Construction Engineering Process and Knowledge Requirements for Fostering Creative Design Solutions on Infrastructure Projects

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Abstract: Construction engineering for major infrastructure projects covers a wide range of activities to evaluate and select the techniques for assembling materials and components. Construction engineering inherently presents a very challenging opportunity for creative design, particularly on infrastructure projects. This construction engineering activity can be described as one of creating and developing workable, cost-effective, low-risk technical solutions for an array of infrastructure construction problems that must be solved from the plans and specifications stage through facility completion. The purpose of this paper is to illustrate a 10-step construction engineering process and define important knowledge requirements to foster creative design solutions using four case studies, including (1) positioning and holding a concrete bridge caisson in a 7-knot tidal current for a 4-month period; (2) skidding a 55,000-t immersed tube tunnel element 200 m on dry land from casting site to launch site; (3) building a major dam without the use of river diversion or on-site dewatering systems; and (4) building underwater bridge piers without the use of conventional bottom-founded cofferdams. The creative design process was able to successfully devise a plan for solving highly technical construction challenges using a process-based approach. The key requirements of knowledge, skill, and experience necessary to perform these activities are presented to assist construction engineers in preparing for these creative opportunities.
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Need for Creative Solutions in Technical Construction Problems

For young engineers seeking a technical challenge and an opportunity to make use of their creativity, imagination, and innovative skills, construction engineering design offers great possibilities. Every infrastructure construction project has its own unique set of technical problems that must be solved prior to commencing on-site work. The number of technical problems on a project and the degree of their complexity may vary from project to project, but very few major projects can be considered routine, and most must be uniquely engineered.

To further complicate the task, most major infrastructure work is performed on a competitive basis in which cost is a major factor in the selection of the construction company or joint venture companies that will build the facility. For this reason, the technical solutions developed for a given project must not only work, but they must also be efficient and cost competitive. In addition, the technical solutions must allow the project to be completed on schedule, provide an end result consistent with the project's specified level of quality, be performed within an acceptable level of risk, and comply with all permits and environmental restrictions.

Usually the technical problems are fully identified during the tendering period, and the method and cost for addressing these problems are fully planned and critiqued before the on-site work commences. However, this is not always the case, and at times these problems come to light only after the work has begun, and the project team must react rather than proact. When this occurs, the work activity with the technical problem is usually on the critical path for project completion, and the available time for identifying and developing the optimum technical solutions is very limited.

Process and Sequence for Attaining Optimal Construction Solutions

The process of identifying, developing, and implementing the optimum construction solution is a team effort requiring a group of construction personnel with a wide range of talent and experience. Although it is essential that some members of the group have expertise or knowledge in the specific type of construction under consideration, it is not essential that they be the same, and in fact, it is often beneficial for individuals with a wide range of experience to participate in the process.

The process and sequence of developing the optimum construction solution can be broken down in the following 10 steps:

1. *Identifying key technical problems on the project*. The technical challenges on major infrastructure projects are usually associated with the unique features of the job. On a marine construction project, these features may include extreme water depth, adverse sea conditions, rapid currents, or heavy vessel traffic in the work area. On a bridge erection project, these features may include a rugged canyon with limited access

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for erection equipment or high winds that affect the placement of bridge segments. On a dam project, primary construction problems may be limited access for concrete placement or high river flow during critical construction stages. A given project may only have one or two technical challenges, but another project may have 10 or 20. Sometimes, the unique challenges on a project are created by the project staff in their effort to attain a cost-competitive edge.

