Using Discrete Event Simulation to Design Geocomposite Membrane Installations

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ABSTRACT

Geosynthetics are currently being incorporated in flexible pavement systems to improve their performance. However, geosynthetics must be installed properly in order to produce good results. This paper discusses the application of discrete-event simulation (DES) to design and analyze the installation of geocomposite membranes in flexible pavements. Data collected from two test sections at the Smart Road project in Blacksburg, Virginia were used for modeling and analysis. STROBOSCOPE was used as the simulation engine. The process used in the development of simulation models is discussed. A number of installation alternatives were studied and simulated to examine their practicality and to investigate their productivity, resource utilization, and unit cost.

INTRODUCTION

The United States' highway system is rapidly deteriorating. Approximately $212 billion are necessary to rehabilitate it (*1*). Stripping and spalling may occur due to the unavailability or ineffectiveness of the drainage layer when water infiltrates into hot-mix asphalt (HMA) pavement. One possible way to build more durable and better highways is to incorporate advanced materials in them and to maintain free water drainage. Geosynthetics, for example, are among the new materials used to improve flexible pavement performance. Geosynthetics can be divided into six main categories: geotextiles, geogrids, geonets, geomembranes, geocells, geosynthetic clay liners, and geocomposites. The application of some geosynthetics as an interlayer in roads and highways has many benefits. Some types of geosynthetics are thought to prevent water infiltration, absorb stress between pavement layers, dissipate strain energy responsible for crack initiation, prevent intermixing of adjacent layers, and allow for good drainage.

The use of geosynthetics may extend the service-life of roads and highways as described above. Unfortunately, geosynthetics may not perform as intended if they are not installed properly. The geosynthetic installation process, which is a key factor in pavement performance, is usually overlooked. This results in contradicting results as to their actual effectiveness in pavement systems.

The installation process must be designed such that the geosynthetics are correctly placed, resulting in an effective life-cycle cost. Geosynthetics are currently installed in the field by trial and error relying on the experience and intuition of contractors, or following guidelines provided by FHWA and/or manufacturers, which usually do not address the installation economics. Experienced contractors can make reasonable assumptions and perform quick calculations that result in acceptable initial installation procedures. A reasonable assumption by a contractor, for example, would be to maximize the area of tack coat spray per pass in order to improve production. The contractor may not realize that this would allow some of the tack coat to cool to the extent that it looses its adhesiveness, and would force the contractor to spray another layer. This may result in too much tack coat and subsequently lead to slippage. A simulation of the process can prevent this from happening by allowing the contractor to see the consequences of applying too much tack coat at the same time. Errors like this are costly if discovered during actual installation, and the corrections that would be quickly made may lead to inefficiencies in other aspects of the operation.

For installation processes that involve new technologies, these installation procedures can be quite inefficient. As the contractor performs an initial installation, the experience gained allows for significant improvements. Subsequent installations with the improved procedure provide yet more experience that allows for even further improvements. Eventually, it is possible to arrive at installation procedures that are quite reasonable. In cases where many pieces of equipment are needed for installation and where the process is complex and subject to variability, numerous iterations may be performed without reaching a truly effective and economical installation procedure.

Contractors want to know the type, size, and number of machines that will make up the fleet. They want to know the production rate of the operation, the unit cost, and the utilization of their equipment. Ultimately, contractors want to be able to try out many installation options and consider different parameters to search for the best installation procedure, but without spending much money. In essence, contractors would benefit from going through the iterative cycle of designing the operation, implementing it, gaining experience from it, and using the experience to re-design it, but without actually investing the time and resources that are traditionally used in doing so. Computer based discrete-event simulation, DES, allows just that. This paper illustrates the use of DES for the design of the installation procedures for a newly developed impermeable geocomposite membrane that may provide strain energy absorption in flexible pavements.

