The Clyde Dam in New Zealand is located in an area more unstable than was thought when it was designed. Therefore, Electricorp has taken additional precautions to ensure the stability of the hillsides surrounding it, constructing an underground grout curtain of 1,362 meters along the Clutha River. A grout curtain is constructed by drilling holes in the rock and injecting concrete into them. With a budget of millions of dollars for hiring drilling rigs, the construction company wanted to minimize the idling time of the drilling rigs and finish the project quickly. We developed a simulation model that enabled it to find an efficient drilling schedule, saving about NZ$580,000 on hiring costs for drilling rigs (seven percent of drilling hours hired) and 10 weeks (about 26 percent of project completion time).

The Clyde Dam took more than 10 years to build. It is the largest concrete gravity dam in New Zealand [Clyde Power Station 1989] and was constructed in the Cromwell gorge near the town of Clyde in the South Island by the Electricity Corporation (Electricorp) of New Zealand Limited. The dam and the power house (which is capable of producing 432 megawatts) were completed in 1989, but filling Lake Dunstan (the reservoir of the Clyde dam) was deferred while extensive stability work was carried out on the landslip areas on one side of the reservoir.

Clyde Dam is built with a "slip joint" to accommodate any earthquake movement.
Geological evidence has shown that most of the landslide areas (marked as "LANDSLIDE" in Figure 1) have been creeping slowly into the base from one side of the gorge at speeds ranging from a few millimeters to a few centimeters a year [Cromwell Gorge Landslides 1989]. Landslides are associated with the processes that formed the Cromwell gorge. Over hundreds of thousands of years, the Clutha river has eroded into the rocks and the schist rock has been faulted and folded. As a result, many seams of clay within the rock and cracks called joints have developed, making the hillsides surrounding the gorge very unstable. Water in the landslide area (Figure 1) is usually an important feature of landslides. It can either soften dry clay materials and cause a loss in strength (by reducing frictional resistance along sliding surfaces) or it can pond behind clay layers or cracks and push the landslide downhill.

Electricorp was very concerned about this because, when Lake Dunstan (the reservoir) was filled, the water could leak into the landslide area through the cracks and make it more unstable. This would eventually cause large masses of rock in the landslide area to slide downslope, developing high pressure on the water, which could damage the Clyde Dam.

To reduce the water level in the landslide area, Electricorp took two preventive measures. One was to construct drainage tunnels (marked as drilling stub in Figure 1) and then drill holes connected with the tunnels into the landslide to drain water from it. A second was to construct an underground concrete blanket (grout curtain).

Figure 1: Water, the main cause of landslide in the Cromwell gorge, is drained out from the landslide areas by drilling holes connected to the tunnels (drilling stub). To prevent water leaking into the landslide from the lake, the company constructed an underground grout curtain on one side of the gorge. It placed fill material (buttressing) at the toe of the landslide area to increase frictional resistance to stabilize landslides [Cromwell Gorge Landslides 1989].
along one side of the gorge to prevent water leaking into landslide areas from the reservoir.

The grout curtain project was undertaken by a foreign company. It invited us to study the construction process and propose a schedule to expedite the process and minimize the idling time of the most expensive resource (the drilling rigs). Constructing the grout curtain involved a number of interrelated activities and a number of constraints, creating a complex problem.

**Construction of the Grout Curtain**

When we first met the project manager, the company had already completed a small portion of the grout curtain. We grasped the complexity of the problem of scheduling the project in looking at the numerous charts hanging in his room that showed the activities in progress on each day of the project. This was the first project of this nature the company had undertaken, and the project manager mentioned that any solution we proposed was going to be of great value not only for this project but also for future projects. From the few holes already drilled, the company had found that drilling rigs were often idle while it pursued interrelated activities. Since it had hired the drilling rigs from an outside company at a cost of NZ$227 per hour, this idling time was a major concern. The company also realized that idling the drilling rigs would delay project completion.

