Construction Engineering Today[1]

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Abstract: The factors that are considered in analyzing technical solutions and the tools used to obtain technical solutions have changed for construction engineers over the past 30 years. This paper discusses these changes and their impacts. It then outlines a process that several heavy civil contracting firms use to generate work plans for their field operations, using the details of the process at Granite Construction as an example. The paper concludes by identifying the key factors in the success of a work plan and providing some thoughts on what construction engineering education should emphasize. **DOI:** 10.1061/(ASCE)CO.1943-7862.0000298. *© 2011 American Society of Civil Engineers.*

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Introduction

Construction engineering has been defined for the purposes of this conference as follows: "Construction engineering is the series of technical activities throughout the project delivery process that support construction and constructability decisions and plans along with field operations; create a safe and productive construction environment; and seek to avoid and solve the engineering issues associated with delivering a project."

Although this definition has been and remains valid, the considerations underlying technical activities have widened from a focus on economics, time, and jobsite safety to a much broader spectrum over the past 30 years. Today's considerations include a greater emphasis on environmental and community impact.

In addition, advances in technology over the past 30 years have made information increasingly available to the general public and easier to analyze and handle, and provided powerful methods of analysis. These advances have resulted in more efficient solutions that increase the requirement to effectively communicate any underlying constraints to the personnel carrying out the field operations.

As a result of the increasing number and complexity of the technical and nontechnical issues that must be addressed by its construction engineers, Granite Construction has put in place a formal process to generate work plans for its field operations. For any project, the process begins with the definition of the operations or activities that require a work plan. The end product is a document or work plan that provides all the information necessary to perform the operation, including expectations and metrics.

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Past Versus Present

Environmental and Community Considerations

Construction engineering's primary focus 30 years ago was on economics, time, and jobsite safety. Environmental and community impacts were minimal considerations.

Environmental mitigation measures such as silt fences, treatment of water from dewatering operations, recycling plans, and other "best management practices" were the exception in the past rather than the rule. Construction engineering now includes requirements for storm water pollution prevention plans (SWPPPs) and spill prevention control and countermeasure (SPCC) plans.

Environmental considerations are now a driver in evaluating means and methods. Bridge projects in wetlands and/or tidal areas that previously would have utilized marine equipment and barges to deliver materials to the work operation no longer have this option because of the limitations on dredging access channels. Erosion control measures must be in place before clearing operations can begin. Equipment selection now must consider air-quality standards and, in some cases, requirements for fuel efficiency.

Community impact mitigation measures are now integrated throughout the project delivery process. Participation in community meetings to address their concerns and issues about construction activities, ongoing noise monitoring, traffic phasing, requirements to maintain access for businesses and residents during construction operations, and other mitigation measures are all standard on large projects today.

Construction engineers assist in the preparation and delivery of community communication plans and take community impact considerations into account when planning the work. For example, construction noise considerations can drive the phasing of operations. Noise-wall construction that would have been built at the end of a project, after access was fully established, is now often one of the first operations completed so the surrounding community is shielded from construction noise. In addition to the sequencing of work, noise considerations also drive equipment design and selection.

The addition of environmental and community impact considerations has broadened the scope of nontechnical issues for which the construction engineer needs to use technical analysis to avoid or solve problems.

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Technology

Thirty years ago, PCs were personal calculators, not personal computers, and information was accessed through networking rather than the Internet. These changes in technology mean that much more information is readily available, large amounts of data can be handled and analyzed, and more powerful tools for analysis can be used on an ongoing basis.

As a result of the Internet, a large amount of information on almost any subject is literally at one's fingertips. The issue is no longer obtaining information, it is deciding what information is relevant to generating a solution. For example, a construction engineer tasked with designing a sheet pile template for a cofferdam can find numerous examples and images of templates and design aids by conducting an Internet search.

The challenge is in limiting the data analyzed to data that provide meaningful rather than interesting information. An example is the collection of data from a haul unit—onboard sensors and automatic data-collection systems make it possible to determine the loading in each shock absorber on an ongoing basis. This information is meaningful in a mining operation in which haul roads can be optimized using this data, and it is interesting but not meaningful in an operation where the haul road varies on an ongoing basis.

Software that provides powerful tools for analysis has resulted in more efficient design solutions in construction engineering. More efficient designs mean more cost-effective designs and fewer safety concerns because the inherent safety factors generated by more conservative or less powerful design tools are gone. Examples of this can be found in the design of temporary structures where commercial software allows the finite analysis of continuous spans rather than the more approximate methods of calculation that were used previously.

The use of software with embedded tables has also made it critical that the construction engineer understand the underlying assumptions and basis for calculations used by the software. For instance, if the construction engineer does not understand that the software's underlying assumption that super plasticizers are not being used in the concrete mix design of formwork for walls where data input is limited to placement rates in terms of feet per hour and ambient temperature, the resulting design could be inadequate. It is also important that the construction engineer communicates this assumption to those utilizing the resulting design.