DISCRETE EVENT SIMULATION

A model is a representation of a real or imaginary system. Models can be studied, changed, and analyzed in an effort to better understand the system they represent. Experimentation with properly designed models may reveal how real systems would respond to real world conditions. Discrete-event simulation is a computer-based modeling and analysis procedure in which the state of the system is assumed to change only at specific, but variably separated, points in time. DES has been used to analyze and design many construction operations (*2*)(*3*)(*4*).

GEOCOMPOSITE MEMBRANE INSTALLATION

Geotextiles, geomembranes, and geocomposites are usually installed as an interlayer in pavements. A number of studies have been conducted on the installation of geosynthetics in the field. According to Wright and Guild (*5*), one of the most important factors in installing geotextiles as moisture barriers is that they be laid perfectly flat with minimum wrinkles or air bubbles on top of a uniformly sprayed tack coat. If wrinkles are greater than 25mm (1 in), they should be cut and laid flat in the direction of the paving. The tack coat application rate directly contributes to the geosynthetic performance. Too much tack coat will cause slippage or rutting, while an inadequate tack coat may result in poor bonding and poor waterproofing. In hot weather, the rubber tires of construction equipment may stick to the laid tack coated geosynthetic and cause it to detach. Sand may be sprinkled on top of the geosynthetic to prevent this from happening (*6*). Seaming of geosynthetic strips can be done by using solvent seams, contact adhesives, tapes and mechanical seams, and hot air and welding (*7*).

This paper focuses on the installation of a newly developed geocomposite membrane. This membrane was installed for performance testing in two test sections at the highly instrumented Smart Road in Blacksburg, Virginia. This geocomposite membrane consists of a polyvinyl chloride (PVC) geomembrane sheet sandwiched between two layers of polyester non-woven geotextile. It has been successfully used as an impermeable material for dams, canals, reservoirs, floating covers, cofferdams, and hydraulic tunnels (*8*). It has also been installed on a bridge deck over the Po River in Italy. However, this was the first time that this geocomposite membrane was installed in a flexible pavement in the United States for water impermeability and absorption of the strain energy responsible for crack initiation. The membrane was installed at two different locations in the pavement system: between the subbase (aggregate) layer and the open-graded drainage layer (OGDL) to quantitatively measure its moisture barrier effectiveness using buried moisture sensors (two types of time domain reflectometers); and within the HMA base layer to quantify its strain energy absorption capability.

The contractor had an initial installation procedure for common membranes based on past experience, but several issues were different for this product. The operation was, therefore, performed on a trial and error basis for the test installations. The equipment involved in the operation included a front-end loader, an asphalt distributor truck, a modified wheel tractor that was specially built to lay membrane rolls (the installer), and a pneumatic compactor. The operation began as the front-end loader lifted a membrane roll that was positioned in advance and mounted it onto the installer as shown in Figure 1.

FIGURE 1 The membrane roll was lifted by the front-end loader.

The asphalt distributor truck then sprayed a PG64-22 heated tack coat binder on the surface of the HMA when the membrane was installed within the HMA layer. No tack coat was needed when the membrane was installed on the aggregate sub base because the friction between the aggregate and the non-woven geotextile is sufficient to prevent any slippage. This paper focuses on the installation of the membrane on the HMA surface. The tack coat was not sprayed unless the installer had a membrane roll mounted and was ready to unroll. It was preferable to deploy the membrane while the tack coat was still hot to attain good bonding. Figure 2 illustrates the asphalt distributor truck spraying the tack coat on the center of the road's surface, with the membrane already installed and compacted on the right side of the road.

FIGURE 2 The asphalt distributor truck sprayed a tack coat on the road's surface.

FIGURE 3 The installer unrolled the membrane on the heated tack coat.

Immediately after the tack coat was sprayed, the installer unrolled the membrane on top of the tack coat as shown in Figure 3. The geocomposite membrane rolls are 1.97m (6.46 ft) wide and 37.00 m (121.39 ft) long. There are two types of rolls. Type A rolls have one 50mm (~2 in)-wide PVC exposed area, whereas type B rolls have two PVC exposed areas. The exposed areas are intended to overlap with an adjacent roll in such a manner that the thickness at the overlap is minimum. Figure 4 shows the details of a geocomposite membrane roll and two overlapped membrane rolls.