To construct the grout curtain, the company performed the following five activities in sequence:
—Drilling the holes,
—Washing out the holes,
—Performing a water test,
—Grouting the holes, and
—Allowing the grout to set.

**Drilling**

The company drilled a row of underground holes along a 1,362 meter stretch of rock (Figure 1) along the bank of Lake Dunstan. To form an efficient grout curtain, it had to drill the holes in a special sequence. It drilled five different types of holes identified according to their depth as primary (P), secondary (S), tertiary (T), quaternary (Q), and quinary (U) (Figure 2).

Primary holes were drilled six meters apart and secondary holes bisected the distance between two consecutive primary holes and so on. In the 1,362 meter stretch, the company had to drill 228 primary holes, 227 secondary holes, 454 tertiary holes, 908 quaternary holes, and 1,816 quinary holes.

Shaded and unshaded blocks in each column of Figure 2 show the number of stages. For example, a primary hole (P₁ or P₂) was 100 meters deep and took nine drilling stages, whereas a quinary hole was nine meters deep and was drilled in only two stages.

Once it completed one stage of drilling for a particular hole, the construction company performed the rest of the activities (washout, water test, grouting, and grout set) before starting the next stage of drilling.

To form the grout curtain efficiently, the company had to drill the holes between two consecutive primary holes in a particular sequence. For this purpose, the holes were ranked from Primary (rank 1) to Quinary (rank 5) with rank 1 considered highest. The company drilled in such a way that the holes with a higher rank were
Figure 2: Primary (P) holes are drilled six meters apart. Secondary (S) holes are drilled in the middle of two primary holes. Tertiary (T) holes are in between primary and secondary holes. Quaternary (Q) holes are drilled between primary and tertiary and tertiary and secondary holes. Quinary (U) holes are drilled between primary and quaternary, quaternary and tertiary, tertiary and quaternary, and quaternary and secondary holes. The horizontal shaded and unshaded strips represent different stages of the holes and the numbers appearing in each block represent the drilling sequence.

always exactly one stage ahead of holes with the next lower rank (Figure 2). The numbers in Figure 2 indicate the drilling sequence of stages of the holes between the first two primary holes. Stages of different holes with the pause number are drilled concurrently. For example, the company drilled stage 1 of the two primary holes P₁ and P₂ concurrently. Then it performed the rest of the activities (washout, water test, grouting, and set grout) on these stages before starting to drill the next stage of the same hole. Once it completed stage 1 of P₁ and P₂, it started drilling concurrently on stage 2 of P₁ and P₂ (indicated by 2). Once it completed this, it began work on stage 1 of the secondary hole S₁ (indicated by 3) and so on.

The company followed the same drilling sequence and pattern of holes for the rest of the holes in the 1,362 meter stretch. It had 12 drilling rigs with the same capacity (32 linear meters per eight-hour rig shift) available 24 hours per day. The drilling rate of each stage varied (on average) according to the rock conditions at different
depths. The average drilling times for states 1, 2, 3, . . . , 9 are 24, 37, 120, 225, 300, 300, 450, 900, and 480 minutes respectively.

**Wash Out**

Once the drilling of a stage was over, the construction crew washed out the hole by pumping water in and out to remove any sediments or deposits, leaving the hole empty and dry. This activity took an average of 15 minutes per stage.

**Water Test**

Once the crew had washed out the hole, it carried out a water test on the empty hole by pumping water into it and measuring the amount of water it absorbed. Water permeability (PM) is measured using the formula:

\[ PM = \frac{L \times P}{M \times D} \]

where
- \( L \) = liters of water pumped,
- \( P \) = pressure,
- \( M \) = number of minutes water is pumped, and
- \( D \) = depth of the hole.

This test gave the company an idea of the absorption power of the rock, which was useful in the next stage of the process. On average, this task took about 30 minutes for each stage.

