Evaluating Risks of Dam-Reservoir Systems Based on Rare Event Simulation

Qianli Deng[a]*, Adiel Komey[a], Gregory B. Baecher[b]

a. Ph.D candidate, Civil and Environment Engineering Department, University of Maryland, College Park
b. Professor, Civil and Environment Engineering Department, University of Maryland, College Park

Abstract:

Overtopping risks for dam-reservoir systems serve as a critical index representing dam safety statuses. Although overtopping is a common failure mode with significant consequences, in most cases this event has a very small probability of occurring. Estimation of such rare event probabilities with so-called, "crude Monte Carlo" (CMC) techniques requires a prohibitively large numbers of trials for which significant computational resources are required to reach satisfactory estimation results. Otherwise, probability estimation of the event is not accurate enough. In order to reduce the computational expenses and improve estimation efficiency, a rare-event-simulation approach is proposed in this study to address overtopping risks. Deliverables of the study comprised the following:

- A reservoir inflow hydrograph model;
- A dam-reservoir system operation model;
- The CMC simulation framework;
- The importance sampling-based Monte Carlo (ISMC) simulation framework; and
- The overtopping risk estimation comparison of both CMC and ISMC simulation.

In a broader sense, the study intended to meet three expectations:

- To address the natural stochastic characteristics of the dam-reservoir system, such as reservoir inflow and outflow rates;
- To construct the fundamental CMC and ISMC simulation frameworks to estimate the overtopping risks; and
- To compare simulation results and computational performance to demonstrate the advantage of ISMC simulation.

The estimation results of overtopping probability can be used to guide future dam safety investigations and to supplement conventional analyses in making decisions on the dam-reservoir system improvements. At the same time, the proposed methodology of ISMC simulation improves overtopping estimation results. The more accurate estimation of probability, the smaller variance of simulation results, and the significantly less CPU time required with the ISMC procedure expand the application of Monte Carlo (MC) technique to evaluate overtopping risks.

Keywords:

Rare event simulation; importance sampling; dam-reservoir system; overtopping risk

1. Introduction

Dam-reservoir systems are a critical component of water infrastructure, providing services such as water, power, flood control, recreation, and many economic possibilities (Vedachalam and Riha 2014). The successful performance of a dam-reservoir system depends on the aggregate satisfactory performance that prevents a failure and uncontrolled release of the reservoir. However, hundreds of dam failures have occurred throughout U.S. history that have caused immense property and environmental damage and have taken thousands of lives. Take the Lawn Lake Dam failure of 1982, for instance. The sudden release of 849,000 m^3 of water resulted in a flash flood that killed three people and caused $31 million of damage. According to the Association of State Dam Safety Officials (2015), 173 dam failures and 587 incidents were reported from January 2005 through June 2013 by the state dam safety programs. Dam failures are not particularly common, but continue to occur (Baecher et al., 2011).

Potential failure modes for dam-reservoir systems were explored by researchers. Overtopping is one of the most common failure modes for the dam-reservoir systems with significant consequences. According to national statistics, overtopping due to inadequate spillway design, debris blockage of spillways, or settlement of the dam crest accounts for approximately 34% of all U.S. dam failures (Association of State Dam Safety Officials 2015). Other causes include piping, seepage, internal erosion (Curt et al. 2010), and inadequate maintenance. A similar proportion has also been concluded by Kuo et al. (2008) and Zhang et al. (2009). In general, overtopping is the most common failure cause of dam-reservoir systems, particularly for the homogeneous earth-fill dams and zoned earth-fill dams. Spillways, foundations, and downstream slopes are the potential locations of the risks. Overtopping flows can erode down through an embankment dam, releasing the stored waters, potentially in a manner that can cause catastrophic flooding downstream as well as a total loss of the reservoir.

Although overtopping results in significant consequences, in reality, such events have a very low probability of occurrence for a specific dam-reservoir system. Those events are defined as rare events. Estimation of the rare-event probabilities with crude Monte Carlo (CMC) simulation requires a prohibitively large number of trials, where significant computational resources are required to reach the satisfied estimation results. Otherwise, estimation of the disturbances would not be accurate enough. Accordingly, computational expense served as one of the prohibitive reasons that the simulation technique has not been widely applied to the reservoir operation. In view of the very large number of options of configuration, capacity and operating policy, simulation without preliminary screening or adjustment would be very time consuming. Understanding the sources of simulation-based estimation errors and minimizing error rates at a reasonable cost are consequently important aspects of these practical problems. In order to fill in the research gap, the rare-event simulation technique is needed and plays a critical role in evaluating the overtopping risks of dam-reservoir systems.

