

CONSTRUCTION OF A DAM EMBANKMENT WITH NONSTATIONARY QUEUES

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ABSTRACT

This paper presents the simulation model for a project involving the haulage and placement of rip-rap for the construction of a dam to illustrate how traffic-related queues are created at locations determined dynamically at simulation runtime. This example also investigates the formation of moving queues of equipment that cannot pass each and travel together like a procession or a convoy. The solution to this problem is outlined conceptually using the activity-scanning modeling paradigm and is described in detail using a simulation model developed in STROBOSCOPE.

1 INTRODUCTION

Applications of simulation modeling to civil engineering construction and in particular to earthmoving often focus on the interaction between dissimilar equipment, such as loaders and haulers or pushers and scrapers. A typical objective may be to model the resource-matching complications introduced by having similar equipment of various sizes and capacities, such as large and small loaders and/or large and small haulers. Typically, hauling and returning to load are modeled as simple activities where the main difficulty is to estimate accurately the distribution of the corresponding travel times.

There are cases, however, where the complexities in an earthmoving project are due to interactions that occur while the equipment are moving in traffic. These phenomena are similar to those in transportation where vehicles traveling on highways often form moving queues. Neither the location of these queues nor the times at which they form are predetermined. In such cases, simulation can be used as a powerful tool to investigate traffic interactions and to evaluate haul and return strategies.

This paper presents an example of this type of problem that involves the placement of rip-rap for the

construction of the embankment for a dam. The primary difficulty in this project is due to the interaction between loaded and empty haulers that travel in a one-way road at the top of the embankment without the ability to overtake each other. Fast haulers must tailgate those in front that are slower (forming moving queues) and queues of stopped haulers occur whenever a hauler stops to dump and blocks the haulers behind it.

A simulation model for this problem is presented using the notation of STROBOSCOPE (an acronym for STate and ResORce Based Simulation of CONstruction ProcEsses). STROBOSCOPE is a simulation language and system designed specifically for modeling construction operations based on three-phase activity scanning and activity cycle diagrams. The STROBOSCOPE language is described in (Martinez 1996). Example applications can be found in (Ioannou & Martinez 1996a, 1996b, 1996c) and (Martinez & Ioannou 1994, 1995, 1999).

2 DAM EMBANKMENT PROJECT

An earth-moving contractor is about to bid on a segment of a project for the construction of a dam that involves the haulage and placement of rip-rap on the embankment opposite the generator outfall. The embankment extends for almost two miles (10,000 ft.) and is within one mile of the material borrow pit. A total quantity of one million bank cubic yards (BCY) is to be taken from this pit and placed along the embankment. Figure 1 presents a diagram of the project site layout.

As shown in the figure, the haul road along the top of the embankment is only wide enough for one truck. When a truck is stopped for dumping, no other truck can pass that position due to the narrow roadway. The proximity to the adjacent residential area precludes a widening of this portion of the road. Noise restrictions in the residential area impose a speed limit of 25 mph for haulers and a maximum of 10 operating hours per day.

The conditions set forth in the construction contract specify that the rip-rap be spread uniformly and that no one embankment area should receive appreciably more

or less material at any one time. Moreover, the work must be done in 1,000 operating hours (100 days), which in turn requires a production rate of 1,000 BCY/hr.

Two construction alternatives are being considered:

1. Build a new return road out in the water beyond the edge of the embankment.
2. Use an existing road that takes trucks over a longer route on the other side of the water channel.

Equipment that the contractor plans to use include:

- Caterpillar 992B wheeled front-end loaders, and
- Caterpillar 772 tractors with 100-ton trailers (converted from bottom-dump to side-dump).

To achieve the required production the contractor must use two front-end loaders whose location within the loading area is indicated in Figure 1. The required number of haulers (tractor-trailers) as well as the preferred construction alternative are to be determined.

Information about the performance of the front-end loaders appears in Table 1. Similar information about the haulers is shown in Table 2. The rip-rap material properties are shown in Table 3. Table 4 shows project-wide cost data. In these tables, the units LCY, loose cubic yards, refer to the volume of material that has been broken up. BCY, bank cubic yards, refer to the volume of material in its original undisturbed or unbroken state.

