwater conditions, construction plan and method, and contract specifications. But regardless of the circumstances, the muck-handling system should provide sufficient support for the TBM operation. In other words, there should be sufficient train capacity to handle the muck generated by the TBM so that TBM advancement is not hindered. Because the overall tunnel advance rate is subject to uncertainty, the train capacity should be determined in such a way that the probability of having train capacity available does not fall below a prescribed threshold.

MODEL FORMULATION

In general, the train cycle time T, in hours, for the situation depicted in Fig. 1 would be

$$T = k + \frac{2(D_o + Xt)}{V} \qquad (1)$$

where k = train loading and unloading time (hr); D_o = initial distance between dumping area and the starting point of the analysis (m); V = average train speed (m/hr); t = time (hr), measured from the starting point of the analysis; and X = a random variable representing tunnel advance rate (m/hr).

Although k and V in (1) may be subject to chance variations, the most important component in this analysis is the tunnel advance rate. This variable, X, has the most impact on the overall project duration and deserves scrutiny at the conceptual planning phase. From (1) one can find the total haul distance L in meters

$$L = D_o + Xt \qquad (2)$$

Eq. (1) can be arranged as follows:

$$T = k + \frac{2D_o}{V} + \frac{2Xt}{V} \qquad (3)$$

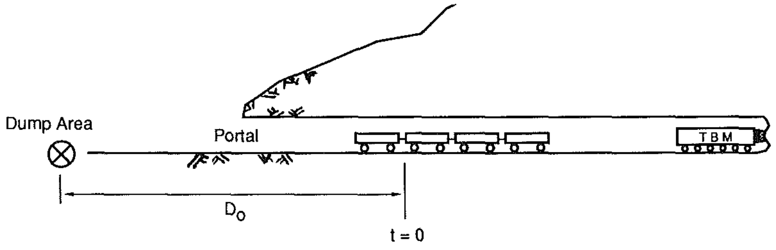

FIG. 1. General Layout of Tunneling Operation

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As can be seen, T, being a function of t and X, is a random process. A random process is defined as a random variable that changes with time.

The muck handling capacity of trains, expressed in m^3/hr, depends on T and is equal to (Vol)/T, where Vol = total train capacity in m^3. The amount of muck generated, expressed in m^3 per hour, would be $[\pi D^2(1 + \mathrm{Sw})X]/4$, where D = tunnel diameter in m; and Sw = swell factor of the excavated material. To ensure the smooth progress of the tunneling operation, the muck-carrying capacity should exceed muck production

$$\frac{\mathrm{Vol}}{T} >= \frac{\pi D^2(1 + \mathrm{Sw})X}{4} \quad (4)$$

Because both T and X are random variables, one can define confidence levels to ensure the adequacy of muck handing system

$$\Pr\left[\frac{\mathrm{Vol}}{T} >= \frac{\pi D^2(1 + \mathrm{Sw})X}{4}\right] >= p \quad (5)$$

where Pr = probability of the argument inside the brackets being true; and p = a confidence level chosen by management depending on their perception of the importance of providing adequate train capacity at all times. By rearranging (5) we have

$$\Pr\left\{XT <= \frac{\mathrm{Vol}}{\left[\dfrac{\pi D^2(1 + \mathrm{Sw})}{4}\right]}\right\} >= p \quad (6)$$