2. Case Study of Little Long Dam-Reservoir System

The proposed overtopping risk evaluation approach has been applied to a dam-reservoir system operated by Ontario Power Generation (OPG) in northeastern Ontario. As an essential part of the Lower Mattagami River Hydroelectric Complex, the Little Long dam creates a forebay and reservoir upstream in the Mattagami River. The flows for the Mattagami Complex are thus provided from the Adam Creek reservoir. The whole Lower Mattagami River System includes the Adam Creek reservoir and a cascade of four generation stations (Little Long, Smokey Falls, Harmon, and Kipling) along the Mattagami River. As shown in Figure 1 below, this study only focuses on the first part, including the reservoir and the Little Long Generating Station dam and sluiceway, and the Adam Creek Control Structure as a system.

The selected Little Long dam-reservoir system is within a modified continental climatic zone. During the winter, cold polar air masses often produce dry, clear, cold weather, and in the summer months, successions of cyclonic storms sweep the area, and warm humid air masses from the south alternate with cooler drier air from the north. The average mean daily temperatures for January and July stay at approximately -19ºC and 17ºC, respectively. And the annual average mean daily temperature for the region is about 1ºC. On average, the area is frost free from mid-May to early September. For precipitation, the average annual total precipitation is about 86 cm (water equivalent mean). Rainfall accounts for 63% of the total precipitation, with the maximum occurring in the summer months. Snow cover is present for about 160 days per year, reaching a maximum depth on the ground in February (average depth 61 cm).

Figure 1. Geographical location of Little Long dam-reservoir system

Hydro units are heavily dependent on precipitation and snow melting. As a consequence, strong seasonal patterns can be identified for the Adam Creek inflow data. Freeze-up usually occurs by late November or early December on the Mattagami River and reservoirs. The inflow volume into the reservoir reduces gradually. By mid-December, ice cover is complete except in the tailraces and rapids, which stay open all winter. The inflows stay small but positive. During peak winter operation, ice hinges form along the shoreline allowing the central ice sheet in each reservoir to move with the changing water elevations without breaking. In late winter, the central ice sheet subsides and, as the inshore ice settles to the substrate, the central floating ice sheet breaks from the inshore ice and can be pushed downstream. The ice breaks and the snow melts quickly during the spring freshet by mid-March. A corresponding large inflow volume usually occurs. Rainfall is heavier and more frequent during the summer as compared to the winter. The inflow rate is consequently larger during the summer.

3. Modeling Inflow Rate under Uncertainty

In general, a 50-year time series data of average daily inflow rate for the Mattagami River is collected for analysis. There are 18,394 records available in total ranging from 08/01/1963 to 12/09/2013. For analysis simplification, the daily data ranging from 01/01/1964 to 12/31/2013 is selected with 18,250 values. Individual missing data is made up through the two-dimensional interpolation techniques. For each year, there are 365 days counted and the extra days of leap year are not taken into consideration. This dataset serves as the foundation for modeling and simulating the stochastic reservoir inflow hydrograph. Detailed data information is plotted in Figure 2.

