Managing Risk with Innovative Deep Foundation Testing Solutions

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ABSTRACT

All construction projects have certain risk components associated with them. Effectively identifying and managing the various risks in any project are critical to a successful outcome. Deep foundations can represent a significant portion of the total project risk. The risk factors associated with deep foundations include safety, quality, foundation performance, cost, and schedule. There are many innovative foundation testing methods available that can help to mitigate these risks. This paper will discuss how foundation testing solutions can help lower the risks by accelerating the construction schedule, assessing the quality and capacity of the foundation, and thus eliminating some of the unknowns and reducing the overall cost to the project. These solutions will be discussed in detail along with selected case histories showing how innovative testing methods are used to reduce project risk.

INTRODUCTION

Risk encompasses many aspects of a construction project and affects all of the involved parties. The owner assumes the ultimate risk in developing any project, and achieving a quality product completing the project on time and within budget are of considerable importance. Failure to control quality and performance risks can lead to remediation, therefore affecting cost and schedule risks. The effect of these risks includes loss of reputation, a reduction in profitability, and may even result in bankruptcy. The engineer or designer assumes liability for his design and relies on a quality foundation installation. Failure to meet the performance requirements may result in foundation failure, perhaps loss of engineering license, to add to losses of standing and future works from his client. Contractors similarly want to install quality foundations to maintain their reputation and obtain future work. Design-build contracts are structured such that the engineer and contractor share their associated responsibilities and liabilities. It is in the best interest of all parties to complete the project satisfactorily so resources can be moved to the next project and maximize usage of personnel and equipment, which then maximizes profits.

Given the risks to the owner, the engineering representative, and the contractor, the control or inspection of the foundation becomes critical. Installation to a specified depth on the basis of only a soil investigation is well known to be imprecise and large factors of safety are required to mitigate the possibility of failure. This often results in overdesigns and excessive costs, while the possibility still remains that the imprecise design may be inadequate. Visual inspection of drilled foundations (drilled shafts, bored piles, ACIP piles, CFA Piles) are generally not possible in slurry constructed or augured foundations. When visual inspection is possible, often the inspector is over-tasked with the amount of information that needs simultaneous documentation. With the advent of electronic instrumentation, beginning in the 1960's and continuously improving through innovative techniques, it is possible to take measurements of deep foundation performance indicators to document their acceptability and hence their performance. Replacing primitive visual inspection with comprehensive targeted measurements reduces or eliminates the risks for a potentially flawed foundation.

MANAGING SAFETY

Workplace safety is paramount to a successful project. Jobsite injuries halt the progress of projects and lead to large monetary compensations to the victims. In extreme cases, a jobsite injury can result in a fatality. Innovative methods of inspection and testing can distance personnel from the zones of danger.

Top-down conventional static load tests (ASTM D1143) have a number of safety issues; tipping of stacked weights, reaction frame failures, lateral ejection of the jack stack elements due to misalignment, etc. Reading manual dial gages adjacent to the test pile subjects personnel to all of these hazards and often at the most critical times i.e., immediately after application of ever-increasing loads. This hazard can be mitigated by electronic sensors for both load and displacement. These sensors can transmit to a remote data recording system, using either wired or wireless connections, and then viewed and recorded at a safe distance from the load application. Bi-directional testing (ASTM D8169) utilizes load cells embedded in the lower portion or at the base of the shaft, locating the energy source below ground and therefore eliminating conventional loading apparatus and their associated dangers.

On large driven pile projects, dynamic testing (ASTM D4945) often reduces the amount of static testing. On smaller projects dynamic testing is often used in lieu of static testing for driven piles.

The sensors to measure the impact force and velocity can be and often are wireless and can be attached to the pile prior to lofting the pile. Wireless sensors allow the engineer to obtain measurements from far outside the radius of danger for pile driving, eliminating the safety risks associated with static testing.