2. *Collecting and reviewing relevant information*. The collection of relevant data and information dealing with a specific identified problem is usually performed by one or two individuals, and the relevant information is distributed to the entire group for independent review prior to any meetings of the group. For a marine project, this information might include sea conditions, current velocity, and on-site weather conditions. For a bridge or dam project, it may include river hydrographical and geological information. For building construction, it may include wind conditions and site access diagrams.
3. *Defining the problem clearly.* A clear definition of the specific problem is critical for attaining the optimum solution. During this stage, all aspects of the problem should be identified to ensure that the final solution is all-inclusive and that the true root of the problem has been exposed.
4. *Identifying available feasible solutions that have worked successfully in the past*. Most technical construction problems have been addressed previously on similar past projects. However, the magnitude of the challenge may have been significantly different. These previous solutions should be identified and reviewed for applicability to the current challenge. The greater the number of past solutions identified, the better the chance of finding the optimum solution. A "lessons learned" database is very effective in this step.
5. *Conceiving or creating new solutions*. Regardless of how many times a construction problem has been solved, there is always the potential for another solution, either completely new or a variation of a prior solution. This step is usually performed with a group of construction personnel familiar with the type of construction under consideration. The wider the range of construction experience within the team, the better it is for generating innovative solutions. This step is sometimes referred to as "brainstorming" or "imagineering." Whatever it is called, the discussion should be open and noncritical. It is important to first get all of the ideas out on the table for discussion before a critical review of each potential solution is fully evaluated.
6. *Confirming the viability of the new solutions*. At the end of Step 5, a number of potential new solutions are usually identified. However, there may be issues of uncertainty about their workability or level of risk. During this step, these issues should be investigated further and resolved to a satisfactory level or the potential solution should be dropped from consideration. A meeting facilitator can effectively mediate this step, and in some instances, it may require additional investigation and testing to answer specific questions.
7. *Evaluating the solution options*. The function of this step is to identify and weigh the criteria by which the range of potential options will be evaluated. The list of evaluation criteria typically includes safety, risk, cost, schedule, quality, and environment. To account for the relative importance of each of these to the specific project, each of these factors is given a weight to be multiplied times its score for each of the criteria. A higher impact criteria is simply given a greater weight.
8. *Selecting the optimum solutions*. After identifying prior viable solutions and potential new solutions, the team of experienced engineering and project staff is reassembled to jointly evaluate and rank the various alternative solutions. It is important that this be a team effort because an important part of this process is getting all project team members to buy into the final solution. This helps to ensure that once a given path has been taken, all members are executing the same plan.
9. *Detailed designing and confirmation testing*. Once the optimum solution has been identified, all aspects of solution are taken to detailed design. Quite often during this stage, additional problems are identified that require resolution, first by the design team and then by review of the entire solution selection team.
10. *Implementing and monitoring*. When entirely new solutions are implemented for the first time, it is essential to monitor the various elements and functions performed to ensure they are consistent with anticipated results. If significant variation exists between performance and planned results, further evaluation of risk should be made and corrective action taken if necessary.

Case Histories of Infrastructure Problems and Solutions

A brief description of four case studies are presented to illustrate solutions identified through the use of the 10-step construction engineering process described previously.

Construction of the Bridge Foundations for the New Tacoma Narrows Bridge, Washington

The New Tacoma Narrows Bridge is located on a narrow channel at the north end of Puget Sound. The most unique features of the site were the 49-m (160-ft) water depth and the rapid 7-knot tidal currents during a 4-month period. These features created the greatest challenge to building the main span foundations. After contract award and performing hydraulic model studies, it was determined that the two main pier caissons would require a total of 64 anchors with a safe working capacity of 500 t each (Bittner and Ellman 2009). The construction engineering process described previously was used to identify, design, develop, and test driven plate anchors as the optimum, most cost-efficient anchoring system. See Table 1 for details concerning this construction solution.

Launching of the Oresund Immersed Tube Tunnel Connecting Denmark and Sweden

Oresund Tunnel Contractors, the successful joint venture contractor for the Oresund Tunnel design-build project, had selected a match-casting operation for fabricating 20 concrete tunnel elements

Table 1. Developing Construction Solution for Tacoma Narrows Bridge Caissons

Step	Action taken
Identify problem	Build main span foundations
Collect and review data	Hydrologic studies, loads
Define problem	Deep water and fast current
Identify solutions	Dead weight and drag anchors
Create solutions	Driven plate anchor system
Confirm solutions	Test-driven plate anchors
Evaluate options	Significant cost differences
Select solutions	Anchors with 500-t capacity
Design and confirm	Calculate working stresses
Implement and monitor	Measure anchor line tension

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Table 2. Developing Construction Solution for Launching Oresund Immersed Tube Tunnel

Step	Action taken
Identify problem	Skid 55,000 t segment in place
Collect and review data	Loads, tunnel dimensions
Define problem	Skid without cracking exterior
Identify solutions	Pile supports, hydraulic jacks
Create solutions	Three-component system
Confirm solutions	Calculations and model testing
Evaluate options	Significant assembly activity
Select solutions	Skid beams react with jacks
Design and confirm	Calculate forces and stresses
Implement and monitor	Measure loads during skidding

(55,000 t each) that make up the 3.5-km long immersed tube tunnel connecting Demark and Sweden. This process involved casting a 22-m long tunnel segment on a fixed casting bed and then skidding it forward to clear the bed for the next casting (Spring et al. 2000; Bittner 2000). This process was repeated eight times to complete a single 176-m long tunnel element, which was then skidded 200 m into the outfitting and launch basin. The key technical problem for this entire project was how to skid a very rigid 55,000-t tunnel element (28 h after casting the prior segment) without cracking the exterior surface of the underwater tunnel. The final solution was found using the 10-step system described previously and consisted of three components: (1) six pile-supported skid beams aligned under each of the six tunnel walls; (2) a total of 288 hydraulic jacks (300-t capacity each) plumbed into three hydraulic circuits that provided a three-point support system; and (3) six hydraulic rams (600-t capacity each) that traveled on top of and reacted against the skid beams. See Table 2 for the process to arrive at a creative construction engineered solution.