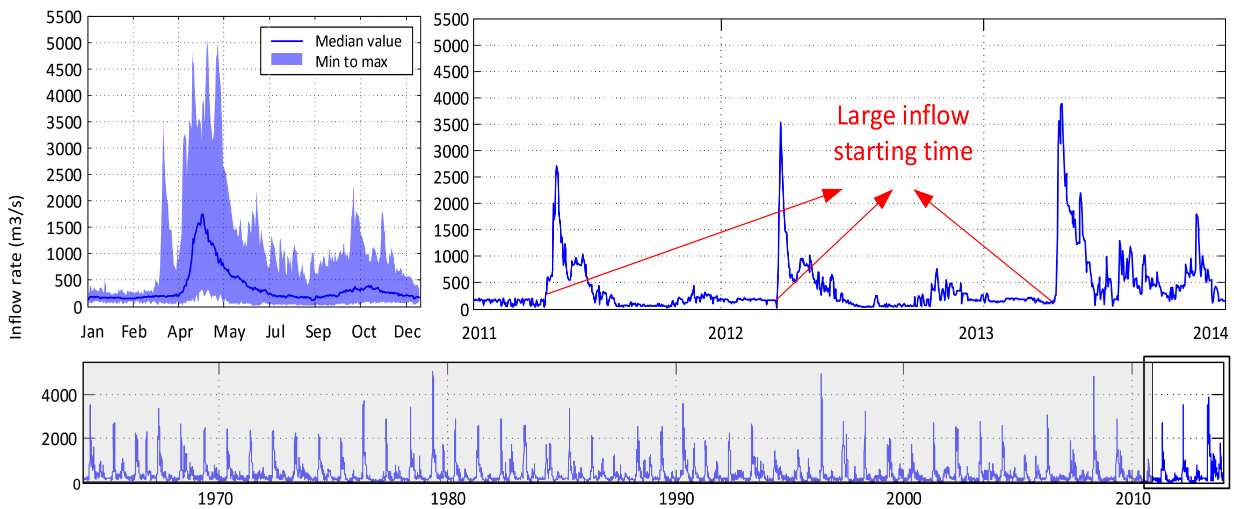

Figure 2. Inflow hydrograph of Little Long dam-reservoir system (1964-2013)

Preprocessing is intended to transform the available reservoir inflow time series into the stationary series, which would be fitted to the ARIMA or seasonal ARIMA models. Three steps need to be conducted as a sequence for preprocessing the reservoir inflow data: 1) obtaining the logarithm of data; 2) conducting the Fourier decomposition for the seasonal pattern identification; and 3) testing the inflows residuals and differencing if needed. In Step 1, the logarithmic transformation is a nonlinear transformation, which compresses the upper end of the distribution and stretches out the lower end. In Step 2, Fourier decomposition, an eight-term Fourier model is fitted to the logarithms of historical inflow data in order to find the annual seasonal cycle. The most recent data ranging from Year 2011 to Year

2013 has been zoomed in. As we can see, two big waves are identified annually in the spring and autumn time, which aligns with the climate characteristics discussed before. Step 3 calculates the residuals of logarithm inflow minus the value of fitted Fourier decomposition model. A seasonal difference is the difference between an observation and the corresponding observation from the previous year. Time series with trends or seasonality would not be stationary, since the trend and seasonality will affect the value of the time series at different times. In general, a stationary time series will have no predictable patterns in the long-term. As a result, differencing and the seasonal differencing have been conducted to make the time series stationary.

4. Modeling Operation Process of Dam-Reservoir System

The Adam Creek Diversion bypasses the Mattagami River plants from above Little Long Generation Station to below Kipling Generation Station and is the primary floodwater route. Dam safety response water levels have been established in accordance with the requirements of Dam Safety Emergency Preparedness and Response Plan standards to guide operators in case of hydraulic emergency. Water elevations in the Little Long reservoir vary slightly from season to season, usually with the maximum water elevations in the spring and fall, and the minimum in the summer and late winter. During daily peaking operations the water elevation in Little Long reservoir fluctuates within the range of ± 0.15 m. In most situations, the water elevation is within the operating headwater level, ranging from 195.10m to 198.12m. The yellow area of energy reserve, ranging from 194.77m to 195.10m, is only used if a system energy emergency occurs. All discharge flows are stopped before this 195.10m limit approaches. Another yellow area of potential failure developing from 198.12m to 199.00m stands for the flood allowance, which is only used to hold water in extreme conditions to reduce downstream flooding. At that time, the sluice gates open and start to release extra water beyond the capacity of water elevation 198.12m. The orange area, ranging from 199.00m to 199.30m, stands for the final buffer before overtopping events occur. All of the sluice gates open and the maximum water releasing capacity has been reached. Overtopping would occur if the water elevation exceeds 199.30m.