Table 1: Loader Data

Model: Caterpillar 992B Wheeled Front-end Loader	
Load per Cycle	
Bucket Size, BS, (CY)	10
Bucket Fill Factor, BFF (poorly blasted with slabs/blocks)	65%
Load per Bucket, BS*BFF, (LCY)	6.5
Loading Cycle Time	
Basic cycle time (minutes)	0.40
Adjustments (minutes)	
Materials (bank or broken)	+ 0.04
Common ownership of trucks and loaders	- 0.04
Constant operation	- 0.04
Mean loading cycle time (minutes)	0.36
(Actual loading cycle time varies uniformly \pm 12% from mean value)	
Breakdown Data (no major breakdowns)	
Minor Breakdown (minutes)	20 \pm 15
Every (minutes)	210 \pm 100
Cost Data	
Ownership hourly cost, (\$/hr)	140
Ownership hourly cost, (\$/hr)	160

Table 2: Hauler Data

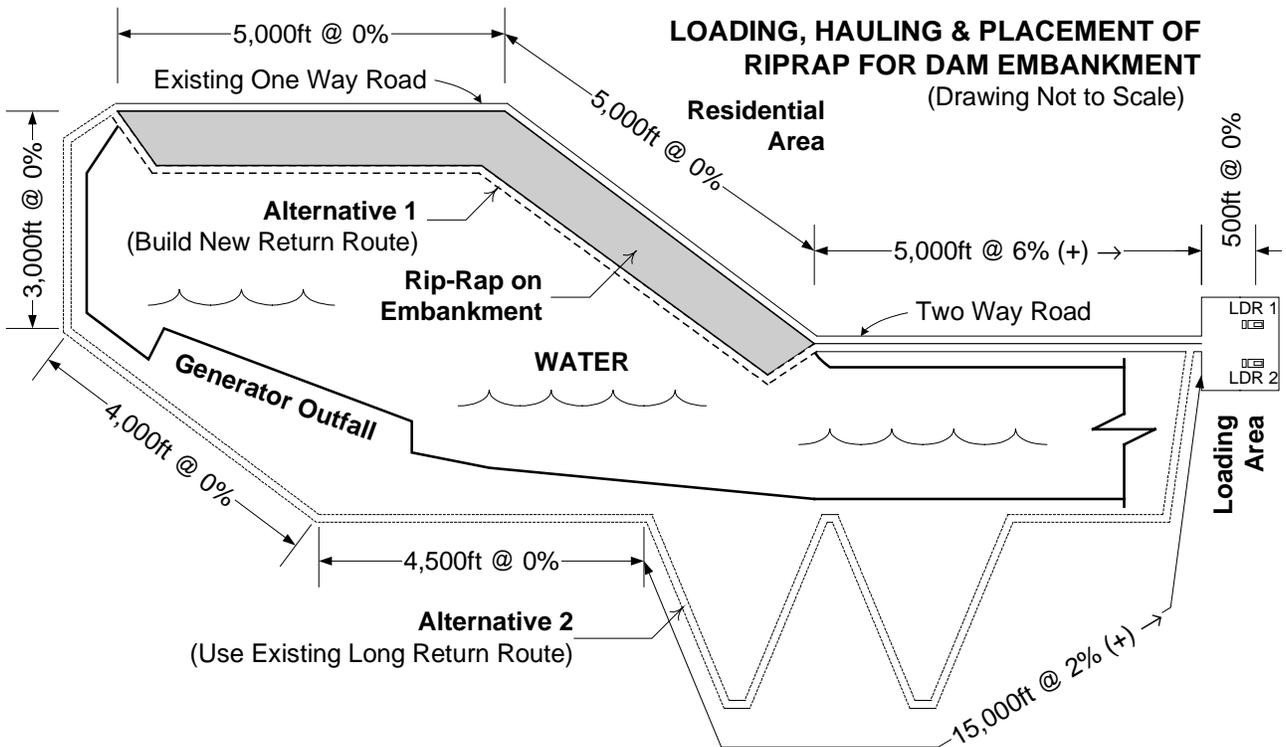


Figure 1: Project Layout for Placement of Rip-rap on Dam Embankment

Model: Caterpillar 772 tractor and trailer	
Size	
Payload (lbs)	200,000
Length (tractor / total)	21' 6" / 65' 7"
Width (tractor / total)	13' 4" / 15' 0"
Loading height	12' 4"
Times (seconds)	
Dump time	50 ± 10
Spot time at loader	20
Pull-out time at loader	10
Acceleration	
Loaded (0% grade): 0-25 mph	50
Empty (0% grade): 0-25 mph	35
Deceleration	
Loaded (0% grade): 25-0 mph	40
Loaded (-6% grade): 25-0 mph	56
Miscellaneous	
Travel time does not vary	
Haul road surface - very hard, smooth, watered (0" tire penetration)	
No altitude correction needed	
No breakdowns	
Cost Data	
Ownership hourly cost, (\$/hr)	50
Ownership hourly cost, (\$/hr)	116

