Proceedings, Construction Congress 95, ASCE
San Diego, California, October 22-26, 1995
C.W. Ibbs, ed.

Evaluation of Alternative Construction Processes Using Simulation

Photios G. Ioannou[1] A.M. ASCE and Julio Martinez[2]

Abstract

The comparison of alternative construction methods is one of the principal reasons for using simulation to model construction processes. The efficiency and effectiveness of such comparisons can be greatly improved by the prudent use of "matched pairs," a variance reduction technique based on dedicated and fully synchronized random number streams. The basic methodology is illustrated by using the Stroboscope simulation system to compare two alternative construction methods for rock tunneling (Conventional vs. the NATM). For this example the effects are dramatic. The probability of choosing the less expensive construction method based on a single run increases from 55% to 96%, the variance of the difference in cost decreases by two orders of magnitude, and the 95% confidence interval for the expected difference in cost given by 4,000 *independent pairs* is given by only 7 *matched pairs*.

Overview

One of the primary objectives of using simulation to model construction processes is to evaluate and compare the performance of alternative construction methods. A common mode of operation is to construct a simulation model for each method, conduct a limited number of simulation experiments (runs), and then compare the competing alternatives based on the resulting average measure of their performance. The problem with this approach stems from the fact that the simulation runs for one construction method are often designed to be independent (in a statistical sense) from those for the competing alternatives. Thus, if the principal causes of uncertainty in the system are not directly due to the methods being compared, but are rather caused by factors external to the methods and inherent to the problem being analyzed, the alternatives will not be compared on an equal basis. The tunneling example presented below is an excellent illustration of this problem. In tunneling, most of the risk is due to geologic uncertainty, which is independent of the chosen construction method. As a result, it is very important that competing construction alternatives be compared under the same geologic conditions. Otherwise, the observed cost differences will be due to differences in the project geology rather than to the construction methods themselves.

---

[1]Associate Professor, Civil & Environmental Engineering Department, University of Michigan, Ann Arbor, MI 48109-2125.
[2]Doctoral Candidate, Civil & Environmental Engineering Department, University of Michigan, Ann Arbor, MI 48109-2125.

Conceptually, the solution to this problem is quite simple. The simulation runs for each alternative must be designed so that uncertainty impacts each construction method in a similar manner. Since all uncertainty in a simulation model is determined by random numbers, the key is to ensure that the random numbers used for each method follow similar patterns. A very simple way to do this, is to start the corresponding simulation replications for all alternative methods using the same set of random number seeds. This approach, however, does not always work well by itself and may even backfire. The exact sequence in which random numbers are used during simulation for the first method (e.g., to determine activity durations) is not necessarily the same as the sequence required by the other construction alternatives.

A much better approach is to dedicate a stream of random numbers to *each* uncertain variable that is common to all alternatives. For example, Stream 1 may be dedicated to determining the durations for the "excavation" activity for all construction methods. Streams are consecutive sequences of random numbers taken out of the "circular chain" of random numbers produced by the same random number generator (RNG). Typically, Stream 0 is the sequence of random numbers starting with a given seed, Stream 1 begins at the 100,000th random number of Stream 0, Stream 2 begins at the 200,000th random number of Stream 0, etc. Thus, a 32-bit RNG with a cycle of over 2 billion, can have more than 20,000 independent random number streams, each having a length of 100,000 random numbers.

In order for this approach to work well, however, no single variable in any simulation run may use more than 100,000 random numbers. Otherwise, the random numbers for one variable will be the same as those for the model variable using the next stream, and the two will be positively correlated. This can be avoided by explicitly skipping streams, or by increasing the spacing between streams. For example, using only streams 0, 2, 4, etc., allows independent random number sequences that are 200,000 long. Similarly, the seeds for successive simulation runs for the *same* construction method must be chosen so that these runs are indeed independent (i.e., they do not in any way re-use the same random number sequences).

To keep the random number streams completely synchronized between the simulation runs for alternative methods, the number of uniformly distributed random numbers used to generate a sample for a non-uniformly distributed variable must be the same for all construction alternatives. For example, the excavation duration for alternative A may be Normal (which may require two random numbers per sample) whereas the excavation duration for alternative B may be exponential (which requires one random number per sample). The easiest way to ensure this, is to generate all samples by using the inverse cumulative method (one random number per sample). This as well as other synchronization problems can also be avoided by discarding a certain number of random numbers at appropriate points during a simulation run.