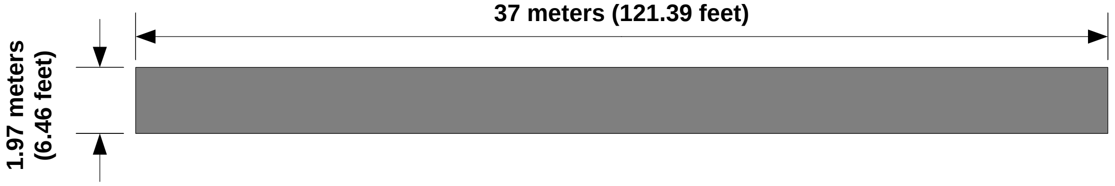

FIGURE 4(a) Plan view of an unrolled geocomposite membrane roll.

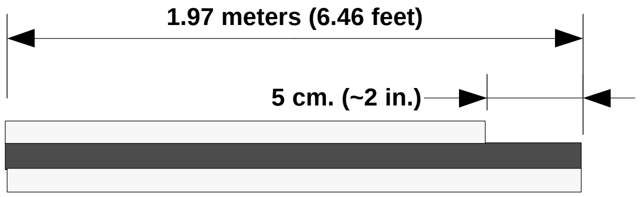

FIGURE 4(b) Cross section of Type A membrane rolls.

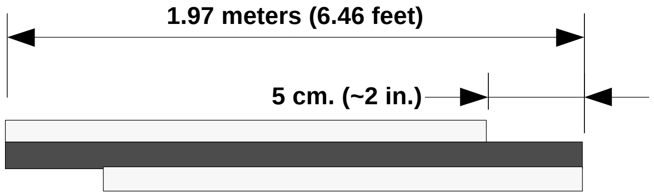

FIGURE 4(c) Cross section of Type B membrane rolls.

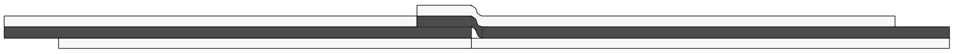

FIGURE 4(d) Two overlapped membrane rolls.

The test sections were on a typical 2-lane highway constructed according to VDOT specifications. The membrane covered a 10-meter (33 feet) wide by 50-meter (164 feet) long section. Five membrane strips were required to cover the width of each section. Two type A rolls were installed at the edges of the road, while three type B rolls were installed in the middle. Since a roll was only 37 meters long, connection joints for two membrane rolls were needed (i.e., between a 37-meter-long roll and a 13-meter-long piece of membrane). Therefore, the membranes were staggered to prevent a continuous transverse joint. After the membrane was laid, the compactor ran over it as illustrated in Figure 5. The tack coat on the surface of the membrane was included in the modeling as it is a normal process when HMA is installed.

FIGURE 5 The compactor compacted the laid membrane.

The installations of this geocomposite membrane were recorded on videotapes, which were observed and stripped to obtain data for activity durations using PAVIC+ (*9*). PAVIC+ (Productivity Analysis with Video and Computer) is a computer-based system in which videotape can be examined frame by frame, to determine if that frame marks the start or end of any activity. The software can determine the duration of an activity by counting the number of frames between its start and end, and can export the list of recorded durations to a database. The data from the database was analyzed using Stat::Fit (http://www.geerms.com/), a software that analyses the activity duration data, and determines the probability distribution and parameters that best describe the process that generates the data. These distributions were later used in the simulation model and are shown in Table 1. In the case where the operation has never been performed, or where video footage is not available, subjective probability distributions from people with similar experience (as in Pert) could be used.