Table 3: Material (Rip-Rap) Data

Large, broken pieces of granite (poorly blasted)	
Unit weight	
Broken, LCY, (lbs per LCY)	2,800
Unbroken, BCY, (lbs per BCY)	4,600
Load Factor (lbs per LCY / lbs per BCY)	61%
Amount of material to load and haul	
Unbroken, BCY	1,000,000
Broken, LCY	1,639,344
Material per trailer load	
LCY: (200,00 lbs) / (2,800 lbs/LCY)	71.43
BCY: (200,00 lbs) / (4,600 lbs/BCY)	43.48

Table 4: Cost Data

Miscellaneous Costs (\$ per 10-hr operating day)	
General & administrative overhead	20,000
Liquidated damages (project T > 100 days)	20,000
Cost of new road for Alternative 1 (\$)	500,000

2.1 Load Time Calculations

The time to load a hauler depends on its size relative to the loader. As shown in Table 1, each scoop of material is 6.5 LCY. Since each hauler can carry 71.43 LCY, it takes 11 scoops to fill a hauler in $11 * 0.36 = 3.96$ min. Adding 0.5 min for the spot and pull-out times gives a mean time of 4.46 min for a hauler to load.

2.2 Number of Dumping Sites

Project specifications require that rip-rap be placed uniformly without any areas receiving appreciably more material than others. An efficient way to achieve this is to start at the west end of the embankment and have each subsequent hauler dump its load immediately behind its predecessor. When the entire embankment receives one load from west to east, the process is repeated again. The advantage to this approach is that loaded haulers can travel to their destination without having to wait for the ones in front to finish dumping. The only time loaded haulers may have to stop is when a hauler dumps at the east end of the embankment at the end of the cycle.

The distances that haulers must travel can be modeled conveniently by dividing the length of the embankment into equal dumping sites, each the length a hauler. Given that the embankment is 10,000' long and the length of a tractor-trailer is 65' 7" we need 152 dumping sites.

A total of 1,000,000 BCY of rip-rap needs to be placed, or 6,579 BCY per site. Since each hauler carries 43.48 BCY, each dumping site must receive 151 hauler-loads. The entire project requires 23,000 hauler-loads.

2.3 Dynamic Queuing Behavior

A schematic showing the haul and return times for this project appears in Figure 2. The innermost loop shows the route that haulers must follow from the loading area (on the right) to the embankment (on the left) and back. The embankment (rip-rap area) is divided into 152 dumping sites numbered from 0 to 151.

The point labeled BOW (Begin One Way) at the right edge of site 151 indicates that the haul road at the top of the embankment is narrow and can accommodate traffic in only one direction. For the same reason, no hauler can overtake another, irrespective of whether the hauler in front is moving or has stopped to dump (or because it is waiting for a hauler in front to finish dumping).

The dumping sequence from site 0 to site 151 and back again safeguards loaded haulers from having to stop and wait prior to reaching their destination. The only exception occurs when the hauler going to site 0 reaches BOW while the previous hauler is still dumping

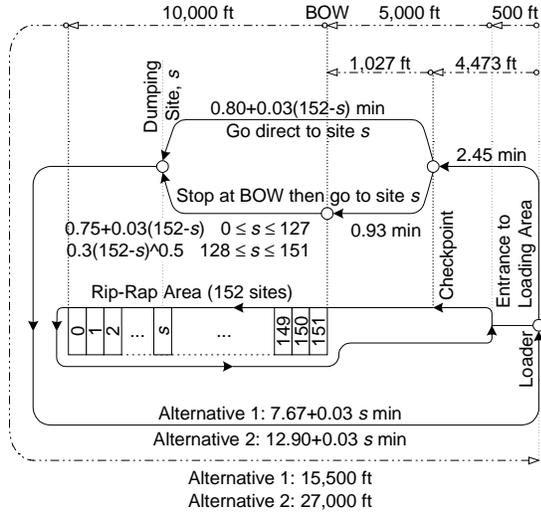


Figure 2: Hauler Travel Times and Distances

at site 151. In this case, it is possible to have a queue of loaded haulers form at the entrance to the embankment.

Even though it is not possible to have a queue of stopped loaded haulers within the embankment, it is possible to have a queue of stopped empty haulers. This occurs when the hauler in front takes too long to dump and blocks the finished haulers behind it. The formation of this type of queue is dynamic both in time and space and can occur anywhere along the embankment.