Inspection of drilled foundation elements via in-hole manual entry is a method of the past and is generally disallowed. Base cleanliness is now assessed with remote methods of visual inspection or physically pushing a cone-like device to obtain quantitative load versus displacement measurements. Shaft excavation shape and verticality is now performed using manual calipers or electronic scanning techniques. Some of these tests require a tripod and winch system placed over the open excavation, with inherent risk, but more recent techniques allow the measurement sensing unit to be attached to the drilling stem or Kelly bar, with the data wirelessly transmitted to a tablet located a safe distance from the open excavation.

Most of the measurable variables associated with auger cast (ACIP) pile installation can be safely observed from the cab of the crane during their installation. Sensors can be mounted on the rig to monitor depth and grout volume to obtain the grout volume versus incremental depth which is displayed to and thus guides the rig operator. The use of automated monitoring equipment on transportation projects is described in the Federal Highway Administration Geotechnical Engineering Circular No. 8 “Design and Construction of Continuous Flight Auger Piles”. (GEC No. 8).

Evaluating the integrity of drilled foundation elements with thermal measurements is accomplished with automated collection of concrete temperature during hydration using sensors attached to the reinforcing cage or auger cast pile center-bar. Quantifiable measurements are obtained while physically separating inspection and testing parties from open excavations and drilling equipment.

Many of the testing methods discussed can be implemented with internet and cloud services to further minimize safety risk. The tests can be performed remotely, with the test equipment operated by the on-site crew and the measurements sent in real time to the engineer located in the office or at home. Aside from typically a one-time training for site personnel in the operation of the equipment, dynamic testing, shaft shape, bottom cleanliness, and thermal integrity testing are often performed without the testing engineer on the site, thus reducing the site safety risk.

MANAGING FOUNDATION QUALITY AND PERFORMANCE RISK

Ultimately, all of the project parties will be held accountable for the quality and performance of a foundation. Poor performance may result in additional investigations, re-engineering, and remediation. Thus, risk associated with foundation quality and performance is also under the umbrella of managing schedule and cost risks.

The most basic foundation design is specifying a depth based on a soil profile. Another method for driven piles uses the rated hammer energy and the observed set per blow in an "energy formula". Both of these methods necessitate a relatively high factor of safety to account for the uncertainties of the assumptions inherent to these methods, and their relatively poor correlation with static load tests. Actual testing provides a quantitative capacity result that removes the uncertainty of the initial design based on static analysis or energy formula, and removing uncertainty eliminates risk. For driven piles the most common methods to measure and evaluate capacity are from either static load testing (ASTM D1143) or dynamic load testing (ASTM D4945).

Compared to static testing, a higher percentage of piles can be dynamically tested at a relatively low cost and reduces the risk associated with site variability. To compare the costs of both test options, a test pile program that was recently completed for an interchange project in Beloit, Wisconsin had two static load tests and a total of fourteen piles, including the static load test piles, to be dynamically tested during initial driving and next-day restrike. The contractor's bid prices were $80,000 for the two static load tests and less than $50,000 for the full dynamic testing scope of work. This yields a per test price of $40,000 for static load testing and $3,500 per test for dynamic testing. Hammer performance, driving stresses, and pile capacities can be obtained during normal pile driving operations. Dynamic testing provides the added benefit of being readily available to assess the integrity of a suspect driven pile, such as piles with unusual blow counts or anomalous pile tip elevations. When a driven pile is impacted, clear tensile reflections prior to the toe reflection indicate a definite structural defect.

While driven piles can be visually inspected prior to installation, and the blow count gives at least indirect assurance of their integrity, drilled foundation elements under slurry lack the ability of direct or even indirect inspection during installation. O'Neill (1991) describes numerous installation issues (such as due to casing removal, concrete placement, or slurry management) that create potential serious integrity problems for drilled foundation elements. Thus, integrity is much less certain. Many innovative testing methods are available to inspect and test the excavation and grout or concrete quality. When the design of a drilled foundation element includes end bearing capacity, confirming base cleanliness is critical. Measurements to investigate the bottom debris thickness (or lack of debris) provide quantifiable results. Most drilled foundation elements have a requirement for verticality, with specifications generally requiring alignment no more than 1% to 2 % from vertical. Ultrasonic scans over the full shaft length allows for assessing the location of the shaft bottom centroid relative to the shaft top prior to concreting to ensure that the drilled foundation element can perform as designed.

