NAC **Executive Insights**

Laws of Improbability

Key Points

- The Law of Inevitability poses that something must happen.
    - As a corollary, we have Borel's Law states sufficiently unlikely events are impossible.
    - In evaluating the risks on large projects, events that appear sufficiently unlikely are ignored, treating them as Borel would, as impossible. Are these ignored events truly as unlikely as perceived?
- The Law of Truly Large Numbers says that with a large enough number of opportunities, any outrageous thing is likely to happen. The improbable is not impossible.
- The Law of Selection says one can make probabilities as high (or low) as desirable if one chooses after the event.
    - Large projects are characterized by tens of thousands of assumptions, most never written down. Many of these assumptions are based on perceptions of values or their trajectory.
- The Law of the Probability Lever says that a slight change in circumstances can have a huge impact on probabilities.
- The Law of Near Enough states that events that are sufficiently similar are regarded as identical.
    - The Law of Near Enough impacts large projects where inadequate float exists in tightly coupled activities.
- The risk lens is somewhat opaque and perhaps even the models used are not well chosen.
- The results of large project performance indicate near enough is not good enough. Risk models must be revisited to effectively assess and manage risks in order to achieve the outcomes desired on large complex projects.

Introduction

In his book, *The Improbability Principle*, David Hand, former president of the Royal Statistical Society, provides a tour de force treatment of uncertainty and how improbable events happen, over and over again. It is a highly recommended read but not for the faint of heart.

In this Executive Insight the lenses described by Hand are used to look at large projects and their unacceptably high failure rates. Application of best practices would suggest these failures should be improbable or at least less frequent than reported failure rates suggest. If the industry repeatedly experiences the improbable, it is perhaps better that the improbable be understood. This will only become more important as projects and their settings become ever more complex.

The lenses can best be described as comprising a set of laws. Each will be examined here and how they shape the views on the failure of large projects.

The Law of Inevitability

The Law of Inevitability, in its simplest terms, says that something must happen. As a corollary to that law, we have Borel's Law[1] which says that sufficiently unlikely events are impossible.

In our evaluation of the risks large projects face we seek to identify and manage top risks. In the process we ignore events that appear sufficiently unlikely, treating them as Borel would, as impossible. But are these ignored events truly as unlikely as we perceive them to be?

Let's consider several highly impactful events that on first consideration might seem sufficiently unlikely as to consider them impossible within a project's context and time frame.

100-Year Storm: A 100-year storm is a weather event with a return period of 100 years. This does not mean that such a storm occurs regularly at 100-year intervals or that it will only occur once in a given 100-year period. Rather, a 100-year storm means that in any given year the probability of such a storm occurring is one percent. As project gestation and delivery times have grown, the cumulative probability of encountering such a storm during the project execution period has similarly grown[2]. This is perhaps one of the underappreciated aspects of large project development, namely, that the **extended project periods are risk aggregating**. When these periods are subject to delays, whether from permitting, agency approvals, design, or construction, the cumulative probability of observing this and many other risks during the project period similarly grows.

A closer look at the one percent risk is perhaps useful. In that rare one-year project, the probability of experiencing the risks during project execution (damaged equipment; destroyed work in progress; extended timeframes resulting in project delays) is one percent, independent of when such an event last occurred. On larger projects with a 10-year project periods, however, that risk has climbed for simplicity to 10 percent. (The cumulative probability of this risk materializing exactly once in the 10-year period is actually calculated as the probability of it not occurring in a given year raised to the nth power, where n is the number of years. In this example $(1.00 – 0.01)^{10}$ or 90.44%)

[1] Borel's law: events with a sufficiently small probability never occur. If an event is so improbable that it would not be in the entire history of the universe, then it is only rational – in practical terms – to regard it as impossible.

[2] This does not consider the fact that the intensity of the 100-year storm itself may be growing with global climate change.

A 10 percent risk of significant project impact is not a risk to typically ignore in risk analysis. In risk assessment, however, such an event may be considered as improbable and lost from the project's risk register and, importantly, not tracked and managed.

Extended Risk Consequence of Disruption: No activity is perfectly executed every time.

