2017

Managing Scheduling Risk due to Geotechnical Uncertainty Using Linear Scheduling

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Every project is most vulnerable to risk at its initial stages when the uncertainty and potential impact in its outcome is at its highest level, and the earliest risk in a construction project is typically the geotechnical risk. The risk of differing site conditions must be carefully analyzed using as much information as possible to develop a project's initial estimates and schedule. This paper focuses on the scheduling aspect of geotechnical risk and proposes an alternative method for identifying and managing it. The alternative method is compared to the traditional format that involves expert interpretation of subsurface information in order to communicate the process properly. The alternative is based on linear scheduling that graphically represents a schedule along with the location of activities. A model was developed using this tool and incorporating stochastic simulations in a way that the impact of geotechnical risk is assessed as a function of the expected underground conditions, which can be displayed directly in the linear schedule. The paper demonstrates its efficacy by applying the linear scheduling model to a case study project from the Panama Canal Expansion Program. The analysis finds that the method effectively provides a better understanding of the risk management effort and introduces a way to incorporate variables into the assessment that otherwise would not be available for quick reference, such as the interpretation of the geological profile of the project site. The paper's contribution to the body of knowledge is to graphically connect the project's geotechnical profile with the linear schedule in a stochastic environment.

Disciplines

Construction Engineering and Management | Geotechnical Engineering

Comments

This is a manuscript of a proceeding published as Tapia, Ricardo M., Douglas Gransberg, and Ali Touran. "Managing Scheduling Risk Due to Geotechnical Uncertainty Using Linear Scheduling." Paper no. 17-01389. In *TRB 96th Annual Meeting Compendium of Papers*. Transportation Research Board 96th Annual Meeting. Washington, DC. January 8-12, 2017. Posted with permission.

MANAGING SCHEDULING RISK DUE TO GEOTECHNICAL UNCERTAINTY USING LINEAR SCHEDULING

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Final accepted manuscript; Published as:
Tapia, R.M. Gransberg D.D. and Touran A., “Managing Scheduling Risk Due to Geotechnical Uncertainty Using Linear Scheduling,” Compendium, 2017 Transportation Research Board Annual Meeting, Paper 17-01389, January 2017.

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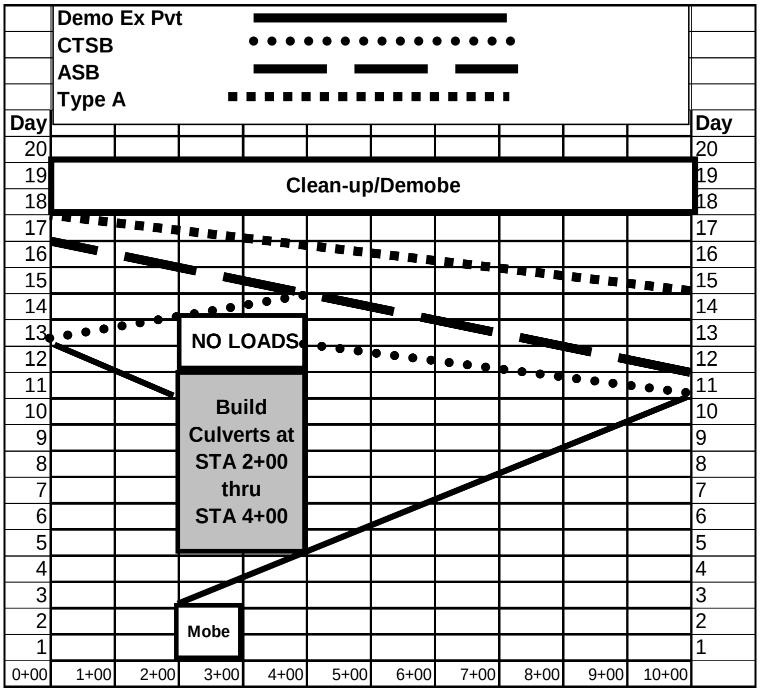
Every project is most vulnerable to risk at its initial stages when the uncertainty and potential impact in its outcome is at its highest level, and the earliest risk in a construction project is typically the geotechnical risk. The risk of differing site conditions must be carefully analyzed using as much information as possible to develop a project's initial estimates and schedule. This paper focuses on the scheduling aspect of geotechnical risk and proposes an alternative method for identifying and managing it. The alternative method is compared to the traditional format that involves expert interpretation of subsurface information in order to communicate the process properly. The alternative is based on linear scheduling that graphically represents a schedule along with the location of activities. A model was developed using this tool and incorporating stochastic simulations in a way that the impact of geotechnical risk is assessed as a function of the expected underground conditions, which can be displayed directly in the linear schedule. The paper demonstrates its efficacy by applying the linear scheduling model to a case study project from the Panama Canal Expansion Program. The analysis finds that the method effectively provides a better understanding of the risk management effort and introduces a way to incorporate variables into the assessment that otherwise would not be available for quick reference, such as the interpretation of the geological profile of the project site. The paper's contribution to the body of knowledge is to graphically connect the project's geotechnical profile with the linear schedule in a stochastic environment.