Thermal measurements (ASTM D7949) during concrete curing, or cross-hole sonic logging (ASTM D6760) a few days after casting can evaluate the integrity as a function of depth for drilled foundation elements. Although incremental grout volume can be measured during installation by automated monitoring equipment, this does not directly correlate with the as-built shape. To obtain the as-built shape of ACIP piles, thermal integrity profiling can be used to obtain a better estimate of the dimensional details.

Each of the abovementioned testing methods can quickly assess various quality aspects of the foundation, assuring the overall foundation quality and performance. For all innovative testing methods, performing the testing itself or even the possibility of performing testing inspires the contractor to a more careful construction process. This additional effort reduces the risk of integrity issues and the likelihood of unexpected problems and delays.

MANAGING COST RISK

The cost of a project is always a major concern, and the risk of cost overruns looms large. The main cost of a foundation system is the material cost itself and reducing the amount of pile material lowers the risk of cost overruns. Deep foundations usually advance through upper weaker soils with minimal contribution to the overall pile capacity. The length of the foundation element in these unsuitable bearing layers cannot be avoided but, once beyond these layers, a relatively minimal amount of additional depth into the suitable bearing layers generally yields significant additional resistance. These higher capacities result in fewer foundation elements required to support the superstructure. This more efficient use of the material allows the support cost (defined as "cost per ton") to reduce, which then reduces the overall foundation cost (Komurka 2015). With fewer foundation elements to install, the time to install the foundation is minimized, reducing cost and scheduling risks for a project.

Utilizing innovative capacity testing methods which allow for lower safety factors (ASD) or higher phi factors (LRFD) results in increased loads per pile and a reduction in required foundation elements. For example, bridge pile foundation design is based on an LRFD platform and the resistance factors associated with the capacity verification methods per AASHTO (2017) can allow significantly higher loads per pile. A pile installed using dynamic testing to determine capacity can be loaded to a capacity of 1.63 times the capacity of a pile installed using the Gates energy formula. Likewise, a pile installed using static load testing results (or dynamic testing on every pile on a project) can be installed to 1.88 times the capacity of a pile installed using just an energy formula. Utilizing both static and dynamic testing allows a pile to be loaded to twice the capacity of a pile controlled by a formula. Higher loads per pile reduce the number of piles and thus significantly reduce the overall foundation cost.

The Indiana Department of Transportation frequently utilizes dynamic testing on their bridge projects. The DOT compiled and summarized their pile projects from 2008 to 2014 (Ortiz 2018). During that period, over 1,050,000 feet of pile were installed using dynamic testing to evaluate pile capacity and establish driving criteria. The cost of those piles, including costs to perform dynamic testing, were compared to the costs if those same piles were installed using the dynamic formula. The total cost savings realized by utilizing dynamic testing was over $10 million dollars.

On larger projects, a separate initial testing program with both static and dynamic testing can compare different alternatives (pile types, pile lengths, pile diameters) to achieve the most economical foundation. The use of multi-level instrumentation on static load tests, or signal matching methods on dynamic load tests, allows for determination of unit resistances versus depth, potentially yielding further refinement of the foundation design. For smaller driven pile projects, static testing or, more commonly only dynamic testing, allows the engineer to compare the design capacity with the achieved capacity, and make any necessary adjustments to assure a safe and cost-effective foundation.