The effect of using all the above techniques is illustrated by the following example that compares two alternative tunnel construction methods. All simulation runs have been performed using Stroboscope (an acronym for STate and ResOurce Based Simulation of COnstruction ProcEsses), a general-purpose simulation programming *language* based on the activity-scanning paradigm. Simulation models in this language are processed by a simulation engine that can receive input either from an integrated development environment (edit-compile-run), or from a graphical user interface that automatically generates the code for a model. The Stroboscope language can set the random number seed, allows any number of random number streams (spaced at any specified multiple of 100,000 random numbers), can perform any number of simulation runs (replications) within each simulation model, allows switching simulation models within a replication, defines any number of normal or weighted statistics collectors, and can selectively clear some of the simulation statistics while keeping others across replications. Furthermore, it can produce any output, in any desired format, and save it to a file so that it may be analyzed by another program. A description of Stroboscope can be found in (Martinez Ioannou & Carr 1994, Martinez & Ioannou 1994). The Stroboscope program and its documentation is available via *anonymous* ftp from "grader.engin.umich.edu."

Example — Tunnel Construction

We shall use as an example the construction of a 1.6 kilometer two-track tunnel between two existing stations. The tunnel is assumed to serve as a connector for two commuter rail systems and thus requires no intermediate stations. All excavation must be performed underground with no intermediate shafts, starting at one of the existing stations. Two construction alternatives will be evaluated, the "Conventional" method and the "NATM" (New Austrian Tunneling Method). Both options use the same excavation method (drill & blast) and muck method (train muck haulage) but differ in the system used for initial tunnel support.

For the Conventional method, initial support for the roof and sides of the tunnel is provided by steel sets and lagging. Steel sets are H beams bent to conform to the rough shape of the excavated tunnel cross section. Wood lagging consists of heavy timber, placed between the steel sets and the rock, to support the walls and roof of the tunnel until the final lining is constructed. The final lining is typically a shell of cast-in-place reinforced concrete.

The NATM method is a special case of the observational or adaptable approach, where the initial tunnel support requirements are not determined during the design phase, but rather during the construction phase by monitoring the rock deformation. This deformation is held to within a specified tolerance by varying the initial support materials: rock bolts, wire mesh, and shotcrete. Proponents of observational techniques such as the NATM point to material (and labor) cost savings by using only the exact amount of initial support required, rather than using an initial support designed for the suspected worst condition in the tunnel. Opponents of these techniques cite the time to make support decisions and the imposed time variations (from varying support requirements) during the construction cycle as having major impacts on total cost. This example ignores the institutional barriers and implied liability transfers from adopting the NATM approach.

For both construction alternatives, the "excavation" activity includes drilling holes into the tunnel face and loading them with explosives. This is followed by "shooting" the rock (retracting the jumbo, wiring the "pig-tails", and detonating the explosives). For simplicity, these times have been made part of the duration of the "excavation" activity and thus "shooting" is assumed to take zero time. "Shooting" is followed by the "smoke" activity that ventilates all the smoke out of the tunnel. In order to bring back the jumbo and resume drilling again, all the muck resulting from the last shot must be removed. When mucking is done, excavation (i.e., drilling and loading) and the installation of the initial rock support can start. Thus, "excavation" and "support" can occur at the same time. In order to "shoot" again, the "excavation" for the next round (drilling and loading of holes) must be complete, and enough initial support must have been installed so that, *after* the rock is shot, the length of unsupported tunnel is less that the maximum allowed for the current rock class. After the rock is shot, the cycle repeats again. The excavation progress in one cycle (drill, blast, muck) is called a *round*.

The tunnel geology is modeled as a discrete-state, discrete-space Markov process. The rock conditions (system states, from best to worst) are represented by three *ground classes* (1 "Good", 2 "Medium", 3 "Poor"). Space is discretized into *steps* (linear segments along the tunnel's horizontal alignment). Ground classes persist for at least the length of one step. The first step starts out in ground class 1. The ground class transition probabilities (from step to step) are shown in Table 1.

Table 1. State Transition Probability Matrix (from step to step)

From	To Ground Class		
Ground Class	1 (Good)	2 (Medium)	3 (Poor)
1 (Good)	0.60	0.25	0.15
2 (Medium)	0.10	0.80	0.10
3 (Poor)	0.05	0.20	0.75

Excavation for both the Conventional and the NATM methods is accomplished by drilling and blasting the rock. The pertinent data for both methods are shown in Table 2. The excavation advance rates (linear meters per hour) in this table have triangular probability distributions defined by (min/mode/max).