Introduction

Linear scheduling is an alternative production-based tool for managing schedules in projects that is particularly useful in the heavy civil construction industry. This method shows time and space in the same graph, in a way that makes it easy to identify and resolve conflicting production rates of the activities in their spatial representation (*1*). The graph consists of plotting time in the "Y" axis and location or distance in the "X" axis in any applicable unit represent activities as lines or blocks. Therefore, the duration, physical length and production rate of any activity can be quickly identified in the chart. The typical linear schedule format is shown in Figure 1 using lines with different patterns and blocks to identify activities and/or crews. This configuration provides an advantage over the more widely used Critical Path Method (CPM), which only displays production rates as a parameter inherent to the activity duration (*2*). CPM has been shown to be inadequate as an accurate representation of production in the construction industry (*3*) and does not show physical-spatial conflicts directly.

Schedule risks are modeled in the construction industry by incorporating uncertainty as a variance in the project's activities durations based on an educated analysis of the potential for an activity to exceed its planned duration. Durations are modeled as random variables and the project duration is then calculated analytically or using a simulation approach. As an example of this stochastic approach, PERT assumes that the critical path is the path with le largest mean value. It should be noted that when uncertainty is incorporated into the project, this may not always be the case, as the critical path can change when impacted by risks (*4*). The inherently abstract nature of the risk analysis effort makes it difficult for a person who was not involved in the process to actually comprehend the analysis and the impact of risks.



Stations 1 Station = 100 linear feet

Figure 1 Linear scheduling for hypothetical highway rehabilitation project (Lopez del Puerto and Gransberg 2008).

Linear scheduling is production-based rather than CPM's activity basis and as a result has been found to be practical for understanding the impact of changes in production rates (*5*). By quickly identifying production conflicts and representing a physical dimension in a single chart, it has the potential to show conflicts and critical path shifting that arise when risks are incorporated into a complex schedule. Therefore, representing risks in this format creates an opportunity for increasing the understanding and utilization of risk analysis efforts in the scheduling knowledge area of project management.

The concept of using linear scheduling for representing risks is applicable to any activity in a project that follows a linear path, for any given risk. For the purpose of this paper, and to better explain the benefits of having location information displayed graphically, the geotechnical risk will be assessed in a real case study baseline analysis. The impact of this risk correlates directly with the geological information included typically in construction contracts, which can be easily represented in a linear schedule to demonstrate the utility of having the location dimension available in the chart. This creates the opportunity for a better risk allocation and impact assessment along with identifying potential mitigation actions or re-adjustments to the model.

Background

Linear scheduling is not a new method, it has been used in the industry since the 1950's (*6*) mainly for highway construction by heavy civil contractors in the United States (*7*) and, at its beginnings, it was also called the Line of Balance Method (*8)*. Once computing systems became widely available, this method was replaced by the CPM solutions that are the mostly common used tools today, mainly because linear scheduling was considered a manual method against its high-speed computational rivals. Despite the ubiquitous use of CPM, it has some limitations when it comes to comparing production rates between activities. CPM also ignores changes in productivities when analyzing concurrent delays (*5*) and cannot ensure continuous resource utilization easily (*9*). This makes it difficult to integrate the CPM scheduling tools with the risk analysis effort in order to communicate the impact of risks effectively.

Schedule risk analysis is typically performed starting from the format that a CPM tool displays, which is basically a table organized by the Work Breakdown Structure of the project accompanied by a bar chart or Gantt Chart. Maintaining the structure of the schedule with all its constraints and relationships and incorporating probability distribution functions into the activities durations using a stochastic model (*10*). This process is done either integrated in the CPM scheduling tool or imported into a stand-alone package. Although the stochastic model maintains and uses all the parameters of the schedule, the results are typically shown in a separate graphical representation, such as tornado graphs or displaying the resulting probability distribution function for the overall project duration.

This way to show the results is adequate in most cases but it requires knowledge of the process and is not intuitive to a person that is not familiar with the details of the project or the risk analysis effort, which is typically the case for the stakeholders that may be the ones to approve any required mitigation action. Therefore, communication of the risk analysis results must be as clear as possible without relying too much in the detailed technical and mathematical aspects of the effort.

The most significant strength of linear scheduling over CPM is the visualization of the schedule and its ease of communication (*11*). Therefore, by being able to better represent production and location of activities, linear scheduling provides an advantage over CPM in analyzing and communicating changes in production, which makes it possible to represent the impact of the risks in the same chart where the schedule is, so the effects of the analysis are depicted immediately, and solutions that potentially would not be apparent in the conventional method could be identified.

Several studies have been performed in the past to automate the process and incorporate uncertainty in linear scheduling. Harmelink (*7*) developed a model to create a linear schedule based on CAD software which also determines the controlling path of a linear schedule (*12*). El-Sayegh (*13*) created deterministic and probabilistic estimates to produce a linear schedule. Also, linear scheduling has been used to create models for predicting changes in production rates due to time and the location dimension of a project (*14)*. These studies provide a foundation for further development of the method, including this research.