**Grouting**

Having finished the water test, the crew used eight grouting machines to inject a mixture of cement and water into the holes under pressure so that the cement mixture entered the cracks of the rock and formed a concrete blanket (grout curtain). This process is called grouting. The eight grouting machines were fixed on the ground.

Each machine had 16 pumps, so they could simultaneously grout 128 (16 × 8) holes. The maximum length of the hoses was 57 meters. Once a grouting machine was fixed at one location, it could service all the holes within a distance of 114 meters (between 20 primary holes). It took 12 hours to move a grouting machine to a new location. We found that grouting times for the different stages were random quantities. From the grouting times observed for each of the nine stages, we found that they followed distributions that are skewed to the right with means of 59.52, 86.76, 99.32, 216.13, 100.34, 102.14, 135, 135 and 135 minutes, respectively (Figure 3).

We used these frequency distributions in the simulation model to simulate the grouting times for the different stages. To form an effective concrete blanket, the company had to wait 16 hours after grouting one stage of a hole before grouting the next stage of that hole.

**Drill Out, Set Grout**

After grouting a stage of a particular hole, the company had to leave it to set for at least six hours before drilling the next stage of that hole.

Sometimes the holes collapsed during drilling because the rock was unstable. There was a special way of handling this situation. If, for example, a hole collapsed after the crew drilled one meter of the four meters of stage one, it would stop drilling and carry out the next four activities (wash out, water test, grouting, and set grout). Then it would continue drilling the remaining three meters of stage one. Every time a collapse occurred, the crew repeated this process.
Even in dealing with collapses, the crew had to maintain the grout-to-grout delay. From the data available for the holes drilled early in the project, we estimated the probabilities of a collapse in primary, secondary, tertiary, quaternary, and quinary holes to be 0.184, 0.107, 0.059, 0.023 and 0.024 respectively.

**Original Plan of Drilling**

When we first talked to the project manager, we realized how keen he was to find some efficient way of doing the drilling. From the few holes the company had already completed, it was clear that the drilling rigs were idle for long periods of time and that completion of the project would be delayed. The company originally planned to divide the 1,362 meters into six arbitrary zones, G-H, H-C10, C10-C8, C8-C5, C5-E, and E-P consisting of 30, 39, 44, 54, 32, and 29 primary holes respectively. It planned to complete these zones one at a time, handing each over before proceeding to the next. According to the project manager, this would be convenient and financially advantageous.

Our task was to find a reasonable block size for zoning that would reduce both the idling time of the drilling rigs (an expensive resource) and the time it took to
complete the project.

**An Overview of the Simulation Model**

Because the drilling process was so complicated, we developed a simulation model to find an efficient drilling strategy (Figure 4). OR practitioners often use simulation [Groebner 1991; Turban 1988] to study complicated real-world systems. Various languages [Banks et al. 1991; Gravel and Price 1991] have been developed specifically for simulation, but we used the high-level language FORTRAN 77 with which the employees of the company were familiar and which they were able to modify if necessary for similar applications in the future.

The simulation program consisted of 1,000 lines, including comment lines. The user can input the following parameter values: the number of drilling rigs; the number of grouting machines; the length of stretch to be grouted; the distance between hole types; the number of stages and their depths for each hole type; the distributions of grouting times per stage; the probabilities of collapse for each hole type; the drilling times for each stage; the wash-out, water-test and set-grout times; the block size; and the moving time for the grouting machines. A block is all the holes between and including a certain number of primary holes, and its size is given as the number of primary holes it contains. For example, a block of size 10 contains 10 primary holes and all the holes between them (10 primary, 9 secondary, 18 tertiary, 36 quaternary, and 72 quinary holes).

The number of steps in the drilling sequence is the sum of the number of stages for primary holes and secondary holes. In our case, the primary holes had nine stages and the secondary holes had seven stages, which meant the drilling sequence had 16 steps (Figure 2). At each step of the drilling sequence, the program decides what type of hole the company should drill and the stage to drill. It also decides what other type of holes it should drill concurrently and the corresponding stages to drill. For example, if it is to drill the fourth stage of a primary hole (step 6), it can drill the first stage of a tertiary hole concurrently. Once the program has decided this, it can calculate the number of holes of each type to drill.