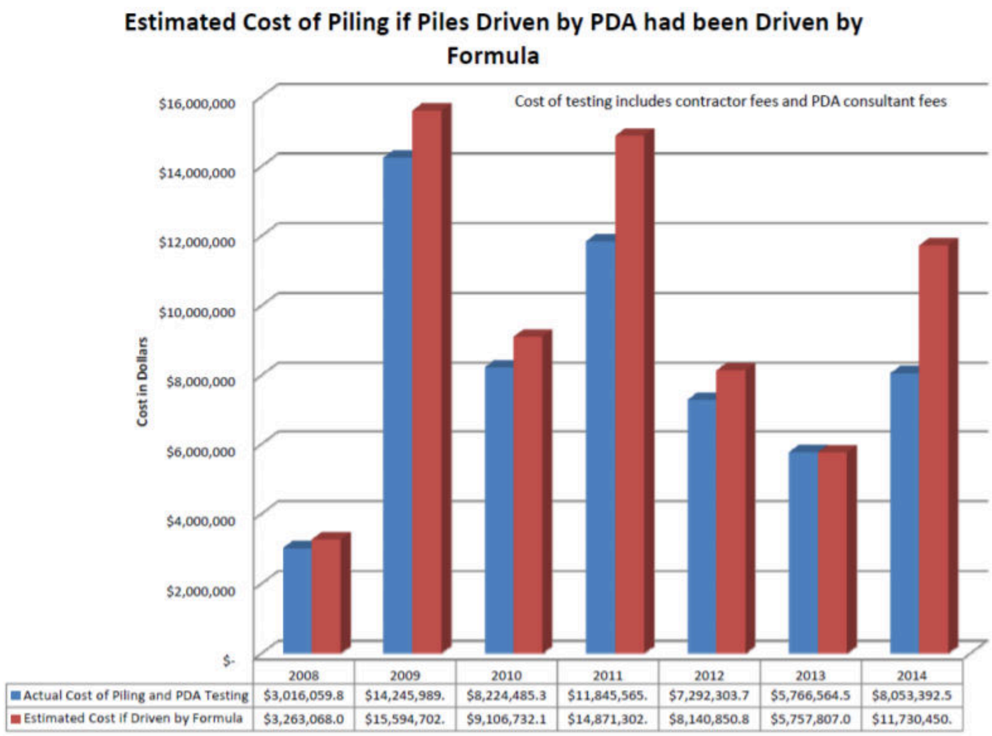

Figure 1. Summary of Pile Installation Costs, Indiana 2008 - 2014

Fewer foundation elements also result in less redundancy and therefore an increase in risk. Testing on a higher percentage of foundations is recommended to manage this risk. With testing costs generally being a small percentage of the overall foundation cost, the savings achieved in fewer or shorter piles will be greater than the cost of testing.

The I-480 Valley View Bridge (White 2019) was installed using a rigorous test pile program with long term testing of 30 to 45 days to take advantage of the soil setup known to exist in the site soils. Both dynamic and static load tests were performed. This project involved the addition of a new structure located between the eastbound and westbound bridges that currently exist and carry approximately 180,000 vehicles per day. Once completed, the other two existing structures built in 1971 will be replaced. The bridges are 4,150 feet (1,265m) long and 250 feet (76m) above the Cuyahoga River valley in Cleveland, Ohio. The foundation chosen consisted of 18-inch (460mm) closed end pipe piles with 0.5-inch (13mm) wall thickness and lengths varied between 120 feet (37m) to 180 feet (55m). The goal for the test pile program was to quantify the soil setup for the various piers throughout the site through dynamic testing both at end of initial drive as well as restrikes that varied from 1 to 9 days after initial driving. The measured soil setup was then applied to all production piles and a driving criterion as a function of depth was developed to optimize pile lengths for each pier. The existing bridges averaged 118 piles per pier and totaled 130,000 lineal feet (39,600m) for each bridge. The test pile program and inclusion of soil setup allowed the final design to be optimized so the total piling was reduced from 130,000 lineal feet (39,600m) to approximately 64,000 lineal feet (19,500m), with the number of piles per pier reduced from an average of 118 to 36 piles per pier. The use of this extensive test pile program saved significant quantities of piling material and the associated installation time, resulting in considerable cost savings and time savings for this project.