Let Z be a random process such that

$$Z = XT = X(A + BX) \quad (7)$$

where

$$A = k + \frac{2D_o}{V} \quad (8)$$

$$B = \frac{2t}{V} \quad (9)$$

So we have

$$Z = g(X) = AX + BX^2 \quad (10)$$

and

$$\Pr[Z \leq z] = F_Z(z) = \int_0^{g^{-1}(z)} f_X(x)dx \quad (11)$$

where $F_Z(z)$ = cumulative distribution function (CDF) of Z; and $f_X(x)$ = probability density function of X; A and B are both positive; and Z = a monotonically increasing function of $X(X >= 0)$ with a unique inverse $g^{-1}(z)$ (Ang and Tang 1975). In this case

$$g^{-1}(z) = \frac{-A + \sqrt{A^2 + 4Bz}}{2B} \quad (12)$$

$$z = \frac{\text{Vol}}{\left[\frac{\pi D^2(1 + \text{Sw})}{4}\right]} \quad \text{(13)}$$

$$F_Z(z) = \Pr\left\{XT < = \frac{\text{Vol}}{\left[\frac{\pi D^2 \, (1 + \text{Sw})}{4}\right]}\right\}$$

$$= \int_0^{(-A + \sqrt{A^2 + 4Bz})/2B} f_X(x)dx \quad \text{(14)}$$

where $X > = 0$; and $1 = > F_Z(z) > = 0$.

Computing $F_Z(z)$ from (14) is convenient because it essentially is the CDF of the random variable chosen for X. So, by selecting any of the well-known statistical distributions for modeling uncertainty in advance rate, one can conveniently compute the probability of meeting the requirements for the muck handling. By changing the values of t in (14) (note that B is a function of t), the point in time where a given train capacity will not be sufficient to handle the excavated material with a certain confidence level can be computed. Train capacities can be increased to develop a family of risk curves to see at what points in time and to what extent additional capacity is required for maintaining the expected progress rate. Expected haul length (L) in m, can be estimated from (15)

$$E(L) = D_o + tE(X) \quad \text{(15)}$$

where E = expected value of the argument inside the parentheses.

EXAMPLE

The model just described is used to estimate train capacity requirements in a hypothetical tunnel with an excavated diameter of 5 m and a length of 5.6 km (3.5 mi). The material is assumed to be uniform soft rock (shale or claystone) with a compressive strength of less than 10,000 psi (68,900 kPa). No unfavorable groundwater conditions are expected. The writer investigated muck handling and TBM advance rates in similar tunneling material and conditions in a previous project (Touran and Asai 1987). The swell factor for the material is assumed to be 50% (Touran and Asai 1987). One TBM is used for tunnel driving and there are no shafts. Two trains are assumed to be used for muck removal. Each train consists of six 5 m^3 muck cars. This gives a total train capacity of 60 m^3. As the tunnel length increases, it is expected that the number of muck cars and eventually the number of trains will be increased. Average train velocity is assumed to be 10 mph (16,090 m/hr). To achieve this velocity, the starting point of the analysis (t = 0) is taken at a distance D_o = 500 m from the dump area. Also assume that the dump area is located 200 m outside the tunnel portal. This assumption puts the starting point of the analysis 300 m inside the tunnel.

Tunnel Advance Rate

The tunnel advance rate, which sets the pace for the whole operation, is assumed to vary between 1 m/hr and 5 m/hr. The choice of statistical distribution depends on the nature of the available historical data and the

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experts' viewpoints regarding the advance rate. If data available are scarce and experts cannot express a perference for a most likely value, a uniform distribution may be used to model the data. If the estimator or the expert has a feeling for the most likely value for the advance rate, then the most simple distribution to use would be triangular ("Tunnel" 1989). In a case in which extensive data are available, the choice of beta distribution seems reasonable because it provides flexibility in fitting the data set (Riggs 1989). In the present example a uniform distribution is assumed. The range was chosen by surveying projects in similar conditions as part of a previous project (Asai 1987; Touran and Asai 1986). It should be noted, however, that the choice of any other distribution with the model presented in (14) is convenient because it is a matter of computing the CDF of the random variable, which is usually readily available.