The end result of these advances in technology is that the need to effectively communicate the assumptions made as part of the design process to the personnel performing the field operations is critical. With more efficient designs and fewer safety factors, there are fewer margins if these assumptions are violated. An example of this is allowable load limits on elevators in which both the weight limit and load limits in terms of number of people are provided.

Work Plans

Overview

The increasing number and complexity of technical and nontechnical issues that need to be addressed for a successful project delivery combined with the requirement for effective communication of the methods, metrics, and expectations associated with field operations has led to the development of a formal process at Granite Construction called a work plan. The process and use of work plans is not unique to Granite as there are similar processes with varying degrees of formality in place for most heavy civil contractors.

A work plan provides the metrics and information needed by field personnel to execute an operation. The work plan can vary from a single page for a simple routine operation, such as fine grading roadway, to a large document for a more complex operation, such as the setting of the precast bent caps on a bridge project. The work plan is prepared by construction engineers working with field personnel.

Content

Each work plan addresses the following items:

- Step-by-step sequence of operations;
- Details for each step including materials required, crew makeup, and equipment;
- Jobsite and third-party safety (job hazard analysis);
- Environmental considerations;
- Community;
- Quality control;
- Responsibilities; and
- Budget and schedule.

In addition, reference materials and community issues are addressed as applicable.

Step-by-Step Sequence of Operations

Each operation's work plan is broken down into a step-by-step sequence. For a relatively simple operation like roadway grading, it may only consist of a few steps, such as an initial step of "set GPS control" followed by "grade roadway."

The precast pile caps at U.S. 90, Bay St. Louis, Mississippi, provide a more complex example in which there are a number of steps in the operation. The U.S. 90, Bay St. Louis project was one of the emergency bridge replacement projects following Hurricane Katrina. The replacement bridge included 51 trestle-type caps with typical dimensions of 1.52 m wide × 1.37 m tall × 28.96 m long (5.0 ft wide × 4.5 ft tall × 95.0 ft long). The caps were precast in two segments, transported to the project by barge, and then set on 610 mm (24 in.) precast concrete piling using barge-mounted cranes. After the two precast segments were set, closure concrete and bearing pedestals were placed, which completed the operations. Figs. 1 and 2 provide an illustration of the operation.

For the precast caps at U.S. 90, the beginning and end of the operation was defined by the steps that the crew and crane had to accomplish at a specific bent before moving to another location. The steps for that operation include:

Fig. 1. Setting precast segment, U.S. 90, Bay St. Louis (photograph reproduced with permission from Granite Construction Company)

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Fig. 2. Completed cap, U.S. 90, Bay St. Louis (photograph reproduced with permission from Granite Construction Company)

- Set crane and material barge;
- Survey piles;
- Set work platform friction collars;
- Set work platform;
- Cut off piles;
- Set cap support collars;
- Set precast caps;
- Form/place/strip pile voids;
- Form/place/strip closure;
- Form/place/strip shear keys and bearing pedestals;
- Remove cap support collars;
- Remove work platform and platform friction collars; and
- Move crane and material barge to next location or bent.

Details for Each Step

In addition to the manning, equipment, and special tools that may be required, detailed information is provided for each step in the operation. For the setting of the cap support collars, a layout of the crane pick for the collars is provided. It consists of the weight of the collar including rigging, maximum pick radius for the crane, and the crane and material barge locations with tolerances. It also provides the torque values for the tie rods used to secure the collars. In addition, pictures of the in-place collars are provided.

Jobsite and Third-Party Safety

For the overall operation, jobsite and third-party safety are considered for each step. Crane safety and access are the primary concerns when setting the cap support collars. This is addressed with information provided about the load collars including rigging, the maximum and minimum distances for the crane barge from the piling at which the collars are set, and specifics of the crane configuration. Access is addressed by the previous step in the operation, setting the work platforms.

Environmental Considerations

In addition to safety, operation-specific environmental considerations are incorporated into the work plan. For example, the disposal of the pile cutoffs to an artificial reef is highlighted as part of the detail for cutting the precast piles. Overall site plans, such as the SPCC plan, address general environmental considerations such as emergency spill kits on each barge and floating turbidity screens.

Community

Similar to safety and environmental considerations, community considerations are also incorporated into the work plan. Typical community considerations include noise, access, protection of property, traffic, and communication. Noise restrictions impact equipment selection and working hours. Maintaining access for businesses and residents in and around construction activities impacts the sequence of work and the amount of room to work. Measures to protect property also need to be one of the initial steps in an operation's work plan. Communication includes temporary signage for businesses, advance notification of affected businesses and residences, and ensuring that the personnel performing the work have the necessary information to direct questions and/or complaints to the appropriate individual with responsibility for community issues.