The next step in the program is to simulate the grouting times for each hole at each stage and to decide whether collapses have occurred. If collapses have occurred, the program determines the delay in the project completion time. The time for the completion of this step is calculated over the block, along with the idling and occupied times for the drilling machines.

The process continues until the program completes all 16 steps in the drilling sequence. Finally, it determines the total project completion time and the total idling and occupied times of drilling rigs.

In our particular case, we assumed that the drilling times for each stage (1, 2, \ldots, 9) were fixed (at average values of 24, 37.5, 120, 225, 300, 300, 450, 900, and 480 minutes, respectively). We assumed the grouting times for each stage to be random, and we resampled the observed distribution to simulate these random variables. The probabilities of a collapse in a primary, secondary, tertiary, quaternary, and quinary hole were assumed to be 0.184, 0.107, 0.059, 0.023 and 0.024, respectively. For example, we simulated a
MODULE 1: Input Parameter Values
Number of drilling rigs; number of grouting machines; length of stretch to be grouted; distances between hole types; number of stages per hole type and their respective depths; distributions of grouting times; probabilities of collapse for each hole type; drilling times for each stage; wash out, water test and grout set times; block size; moving time of grouting machines.

MODULE 2: Initial decisions
Decide on the type of hole (either primary or secondary) and the stage to be drilled. Decide other type of holes that could be drilled concurrently and the stages to be drilled. Calculate the number of holes of a given type to be drilled. Also a decision is made as to whether no collapse, one collapse or two collapses occurred at the given stage.

MODULE 3: Sampling
Sampling of the grouting times is performed for each one of the stages.

MODULE 4: Main Module
Performs the simulation and computes the project completion time per stage and the idling time and occupied time for the drilling rigs.

OUTPUT INFORMATION:
1. Total project completion time; 2. Total idling time of drilling rigs; 3. Total occupied time of drilling rigs.

Figure 4: The simulation model consists of four modules: (1) receives the information about grouting times and other system parameter values; (2) computes the total number of holes of each type to be drilled and finds out whether there are collapses in the particular stage or not; (3) samples the grouting time for each stage using the frequency distributions and; (4) performs the simulation and presents the output information.
collapse in a primary hole by generating a random number between 0 and 1. If the number was less than or equal to 0.184, we assumed a collapse had occurred; otherwise not. We simulated two collapses in a similar manner with, for example, the conditional probability of a second collapse, given that a collapse had already occurred, being 0.184 for a primary hole.

**Verification and Validation of the Simulation Model**

The project manager, Peter Wagner, and his staff were constantly in touch with us to verify the input information and the logic of the simulation model to ensure that our model accurately reflected reality.

The nature of the model and the problem it examines makes validation difficult, but we received no negative comments from the project team after they had studied the model and its output.

We simulated the system on an NEC 386SX (16MHZ). To get an idea of how the idling time of drilling rigs and the project completion time vary with the block size, we simulated the system for every possible block size (two to 228) for each of the following cases: (a) fixed grouting and drilling.

![Graph](image)

**Figure 5:** The project completion time in hours varies for the possible block sizes, from 20 up to 228. The graph represents the project completion times when grouting time is random and two collapses are allowed for. Big drops in the graph occur at block sizes 27, 30, 34, 39, 47, 58, 77, 115, and 228. The magnitudes of these drops are 245, 487, 341, 339, 329, 414, 289, 353, and 262 hours respectively. We observed similar patterns in three other cases: fixed grouting and drilling times; random grouting times; and random grouting times and the probability of a collapse.
times; (b) random grouting times; (c) random grouting times and the probability of a collapse; and (d) random grouting time and a possibility of two collapses. For each block size, we used 1,000 trials to calculate the average project completion time and average idling time of drilling rigs (Figures 5 and 6).