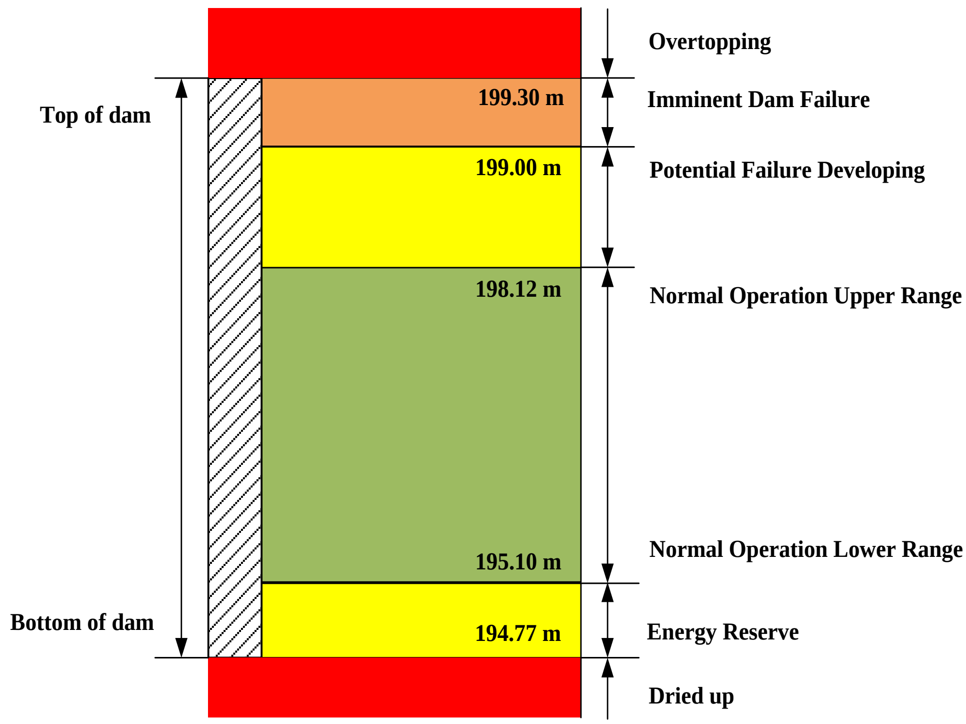

Figure 3. Water elevation boundaries for Little Long dam-reservoir system

To determine the available storage capacity of the Little Long Dam-reservoir system, engineering surveys have been conducted to represent the physical characteristics, such as storage volume, surface area, outlet capacity, and elevation tables. The volume of storage to be allocated to each of the reservoir storage levels must also be specified. For accurate determination of the capacity, a topographic survey of the reservoir area is usually conducted, and a contour map of the area is prepared. The storage capacity and the water spread area at different elevations can be determined from the contour map. For the normal water elevation ranging from 195.10m to 198.12m, the storage capacity is reached in 1,874 m^3/s-days. For energy reserves ranging from 194.77m to 195.10m, the storage capacity is 142 m^3/s-days. For absolute operational water elevation ranging from 194.77m to 198.12m, the storage capacity is 2,016 m^3/s-days.

Including all logical information, a Simulink model has been built in order to demonstrate the general dam-reservoir system operation process in Figure 4. The best efficiency flow capacity, which generates the highest electrical output per unit of water, for the appropriate number of hours matches daily average outflow to inflow and storage. When the inflows are less than the capacities of generating stations, there is no spill to Adam Creek and the local inflows and water elevations in the Mattagami River are low. During periods of high inflow, such as the spring runoff, the spillway at Adam Creek will be operated in conjunction with the Little Long generating station to pass the full Mattagami River flow.