TABLE 1 Distributions of Activities Using Data Obtained From the Video

Activity	Distribution (seconds)
Setup distributor truck	Pearson5 (0, 66.1, 24.7)
Spray one meter of tack coat	Pearson5 (0, 25.6, 0.382)
Mount	Pearson5 (1, 30, 32.9)
Setup Installer	Erlang (1, 13, 0.044)
Unroll one meter of membrane	Lognormal (0, -2.8, 0.0856)
Installer travels one meter	Uniform (0.00501, 0.005667)
Compact one meter	Uniform (0.027667, 0.027767)

MODELING THE OPERATION

The process involved in the installation of this geocomposite membrane was modeled using STROBOSCOPE (*10*). Stroboscope is a discrete-event simulation programming language designed for modeling complex operations. A Stroboscope model describes the details of how the operation takes place by generating input processes (such as the duration of activities) from probability distributions, carrying out the processes as described by a model network, and recording the consequences or outcomes of the operation (e.g., production rates and resource utilization). Proof Animation (*11*), a post-processing general-purpose animator, was used for computer-animated output.

The design of the installation process involved several participants. These included a geosynthetics expert; a simulation modeling expert; the geocomposite supplier; and the installation contractor, who has extensive experience in geosynthetics installation. In the model, the installation process was designed on a section basis. A section consisted of a number of membrane strips. The number of membrane strips required was calculated from the width of the road and the width of the membrane roll. For example, on a 10-m (33ft) wide section, five 2-m-wide (6.60 ft) rolls were used. The length of a section was equal to the length of the membrane roll. Figure 6 shows a plan view of the designed installation process for two sections.

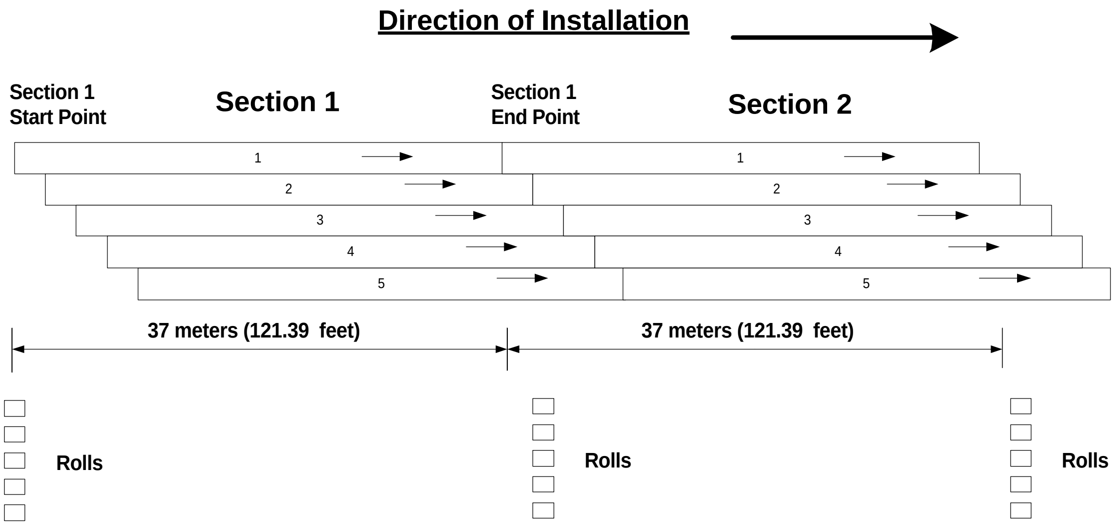

FIGURE 6 Plan view of a designed installation process.

In this particular example, the operation starts in section one. Five strips of membrane are installed in the order shown. Each strip is always laid from the section start point to the section end point (from left to right). This means that after finishing one membrane strip, the equipment travels back to the section start point. After the equipment finishes installing five membrane strips, i.e., finishes section one, it moves to the start point of section two and the process starts over again.

The membrane is designed for left to right installation to prevent gaps at the joints and cutting excessive membrane. When installed backward, i.e., from the section end point to the section start point, it is very difficult, if not impossible, to ensure that the new strip will end exactly where the laid membrane strip of the previous section ends. In these cases there is a chance of having either a gap, or excessive membrane at the joint where two membrane strips meet. In addition, it would be necessary for the rolls to be rolled in reverse order, which would introduce confusion. Therefore, the installation is designed in only one direction.