Table 2. Excavation Data for Conventional Method and NATM

	Ground Class		
Drill & Blast Excavation Data	1 (Good)	2 (Medium)	3 (Poor)
Advance rate (linear meters/hr) (min/mode/max)	.37/.38/.43	.32/.33/.40	.13/.17/.32
Operating cost ($/hr), including labor	2,019	1,760	1,750
Overbreak volume (% of desired excavation)	10%	15%	30%
Max distance of support to the tunnel face (m)	16	8	4

The type of initial tunnel support is the fundamental difference between the Conventional method and the NATM. The Conventional method uses steel sets and lagging, which are designed to withstand the *worst* possible rock conditions (ground class 3). The NATM uses rock bolts, wire mesh, and shotcrete, the amounts of which *vary* depending on the current ground class. Table 3 shows the cost of the support for each type and method ($/m), and the rate at which it can be installed. The support placement rates (linear meters per hour) in this table have uniform probability distributions in the range (min/max).

Table 3. Initial Support Cost ($/m) and Placement Rates (linear meters/hr)

Ground	Support Cost		Support Placement Rate (min/max)	
Class	Conventional	NATM	Conventional	NATM
1 (Good)	1,400	940	.35/.45	.55/.65
2 (Medium)	1,400	1,160	.35/.45	.37/.47
3 (Poor)	1,400	1,350	.35/.45	.15/.30

When using the NATM, the decision to change the support (because of a new ground class) at the end of each step is associated with a cost and a time delay as shown in Table 4.

Table 4. Time and Cost to Decide/Switch the Support Type (NATM only)

From	Time (hrs)			Cost ($)		
Ground	To Ground Class			To Ground Class		
Class	1 (Good)	2 (Medium)	3 (Poor)	1 (Good)	2 (Medium)	3 (Poor)
1 (Good)	0	8	12	0	2,000	5,000
2 (Medium)	8	0	4	1,600	0	3,000
3 (Poor)	12	4	0	3,800	2,300	0

Table 5 shows the rest of the data needed to construct the simulation models.

Table 5. Miscellaneous Data

Tunnel length =	1,600 meters
Step length =	100 meters
Round length =	4 meters
Finished (inside) tunnel diameter =	6 meters
"B-line" (excavation) diameter =	7 meters
Initial Capital Cost (for either method) =	$400,000
Salvage Value as a % (for either method) =	30%
"Smoke" time after every blast =	30 minutes
Muck rate for all options =	22 cubic meters/hr
Mucking costs for all options =	$10/cubic meter.
Concrete unit cost (including labor) =	$70/cubic meter
Overhead Cost per Day (24 hr) =	$12,000

The network model for both the Conventional method and the NATM is illustrated in Figure 1. At an abstract level, the Combis, Normals, and Queues in a Stroboscope network are similar in appearance and function to those in Cyclone. A Stroboscope network, however, defines only the basic model structure. Its underlying logic is determined by programming statements that define the network element *attributes* and other modeling entities not shown in the figure. Some of these are outlined below.

Network links are named, by convention, with 2 letters (that abbreviate the type of resource that flows through) followed by a number. In this model, RD is the abbreviation for the generic resource type *Round*; SR indicates the characterized resource type *SupportRound*. These names are used in programming statements to set link *attributes.*

The basic cycle of *Excavate* (drill holes and load explosives), *Shoot*, *Smoke*, and *Muck* is shown by the sequence of links RD1 to RD6. The queue *RoundToDo* is initialized with one resource of the *generic* type *Round*, which cycles through this series of links. The associated ground class for this cycle is given by a *SaveValue* (i.e., a global storage location similar to a *variable* in a conventional programming language) called *CurGClass* whose value is set to one of the three ground classes (1,2,3). The value of *CurGClass* changes every time a transition to