Train Load and Dump Times

The average train loading and unloading time (k) consists of a loading time that varies with train size and the unloading time and minor delays that can be assumed as a fixed value. The load time can be estimated by multiplying the number of muck cars in the train by the time needed to load one car. The time needed to load a car can be estimated by considering the TBM penetration rate. The TBM penetration rate is generally higher than the overall tunnel advance rate because overall tunnel advance rate depends also on factors such as primary support system and tunnel lining method, various delays, and so forth. One can further investigate the correlation between tunnel advance rate and TBM penetration rate in order to incorporate the variability of the latter into the model. The writer considered a linear relationship between these two variables and found that the final model output was not significantly different from the output of the present model.

In this example, the unloading time and the minor delays are assumed to take an average of 10 min (0.167 hr). The loading time per car is computed as 2.5 min (0.042 hr) based on an assumed TBM penetration rate of 4 m/hr. So, $k = 0.167 + 0.042n$; where n = number of cars in a train.

Results of Analysis

By substituting the uniform distribution for X in (14) we have

$$X = \text{Uniform } (a,b) \quad \text{.......} \quad (16)$$

$$F_Z\left\{\frac{\text{Vol}}{\left[\dfrac{\pi D^2(1 + \text{Sw})}{4}\right]}\right\} = \int_a^{(-A + \sqrt{A^2 + 4Bz})/2B} \frac{dx}{b - a}$$

$$= \frac{1}{b - a}\left(\frac{-A + \sqrt{A^2 + 4Bz}}{2B} - a\right) \quad \text{.......} \quad (17)$$

For $F_Z(z)$ to be between 0 and 1 we should have

$$a(Ba + A) = < z < = b(Bb + A) \quad \text{.......} \quad (18)$$

Now the parameter values are inserted in (8), (9), (17), and (18)

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$$A = 0.167 + 0.042n + \frac{2D_o}{V} = 0.167 + 0.042 \times 6$$

$$+ \frac{(2)(500)}{16{,}090} = 0.481 \quad (19a)$$

$$B = 1.243 \times 10^{-4}t \quad (19b)$$

$$a = 1 \quad (19c)$$

$$b = 5 \quad (19d)$$

$$F_Z(z) = F_Z\left(\frac{\text{Vol}}{29.45}\right) = 0.25$$

$$\times \left[\frac{-0.481 + \sqrt{0.231 + 4.972 \times 10^{-4}tz}}{2.486 \times 10^{-4}t} - 1\right] \quad (20)$$

$$1.243 \times 10^{-4}t + 0.481 <= z <= 3.108 \times 10^{-3}t + 2.405 \quad (21)$$

Using (19), one can use Vol = 60 m^3 and vary t to get corresponding values of probability of the train capacity exceeding the muck volume generated. Also, as the probability values are diminished below an acceptable threshold one can increase Vol and repeat the computations to develop risk profiles for various train capacities. Fig. 2 is developed using (20).

Each curve relates to a given total train capacity. If, for example, the management decides to ensure with a 60% probability that muck-handling capacity exceeds generated muck volume, then the analysis reveals that two trains each consisting of six muck cars are sufficient until t = 300 hr, after which time train capacity should be increased. If two 5 m^3 muck cars are added to each train, increasing total capacity to 80 m^3, the configuration will suffice until t = 550 hr. In the next step, a three-train configuration can be used, each train consisting of eight 5 m^3 muck cars. With this capacity