Originally, the operation was modeled such that the truck could spray the tack coat as soon as it was ready, i.e., as soon as it returned to the section start point. However, after observing the animation of the process, it was decided that the truck should wait for the installer to be ready to unroll the membrane before spraying asphalt to assure that the asphalt binder is still hot. The model was therefore adjusted such that the truck would not spray the tack coat unless the membrane roll was mounted onto the installer and ready to unroll.

Although it appears cost effective for the compactor to start compacting as soon as the membrane is laid, it is difficult to correct the alignment when, for some reason, the membrane is not properly aligned. Consequently, the compactor was modeled such that it started compacting only after one membrane roll was completely placed. Setting up the operation properly is important because correcting errors is cumbersome. Once the membrane is compacted, it is very hard to redo the work. Therefore, the compactor will not start compacting until an unrolled membrane strip is satisfactorily straight and free of wrinkles. In addition, the compactor can compact the membrane in either direction (left to right or right to left). The compactor does not have to travel to the section start point every time it finishes one membrane strip.

The loader, on the other hand, is modeled to stay at the section start point at all times because the other equipment will eventually return to that point. After the loader mounts all the geocomposite membrane rolls required for one section, it moves to the start point of the next section.

DEVELOPMENT OF SIMULATION MODELS

The amount of time between spraying the tack coat and the placement of the geocomposite membrane is critical. The tack coat exposed time was therefore one of the guiding criteria in modeling the operation. In the initial model, the installer followed the tack coat truck closely in an attempt to limit the time during which the tack coat was exposed. However, observations of the computer animation showed that the truck had to start and stop many times, leaving thick spots of tack coat which may lead to slippage and rutting. Consequently, the model was developed such that the truck only stopped when it finished spraying an entire strip of tack coat.

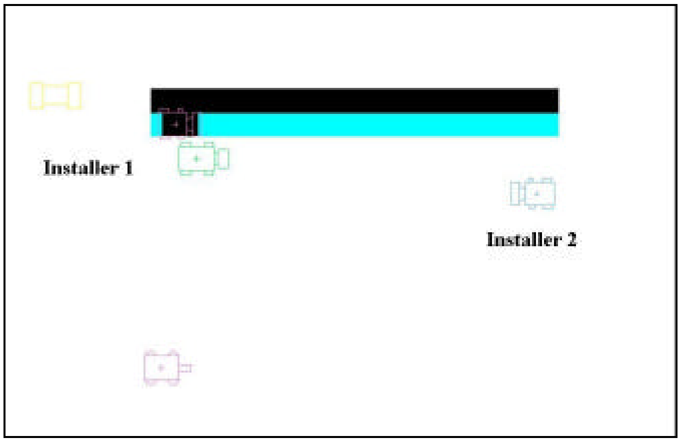

FIGURE 7 The operation with two installers.

The authors also thought of using two installers in the operation, as shown in Figure 7. Two installers could work alongside one another with a few meters of lagging distance. The authors decided, however, that the second installer should start unrolling only after the first installer finished unrolling a membrane strip. This was to ensure that the first membrane strip was satisfactorily straight and free of wrinkles. When two installers were used, the truck would spray the tack coat wider to accommodate two membrane strips. The setup time and the duration of spraying the tack coat was relatively constant regardless of the spraying width. Hence, the width of the tack coat was insignificant to the calculation in the simulation model. However, the exposed time of the tack coat was very important in this case. The longer the first installer took to unroll one membrane strip, the longer the tack coat remained exposed. Figure 8 shows a snapshot of the distributor truck spraying the tack coat twice as wide as the normal width.