When haulers cannot pass each other they tend to form bunches (or moving queues) that travel together like a train with the slowest hauler leading the group. When such a train reaches the leader's dumping site, all haulers are positioned at their respective sites and can start dumping at the same time. Thus, all haulers may finish dumping close to the same time and this in turn creates the ideal conditions for the formation of queues of stopped empty haulers as described above.

2.4 Haul and Return Travel Times

The calculated haul and return travel times are shown in Figure 2 using a cyclic activity-on-arrow network. This network forms the middle loop in the figure and has event nodes drawn as circles. As explained above, the inner loop in this figure shows the route followed by the haulers, while the directed arrows in the outer loop indicate the distances in feet that the haulers must travel.

Of particular significance in this figure is the location labeled *Checkpoint*. As loaded haulers leave the loading area, they accelerate to 25 mph and continue for 2.45 minutes until they reach this point. There the driver must decide whether to continue at 25 mph and proceed to the dumping site, or brake and stop at the beginning of one-way (BOW) at the entrance to the embankment. These

two choices are shown in Figure 2 as “Go direct to site *s*” and “Stop at BOW, then go to site *s*”. The location of the checkpoint is 1,027 ft before BOW which equals the braking distance traversed by a hauler during the 56 seconds (0.93 minutes) it takes to decelerate and stop from 25 mph at -6% grade.

The time in minutes for a hauler that continues past the checkpoint (without stopping at BOW) to reach its destination (dumping site *s*) is $0.80+0.03(152-s)$. The time for a hauler that stops at BOW to reach its destination depends on whether dumping site *s* is far enough for the hauler to accelerate to a full 25 mph before it must decelerate to stop and dump. If there is enough distance from BOW to site *s* for the hauler to reach 25 mph (i.e., $0 \leq s \leq 127$) then travel time equals $0.75+0.03(152-s)$. If site *s* is too close to BOW (i.e., $128 \leq s \leq 151$), the hauler accelerates and immediately decelerates without reaching a steady cruising speed and its travel time is $0.3(152-s)^{0.5}$.

The time to return back to the loading area depends on the location of dumping site *s* and the construction alternative being modeled. For alternative 1 this time is $7.67+0.03s$, and for alternative 2 it is $12.90+0.03s$.

3 SIMULATION MODEL

The activity-based network for the simulation model for this problem is shown in Figure 3. At the start of simulation the two front-end loaders are located in queue *LoaderQ* and all haulers are in queue *HaulerQ*. Activity *Load* is a combi (i.e., conditional) activity that can start whenever *LoaderQ* and *HaulerQ* are not empty. When *Load* starts it removes a loader from *LoaderQ* and a hauler from *HaulerQ*. When it finishes it returns the loader to *LoaderQ* and releases the loaded hauler to the normal (i.e., bound) activity *Haul2CheckPoint*.

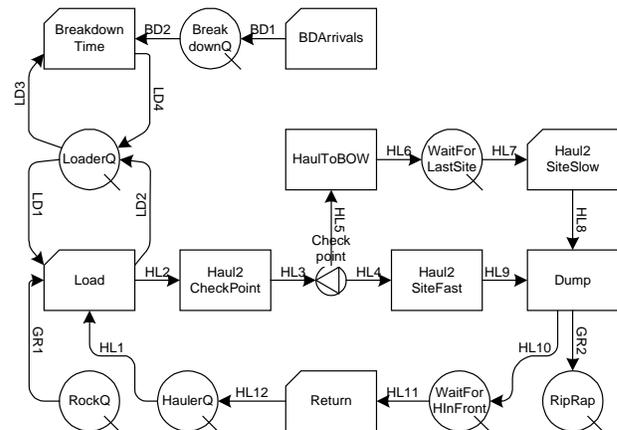


Figure 3: STROBOSCOPE Simulation Model Network

At the end of this activity the hauler proceeds to fork *Checkpoint* where a dynamic decision is made whether to continue through link *HL4* or *HL5*. Link *HL4* routes the hauler to the normal activity *Haul2SiteFast* that models traveling to the appropriate dumping site without stopping at BOW. Link *HL5* routes the hauler to the normal activity *HaulToBOW* that represents the time it takes the hauler to come to a full stop at BOW. At this point, the hauler enters queue *WaitForLastSite* where it waits until the last site (i.e., site 151) becomes free. When this occurs, combi activity *Haul2SiteSlow* can start. At the end of *Haul2SiteSlow* or *Haul2SiteFast* the hauler reaches its destination site and continues with activity *Dump*. It then enters queue *WaitForHInFront* where it waits until the site in front of it is free and combi activity *Return* can start. At the end of *Return* the hauler returns to *HaulerQ* and completes its cycle.