Komurka (2017) discussed a case history of a driven pile foundation for a 33-story high-rise building with a similar rigorous test pile program, utilizing both static and dynamic testing and long-term testing to confirm setup. The driving criteria was periodically confirmed with dynamic testing during production. The testing resulted in an estimated savings of $3.3 million dollars and eliminated 143 days of construction time, as compared with installation controlled by energy formula and disregarding setup.

MANAGING SCHEDULE RISK

The cliché "Time is money" has a direct application to construction; anything that can reduce construction time is welcome. As previously discussed, the added benefit of reducing costs by increasing design loads is fewer foundation elements, which then also means less total installation time. Reducing construction schedules by days or weeks lessens equipment and crew costs and results in the structure being in service sooner.

Driven pile foundations can be tested during installation and, can generally be tested on short notice to address concerns. Dynamic testing provides guidance for installation procedures to control driving stresses, which minimizes the potential for damaged piles. Periodic testing on larger projects allows for timely modification of procedures to account for site variability. Changes in hammer performance, if undetected, can also affect production pile installation so periodically measuring the energy transferred to the pile is important for quality control of larger projects.

When unexpected events or suspect quality issues occur in drilled foundations, the result is often a major delay in construction. Further investigation of drilled foundations often means coring, which is costly, time consuming, and may be inconclusive. Additional time is lost while the team investigates the issues and determines the next course of action. Then re-engineering or remedial action is implemented, if required. If issues are detected in the drilled foundation elements installed at the beginning of a project, then altered installation procedures can be implemented to correct the problems before significantly more questionable drilled foundation elements are installed. For a project with 154 drilled foundation elements, Schoen (2018) reported that thermal measurements showed seven of the first ten drilled foundation elements had anomalies. The contractor was quickly advised to modify his double casing installation to a single casing method. Of the remaining production drilled foundation elements only eleven indicated anomalies, a significant reduction in the percentage of shafts with problems to be addressed.

Hyatt (2019) details a project where seven drilled foundation elements for a bridge sub-structure had both CSL and thermal testing performed. Anomalous zones were identified with both testing methods, and the issue was verified by coring one drilled foundation element. The thermal tests inspected the entire cross-section of each drilled foundation element, including the concrete cover, and identified a quality issue in one drilled foundation element while avoiding the questionable results obtained on several drilled foundation elements via the CSL test method. Thermal testing can be sufficiently adequate to evaluate drilled foundation elements integrity and was approximately half of the cost of CSL testing. On average, completion of data collection for analysis occurred 6 days sooner utilizing TIP testing than using CSL.

Table 1. Summary of Time Advantage of TIP Testing

	Time	Shaft 1	Shaft 2	Shaft 3	Shaft 4	Shaft 5	Shaft 6	Shaft 7	Average
Time difference between TIP and CSL Results	hrs	125.5	176	171	146.75	197.5	52	142.75	144.5
	days	5.2	7.3	7.1	6.1	8.2	2.2	5.9	6.0

CONCLUSIONS

Many innovative testing tools are available to minimize risk during installation of a foundation. Pile load testing allows for higher design loads and less foundation elements, reducing the risk of excessive costs. The benefits of testing are greatest during pre-production or at the beginning of foundation installation. This allows for rapid identification and correction of installation issues, along with assessment of additional testing that should be performed throughout the project. Early detection of either capacity or integrity issues, and then taking appropriate corrective action, results in improved construction procedures. This then reduces the risk of unplanned schedule delays due to issues requiring additional investigation, resolution, and possible remediation.