Quality Control

The work plan incorporates both formal and informal quality control measures. Formal measures include the inspections and testing required by the contract specifications and/or project quality control plan. Informal measures are included in the details for each step in the operation and are checks on the work for which no formal records are kept. Examples of formal measures are the prepour inspections performed before a concrete placement and the ongoing testing of the concrete during the placement. An informal measure is using a string line to check that the cutoff grades that were set individually at each pile are in alignment across the pile bent to ensure no individual errors were made.

Responsibilities

As part of the work plan, the activities surrounding and directly involving the operation are assigned with clear expectations and accountability. Table 1 provides some of the assignments that were made for the pile caps at U.S. 90.

Budget and Schedule

The work plan also provides budget and schedule metrics for the operation. These metrics are typically expressed in terms of productivity (units/time such as square meters per work-hour) rather than unit costs (U.S. dollars/unit, e.g., US$1.50 per cubic meter) and durations. The complexity of the operation determines the number of metrics. For example, a roadway grading operation may have only one budget metric of *X* square meters (feet) per shift. The pile cap operation at U.S. 90 had several budget metrics. Examples include setting the precast cap collars at 1 bent per shift (four collars) and setting the caps at two pieces per shift.

Productivity metrics are used because the expectations are easily explained and understood. However, productivity metrics are based on a predetermined crew (labor and equipment). If the crew or equipment is changed for that operation, the productivity metric may no longer provide an accurate measure against budget.

Table 1. U.S. 90, Bay St. Louis, Precast Cap Work Plan Assignments

Assignment	Individual responsible
Procure rigging for precast caps	Field engineer—F. Smith
Coordinate crane and material barge movement	Marine superintendent—J. Jones
Survey pile cutoffs	Survey chief—T. Clark
Install rebar	Subcontractor foreman—A. Marks
Wet concrete testing (including transport of cylinders)	Subcontractor testing technician—To be determined

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The increasing use of electronic time cards and field information systems has allowed the increased use of unit costs as the metric because the actual unit costs are available on-screen as soon as the quantities, labor, and equipment are input. A metric based on unit costs provides a more accurate measurement because it reflects the impact of changes in manning or equipment. Schedule expectations are then provided as a separate metric.

Reference Materials

Reference materials may be included with the work plan as applicable. Typical reference material may include contract drawings, specification sections, equipment specifications, shop drawings, and/or excerpts from other project plans. For the U.S. 90 pile cap work plan, reference materials included marine load charts for the cranes, assembly drawings for the friction collars and platforms, and the applicable specification sections.

Work Plan Process

Define Number and Scope of Individual Work Plans

The work plan process begins with a definition of the field operations on a project requiring an individual work plan. It ends with an individual document for each work plan. The document provides personnel with the expectations and metrics for that operation and any other information necessary to perform the operation.

A work plan is put together for all significant operations. Significance is determined by the project staff and can be on the basis of any number of criteria such as dollar value, risk, complexity, safety considerations (jobsite or third party), community concerns, quality, or environmental concerns. Examples of the primary considerations behind a number of work plans are shown in Table 2. After determining the work plans required, a schedule is developed for the preparation of the individual plans and resources and personnel are assigned to each plan.

Develop the Individual Work Plan

Define the Problem

The first step in developing a work plan is to define the scope, constraints, and requirements for that particular operation. The constraints and requirements definitions are the most critical elements in the work plan development because these may limit the potential solution. For example, the use of precast caps was not reflected in the preliminary design drawings for U.S. 90, which had a design-build project delivery system. The construction engineer understood that although a precast alternative to the cast-in-place cap was not shown, the preliminary drawings allowed a bent cap alternative with no constraints on the method.

The scope is largely derived while determining which work plans are required. The scope defines the start and end points and the extent of the particular operation that the work plan is addressing. Continuing with the precast cap example, the work plan's extent was the trestle section of the bridge over water. The starting point was the supporting piles below the cap in place but not cut off. The end point was the completion of the cap including girder shear keys and bearing pads.

Constraints and requirements are obtained from project specifications and/or plans, permits, and physical conditions and from the estimate (budget) and schedule. For example, one constraint for the caps was the capacity of the cranes available for the project. If the cap was precast in one piece, its weight would be approximately 150 tons, or much more than the available equipment could handle. The solution was to precast it in two segments.