Combi activity *BDArrivals* represents the interarrival time between loader breakdowns. At any given point in time there is exactly one instance of this activity going on. When *BDArrivals* finishes, it generates and places a breakdown resource in queue *BreakDownQ* to allow activity *BreakdownTime* to start and capture a loader from *LoaderQ*. The captured loader is not available for starting a *Load* activity until *BreakdownTime* finishes and the loader is returned to *LoaderQ* where it becomes available for loading haulers again.

3.1 STROBOSCOPE Simulation Code

This section describes the statements for a complete model implemented in STROBOSCOPE to illustrate how the dynamics of this problem may be modeled in an activity scanning simulation system.

First we define some parameters and global storage locations that are useful for sensitivity analysis:

```
VARIABLE    nLoaders    2; / # of loaders
VARIABLE    nHaulers   10; / # of haulers
VARIABLE    nSites     152; /dumping sites
SAVEVALUE   NextSite   0; /site to go to
SAVEVALUE   SiteNBusy  0; /site 151 busy?
ARRAY       SiteETA    nSites;
```

Savevalues are storage locations that behave like variables in conventional programming languages. Here, *NextSite* stores the number of the site (0-151) to which the *next* loaded hauler will be assigned. *SiteNBusy* is a (0/1) flag indicating whether the dumping site at the entrance to the embankment is busy. *SiteETA* is an array with elements numbered from 0 to 151 that hold the arrival time of the last hauler to be assigned to the corresponding dumping site.

The following types of resources are defined:

```
GENTYPE     Loader; / Front-end loader
GENTYPE     Granite; / Rock for rip-rap
GENTYPE     Breakdown; / loader breakdown
CHARTYPE    Hauler      Payload;
SUBTYPE     Hauler      C772    200000; /lbs
SAVEPROPS   Hauler      Site     LoadNo;
```

The first three resources are defined as *generic resources* because they do not need to be associated with any static or dynamic properties. Type *Hauler* defines a characterized resource type that has the property *Payload*. The only subtype of *Hauler* that needs to be defined is *C772* with a payload of 200,000 lbs. Each resource of type *Hauler* has two saveprops (storage locations) called *Site* and *LoadNo*. *Site* stores the number of the site (0-151) to which the hauler must travel and dump. *LoadNo* is the serial number of the load carried by the hauler (1, 2, ...).

```
DRAWAMT     GR1 43.48; /BCY
DURATION    Load Uniform[3.9,5]; /minutes
```

Every time activity *Load* starts it removes 43.48 BCY of *Granite* from *RockQ*. Its duration is distributed uniformly from 3.9 to 5 minutes, (i.e., mean = 4.46 min).

```
ONRELEASE   HL2 ASSIGN LoadNo
              Load.TotInst-Load.CurInst;
ONRELEASE   HL2 ASSIGN Site NextSite;
ONRELEASE   HL2 ASSIGN NextSite
              Mod[NextSite+1,nSites];
```

The above three actions take place when activity *Load* releases a *Hauler* through link *HL2*. The first assigns to *LoadNo* the total number of finished instances of activity *Load* up to now (1, 2, ...). The second stores into *Site* the current value of *NextSite*, and the third increments the value of *NextSite* (using modulo division to reset its value to zero after the value 151).

```
DURATION    Haul2CheckPoint 2.45; /minutes
```

This simply defines the duration of *Haul2CheckPoint*. When a hauler reaches fork *Checkpoint*, it follows either link *HL4* or *HL5* based on their relative strengths.

```
STRENGTH    HL4 '!(HaulToBOW.CurInst |
              WaitForLastSite.CurCount |
              SiteNBusy)';
STRENGTH    HL5 'HaulToBOW.CurInst |
              WaitForLastSite.CurCount |
              SiteNBusy';
```

These strength expressions are logical opposites; when one equals 1 the other is 0. Thus, even though forks in general route resources probabilistically, *Checkpoint* behaves like a decision node. A hauler follows link *HL5* and stops at BOW, if there are any instances of *HaulToBOW* currently going on (other hauler(s) in front are about to stop), or there any haulers

already stopped in queue *WaitForLastSite*, or site 151 is busy. Otherwise, it follows link *HL4*.

```
DURATION    Haul2SiteFast 'Max[
0.80+0.03*
    (nSites-Haul2SiteFast.Hauler.Site),
SiteETA[ Mod[nSites -1 +
    Haul2SiteFast.Hauler.Site, nSites]]
    - SimTime]';
```