Table 1 shows estimates of a 95 percent confidence interval of the average hours to project completion for some selected block sizes. By looking at the standard errors of the mean, we can see that 1,000 trials per simulation run give adequate accuracy for estimating the means.

The bigger the block is, the faster the completion time and the lower the rigs’ idling time (Figures 5 and 6). Project completion times drop dramatically as block sizes increase, with block sizes 27, 30, 34, 39, 47, 58, 77, 115, and 228 offering the greatest improvements. In between these points, project completion time increases slightly; for block sizes larger than 115, this increment is very small (approximately 10 hours when the block size is increased by 24 from 115).

This slight increase in the project completion time between points is caused by the smaller size of the remaining block. For example, if there are 228 primary holes and if the block size is 30, the remaining

Figure 6: The percentage idling time of drilling rigs for all the possible block sizes decreases dramatically as block sizes increase.
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Table 1: Estimates, standard errors, 95 percent confidence limits, and 95 percent confidence interval width for the average project completion time in hours, for selected block sizes.

block size was 18 (= 228 – (30 × 7)). This smaller block slightly reduces the gain in project completion time obtained by using a larger block size.

**Conclusion**

Based on the simulation results, we advised the project team that the small arbitrary block sizes planned originally would slow the project completion time and cause the idling time of the drilling rigs to be unnecessarily high. When the members of the project team decided on the original plan, they were unaware (in quantitative terms) of the extent to which block size affects the project completion time.

The company could minimize project completion time by working on a single block whose size was equal to the total number of primary holes (in this case 228) in the stretch. If the project must be finished in sections, the company should choose a block from one of the sizes (27, 30, 34, 39, 47, 58, 77, and 115) that correspond to big drops in project completion time. In this case, management has to trade off between block size and project completion time.

After considering the simulation results,
we proposed a block size of 115 primary holes for the following reasons:
(1) The project team objected to a single block of size 228 for two reasons: handling the project would be inconvenient, and being paid for each completed section before moving on to the next eased the company’s financial burden.
(2) Since a block of size 228 was not feasible, the next best option was to proceed in blocks of size 115. In this case, the project completion time would be about 262 hours (about two working weeks) greater than for the block of size 228. The next best solution with an even smaller block size was to use a block size of 77, for which the project completion time would be about 615 hours (five working weeks) greater than the optimum.

Taking into consideration the advantages and constraints discussed above, the team agreed on a block size of 115, foregoing a saving of two weeks in project completion time.

Numerical results from the simulation showed that the estimated project completion time with this block size would be 27 weeks, a 26-percent reduction in project completion time compared to the original plan of drilling in zones. The total drilling hours to be hired would be 34,011, about a seven percent reduction compared to the original plan. This would save an estimated NZ$580,000 computed at the rate of NZ$227 per drilling hour. The proposed drilling criteria also reduced the idling time of drilling rigs by 692 hours.

Acknowledgments
We thank Peter Wagner (project manager), Norm Howell (construction manager), Geoff Batley (principal quantity sur-
veyor), and their team for the cooperation they extended to us right throughout the project. Peter Wagner provided us with the expertise to build the simulation model; Norm Howell helped by giving us information about the various tests carried out and the geological aspects of the project. We also thank Peter Openshaw, the chairman of the company, for his support and for permitting us to publish this article. Our thanks also go to Frederic H. Murphy, Michael H. Rothkopf, and the referees for their valuable comments.

References

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Mr. Peter Openshaw, Bachy Company, 11 Knight Street, Lansvale, 2166 New South Wales, Australia, writes “This is to inform you that the Department of Finance and Quantitative Analysis at the University of Otago carried out a study on scheduling of drilling rigs at Clyde Dam at our request. The results of the analysis were of assistance in programming the works. They will be also of assistance on future grouting projects.”

March–April 1996 91