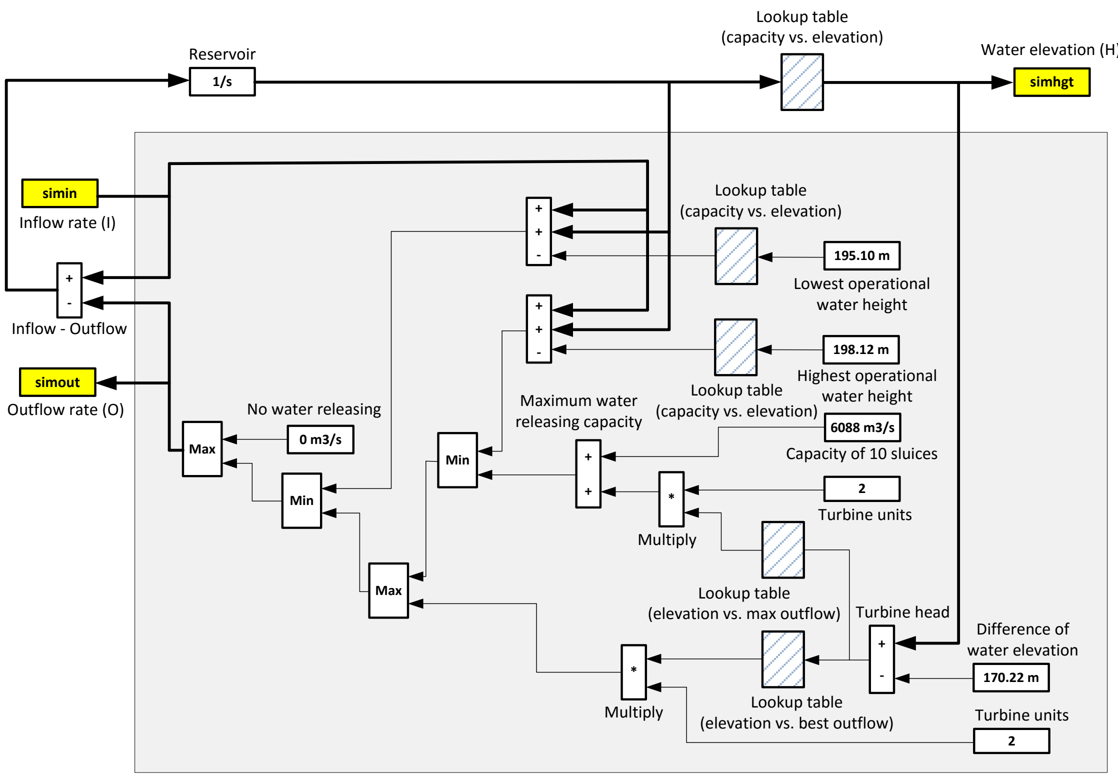

Figure 4. Simulink framework of Little Long dam-reservoir system operation

5. Simulation of Overtopping Risks

For both the CMC and the ISMC simulations, the final objective is to assess the overtopping risk probability of the dam-reservoir system within a specified time scale, which is rather hard by analytical solutions in real practice. MC simulation is implemented to model the operation of the dynamic dam-reservoir systems. In order to estimate the probability of overtopping events within a certain time scale, the following simulation framework is proposed in this section as a dynamic process shown in Figure 5.

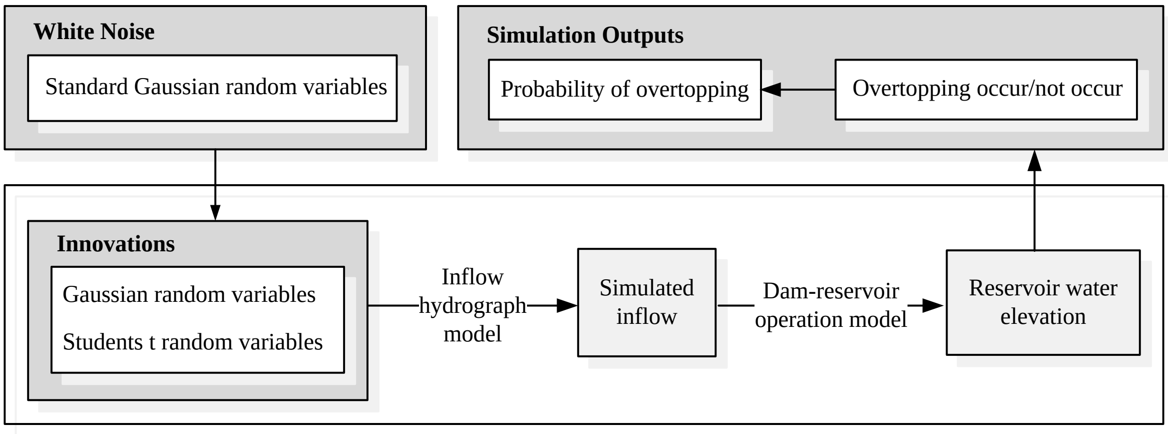

Figure 5. Framework of CMC simulation for overtopping risks estimation

For the one-time simulation, a standard Gaussian random series is generated with the same length of given simulation period first. Each element within the series is generated i.i.d. Based on the initial white noise, a series of Gaussian random variables or a series of Student's t random variables are generated with the adjustment parameters coming from existing inflow hydrograph model. These variables serve as the simulated residuals for the constructed ARIMA and seasonal ARIMA models. The simulated future inflows are reconstructed by adding the seasonal cycle back, which are derived from Fourier decomposition and logarithmic transformation. Then, the reservoir water elevations are simulated based on the dam-reservoir operation model. According to the reservoir water elevation series, the overtopping occurrence would finally be counted as a binary variable. Thus, for multiple simulations, the frequencies of overtopping occurrence are counted and the probability is calculated as the final simulation outputs.