Something must happen. Even the smallest "off normal" performance[3] has the ability to impact (directly and indirectly) coupled project execution activities. This disruptive impact may have a range of values, and while the mean disruption may be infinitesimally small, it will not be in every case. Consider that a significant disruption from just "off normal" performance of an activity is extremely rare, so improbable that Borel would treat it as impossible. That is to say in the way of an example, such extensive disruptions from mere "off normal" performance happen only once out of every million executions of an activity.

Now think about large projects with 100,000 or more activities. The probability of experiencing measurable disruptions in the course of "normal" project execution grows measurably, even without a significant "event" risk that may have been considered in risk assessments. At a simplistic level, there is now a 10 percent chance of one activity's "off normal" performance leading to a significant disruption. This ignores the cascading impacts from consistent "off normal" performance that may be the result of poor planning and estimates (optimism bias as seen in Kahneman's[4] planning fallacy) or more systemic underlying issues (inadequate project alignment, labor skill levels or relations; general environmental conditions). It also ignores indirect coupling of constraints (*Executive Insight, Coupled Constraints*) that can greatly exacerbate the impacts of seemingly inconsequential "off normal" performance.

As other laws that Hand describes are presented here, it is not unusual for one or more of these laws to be acting on project performance simultaneously.

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[3] "Off normal" performance can range from relatively inconsequential (and more common) events such as a tool failing during use or wrong part supplied to rarer but more consequential events such as the failure of a contractor's bonding company (potentially cascading across multiple contractors on a project) to uncovering significant archaeological or human remains in an area long regarded as never having had such presences.

[4] D. Kahneman, *Thinking, Fast and Slow*, 2011

The Law of Truly Large Numbers

With a large enough number of opportunities, any outrageous thing is likely to happen. Large projects provide myriads of large pools of opportunities for outrageous things to happen. And they do. Some of these scaled opportunities found in large projects include:

- **Total project durations** (from planning through commissioning) sometimes measured in decades (a 30-year planning, permitting, development, design and construction project is not unusual for many large-scale public works projects. Perhaps this is a key driver in why large public projects seem to be particularly prone to large overruns and project delays in construction.)
- **Project schedules** with tens of thousands to a 100,000 or more activities
- **Work forces** that number from the thousands to tens of thousands to 50,000 or more
- **Miles** of welds
- **Thousands** of field connections
- **Thousands** of tons of modules and pre-fabricated assemblies moved, collectively, tens of thousands of miles
- **Countless thousands** of inspections

The improbable is not impossible (the Law of Inevitability). Something must happen. Things go wrong. The Law of Truly Large Numbers makes the opportunity for a risk to be realized a lot less improbable and in fact almost assures its occurrence. Even the possibility that the realized risk will be severe in its impacts grows as large projects scale into the realm of the Law of Truly Large Numbers. Current risk analyses do not adequately address this concern.

Two examples follow, first a rare event and then one less rare in the world of large projects.

Lost Shipping Container: Large projects focus on increasing logistical efficiency, using barcodes and RFID tags to provide better end-to-end tracking of cargo required at the project site. Additionally, shipment efficiencies are being sought through the use of standard shipping containers. Much of these containerized shipments will travel by ship at some point in the journey to the project.

Containers, however, get lost at sea. This happens through both routine losses (container overboard) and catastrophic losses (ship sinks). Are either of these a risk that has been considered and provided for? Is it something of concern?

From 2008–2013, annual shipping container losses at sea from all causes averaged 1,679 containers per year. This must be viewed in perspective. In 2013 there were approximately 120 million container shipments, resulting in a probability of a container being lost of 0.0014 percent. Not a high probability risk?

Now consider a large construction project where one might expect 1,000 containers. What is the probability one is lost at sea?

0.0014%	Probability that a shipping container will be lost at sea
99.9986%	Probability that a Given Container will not be lost
98.6097%	Probability that none of the containers is lost
1.3903%	Probability that one container is lost

The last figure, 1.39 percent, is not a large risk, but is much more measurable than first believed. One large military project involved the shipment of 80,000 containers. The probability of losing at least one at sea is a virtual certainty. The key question is what was in that container.

Now a more likely scenario is presented. Think about how well risks are provided for.

***Delayed Critical Component*:** In the previous project example, a container was lost at sea 1.4% percent of the time. In this example, consider the significantly delayed availability of a critical component required for a work activity. Its delayed availability will impact project sequence and will add to disruption and workaround costs.