Methodology

The analysis that this paper presents consists of using linear scheduling to provide a more intuitive risk assessment tool than the traditional outputs from stochastic simulations such as tornado graphs or probability/cumulative density functions. Based on the same fundamental calculations as traditional risk modeling techniques, a new risk assessment model is proposed by incorporating a different visualization scheme in order to make it easier for stakeholders to assess and understand the risks and their impacts in a project schedule. The model is created to illustrate how a stochastic analysis of the individual activities durations can be represented in a linear scheduling format. This creates the opportunity to identify physical and logical conflicts arising from the impact of risks in the schedule in a visual manner, which helps in understanding the effect of risks in the project schedule more intuitively.

The risk analysis is first performed using Monte Carlo simulations to incorporate uncertainty into the duration of the project activities (*15*). In order to achieve that, every risk identified in the project must be quantified in terms of its impact in the duration of the activities that are going to be impacted. Since the analysis is based on a Monte Carlo simulation, a probability distribution function is assigned to the impact of the risks, which are multiplied by their probability in order to obtain the expected value in terms of duration. The impacted activity duration is then represented in a linear schedule format as additional lines with a different shade or color than the original duration.

In that scheme, the impacted duration can be depicted as several lines representing different confidence intervals for the risk impact. This creates the advantage of not only representing the impact of a risk in the schedule itself, but to represent a sensitivity analysis for the different confidence intervals that can be selected for specific risks. A decision maker could prefer to assume more risk by choosing a lower confidence interval if a conflict is identified, giving the opportunity to have a tangible justification for choosing a confidence interval in the risk assessment process. This degree of confidence is important for establishing a project's schedule contingency (*16*).

By identifying the activities that create additional logical or physical conflicts with their successors due to the impact of risks, mitigation actions can be tailored to specific activities or locations in the project based on supporting information that can be introduced in a linear schedule format. However, the stochastic simulation of risks in a project must be performed by combining the effects of risks in all the activities in the schedule at the same time to produce an overall impact to the completion date. This method does not intend to replace that effort, but provides an additional tool for deciding the parameters used to model risks in specific locations or time in a project schedule.

It is important to note that, due to the nature and underlying assumptions of linear scheduling, this method works best for risks that impact the production rates of activities; and that impact is assumed to be linear along the physical length of the activity. Risk events can also be included in the analysis but there is no additional benefit from using this method when risks are events not related to changes in production rates.

Having the model built, a validation process is performed with an actual project as a case study to demonstrate the linear schedule representation of the project risks and their impact on the project schedule. The overall results are expected to be the same, but the representation of the output will be evaluated as a communication tool for understanding the impact of risks in each specific activity and to identify any immediate logical or physical conflicts due to risks -if any- that could be easily avoided if identified.

Linear Scheduling Risk Representation Model

In order to represent risks in the linear scheduling format, a spreadsheet was built using commercial software. The impact of the risks and their probabilities are tied to specific activities in the schedule. The impact values of the risks are modeled within the spreadsheet using Monte Carlo simulation software to create a stochastic simulation. In order to simulate the uncertainty, more than one value must be entered in the model in order to represent the behavior of the risks either historically or within estimated ranges from a subject matter expert.

For the purpose of illustrating the process, three-point estimation from subject matter experts was assumed to be the input and Optimistic, Pessimistic, and Most Likely values are obtained. Another assumption is that a triangular distribution function will be used to model the variation. This distribution function is deemed appropriate to represent the skewness in the perception of the risks. Regardless of these assumptions, the methodology can work with any distribution function that better represents the behavior of the source of information.

Having all the information of the risk impact and the stochastic model run to a proper number of iterations to fit the function, the activities of the schedule are then represented in a scatter chart. In order to compare the impact of risks with the original schedule, the activities are plotted using both their original durations, represented as black lines, and their impacted durations at different levels of confidence, represented as colored lines.

Hypothetical Example

A hypothetical project has six sequential activities both in time and location, all with the same duration of 10 days and length of 200 meters. Additionally, assume that all of them are affected independently by a risk with a 50% probability of occurrence and the following estimated impacts in time: Minimum Impact = 5 days; Maximum Impact = 20 days; and Most Likely Impact = 10 days. These values are then introduced in the model as input for a triangular probability distribution function. If the desired levels of confidence in the linear schedule are 50%, 60%, 70%, 80%, 85%, 90%, 95%; the risk impact will be represented as a spectrum of lines next to each activity corresponding to each of the levels of confidence. The effect of risks on each activity is modeled independently from the cumulative impact carried from its predecessor, i.e., the original start dates of the analyzed activities are maintained. This intends to show how the risk impacts each activity in the original schedule to provide insight on how the activity impacts its location-based successor. The result of this hypothetical model is the chart depicted in Figure 2.