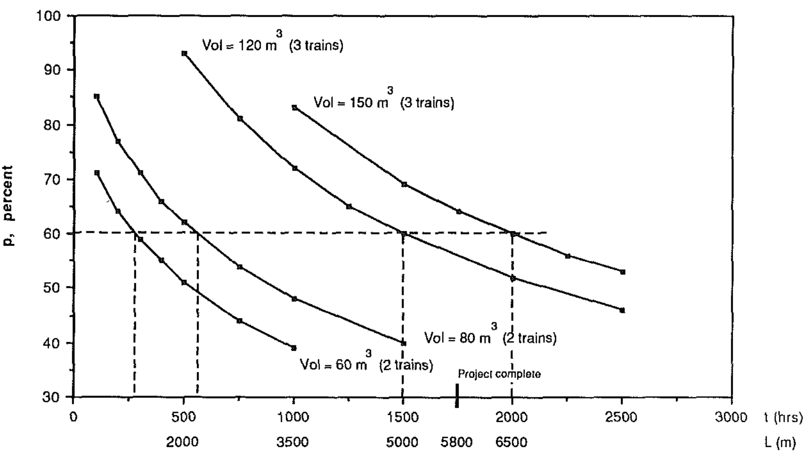

FIG. 2. Probability of Meeting Muck-Handling Requirements Given Various Train Configurations

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TABLE 1. Results of Deterministic Analysis

Number of trains (1)	Number of cars per train (2)	Total capacity (m^3) (3)	t smaller than (hr) (4)
2	6	60	530
2	8	80	920
3	8	120	2,130
3	10	150	2,820

(120 m^3), the muck-handling capacity will suffice until t = 1,500 hr. Finally, three trains, each consisting of ten 5 m^3 muck cars (150 m^3), may be used to accomplish the last phase of the job. The expected haul distance at various stages is computed by (15) and is provided in Fig. 2. So, the analysis can be used regarding the increase in train capacity relative to the haul distance (or length of tunnel excavated) if desired.

Comparison of Results with Deterministic Approach

To compare the results obtained from the probabilistic analysis described with the outcome of a conventional analysis, (3) and (4) are used except that a deterministic value of 3 m/hr is assumed for X, the tunnel advance rate. Inserting the data of the given example into (3) and (4) results in (22)

$$T = 0.167 + 0.042n + \frac{(2)(500) + (2)(3)(t)}{16{,}090} = 0.229 + 0.042n + 3.72 \times 10^{-4}t \quad \text{(22a)}$$

$$\frac{\text{Vol}}{0.229 + 0.042n + 3.72 \times 10^{-4}t} > = 88.3 \text{ m}^3/\text{hr} \quad \text{(22b)}$$

$$20.22 + 3.71n + 0.03285t < = \text{Vol} \quad \text{(22c)}$$

Table 1 presents the results of the deterministic analysis. It shows that the two trains consisting of six cars can support the TBM until t = 530 hr, after which eight cars should be used with each train until t = 920 hr. After that point three trains are recommended with eight cars, and this configuration should be sufficient for the whole length of the project. Usually these capacities are multiplied by a safety factor. Comparing these results with Fig. 2 shows that the values obtained deterministically have a 50% chance of being insufficient (assuming the choice of uniform distribution is correct). Also, although one can safeguard against irregularities in productivity by implementing safety factors, the level of confidence cannot be explicity quantified. Safety factors considered cannot be realistically evaluated from project to project, because they are not tied to a specific confidence level. Because of this the consistent implementation of a safety factor is not feasible. In other words, the management will not know how "safe" the selected safety factor is.

Conclusions

A model was presented that allows the probabilistic analysis of operations in which nonstationary cycle times have a major impact on production.

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Although the approach is general enough to be used with various types of construction projects, the specific model was developed for tunneling operations. The model predicts the muck-handling requirements of the tunneling operation at the desired confidence levels. Model application was shown through a numerical example and the results were compared with the results of a conventional deterministic analysis.

Appendix I. References

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Appendix II. Notation

The following symbols are used in this paper:

D = tunnel diameter (m);
D_o = initial distance between dump area and starting point of analysis (m);
F_Z = cumulative distribution function (CDF) of Z;
$f_X(x)$ = probability density function (PDF) of X;
k = train loading and unloading time (hr);
L = total haul distance (m);
n = number of muck cars per train;
Sw = excavated material swell factor (%);
T = total train cycle time (hr);
t = time (hr) measured from starting point of analysis;
V = average train speed (m/hr);
Vol = total capacity of trains (m^3); and
X = random variable representing tunnel advance rate (m/hr).

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