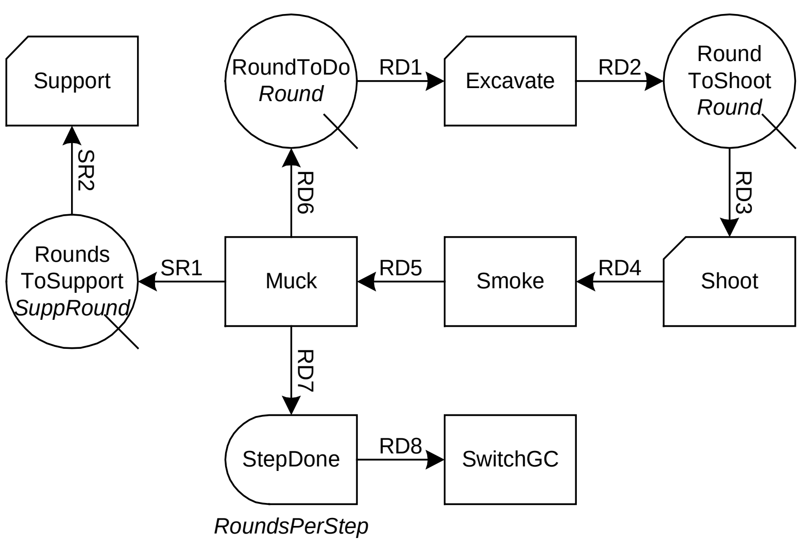

Figure 1 - Stroboscope Network for Tunnel Construction

a new ground class is made, and serves as a "index" to the correct parameters for the excavation advance rate and cost that are used to simulate the associated drill and blast operations. All data shown in Tables 1 - 4 are stored in one- or two-dimensional arrays and are accessed by using *CurGClass* as an array index.

The normal activity *Muck* "generates" (i.e., creates) one characterized resource of type *SupportRound* every time it finishes. This is released through link SR1 to queue *RoundsToSupport*. The discipline for this queue is first-in-first-out. The node *StepDone* is a *Consolidator*. It receives one *Round* every time *Muck* finishes and stores it until a total of 25 *Rounds* are accumulated. When this happens, *StepDone* finishes and passes all 25 Rounds to activity *SwitchGC*, which is then allowed to start. Thus, activity *SwitchGC* occurs only at the end of each 100 m *step*. When *SwitchGC* starts, it determines the next ground class by using Monte Carlo sampling and the transition probability matrix shown in Table 1. The next ground class is stored in SaveValue *NextGClass*. For the NATM, the duration of the *SwitchGC* activity and the associated cost are given by Table 5 depending on the values of *CurGClass* and *NextGClass.* For the Conventional method they are set to zero.

Comparison of Alternatives

Figure 2 shows the simulation results as 8,000 points of the form (Conventional cost, NATM cost). The 4,000 "hollow" points correspond to "independent pairs" and the 4,000 "filled" points to "matched pairs". By design, the two costs in each "independent pair" are independent (i.e., they are based on a different geologic profile) whereas the two costs in each "matched pair"

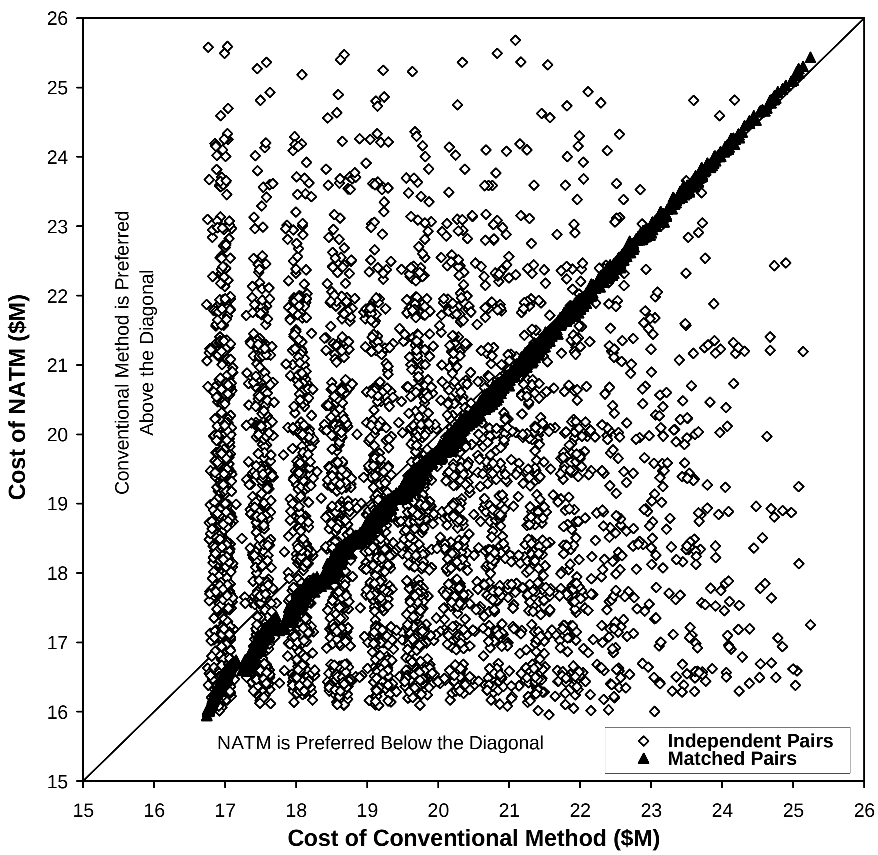

Figure 2 — Cost of Conventional Method vs. cost of NATM (4,000 ind. pairs & 4,000 matched pairs)