Most of the testing tools available allow sufficient physical separation of personnel from safety hazards. The risk of personal injury is reduced since testing staff do not need to approach the pile or drilled foundation elements during installation and in some cases the engineer need not even be on site. A well-planned use of the appropriate testing methods can reduce nearly all of the risk components associated with a deep foundation project.

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Resilient and Sustainable Infrastructure Begins with Foundations

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ABSTRACT

Sustainable infrastructure emerges when environmental, economic, and social factors find common ground during the infrastructure lifecycle, resulting in an efficient and accelerated construction without compromise in quality. Resilient infrastructure is able to recover to full designed functional capacity after extreme natural or man-made events. Optimum sustainability is achieved through (1) reduced wastage of global construction materials and (2) data-driven maintenance procedures based on need, instead of periodic maintenance based on past practice—there is a transformation from maintenance on a schedule to maintenance on demand. Can we measure resiliency and sustainability? The answer is yes. Are there case studies that show that resiliency and sustainability are achievable together and measurable in infrastructure? The answer again is yes, with the use of embedded sensors and wireless communications. Modern technologies such as embedded sensors and wireless communications have rapidly advanced, becoming ubiquitous in many a human endeavor. As these technologies mature, stakeholders are learning to apply them to bridge structures, creating smart transportation infrastructure. Data are collected wirelessly over an IoT-based cloud architecture to facilitate monitoring real-time and/or on as-need basis. This enables communications between various elements of smart infrastructure even beyond the transportation industry, enabling quantification of resiliency and sustainability. This paper discusses the concepts and a case study of recent deep foundation projects in Florida involving smart infrastructure that achieved resiliency and sustainability.

INTRODUCTION

Infrastructure is the backbone of future growth for every country, compelling political and economic leaders to prioritize rapid infrastructure expansion. Engineers and technologists, while facing the pressure of limited resources, realize that these top infrastructure goals are best achieved by planning, designing and constructing infrastructure that incorporates modern technologies that help boost resiliency and sustainability. Quantification of resiliency and sustainability enables optimal use of monies, materials and labor. Today's infrastructure foundations are largely designed to allow for a significant window of waste. Using embedded sensors and ongoing monitoring, infrastructure can enjoy greater construction efficiency and lower life-cycle costs, all while improving foundation quality and decreasing the use of cement and steel – two of the world's most carbon-intensive industries. This paper presents a new and emerging application of an existing technology that will improve infrastructure resiliency and sustainability while generating savings and pleasing the planet.

2.0 INFRASTRUCTURE RESILIENCY

Today's infrastructure is designed to take care of uncertainties based on qualitative data, and therefore provide for a large window of waste. If we don't know exactly how much wear and tear a facility can withstand from everyday use or earthquakes or hurricanes, it is overdesigned. Similarly, questionable assumptions may lead to the 'under design' of infrastructure. Under these circumstances, after a disaster hits, a structure might be closed down for a period to check structural integrity by visual inspection and ensure it is safe to be used again.

Unfortunately, when a structure is closed, it may take some time reopen. That is because our answers to important questions about structural integrity are often based only on visual inspection or experience or intuition; they are not data driven.

What tasks are critical and urgent? How quickly can the structure be reopened for public use? What elements of the structure are damaged? Where is the damage? What is the extent of the damage? How will structural integrity be accurately checked or measured? Engineers and administrators must know how soon they can get back to normal, safe operations. Having quality data about an infrastructure before, during and after a disruptive event would enable data-driven quality decisions to evaluate the status of infrastructure at any given time. Two straightforward examples of economic damage after hurricanes elucidate this concept:

Table 1: Economic Impact after Hurricanes

Hurricane Sandy (2012)	**Hurricanes Harvey and Irma (2017)**
• $75B in economic damage; $30B insured • $5B damage to New York Metropolitan Transportation Authority; <$1B insured	$200-$300 B in economic damage; $70B insured