Consider the case where one in a thousand critical components on a project is significantly delayed as defined here. To put this in context for a large project with 100,000 activities, it means that one in a hundred of those activities include a component critical to undertaking and completing the activity. This means the probability that a critical component is delayed is 0.1 percent or conversely that the probability that a given critical component is not delayed of 99.9 percent. On the project with 1,000 critical components (1 out of 100 activities requires a critical component), the following occurs:
The probability that at least one critical component is significantly delayed is over 63 percent.

0.10%	Probability that critical component is significantly delayed
99.90%	Probability that a given critical components is not significantly delayed
36.77%	Probability that none of the critical components is significantly delayed
63.23%	Probability that critical component is significantly delayed

If instead, one out of 10 project activities requires a critical component (there are now 10,000 on the project), the probability that at least one is delayed rises to essentially 100 percent.

The Law of Selection

The Law of Selection says probabilities can be as high (or low) as desired if one chooses *after* the event. Large projects are characterized by tens of thousands of assumptions, most never written down. Many of these assumptions are made based on perceptions of values or their trajectory. Sources for many other values assumed are mean values, yet they reveal nothing about extremes or distribution of values. In yet other cases, assumptions are based on adjusted performance, where extremes are thrown out. (Ignore the sinking of a container ship to arrive at a lower average number of containers lost annually in the earlier example). Below are two examples of how the Law of Selection can come into play and impact large projects, recognizing that these sometimes unconscious selections can come from multiple sources, combining for truly significant impacts on large projects.

***Folly of Averages*[5]:** In planning of large projects, average values are often used that are treated as constant throughout the project period. One of these constant average values often encountered is general inflation or other similar escalation factors. For simplicity, select the best estimate of what an average value may be over a project period and utilize that value constantly over the planned project duration. Such a selection can impact the outcome of a large project by considering three simple inflation cases. In each, the real rate of work performed is assumed to be constant in each and every year of a 10-year project and in all three cases the average annual inflation rate over the 10-year period is exactly three percent. The three cases include:

[5] NAC Executive Insight, Folly of Averages

• Constant three percent annual inflation rate
• Growing annual inflation rate; average of annual rates three percent
• Declining annual inflation rate; average of annual rates three percent

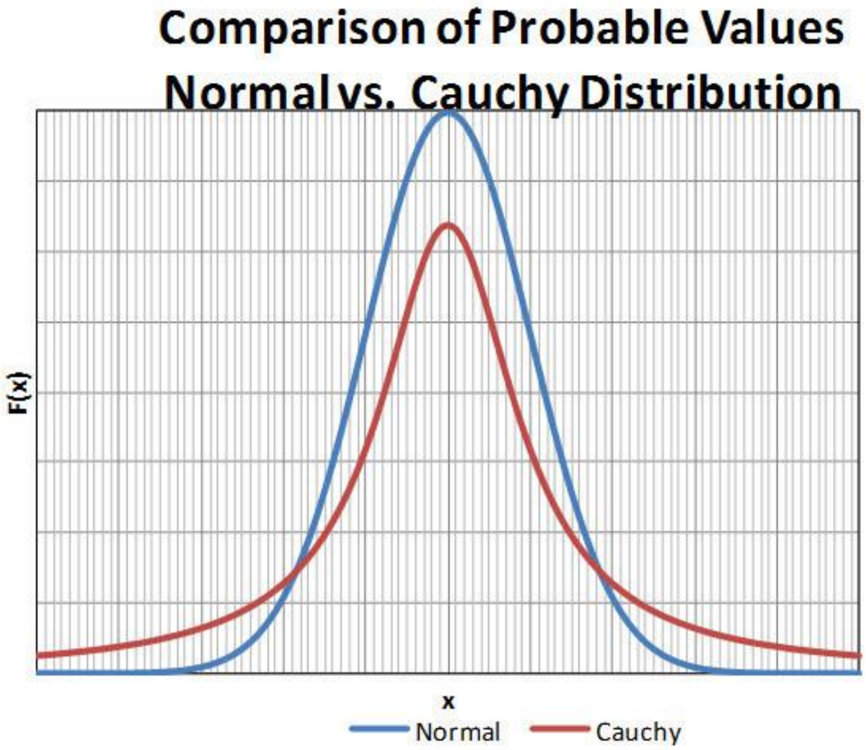
Taking timing of inflation rates into account can change the expected project cost by 3.3 percent in this simple example, just one of many selection decisions that focus on simplifying analysis.