are based on the same random numbers and thus on identical geologic profiles. This is the main reason for the striking difference in *scatter.* To allow a fair comparison between the cost results given by independent and matched pairs, the 4,000 geologic profiles for the Conventional Method are the same in both cases (producing a range from $16M to $26M).

If we let ΔC = (Total cost of the NATM) - (Total cost of the Conventional method), then the selection of construction method depends on whether $E[\Delta C]$, the true expected value of ΔC, is positive or negative (the average ΔT is small and will be ignored). Table 6 shows the Cost and Time given by the first 10 as well as the 4,000th replications for each construction alternative. The last four rows give statistics for the entire set of 4,000 runs. The (NATM-Conv.) columns show ΔC for each replication. The two running average columns show how the average of the ΔC values changes as more simulation runs are performed.

Table 6 — Total Cost & Time of Conventional Method vs. NATM Independent and Paired Pairs

	Conv. Method		Independent Pairs					Matched Pairs				
			NATM		NATM - Conv.		Running	NATM		NATM - Conv.		Running
Repl.	Cost $M	Time days	Cost $M	Time days	ΔC $M	ΔT days	AvgΔC $M	Cost $M	Time days	ΔC $M	ΔT days	AvgΔC $M
1	18.480	352	20.072	401	1.592	49	**1.592**	18.049	357	-0.431	5	**-0.431**
2	19.594	370	21.811	434	2.218	64	**1.905**	19.171	377	-0.423	8	**-0.427**
3	17.477	336	18.162	360	0.685	24	**1.498**	16.990	336	-0.487	0	**-0.447**
4	16.890	322	17.848	355	0.958	32	**1.363**	16.309	320	-0.581	-2	**-0.480**
5	19.760	377	17.004	337	-2.757	-39	**0.539**	19.418	384	-0.342	7	**-0.453**
6	16.989	326	16.385	323	-0.605	-3	**0.348**	16.472	326	-0.518	-1	**-0.464**
7	16.952	325	22.553	450	5.601	125	**1.099**	16.389	322	-0.563	-2	**-0.478**
8	18.585	360	16.444	325	-2.140	-35	**0.694**	18.297	366	-0.288	6	**-0.454**
9	19.630	378	18.190	361	-1.439	-18	**0.457**	19.400	387	-0.229	9	**-0.429**
10	17.026	331	16.168	315	-0.857	-16	**0.326**	16.588	330	-0.437	-1	**-0.430**
...	...	...	...	...	...	...	**...**	...	...	...	...	**...**
4,000	18.694	361	18.028	353	-0.666	-8	**-0.291**	18.360	365	-0.335	4	**-0.312**
Aver.	19.337	371	19.047	378	-0.291	6.9		19.025	378	-0.312	6.5	
StDev	1.878	36	2.022	41	**2.762**	55.0		2.037	42	**0.169**	5.9	
Max	25.244	485	25.680	513	8.819	196.6		25.433	510	0.192	25.6	
Min	16.738	312	15.958	307	-8.647	-158.2		15.942	307	-0.797	-5.1	

The ΔC given by independent pairs *vary significantly* from one replication to the next. Moreover, stopping at any $n<=10$ replications using independent pairs gives a *positive* average ΔC, indicating that the Conventional method is the better choice. For the given data, however, this conclusion is wrong. NATM is the better choice because as shown by 4,000 runs the $E[\Delta C]$ is *negative*. The initial independent pairs happen to point to the wrong conclusion because of the *large variability* in ΔC. This variability is mainly caused by the fact that the two costs in each pair can correspond to two different simulated project geologies.