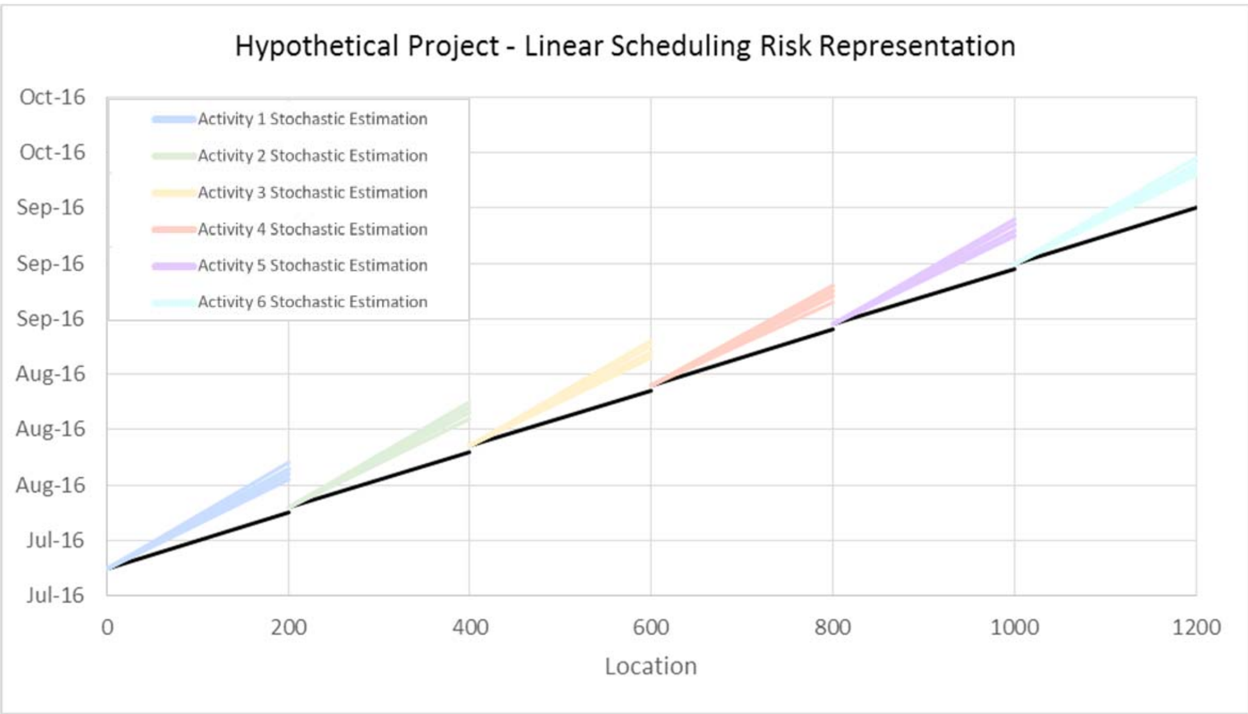


Figure 2 - Hypothetical Linear Schedule with risk representation

The hypothetical example serves a way to illustrate how the risks are represented in the proposed format, but it’s not intended to be an illustration of a real construction schedule. In a real construction schedule in which linear scheduling is useful, additional activities will most likely occur in the same locations (or with different physical lengths) but in different time, with dependencies established by a sequence of logic, making a tool like the one proposed in this paper useful by increasing the understanding of how the risk in one activity impacts the possible start of a subsequent activity.

If a subsequent additional activity is expected to be performed at the same space and time as the one where the spectrum of risk impacts is represented in the chart, a conflict between the two activities will occur if the risk is realized. If conflicts occur due to the risks, several actions can be taken to mitigate or avoid its impact, some of them are detailed as follows:

1. Increase production by assigning more resources to the high risk activity, thus reducing its duration to accommodate for the potential impact of realizing the risk.
2. Modify the logic of the schedule to avoid the risk impacting the critical path of the project.
3. Allocate float, if any, to the activity with potential occurrence of a risk-induced conflict.
4. Analyze the model's sensitivity to confidence interval selected for the risk simulation.

In order to assess the effectiveness of any of the above mitigation actions, supporting information regarding the project schedule structure and those conditions that might influence the activities is required. For most risks, linear scheduling provides a way to display such information in the same chart, promoting expeditious decision making, as well as providing a visual explanation of potential risk impacts.

Panama Canal's Borinquen Dam Example.

The following section will illustrate the proposed model with an example from an actual project, the Borinquen Dam at the Panama Canal Expansion program. This project had extensive risk analysis during its execution and the schedule has been studied by the authors to make reasonable assumptions to simplify the model to fit the TRB paper limitations. It is also important to note that the primary author was the cost and schedule control engineer for the Panama Canal Authority during the construction project. Thus, the simplifying assumptions are made from in-depth knowledge of the project. The Borinquen Dam is part of the $5.3 billion Panama Canal Expansion Program. It is a 2.3-kilometer long rockfill dam with a residual soil impervious core and several zones for filters and blankets. It features extensive foundation treatment works and a 16-meter deep grout curtain. The project has been recently completed and it has been subject to a number of changes due to the occurrence of identified risks. The Panama Canal Authority performed monthly risk assessments of this project during its entire life time and continuous monitoring was enforced in order to take mitigation actions as soon as it was possible.