***Fat Tails*[6]:** Large projects are complicated and often sophisticated endeavors. Improving the quality of time and cost estimates is often achieved by accounting for certain quantitative uncertainties in estimates. This is clearly a step in the right direction, but as the results of large project performance would suggest, not good enough. Perhaps some of the laws of improbability come into play here. Maybe the Law of Selection impacts the best efforts to address uncertainty of estimates in the risk analysis.

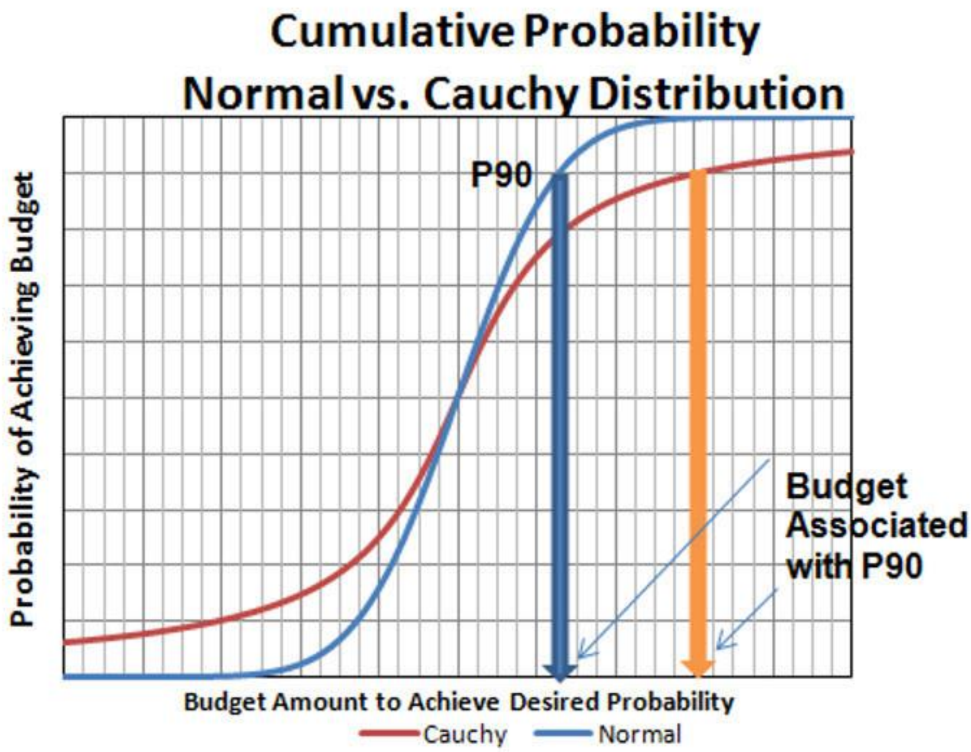
Now consider a given estimated value where a normal distribution around a mean value is assumed. Is the data set for calculating the mean chosen in such a way as to dismiss so called outliers? Or potentially more common, is a distribution around a mean that dismisses these outliers without any direct action other than the selection of the probability distribution itself. One place where these distribution assumptions come together with direct impact on the perception of likely (vs. actual) project performance is in project risk analysis.

Consider the typical case where a Monte Carlo analysis is run utilizing a normal distribution. Implicit is an assumption that extreme outliers are so improbable as to be impossible under Borel's Law.