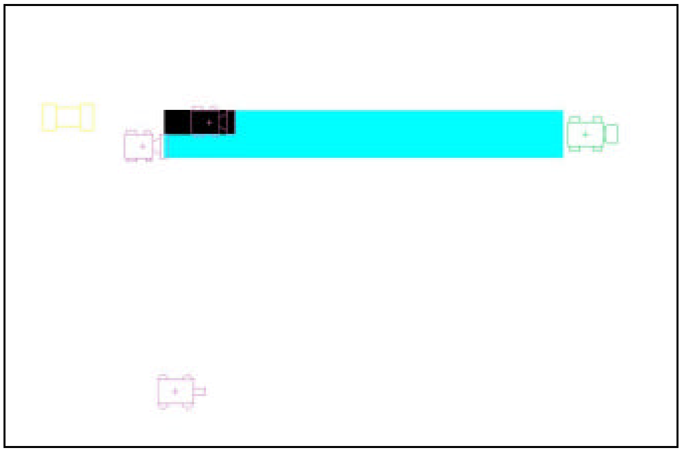

FIGURE 8 The asphalt distributor truck sprays the tack coat two membrane rolls wide.

ANALYSIS OF INSTALLATON ALTERNATIVES

There were several improvements in installation that were thought possible, including changes in the width and length of the membrane rolls. While manufacturing longer rolls is not an issue, making them wider requires a substantial capital investment. Both cases increase the weight of the rolls and may require larger installers. Thus, there is a tradeoff between the capital investment in new installers by the contractors and the capital investment in new manufacturing equipment by the manufacturer. The models, however, are based on the assumption that it is possible to manufacture rolls of various widths and lengths. Table 2 summarizes the results from possible alternatives for installing the geocomposite membrane.

TABLE 2 Summary of Results From Various Possible Alternatives

Covered Distance 350 Meters

Num. Installers ea	**Installer Capacity lbs**	**Roll Width m**	**Roll Length m**	**Road Width m**	**Covered Area m^2**	**90% CI Oper.Time hrs**	**90 % CI Unit Cost $\$/m^2$**	**90% CI Productivity m^2/min**
1	500	2.05	35	8.2	2870	4.77 – 4.79	0.39 – 0.39	12.22 – 12.28
1	1000	2.05	70	8.2	2870	3.18 – 3.19	0.27 – 0.27	17.99 – 18.07
1	1000	4.1	35	8.2	2870	2.28 – 2.30	0.16 – 0.17	30.18 – 30.37
2	500	2.05	35	8.2	2870	2.29 – 2.30	0.23 – 0.24	20.75 – 20.87
2	1000	2.05	70	8.2	2870	1.80 – 1.81	0.18 – 0.18	25.56 – 26.63

The confidence intervals of each alternative were calculated from simulation results of 10 replications. When one installer was used in the operation, the 90% confidence interval for the productivity was [12.2, 12.3] m^2/min. This means that there is a 90% chance that the true average productivity is between 12.2 and 12.3 m^2/min. The mean unit cost for this alternative was $\$0.39/m^2$. If the membrane rolls were made longer (70 meters long), results showed that the 90% confidence interval for the productivity was [18.0, 18.1] m^2/min with a $\$0.27/m^2$ mean unit cost. The improvement was a result of the ability to unroll the membrane twice as long before stopping. In addition, the loader would not have to load membrane rolls as often. When wider rolls were used, the production rate and the unit cost improved significantly, and with 90% certainty were estimated to be [30.2, 30.4] m^2/min at [0.16, 0.17]$\$/m^2$. In this case, the installer unrolled two strips of membrane simultaneously and thus reducing the number of passes needed per section. Wider rolls may be more difficult to handle and may require greater care during installation to avoid excessive wrinkles. In addition, it would be more difficult to coordinate the wider rolls with various road widths, because the road width may not be divisible by the roll width. However, wider or longer rolls are advantageous because there are fewer joints, which are assumed to be the weak points of the system.

Simulation results also revealed a substantial improvement when two small installers were used with regular rolls. The 90% certain production rate increased to [20.8, 20.9] m^2/min and its unit cost fell to [0.23, 0.24] $\$/m^2$. The authors felt that this option was the best alternative if two installers were used because small installers are already available in the market. The last alternative was to use two big installers and membrane rolls that are 70 meters long. Simulation results showed that the 90% certain production rate would be [26.5, 26.6] m^2/min at a \$0.18/m^2 mean unit cost. Although this alternative yielded a very high production rate, it may require significant investment by the contractors.