For the purposes of this paper, the geotechnical risk is analyzed by incorporating the stochastic simulation of the duration uncertainty associated with geotechnical-related risks identified in the project's risk register on the baseline schedule in a linear scheduling format. Additionally, the interpretation of subsurface investigation included in the contract documents is incorporated into the chart at the "x" axis to provide a reference for further assessment of the risk impact and mitigation actions. The interpretation is presented in a color code format that derives from the geological profile in the dam's foundation alignment, where the color red represents 'severe conditions', yellow represents 'adverse conditions', and 'good conditions' are represented by the color green. This interpretation was performed by Canal Authority experts of the initial subsurface conditions. As this is a planning tool, it is based on preliminary studies, acts as a baseline for all the activity duration estimates. A segment from the geological profile of the project and the superimposed color code is shown on Figure 3 as a conceptual illustration:

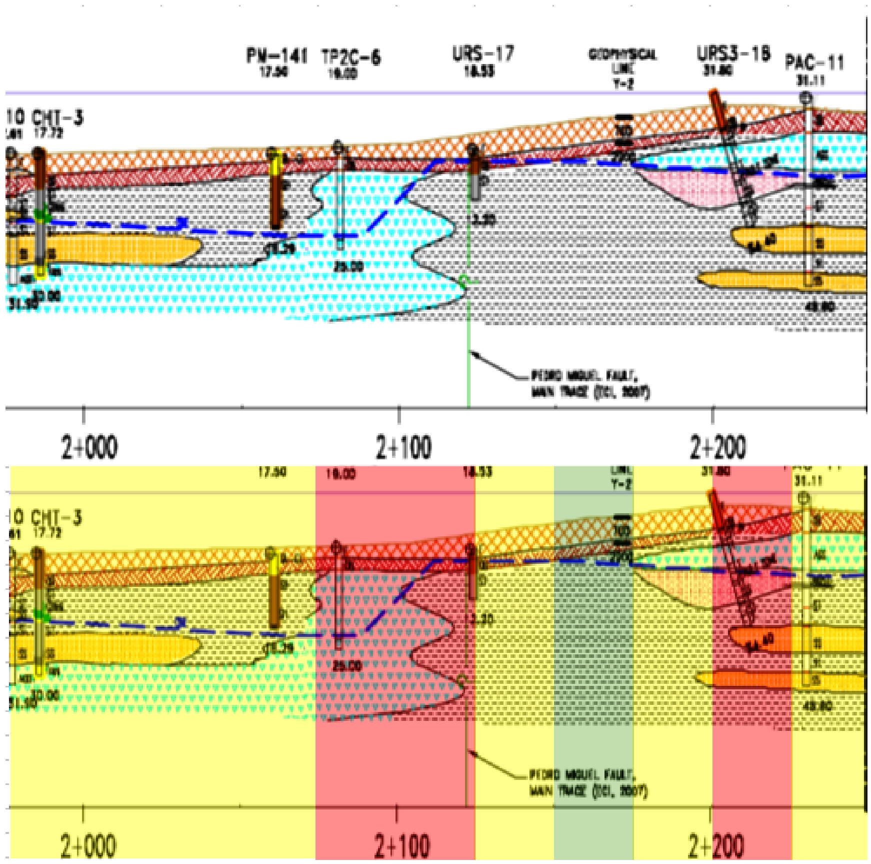


Figure 3 – Color coding for a section of the Borinquen Dam 1E foundation geological profile.

To demonstrate the method, two critical activities are selected from the schedule in five summarized work fronts along the entire dam to make the chart readable in a paper format, while maintaining the logic, durations and location true to the project baseline schedule. The first activity selected for this case is the construction of a grout curtain below the foundation of the dam, which is highly affected by geotechnical conditions at the site; and the second activity is its successor: the construction of the embankment's impervious core. The details of the selected activities are shown in Table 1 as follows:

Table 1 - Activities from the Borinquen Dam Baseline Schedule

Activity	Crew #	Duration (days)	Start Date	Finish Date	Start Station*	End Station*
Grout Curtain 1	Grout-1	175	19-Jun-11	11-Dec-11	0+455	1+000
Grout Curtain 2	Grout-2	175	19-Jun-11	11-Dec-11	2+800	2+400
Grout Curtain 3	Grout-1	175	12-Dec-11	4-Jun-12	1+000	1+400
Grout Curtain 4	Grout-2	175	12-Dec-11	4-Jun-12	2+400	2+000
Grout Curtain 5	Grout-1	142	5-Jun-12	25-Oct-12	1+400	2+000
Embankment 1	Bank-1	181	2-Aug-11	30-Jan-12	0+455	1+000
Embankment 2	Bank-2	181	2-Aug-11	30-Jan-12	2+800	2+400
Embankment 3	Bank-1	181	13-Feb-12	12-Aug-12	1+000	1+400
Embankment 4	Bank-2	181	13-Feb-12	12-Aug-12	2+400	2+000
Embankment 5	Bank-1	109	13-Aug-12	30-Nov-12	1+400	2+000
* Stations are shown in metric stationing.						