Economic damage assessments like these raise the question: Could this damage have been less? Maybe the economic damage is high because recovery was too slow due to lack of data before, during and after the disaster. A lack of information about the level and nature of the damage impedes recovery efforts. In the case of the of I-35W bridge collapse, Minneapolis (2007), the Mississippi River bridge was an eight-lane, steel truss arch bridge that carried Interstate 35W across the Saint Anthony Falls. Since 1993, the bridge was inspected annually by the Minnesota Department of Transportation. The federal government gave the I-35W bridge a rating of "structurally deficient". Questions arise as to whether or not the bridge collapse could have been predicted and failure prevented? Maybe the inspections did not provide reliably measured time-based data on damage occurrences to enable such a prediction? There is an alternative: Whatever the reason is for failure and failure type, What if, we knew when a structure was compromised? Engineers would be able to predict the possible outcomes of a disastrous event. Before this paper tackles how infrastructure data can be quantified (through recent advancements in data measurements collected by sensors embedded in concrete and steel), let us see how resiliency is quantified.

What if engineers and administrators had enough data to design and validate the design with just enough cement and steel for the probable risk?
There would be savings in materials, construction and Operations & Maintenance (O&M), and of course, there would be enhanced utilization.

2.1 QUANTIFYING INFRASTRUCTURE RESILIENCY

In simple terms, the Resilience of the infrastructure is its ability to come to functional normalcy after a disaster event. The Resilience of infrastructure is determined by its preparedness, robustness, responsiveness and recoverability from the effects of the event. The Resiliency capacity/performance of the infrastructure over time (before, during, and after the disaster) is illustrated by Figure-1.

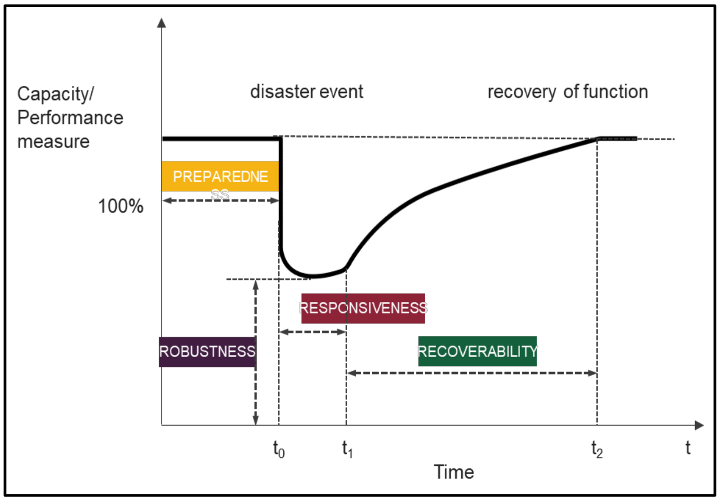

Figure 1: Determining the Resilience of Transport Critical Infrastructure Element (T. Loveček et al. (Proceedings of 21st International Scientific Conference. Transport Means 2017).

Infrastructure 'preparedness' to meet the challenges of a disaster reflects preventive maintenance. Well-designed preventive maintenance programs will enhance performance of the assets and ensure they deliver optimum results consistently. Some of the well-known benefits of preventive maintenance are:

- Increased lifespan
- Minimized risk
- Reduced downtime and disruption (with early notification of issues, repairs and rehabilitation can potentially be managed during idle time, and/or can be repaired before a small problem turns into a major issue that might require a longer closure window)
- Enhanced customer service

While preventive maintenance is important, prescriptive maintenance can take preparedness to the next level. The introduction of prescriptive maintenance depends on the engineer's inclusion of advanced technologies in the Plan/Design, Construction and O&M phases of a structure's life cycle. This paper addresses how it is possible to include these advanced technologies in deep foundations of civil infrastructure.

The 'robustness' of a deep foundation is its capacity and structural integrity. Standard engineering practice today allows only an estimate of robustness. But with instrumentation embedded in the deep foundation, data is measured before during and after the event, and comparison between events is possible, leading to faster, better response and recovery.