Construction of Braddock Dam on the Monongahela River, Pennsylvania

The U.S. Army Corps of Engineers wanted to improve their construction methods for building locks and dams on U.S. inland waterways. Their first trial project was located on the Monongahela River upstream from Pittsburgh and envisioned construction of the dam using float-in techniques rather than river diversion with circular cells and site dewatering. Experienced construction engineering staff from Ben C. Gerwick, Inc. and the U.S. Army Corps of Engineers used the steps detailed previously to develop innovative construction solutions that met the Corps end objectives (Gerwick 2007). The final solution consisted of two precast shells of the dam (102 and 81 m long, 38 m wide, and 12 m high; or 333 ft and 265 ft long, 125 ft wide, and 40 ft high) constructed off-site at a downstream dry dock location. While the precast segments were being built, the dam cut-off walls and drilled shaft foundations were constructed through the water. After completion of the foundations, the two dam segments were launched and towed 35 km (22 mi) upstream to the dam site for outfitting and placement on the drilled shaft foundations. After landing and leveling the segments, they were locked to the drilled shafts with tremie concrete. Table 3 summarizes the steps in engineering the precast segment installation.

Construction of Bridge Piers for the Bath-Woolwich Bridge, Bath, Maine

Large diameter drilled shafts 1.8–3.0 m (6–10 ft) in diameter are being used more frequently for bridge foundations. These large diameter piles can enhance lateral stiffness for the bridge piers. This greater stiffness creates an opportunity to position the pile caps off the waterway bottom and attain a significant cost advantage in deep water, where conventional cofferdams become very expensive or unfeasible. It was in response to this situation that the 10-step process detailed previously was used to develop an innovative float-in cofferdam system for the construction of six piers for the Bath-Woolwich Bridge across the Kennebec River in Maine. The concept was based on precasting shells of the bridge pier on shore while the drilled shafts were installed and cut off under water (Bittner and Ellman 2009). Following launch of the pile cap shells, a steel cofferdam was then attached to the top of the precast shells, and the complete assembly was positioned over the top and lowered on to the drilled shafts. After leveling, the gap between the precast shell and the drilled shaft casing was sealed, and tremie concrete was placed to lock the shell on the drilled shaft. The cofferdam was then dewatered, and the pier pile cap and shaft were constructed in the dry using conventional methods. The final step was to strip off the follower cofferdam for reuse on the next pier. Table 4 summarizes the steps in engineering the bridge pier assembly.

Table 3. Developing Construction Solution for Braddock Dam Float-In Precast Segments

Step	Action taken
Identify problem	Construct using alternate means
Collect and review data	Cast-in-place or precast
Define problem	Avoid river diversion/dewatering
Identify solutions	Precast segments
Create solutions	Fabricate off-site and float in
Confirm solutions	Confirm precast shell size
Evaluate options	Cost, schedule, and risk advantage
Select solutions	Off-site fabrication
Design and confirm	Calculate installation stresses
Implement and monitor	Verify in-place dimension

Table 4. Developing Construction Solution for Bath-Woolwich Bridge Piers

Step	Action taken
Identify problem	Float-in cofferdam for piers
Collect and review data	River depth, bridge dimensions
Define problem	Sequence pier assembly
Identify solutions	Precast bridge pier shells
Create solutions	Float in shells and attach to shafts
Confirm solutions	Dimension shaft connection
Evaluate options	Shell float-in is significant act
Select solutions	Position, level, lock connection
Design and confirm	Calculate lock connection
Implement and monitor	Measuring during installation

Key Knowledge, Skill, And Experience Requirements for Providing Creative Solutions to Technical Challenges of Infrastructure Construction

The previous sections outlined and illustrated a 10-step construction engineering process to foster creative design solutions on infrastructure projects. In this section, important knowledge, skill, and experience requirements are enumerated that enable a successful construction engineering process. Identifying, developing, and implementing creative solutions is truly a team effort. It is therefore

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not necessary that any one individual fulfill all of the requirements, but it is important that the set of knowledge, skills, and experiences is available and shared within the group. The team working on these problems typically includes experienced cost estimators, schedulers, engineers experienced in design of temporary facilities and structures, and field superintendents that have successfully executed similar types of work in the past and fully understand the problems encountered with the specific type of construction under consideration.