The representation of the activities in the linear schedule format is depicted in Figure 4, the color code from Table 1 will be maintained as a quick reference of the activities in the linear schedules, and a similar format must be used when this method is applied due to the complexity of construction schedules and the visual nature of the tool. To clarify, Figure 4 shows that on June 19, 2011 the Grout-1 crew starts at Station 0+455 working toward the center of the dam while the second grout curtain crew (Grout-2) starts on the opposite end and works toward the center at the same time.

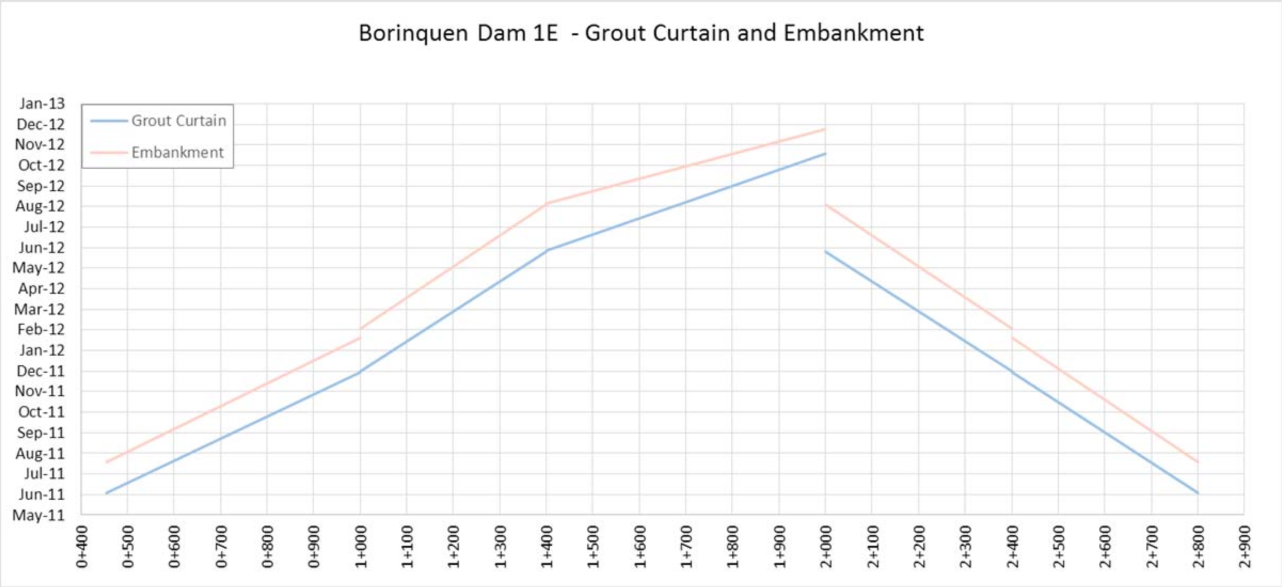


Figure 4 – Simplified Borinquen Dam Activities in the linear scheduling format.

In order to illustrate the impact of risks in the schedule using this format, the risks shown in Table 2 were selected from the Borinquen Dam risk register used in the project.

Table 2 - Selected risk events with their associated probabilities and impacts.

Risk Event	Activity to Impact	Probability	Minimum Impact (days)	Maximum Impact (days)	Most Likely Impact (days)
Variation in production rate for grouting	Grout Curtain	50%	-21	175	0
Variation in embankment production	Embankment	50%	-40	40	0

Once all the risks are quantified with their three-point estimates and probabilities, the stochastic model can be built and the values associated with different confidence intervals can be obtained and plotted in the linear schedule. The selected confidence intervals are the same as the ones used for building the hypothetical linear schedule in Figure 2, and the color code for the impacted activities is the same as in Table 1, while the non-impacted activities are represented as black lines. Additionally, the soil profile color codes from Figure 3 are added to the x-axis to provide a third point of visual reference. The resulting linear schedule is shown in Figure 5 as follows:

