CORRELATED PROBABILISTIC ANALYSIS
OF THE EXCAVATION TIMES AND COSTS IN TUNNELING

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A new calculation procedure, called PACT, is presented for the probabilistic analysis of the construction times and costs of tunneling. Once the tunnel strength is divided into homogeneous sections, it is necessary that all the operations on the critical path and the quantities of materials used for each of the previously identified classes are described in analytical terms. A selection is made from the parameters that show a certain degree of uncertainty. A standard deviation of the probabilistic distribution is defined for these parameters. The final result is the identification of the probability ellipses with a certain degree of reliability. The ellipses define the total field of variability of the construction times and costs of the tunneling. The procedure was successfully applied to the pilot tunnel of the Italian section of a 13-km long alpine tunnel. It proved possible to obtain the joined probabilistic description of the times and costs as a result of the evaluation of 95 elementary parameters, 25 of which are considered probabilistic ones because of the uncertainties of their estimation.

Tunneling, probabilistic variables, reliability estimation, construction operations, drill and blast technologies, Gaussian distribution, covariation factors

INTRODUCTION

The evaluation of the times and costs of a tunnel is one of the most delicate phases of tunnel design. At the initial stage, the construction companies present a tender for the realization of the work, that must be done within the established time. However, many uncertainties can arise when it comes to designing a tunnel as it involves dealing with natural materials (rocks or soils) that can usually vary along the stretch and which can never be known completely. The uncertainties increase considerably in long and deep tunnels when geological and geomechanical investigations are not exhaustive enough. In these circumstances, it is not possible to proceed with an evaluation of the times and costs in a deterministic way but it is instead necessary to face the problem in probabilistic terms [1–3]. As the costs partially depend on the time necessary to excavate a tunnel, these two magnitudes (times and costs) should be considered as probabilistic intercorrelated variables.

In this paper, a new calculation method called PACT (probabilistic analysis of costs and times in tunneling) is presented. This method provides the statistical estimation of the excavation times and costs through probabilistic ellipses with a certain degree of reliability. The method requires an analytical description of the times and costs of the individual elementary operations in the homogeneous sections that a tunnel has been divided into. The input parameters are probabilistic variables described through the probability normal curve (Gaussian distribution) [2].

The proposed approach allows the effective comparison of alternative tunnel construction projects to choose the solution that appears to be the most convenient from all those that guarantee the work to be finished within the pre-established times with an acceptable level of reliability.

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1062-7391/06/4203-0269 ©2006 Springer Science + Business Media, Inc.
PROBABILISTIC ANALYSIS OF COSTS AND TIMES IN TUNNELING

The method *PACT* has been set up to evaluate the excavation costs and times of a tunnel in probabilistic terms (scheme of *PACT* is given below). The method requires the identification of mining and support classes in the homogeneous sections that a tunnel stretch has been divided into. The definition of the mining classes and support classes leads to the identification of excavation classes.

Hence, each excavation category has a specific mining scheme and a specific support type and also its own organization of the working times of each single operation stage and its own total costs per meter of a tunnel. Thus, the problem can be ascribed to the definition of excavation categories for the single homogeneous sections of the tunnel and to the determination of the following parameters in analytical terms for each excavation category:

— the times of each site operation;
— the mean velocity of advance, starting from the organization of the time table;
— the overall time required to advance in each excavation category;
— the quantity of materials used for each meter of a tunnel and for each excavation category;
— the total costs of a tunnel, including the costs of the used and supply materials, the costs of the personnel, the equipment depreciation costs (in the course of the construction times) and the fixed costs.

These magnitudes are described by multivariable functions [4]. For example, for borehole drilling operation, reference is made to the mining scheme that is defined for that specific excavation category. Time required for this operation is expressed in function of the drilling velocity and the time necessary to move the machine from one borehole to another. For mucking, the time is expressed as a function of the time cycle of the loader and the manoeuvring time of the dumper. Similarly, the cost of each tunnel meter can be assessed.

At the end of this stage, the length of the tunnel sections is associated to each excavation class. If the advance velocity for each class and the overall length of the sections associated to them are known, it is possible to calculate the construction times of the tunnel. In a similar way, if the quantities of the materials and the work per meter of each excavation class and the overall length of each class are known, the total cost of the tunnel can be determined taking the costs referred to the personnel, depreciation of machines and fixed costs.

Each elementary parameter (e.g., the drilling velocity for a certain type of rock, the loading time of explosive, etc.) is then treated in probabilistic terms, and the statistical distribution is obtained if the standard deviation is known. Finally, the joined probabilistic analysis makes it possible to evaluate not only the standard deviation of the costs and times but also the correlation coefficient between the two previously mentioned probabilistic variables.

The study results can be analyzed through a 2D probabilistic distribution of the two probabilistic variables, based on hypothesis that their distribution is normal. The interpretation is immediate when using the probability ellipses that describe directly the dimensions of the field of existence of the times and costs for the prescribed reliability level.

The different stages of the *PACT* method are here analyzed in detail (Fig. 1).

*STATEMENT OF THE PROBLEM*

At the first stage, the geometric characteristics of the tunnel (dimensions, length and depth) that affect the evaluation of the construction times and costs are defined. The dimensions and the depth of the tunnel affect the support works necessary to guarantee stability of the tunnel, while the length obviously directly affects the times and construction costs.

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