The measures of performance obtained by the simulation are those of the model, and not necessarily those of the system represented by the model. Generally speaking, it is impossible for a model to accurately include each and every aspect of the system it represents. If coffee breaks are not included in a model, for example, the performance measures obtained by simulation will be better than those observed in the field. This is common and typically recognized by simulation modelers, and does not adversely affect the value of simulation studies as might seem to appear at first glance. This is because simulation is mostly used to make decisions, which by definition implies the selection of one alternative from among several.

If we assume that the difference between a model and the system it represents is constant across all alternatives, the difference between the measures of performance among models and among the systems they represent are minimal. Assume for example, that including coffee breaks increases the costs of a certain operation by \$0.15/m^2. A model for one alternative may indicate a unit cost of \$0.35/m^2 when in effect the unit cost of the system it represents is \$0.50/m^2. A model for another alternative may indicate a unit cost of \$0.38/m^2 when in effect the unit cost of the system it represents is \$0.53/m^2. Although the costs obtained by each model are off by \$0.15/m^2, the difference in cost between the two models can be fairly accurately estimated to be \$0.03/m^2. The decision to choose the first alternative based on the cost reduction of \$0.03/m^2 given by the models would be a good one.

The key to the validity of models is, thus, to exclude from them only those realities that are thought to impact all alternatives equally. As long as this is the case, the decisions made by observing the performance of models are likely to be the same as the decisions made by experimenting with the alternatives in reality. This issue is discussed in detail within the context of construction operations by Ioannou and Martinez (*12*), and in general by Law and Kelton (*13*).

Sometimes the purpose of simulation models is to predict the absolute performance of a system rather than to select from among alternatives. This is the case, for example, when simulation is used to estimate the cost of a proposed system that will be compared with an existing system for which actual costs are available. In these cases, the simulation model must include as much detail as possible (e.g., machine breakdown frequency and downtime, coffee breaks, shift and overtime work, rework, disruptions and weather). In addition, additional factors such as the frequently assumed 50-minute hour may be used to account for details that have not been explicitly modeled.

Using computer animations as a visual tool greatly helped the development of the simulation model. The computer animations allowed experts to visualize the operation. They were able to make comments and to decide whether or not the operation was sound. The researchers then modified the simulation model according to the comments and again discussed it with the experts. This process was repeated several times until the researchers and the participants were satisfied. Had there not been computer animations, it would have been very difficult for participants to visualize the operation and make comments.

The use of discrete-event simulation and computer animations had a very significant impact on the design of this geocomposite membrane installation. The process forced the participants to think hard on the installation process. Obvious mistakes were found and eliminated by just looking at computer animations. Many issues were raised and clarified by observing preliminary simulation results. Computer animation helped facilitate the communication among participants. The participants worked as a “team” to come up with a good installation process. The expertise from each participant was effectively shared and input into the design process. This “team” effort in the design process was a key benefit of using discrete-event simulation and computer animations to design the operation.

SUMMARY AND CONCLUSION

Geosynthetics are widely used to improve flexible pavement performance. However, they may not perform as intended if they are not installed correctly. One of the most important factors, the installation process, which directly contributes to their success, has not been sufficiently studied. The installation of a geocomposite membrane at the highly instrumented Virginia Smart Road is an example of an installation of a geosynthetics material in flexible pavements.

The method used to design and analyze the installation process was discrete-event simulation. STROBOSCOPE was used as the simulation engine. The activity durations were stripped from the videotapes recorded at the test sections, analyzed, and then used in the simulation. Simulation is a cost-effective technique to design and analyze construction operations. Simulation allows experimentation with different parameters and exploration of various installation strategies in a virtual world. It helps accelerate the learning process without having to carry out actual installations, which may be very costly. Computer animations make it possible to obtain input from people who know little about simulation, and to allow for participation from everybody. Using discrete-event simulation and computer animations during the design process helps plan and execute the installation more efficiently, productively, and cost effectively.

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