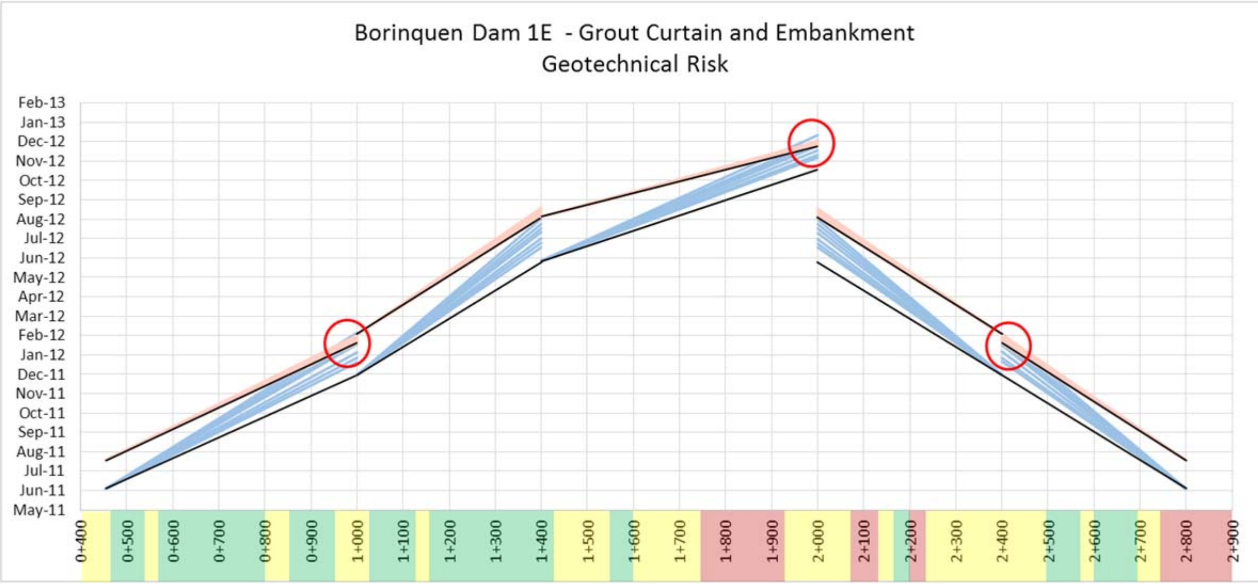


Figure 5 - Stochastic linear schedule for the Borinquen Dam

The points in time where realized risk could create activity conflicts are shown by the red circles in Figure 5. These three spots are points where the grout curtain activity's spectrum of potential risk shown in blue overlaps with the scheduled start of the subsequent activity (black line). That means the risk associated with the grout curtain for an individual activity can potentially create a delay in the subsequent activity at that location and set back the entire schedule if the identified risks are realized. To analyze the impact of each individual risk in the entire schedule, every start and finish date of subsequent activities must be recalculated while maintaining the logic and resource allocation from the baseline assumptions. The colored spectrum of lines in each of the segments shown in Figure 5 represent the initial step of that recalculation as if each segment were to be analyzed separately. This provides information regarding the degree in which the risk associated to each activity contributes to the cumulative delay due to location conflicts, which is important information that cannot be derived when analyzing the overall impact to the schedule by recalculating the start and finish dates of all the activities. As shown in Figure 5, some sections of the project contribute more than others in the overall delay due to direct conflicts with their successor activity in terms of location, not just the cumulative delay carried from previous activities.

Knowing this the scheduler can consider taking corrective actions to mitigate the risk of delay. Among the possible remedies would be to add resources to the grout curtain crews and increase their production rates to the point where the overlap no longer exists, essentially planning to crash the activities that begin at stations 0+455 and 2+800 to create enough float to be able to reach station 2+000 before October 25, 2012, which permits the embankment to be completed as scheduled by November 30, 2012. A second possibility could be to reorient the sequence of work for the Grout 1 crew by having it start at station 2+000 where the most difficult soil conditions exist and proceed to station 0+455. This option would have both grout curtain crews working in the worst soil regimes where production rates would be expected to be lower at the start of the job. Then once each crew passed through the red zones shown in Figure 5, the schedule could be reassessed to determine if crashing of subsequent grout curtain activities is necessary to complete on time.

Perceiving the individual impact of risks graphically in the schedule as shown in Figure 5 permits the following conclusions to be drawn:

1. The geotechnical risk has the potential to impact the project's critical path and overall duration due to its impact on production rates.
2. From the geological interpretation displayed in the horizontal axis in color code, it can be observed that there are three different geotechnical conditions according to the preliminary studies. Each soil condition will impact the production of the grout curtain crews and should be considered in the original duration estimates. This also means that the exposure to risk is not the same across every section of the project. Therefore, the geotechnical-related risks should be treated according to the expected conditions in order to avoid over or under estimating the risk and its impact on the project.
3. The spectrum of confidence levels in the example schedule were selected for convenience. Hence if information is available, an expected probability could be associated with each of the three soil conditions interval, allowing the impact of risk to be reassessed. In the example, if the desired level of confidence for each soil condition could be capped at 70%, the impact of the realized risk in a specific section would not cause an appreciable delay in the project completion.
4. Mitigation actions can be planned to minimize the impact of the risk by increasing planned production rates, changing the sequence of work, or crashing individual activities as described in the previous section. By representing the risks as changes in production rates in a linear schedule, an analysis can be performed to determine which activity should be accelerated to avoid delays on the project, since production rates are easily identified as the slope of the lines.