In contrast, matched pairs (where the cost of the Conventional method and the NATM correspond to exactly the same geology) give ΔC values that are much smaller and closer together. Thus, even though the total costs for the two construction methods vary significantly from one matched pair to the next (because the simulated geology changes), the variability in ΔC is now much smaller, indicating that given the same project geology, the costs for the two methods are quite close. Table 6 shows that the use of matched pairs reduces SD[ΔC] by one order of magnitude (from $2.762M to $0.169M) and thus Var[ΔC] by two orders of magnitude.

Figure 4 shows how the 95% confidence intervals for E[ΔC] change as more replications are performed. For independent pairs these intervals are very wide, reflecting the corresponding high SD[ΔC]. Moreover, they are centered over positive values of E[ΔC] (which leads to the wrong conclusion) and include both positive and negative regions for E[ΔC] (indicating ambiguity as to which method is less expensive). In contrast, the intervals for matched pairs are very tight and stable. In fact, the width of the confidence interval given by 4,000 independent pairs can be achieved with as little as 7 matched pairs.

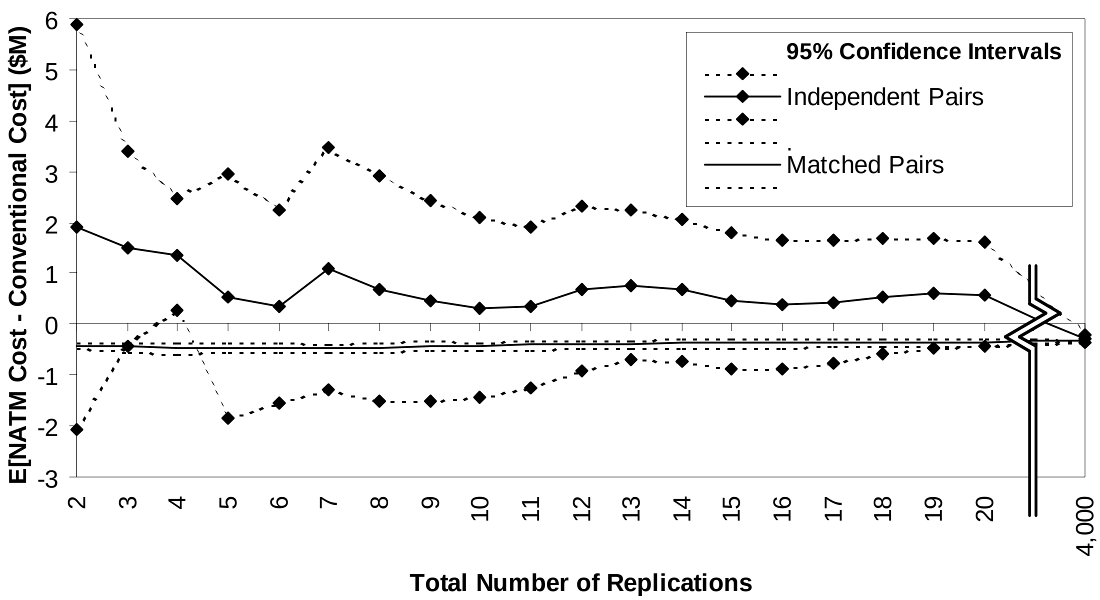

Figure 4 — 95% Confidence Intervals for the Expected Difference in Cost (E[ΔC]) between the NATM and the Conventional Method as a Function of the Number of Replications

In Figure 2 a total of 2,213 independent pairs (or 55%) are below the SW-to-NE diagonal. For matched pairs there are 3,826 such points (or 96%). Thus, matched pairs increase the chance that *a single* ΔC would be negative (and lead to the correct conclusion that E[ΔC]<0, i.e., that NATM is expected to be less expensive) from 55% to 96%. Seen from a different viewpoint, this also means that if NATM is actually used on *this project,* it should be less expensive than the Conventional method for 96% (and not just only 55%) *of the possible geologic profiles* that may be encountered during construction. This is perhaps the most important conclusion that can never be reached via independent pairs, no matter how many replications are performed.

Appendix I - References

Law A.M., and Kelton W.D. (1991), *Simulation Modeling and Analysis*, 2nd Ed., McGraw Hill.

Martinez J.C., Ioannou P.G., and Carr R.I. (1994), "State- and Resource-Based Construction Process Simulation", *Proceedings, ASCE First Congress on Computing in Civil Engineering*, Washington, DC, June 20-22, 1994.

Martinez J.C., Ioannou P.G. (1994), "General Purpose Simulation with Stroboscope", *Proceedings, 1994 Winter Simulation Conference*, Orlando, FL, Dec 11-14, 1994.