Since haulers cannot overtake each other, the time a hauler arrives at its destination *Site* cannot be less than the arrival time for the hauler in front. The modulo division in the index of array *SiteETA* above ensures that when *Site* is 0 we access *SiteETA*[151] (and not the erroneous *SiteETA*[-1]).

```
ONSTART Haul2SiteFast ASSIGN SiteNBusy
PRECOND
    (Haul2SiteFast.Hauler.Site+1)==nSites 1;
ONSTART Haul2SiteFast ASSIGN SiteETA
    Haul2SiteFast.Hauler.Site
    SimTime+Haul2SiteFast.Duration;
```

The above on-start actions occur after an instance of activity *Haul2SiteFast* has been created and its duration has been determined. The first assigns to savevalue *SiteNBusy* the value 1 (true), if the destination of the hauler in this instance of *Haul2SiteFast* is site 151. Notice that *SiteNBusy* is set at the start of *Haul2SiteFast*, i.e., at the same simulation clock time that fork *Checkpoint* was resolved last. Thus, the next time fork *Checkpoint* is resolved *SiteNBusy* will indicate that site 151 is occupied even though the hauler that will dump there may not have reached its destination yet.

The second of the above on-start actions stores into the corresponding *Site* element of array *SiteETA* the time when the hauler in *Haul2SiteFast* will arrive at its destination. As explained earlier, array *SiteETA* is used to prevent haulers from overtaking their predecessors.

```
DURATION    HaulToBOW '0.93';
SEMAPHORE  Haul2SiteSlow '!SiteNBusy';
DURATION    Haul2SiteSlow
    'Haul2SiteSlow.Hauler.Site<=127?
    0.75+0.03*(nSites-
    Haul2SiteSlow.Hauler.Site)
    : 0.3*Sqrt[nSites-
    Haul2SiteSlow.Hauler.Site]';
ONSTART Haul2SiteSlow ASSIGN SiteETA
    Haul2SiteSlow.Hauler.Site
    SimTime+Haul2SiteSlow.Duration;
```

The duration of activity *HaulToBOW* is 0.93 minutes. A hauler then enters queue *WaitForLastSite* where it waits until activity *Haul2SiteSlow* can start. This occurs when its semaphore becomes true, i.e., when site 151 is no longer busy. As explained earlier, the duration of activity *Haul2SiteSlow* depends on the distance the hauler must travel to its dump site (i.e., whether

Site<=127). Array *SiteETA* is updated to indicate the hauler's arrival time at its *Site* as explained above.

```
DURATION    Dump Uniform[40,60]/60; /minutes
BEFOREEND  Dump ASSIGN SiteNBusy
    PRECOND (Dump.Hauler.Site+1)==nSites 0;
RELEASEAMT  GR2 43.48; /BCY
```

The duration of activity *Dump* is uniform from 40 to 60 seconds. If the hauler is dumping in site 151 then at the end of *Dump*, savevalue *SiteNBusy* is reset to zero to indicate that the entrance to the embankment is no longer blocked. *Dump* releases 43.48 BCY of *Granite* through link GR2 that are deposited in queue *RipRap*. The current contents of *RipRap* reflect total production.

```
DISCIPLINE WaitForHinFront LoadNo;
ENOUGH HL11 'WaitForHinFront.CurCount &
    (WaitForHinFront.LoadNo.MinVal ==
    (Return.TotInst+1))';
DURATION Return '(Alternate==1?7.67:12.90)
    +0.03*Return.Hauler.Site';
```

After *Dump*, a hauler enters queue *WaitForHinFront* where it waits until all haulers in front have finished dumping, too. The order of haulers in this queue depends on their relative position along the embankment and not on who finished dumping first. This is an important point because it is exactly the reason why this queue is formed. When a hauler enters *WaitForHinFront* it is positioned based on the queue's *discipline* which (as shown above) arranges haulers based on *LoadNo* (or *Site*) with the smallest value in the front of the queue.

A hauler cannot leave this queue until the *enough* attribute of link HL11 becomes true (which is a prerequisite for activity *Return* to start). As indicated by the *enough* statement above, this occurs when there is at least one hauler waiting in *WaitForHinFront*, and the *LoadNo* of the hauler at the front of this queue is one more than the number of *Return* instances this far. This would indicate that the hauler in the front of the queue is the next in line to return. The duration of activity *Return* depends on the construction alternative (1 or 2) that is being modeled.

```
DURATION    BDArrivals
    Uniform[110,310]/nLoaders;
SEMAPHORE  BDArrivals
    !BDArrivals.CurInst&RockQ.CurCount;
RELEASEAMT  BD1 1;
PRIORITY    BreakDownTime 10;
DURATION    BreakDownTime Uniform[5,35];
```

Since there are two front-end loaders, the limits for the uniform distribution of *BDArrivals* (breakdown arrivals) are divided in half. Its semaphore allows only one current instance and then only when queue *RockQ* is not empty. When there is no more *Granite* to load and haul the simulation should stop (including breakdowns).