Conclusions

Due to the nature of stochastic modeling, risk analysis is typically one of the knowledge areas of project management that is not widely understood by all the stakeholders involved in a project, and the results of the analysis are sometimes underestimated when there is not a comprehensive understanding of the process. By incorporating linear scheduling concepts in the effort, the details inherent to the project planning and execution are integrated into the results of the analysis, making the assessment a visual one, which is hopefully more intuitive and easier to interpret by stakeholders not well-versed in risk-based scheduling.

As shown in this paper, linear scheduling provides an effective format to analyze the geotechnical risk construction projects by correlating the expected/actual site conditions with the schedule and the risk assessment effort. This quality makes it possible to tailor the assumptions used in the risk analysis model to specific activities or locations, and to make adjustments to the logic or production rates based on the identified impact of each risk.

The Borinquen Dam example illustrated the applicability of the concept and can act as a simplified reference which is provided for further implementation of the method. The fundamental value of the method was demonstrated as a seminal example of the analytic capabilities derived from the graphical nature of linear scheduling.

This method should be applied to projects that follow a linear path such as roads, bridges, pipelines or dams in order to maximize its efficiency. Applying this method to non-linear projects rapidly increases the complexity and makes the analysis more abstract, diminishing the benefits that result from an easy-to-follow graphical tool, which its primary advantage over conventional risk analysis methods.

The complexity and number of activities or desired confidence levels that can be analyzed with this method depends purely on the ability to easily interpret the results. The example used a reduced number of activities to clearly communicate the concept in this paper. However, there is no theoretical limitation beyond that found in the software platform used to develop the linear schedule. Given the computing capacity, the risk analyst can apply the principles described in this paper to evaluate the combined effect of risks on the overall project or at a lower level, the risks in several subnets of a schedule can also be produced and integrated.

References

(1) Lopez del Puerto, C., and D.D. Gransberg. “Fundamentals of Linear Scheduling for Cost Engineers,” *Transactions, AACE, International, Toronto, Ontario, Canada,* 2008, PS.05.01-PS.05.08

(2) Marchman, D.A. "*Construction Scheduling with Primavera Project Planner* ®". Delmar Publishers, Albany, NY, 1998, pp. 97-118.

(3) Lee, J.-S., and J. E. Diekmann. “Delay analysis considering production rate.” Canadian *Journal of Civil Engineering,* Vol. 38, No. 4, 2011, pp. 361–372.

(4) Nasir, D., B. McCabe, and L. Hartono. “Evaluating Risk in Construction–Schedule Model (ERIC–S): Construction Schedule Risk Model.” *Journal of Construction Engineering and Management*, Vol. 129, No. 5, 2003, pp. 518–527.

(5) Lee, J.S. “Delay analysis using linear schedule in construction,” *AACE 403 International Transactions,* Annual Meeting, Vol. 404, 2007, pp. 1-6.

(6) Johnson, D. W. "Linear Scheduling Method for Highway Construction." *Journal of the Construction Division*, Vol. 107, No. 2, 1981, pp. 247-261.

(7) Harmelink, D.J. “Linear scheduling model: The development of a linear scheduling model with micro computer applications for highway construction project control”, *PhD Dissertation, Iowa State University*, Ames, Iowa, 1995.

(8) Arditi, D., and M. Z. Albulak. “Line of Balance Scheduling in Pavement Construction.” *Journal of Construction Engineering and Managemen*t, Vol. 112, No. 3, 1986, pp. 411–424.

(9) Harris, R. B., and P. G. Ioannou. “Scheduling Projects with Repeating Activities.” *Journal of Construction Engineering and Management,* Vol 124, No. 4, 1998, pp. 269.

(10) Ke, H., and B. Liu. “Project scheduling problem with stochastic activity duration times.” *Applied Mathematics and Computation*, Vol. 168, No. 1, 2005, pp. 342–353.

(11) Yamín, R. a., and D. J. Harmelink. “Comparison of Linear Scheduling Model (LSM) and Critical Path Method (CPM).” *Journal of Construction Engineering and Management*, Vol. 127, No. 5, 2001, pp. 374–381.

(12) Harmelink, D. J., and J. E. Rowings. “Linear scheduling model: Development of controlling activity path.” *Journal of Construction Engineering and Management*, Vol. 124, No. 4, 1998, pp. 263–268.

(13) El-Sayegh, S.M. “Linear construction planning model (LCPM): A new model for planning and scheduling linear construction projects.” *Ph.D. thesis, Texas A&M Univ*., College Station, TX, 1998.

(14) Duffy, G. A., G. D. Oberlender, and D. H. Seok Jeong. “Linear Scheduling Model with Varying Production Rates.” *Journal of Construction Engineering and Management*, Vol. 137, No. 8, 2011, pp. 574–582.

(15) Khedr, M. K. “Project Risk Management Using Monte Carlo Simulation.” *AACE International Transactions*, 2006, pp. 1–10.

(16) Mulholland, B., and J. Christian. “Risk Assessment in Construction Schedules.” *Journal of Construction Engineering and Management*, Vol. 125, No. 1, 1999, pp. 8–15.