The main idea of IS is to make the occurrence of rare events more frequent by carrying out the simulation under a different probability distribution and to estimate the probability of interest via a corresponding likelihood ratio (LR) estimator. According to the proposed CMC simulation approach, the efficient ISMC simulation framework is proposed. Detailed information and the improvement part are shown in Figure 6.

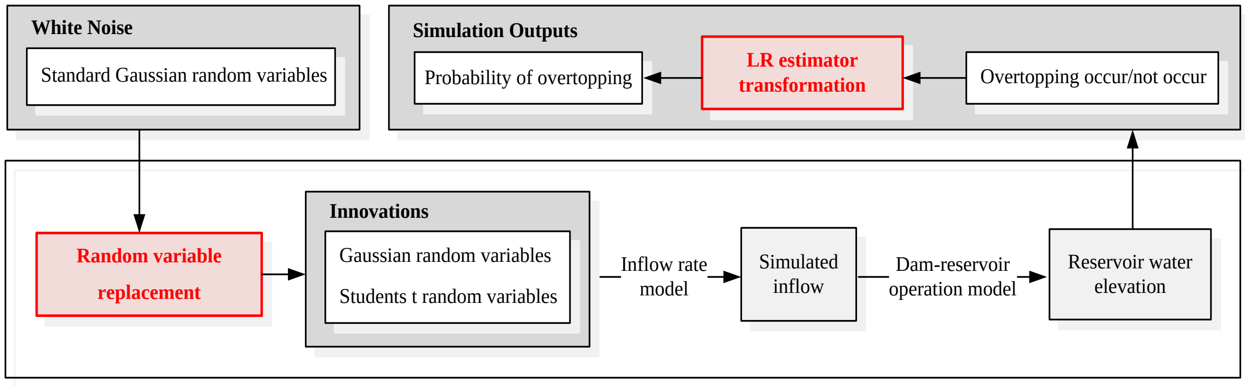

Figure 6. Framework of ISMC simulation for overtopping risks estimation

It is the same as for the CMC simulation: a standard Gaussian random series is also generated with the same length of a given simulation period at the start of simulation for one time. Each element within the series is generated i.i.d. Then, a transformation has been performed to make the series follow the selected new probability density. Based on the updated random variables, the series of Gaussian random variables or Student's t random variables are generated with the adjustment parameters from inflow hydrograph model. The simulated future inflows are reconstructed as a following with the seasonal cycle added back. Then, the reservoir water elevations are simulated based on the dam-reservoir operation model. According to the reservoir water elevation series, the overtopping occurrence would finally be counted as a binary variable. The LR estimator is also calculated based on the proposed new variable density. Finally, the frequencies of overtopping occurrence are counted and the probabilities are reached as the simulation outputs.

6. Conclusions

Results of the overtopping risk estimation for both the CMC and ISMC simulations demonstrate that the proposed ISMC approach could not only improve the estimation accuracy, but also save the computational resources at the same time. This research addresses the natural stochastic characteristics of the dam-reservoir system, such as the reservoir inflow rate and the system operation process. Two major contributions could be concluded from this study: 1) the industrial contribution to the dam-reservoir system, and 2) the theoretical contribution to the rare event simulation on infrastructure systems.

From the industrial perspective, the final estimation results of overtopping probability would be used as importance indexes to guide the future dam safety investigations and studies. Based on the existing dam-reservoir system design, knowing the corresponding overtopping probability would not only inform the decision maker potential loss risks, but also supplement their knowledge and judgement on necessity of renovation and improvements. The proposed modeling and simulation procedures are also compatible if changing the precipitation settings or the operation rules

From the theoretical perspective, the proposed methodology of ISMC simulation is reasonably robust and proved to improve the overtopping risk estimation. The smaller variance of simulation results and the less computational elapsed time, expand the application of the Monte Carlo technique on evaluating rare event risks for infrastructures.

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Authors Contact Information

*Corresponding author: Qianli Deng (Shally)

Tel.: +1 202 285 4227

E-mail: dqianli@gmail.com

Adiel Komey

Tel.: +1 202 250 4764

E-mail: adielkomey@gmail.com

Dr. Gregory B. Baecher

Tel.: +1 202 285 3902

E-mail: gbaecher@umd.edu