Understanding of the Forces of Nature

The major portion of technical problems on infrastructure construction projects deal with the forces of nature in one way or another. Such forces include wind, current, hydrostatic, seismic, impact, friction, earthen pressure, and their associated interaction with structures. It is critical that the type and magnitude of these forces be clearly identified in advance to ensure that the considered solutions adequately address their impact.

Ability to Clearly See and Define the Problem

Before commencing with solving the technical problem, it is essential to first define the problem and to have a clear understanding of all aspects. Quite often during the course of solving one problem, another is created. When this occurs it is important that these additional problems are identified and either resolved or eliminated before proceeding too far with the initial solution. For example, on the Oresund Immersed Tube Tunnel project, opposing forces from skid beams and hydraulic rams must be spatially understood for an effective installation.

Sound Basis in Engineering Fundamentals

A sound engineering background is essential to defining the problem, identifying options, and then arriving at an efficient technical solution that meets the requirements of the project. Education and training programs are essential to develop knowledge and skills for projects with increasing complexity.

Facility with Analytical Tools for Structural Analysis

Advanced structural analysis is often required to achieve a clear understanding of the forces and their interaction with the permanent structure and the temporary structures used by the contractor. Continuing education courses, seminars, or web seminars may address deficiencies or strengthen prior knowledge concerning the subject matter.

Ability to Communicate Ideas

The ability to effectively communicate includes not only written and verbal presentations, but also the ability to communicate ideas clearly by well illustrated sketches, drawings, and diagrams. It is important that any sketches and drawings be to approximate scale. Drawings or sketches out of scale have the potential to distort the true situation and can lead to incorrect solutions. The process of preparing sketches and drawings greatly facilitates the thinking and creative solution development process. Many successful large-scale infrastructure contractors require the project team to prepare and submit a detailed work plan with to-scale drawings. Writing the work plans demonstrate commitment to the ideas and concepts.

Ability to Work within a Team and, If Necessary, to Lead the Team

Teamwork is essential to identifying the available technical solutions to a particular problem and then fully evaluating them. The feedback and interchange between team members can be compared to a nuclear reaction requiring a critical mass to accelerate. At times it is essential that leadership and direction be given to the team to guide it through the process, keep it focused on the specific problem at hand, and reach a consensus at the end of the process.

Understanding of Construction Costs

It is essential when considering various solution options to have a basic understanding of construction costs and the relative trade-offs among material, labor, equipment, and overhead costs. Fundamental construction engineering must be capable of detecting a least-cost solution and determining whether it is more advantageous to increase one cost to decrease the entire project cost.

Understanding of Construction Scheduling

The evaluation team should have the ability to identify the relative time difference in selecting one option over another. They need to know whether a given course of action will or will not allow concurrent work activities, and if not, then what can be done to allow concurrency. The team should be able to identify the critical path for various options and clearly see the time difference between various construction options. It is important to have an understanding of work activity sequencing and an ability to identify options for creating concurrent work paths. For example, the lengthy lead time for float-in operations can be mitigated with thoughtful advance planning.

Ability to Identify, Evaluate, and Mitigate Potential Risks

The project team needs the ability to identify, quantify, and control specific risks for a given technical solution. Once the risks have been identified, the team must be able to determine the probability and severity of the potential risk. The team should have the ability to evaluate options that engineer or mitigate the identified potential risks. A risk management plan, existing or new, is very useful in this effort.

Ability to Identify and Evaluate Potential Environmental Impacts

The team must have a clear understanding of all environmental regulations and/or permit requirements applicable to the project. Every solution under consideration for a given technical problem on the project must be evaluated relative to these requirements. Specific permits issued for the project by the U.S. Army Corps of Engineers or the U.S. Coast Guard are not readily changed or amended in short order.

Conclusions

Construction engineering is an exciting field with a lifetime of challenges and opportunities for creative endeavors. One of the most challenging activities within this discipline is creating and developing innovative optimized solutions for the many technical problems associated with construction of major infrastructure. A 10-step procedure for creating and developing these optimum technical solutions has been used successfully in the past on a wide variety of construction projects. Four case studies illustrated the steps in the process. This procedure is a very much a team effort that requires a wide-ranging mix of skills, talent, knowledge, and experience. Guidance for obtaining important knowledge, skill, and experience was enumerated to assist in achieving successful construction engineered solutions. This mix covers not only estimating, scheduling, cost control, and project planning, but also

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structural and hydrodynamic analysis, risk evaluation, analysis, and mitigation, and an understanding of environmental impacts of construction and how to minimize them.

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