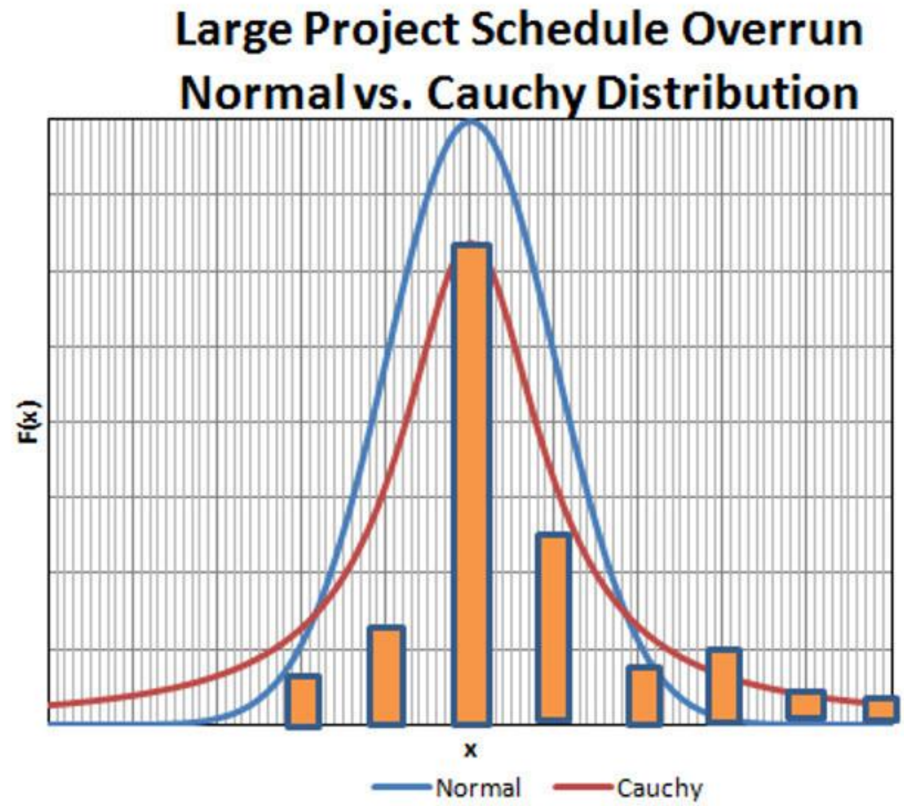
[6] NAC Executive Insight, Fat Tails



The normal distribution’s characteristic thin tails are contrasted with the thicker tails associated with the Cauchy distribution. It is in these thicker tails that one might expect to see Black Swans or even less exotic but extremely significant “off normal” events that combine for project failure in large projects. Consider these distributions from a slightly different perspective by looking at the cumulative probabilities. In order to achieve higher confidence levels (say P90), the Cauchy distribution and its inherent inclusion of the possibility of off normal events would include a significantly higher budget amount.



Finally, the results presented below represent the various improbabilities discussed in this paper in the "failed" performance of large projects. The figure shows the distribution of project schedule overruns for a sample of large industry projects. Note the better fit of the Cauchy distribution for overruns larger than the mean overrun. The fatter overrun tail better describes the "failed" project performance seen in large projects.



The stark difference in the views of the two distributions as it relates to improbable events should cause one to reconsider the choice of distributions for select parameters in the overall Monte Carlo risk assessments or at the very least confirm that the parameters being modeled actually vary as the normal (or other assumed) distribution would suggest.

Probability of the Improbable		
	Normal	**Cauchy**
5 sigma event	1 in 3.5 million	1 in 16
10 sigma event	1 in 1.3×10^{23}	1 in 32
20 sigma event	1 in 3.6×10^{88}	1 in 63
30 sigma event	1 in 2.0×10^{197}	1 in 94

The Law of the Probability Lever

The Law of the Probability Lever says that a slight change in circumstances can have a huge impact on probabilities. The focus on unconventional oil and gas development has its roots in hydraulic fracturing (1940s) and horizontal drilling using mud motors (1970s). It was the combination of these two technologies and their progressive improvement that led to the boom in unconventional oil and gas. The rapid advancement in shale development has had a tremendous impact on large scale oil and gas projects:

- Shifting the need for LNG terminals from import oriented to export oriented in the U.S., causing some projects to be canceled, new ones to move ahead, and impacting capital efficiency in a broad portion of the market.
- Shifting the nature of facilities to be constructed to handle these unconventional energy supplies and the locations and required supporting infrastructure for these projects.
- Indirectly influencing CAPEX costs of new oil and gas projects as energy, a significant cost component in new construction, dropped in price within the U.S.

Sharp global oil price drops driven by both supply and demand challenges have had significant impacts on large oil and gas projects, with a high percentage either cancelled or deferred.

In the first instance, the rapid adoption of a combination of two existing technologies fundamentally shifted a major portion of the large project market, while in the second instance policy decisions by OPEC[7] and the later COVID-19 pandemic had similarly extreme impacts. Preceding each event, the probability of energy independence by the U.S. was viewed as a highly unlikely scenario.