The priority of *BreakdownTime* is set high (above the default of zero) so that when *BreakdownTime* and *Load* compete for the acquisition of a *Loader* from *LoaderQ*, *BreakdownTime* will be started first and draw the loader and keep it out of work anywhere from 5 to 35 minutes.

```
INIT RockQ 1000000; / Total BCY of riprap
INIT LoaderQ nLoaders;
INIT HaulerQ nHaulers C772;
SIMULATE;
REPORT;
```

These statements initialize the queues with resources and start the simulation. The simulation ends when queue *RockQ* becomes empty and there is no more rock to load and haul. More complicated simulation control statements can be used to effect multiple replications, common random numbers, and other variance-reduction techniques. The results shown in Table 5 and Figure 4 were collected after a warm-up period of 3 hr based on 10 samples of 10 hr (separated by 2 hr intervals).

As shown by the STROBOSCOPE simulation results the two construction alternatives are quite sensitive to the chosen number of haulers. The optimum number of haulers for alternative 1 is 9 and for alternative 2 is 12. This is as expected since the haul and return cycle time for alternative 2 is longer. The associated average total costs are \$4,541,165 and \$4,332,773 respectively. Thus, alternative 2 is preferred unless the cost for the new return road required by alternative 1 can be reduced.

4 CONCLUSION

The STROBOSCOPE model for this example can be expanded relatively easily to produce an animation trace file for PROOF Animation. This animation has been used to verify that the model is indeed correct, to investigate the effect of various traffic policies and to present the results to others. The layout for the animation is identical to Figure 1.

One of the shortcomings of animating this type of problem is due to the need for geometric precision, especially when representing the size of the haulers relative to the length of the embankment. Since haulers must be drawn 152 times smaller than the embankment, they appear very small. Thus, it is best to view the animation on a large high-resolution computer monitor.

STROBOSCOPE, its documentation, and several solved examples are available at <http://grader.engin.umich.edu> and <http://strobos.ce.vt.edu>.

ACKNOWLEDGMENTS

The author wishes to thank the National Science Foundation (Grant CMS-9415105) for supporting

portions of the work presented here. Any opinions, findings, and conclusions or recommendations expressed in this paper are those of the author and do not necessarily reflect the views of NSF.

REFERENCES

- Ioannou, P.G. and J.C. Martinez. 1996a. Comparison of Construction Alternatives Using Matched Simulation Experiments. *Journal of Construction Engineering and Management*, ASCE, (122)3:231-241.
- Ioannou, P.G. and J.C. Martinez. 1996b. Simulation of Complex Construction Processes. *Proceedings, 1996 Winter Simulation Conference*. Society for Computer Simulation, San Diego, CA, 1321-1328.
- Ioannou, P.G. and J.C. Martinez. 1996c. Scaleable Simulation Models for Construction Operations. *Proc. 1996 Winter Simulation Conference*. Society for Computer Simulation, San Diego, CA, 1329-1336.
- Martinez, J.C. 1996. STROBOSCOPE: State and Resource Based Simulation of Construction Processes. Ph.D. Dissertation, Department of Civil and Environmental Engineering, University of Michigan, Ann Arbor, MI.
- Martinez, J.C. and P.G. Ioannou. 1994. General Purpose Simulation with STROBOSCOPE. *Proceedings, 1994 Winter Simulation Conference*, Society for Computer Simulation, San Diego, CA, 1159-1166.
- Martinez, J.C. and P.G. Ioannou. 1995. Advantages of the Activity Scanning Approach in the Modeling of Complex Construction Processes. *Proceedings of the 1995 Winter Simulation Conference*, Society for Computer Simulation, San Diego, CA, 1024-1031.
- Martinez, J.C. and P.G. Ioannou. 1999. General Purpose Systems For Effective Construction Simulation, *J. of Construction Engineering and Management*, ASCE, (125)4, July-August.