Now the probability lever comes into play in catastrophes, where a slight change leads to a broader dramatic change (Hurricane Katrina's impact of levees being overtopped that led to flooding of New Orleans); in observed domino effects (construction delays) or cascading failures (key supplier or subcontractor fails and brings down the prime); and a tendency to incorrectly estimate probabilities (for example, estimating a project risk based on prior experience or, conversely, underestimating those not experienced).

Two more examples show how a small change can have an extensive impact.

Details Matter**:** Today's large projects often require extensive welding and other highly specialized construction operations. Specifications for these specialized operations are often referenced in contract

[7] OPEC - Organization of Petroleum Exporting Countries

documents. It is not unusual, however, for the supporting documents, incorporated by reference, to not be similarly defined.

On one large project involving highly specialized operations, the base specification and version was referenced in the contract, but the acceptance test incorporated by reference did not contain a revision number or date. During construction, the acceptance criteria in the referenced document changed significantly such that the resultant construction that would have passed the earlier acceptance test could not meet the revised, more stringent testing and acceptance regime. This small change contributed to extensive cost and schedule overruns.

***Nuts and Bolts*[8]:** On a large project, the drive for capital efficiency resulted in a blanket policy for design optimization. It became a stated project goal. The result of a good idea out of control was a dramatic increase in the number of SKUs (stock keeping units), best represented by one hopper that contained eight different size nuts and bolts. The optimization by the design engineer to use smaller bolts wherever possible (since smaller bolts cost less than larger bolts) resulted in $157 in bolt savings on the hopper and over $30,000 in added labor and supply chain costs in this labor-short, extreme environment. Similarly, optimization of structural steel shapes to reduce steel tonnage resulted in 30 percent of major structural members being custom shapes with significant net addition to project costs despite the steel tonnage savings.

The Law of Near Enough

The Law of Near Enough builds on the prior four laws, which include the laws of inevitability, truly large numbers, selection, and the probability lever.

The Law of Near Enough states that events that are sufficiently similar are regarded as identical. This presents a challenge when ascertaining the root causes of near-miss safety events on large projects. While the near miss of a hand injury may be ascribed to putting one's hand into a tight space that can move, it is important to understand why the hand needed to be there (is it a design issue or a means and methods issue?); what causes the movement that puts the hand at risk (is the worker in an unsteady position or does the construction approach cause the movement or other?). We see the Law of Near Enough impact large projects, where inadequate float exists in tightly coupled activities. While durations in actual performance may be as near enough to be consistent with planned durations, late starts or completions can create a probability of disruption when the Law of Near Enough seems to have governed in assessing project risks the disruptive ripple effect through the project.

***Coupled Constraints*[9]:** Consider the situation where an activity not on the critical path begins late

[8] NAC Executive Insight, Nuts and Bolts of Engineering and Construction
[9] NAC Executive Insight, Coupling in Large Complex Projects

but near enough to the original plan to stay off the critical path. No problem? It will not be if that key resource it uses does not arrive on time for a critical path activity. The complexity of large programs masks a raft of hidden, coupled constraints that can then cascade. Near enough is not good enough. The complexity of large programs needs to consider the probability of disruption when the Law of Near Enough seems to govern assessing project risks.

Conclusion

The focus is often on the probable. Best efforts are made to account for the uncertainties likely to be encountered in project planning and risk provisions. Planning for dealing with the probable that has been underestimated, however, reveals the possibility of what is believed to be improbable. The risk lens is somewhat opaque. Perhaps even the models used are not well chosen. The results of large projects shows that near enough is not good enough. The world of complex projects is more like complex financial markets, catastrophic events, or analysis of fuzzy data, all of which benefit from "fatter tails" and consideration of the improbable. Large projects may not live in a neat Gaussian (that is, normal distribution) world. The improbable is not impossible, and the performance of large engineering and construction projects suggests that the execution of projects be revisited as well as the basis of planning and risk.

References

D.J. Hand, *The Improbability Principle*, 2014
D. Kahneman, *Thinking, Fast and Slow*, 2011
R. Prieto, *Theory of Management of Large Complex Projects*, 2015

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Bob Prieto was elected to the National Academy of Construction in 2011. He is a senior executive who is effective in shaping and executing business strategy and a recognized leader within the infrastructure, engineering, and construction industries.