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Table 5 – STROBOSCOPE Simulation Results For Alternatives 1 and 2
 (Sampling: 3 hr warm-up period, followed by 10 samples of 10 hrs each with 2 hr separations)

Construction Alternative 1 (Build New Return Road)							
Number of Haulers	6	7	8	9	10	11	12
Number of data samples	10	10	10	10	10	10	10
RipRap dumped (BCY)	7,308.70	8,295.65	9,334.78	10,152.17	10,473.91	10,669.57	10,669.57
Est. Project Duration (days)	136.90	120.48	107.15	98.58	95.56	93.74	93.74
Contract Delay (days)	36.90	20.48	7.15	0.27	0.05	-	-
Total Loader Cost (\$)	821,420	722,898	642,888	591,460	573,333	562,455	562,455
Total Hauler Cost (\$)	1,363,557	1,400,013	1,422,925	1,472,735	1,586,221	1,711,739	1,867,351
G&A Overhead Cost (\$)	2,738,065	2,409,661	2,142,960	1,971,533	1,911,109	1,874,851	1,874,851
Liquidated Damages (\$)	738,065	409,661	142,960	5,437	940	-	-
Cost Of Extra Road (\$)	500,000	500,000	500,000	500,000	500,000	500,000	500,000
Total Cost Alternative 1 (\$)	6,161,107	5,442,233	4,851,732	4,541,165	4,571,602	4,649,045	4,804,657

Construction Alternative 2 (Use Existing Long Return Road)							
Number of Haulers	8	9	10	11	12	13	14
Number of data samples	10	10	10	10	10	10	10
RipRap dumped (BCY)	7,721.74	8,617.39	9,278.26	10,065.22	10,604.35	10,600.00	10,669.57
Est. Project Duration (days)	129.47	116.12	107.82	99.42	94.35	94.36	93.76
Contract Delay (days)	29.47	16.12	7.82	0.60	-	-	-
Total Loader Cost (\$)	776,830	696,693	646,922	596,541	566,129	566,158	562,538
Total Hauler Cost (\$)	1,719,383	1,734,764	1,789,816	1,815,474	1,879,548	2,036,280	2,178,897
G&A Overhead Cost (\$)	2,589,433	2,322,308	2,156,405	1,988,471	1,887,096	1,887,192	1,875,126
Liquidated Damages (\$)	589,433	322,308	156,405	12,086	-	-	-
Total Cost Alternative 2 (\$)	5,675,079	5,076,073	4,749,549	4,412,572	4,332,773	4,489,630	4,616,561

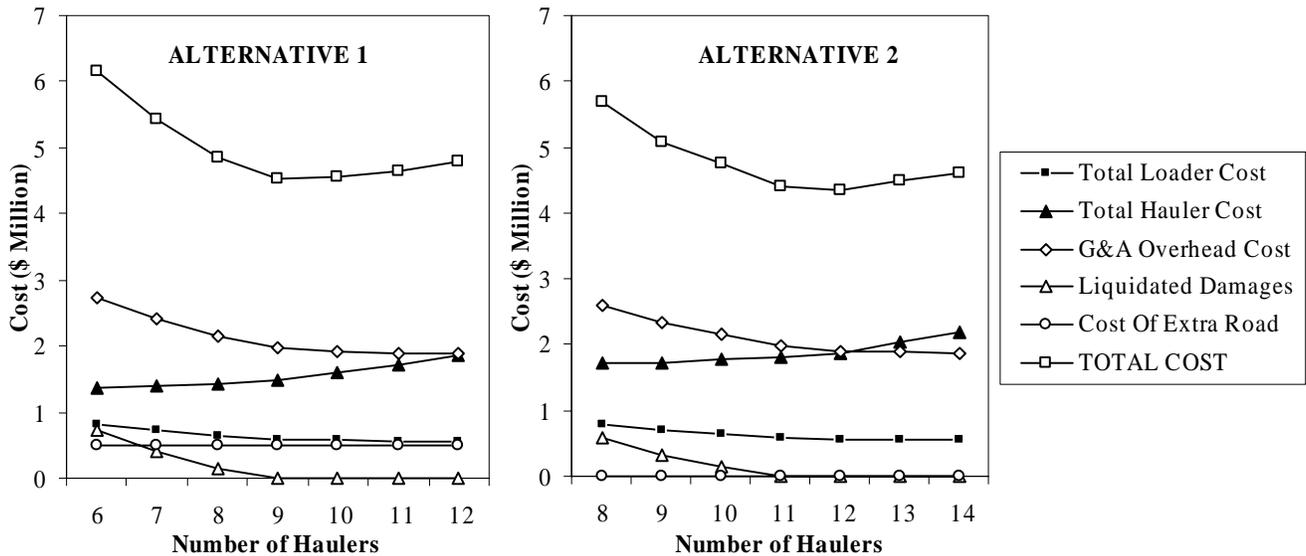


Figure 4: STROBOSCOPE Simulation Results for Alternatives 1 and 2