Develop a Solution

The development of a solution begins by revisiting the method contained in the estimate for the project. Once the method from the estimate has been reviewed to confirm that it satisfies the previously defined constraints and requirements, it becomes the baseline against which other solutions are evaluated. The development of the solution is a collaborative process that is led by the construction engineer. The construction engineer will seek input from the field personnel performing the operation, the designers of the project, other project staff, and the estimators for the project, in addition to internal and/or external experts. Information may be gathered on an informal basis or there may be several brainstorming sessions. The potential solutions will be developed in sufficient detail so that they can be evaluated against the baseline solution, which is the solution contained in the estimate.

In the case of the caps at U.S. 90, several solutions were evaluated including precast caps, partially precast caps (bottom soffit only or a shell), and cast-in-place alternatives. The potential solutions were the result of consultations with the estimators, designers, internal experts, and project personnel, including the front-line supervision that would be performing the work. Following an initial evaluation, the potential solutions for the caps were narrowed down to a cast-in-place alternative and precasting the cap in two pieces. These solutions were then developed to the point that the required equipment and relative costs and durations for the solutions could be evaluated. At this point in the process, additional information was obtained from concrete form suppliers and precast concrete suppliers. Once the precast alternative was selected, the steps involved in the operation were determined and a solution was developed for each of the steps. The alternatives examined for precasting the caps were either self-performing the work or subcontracting it. The evaluation looked at available space for the precasting operation, storage, load-out of the completed segments, and the marine equipment needed to transport the equipment.

Once the evaluation and analysis is completed, an initial draft of the work plan is prepared. The initial draft includes the following:

- Step-by-step sequence,
- Details for each step,
- Template for job hazard analysis (safety analysis),
- Quality control checklist (if applicable),
- Work assignment list,
- Production and schedule metrics, and
- Reference material.

Table 2. Primary Considerations Behind Work Plans

Project	Work plan (operation)	Primary considerations
U.S. 90, Bay St. Louis	Precast pile caps	Complexity, risk
Intercounty connector, contract A	Culvert AA	Environmental
Florida Turnpike	Traffic control	Safety (public and jobsite)
Brighton Line, 5 stations	Platform demolition, Avenue M	Public safety, environmental (hazardous materials)

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The draft solution is then peer reviewed by another engineer and the superintendent who will be responsible for the implementation of the work plan.

Finalize the Plan

The construction engineer and superintendent responsible for the work present the work plan to the contractor's personnel who will be supporting the operation, including safety managers, quality control personnel, project controls personnel, field supervisory staff, and project management. At this meeting, the overall plan is reviewed with an emphasis on identifying potential shortcomings and risks. Following the meeting, any necessary revisions and contingency plans are made and incorporated into the plan. An issue identified at U.S. 90 was the need to set the precast caps at a slight angle relative to the top of the piling to facilitate setting the precast cap over the reinforcing steel dowels from the piling. A minor change to the design for the rigging used to set the precast caps was made to accommodate this.

The plan is also presented to the client's personnel and consultants for their informal input and comments. At U.S. 90, the client's project management team identified some potential issues that were addressed at a stage when the impact was minimal. This would not have been the case if those issues had not been addressed in the planning stage.

Presenting the plan to the field personnel who will be performing the operation is the last step. This meeting typically includes the superintendent, foreman, key members of the crew, quality control inspector for the operation, and the safety manager. At this meeting, the operation is reviewed in detail and the job hazard analysis is completed.

Communication

Involving field personnel in solution development and presentations to the various parties outlined in the previous paragraphs is only the start of the ongoing communication of the work plan and its associated metrics. As part of the project management process, there are daily coordination meetings for the overall project and for the individual crews. There are also weekly meetings at which budget and schedule metrics are distributed and reviewed. If the work plan is an ongoing operation, process improvement discussions will also take place at the weekly meetings.

At the daily coordination meeting for the overall project, the foreman or superintendent responsible for the operation will provide a brief update of the operation's status, the activities planned for that day, and any general information that needs to be communicated to the team. For the caps at U.S. 90, the general information included planned barge movements and availability of a bent for follow-up activities.

The crew's daily coordination meeting includes a review of the planned activities for the day and their individual roles, a review of the hazards and environmental issues surrounding the activities, and the expectations for quality and production for that activity. The meeting would be conducted by the foreman with the construction engineer in attendance. The basis of the discussion points is the work plan.

The weekly budget and schedule meetings are also held at both the overall project and crew levels. Typically, the information is distributed at one of the coordination meetings and briefly discussed. The construction engineer is responsible for distributing and reviewing the results with the crew. If the operation is ongoing, a discussion will follow on how the operations can be improved.

Metrics

A key item in the implementation of the work plan is the selection of the key metrics for that operation. The key metrics are used not only to determine overall success but to evaluate changes to the operation. Key metrics include the productivity (units/time) or unit cost (dollars/unit) metric that may be used on a daily basis and the schedule metric that may be used. For the caps at U.S. 90, there were several productivity metrics that were used on a daily basis. They included setting an entire cap or two precast pieces per shift,

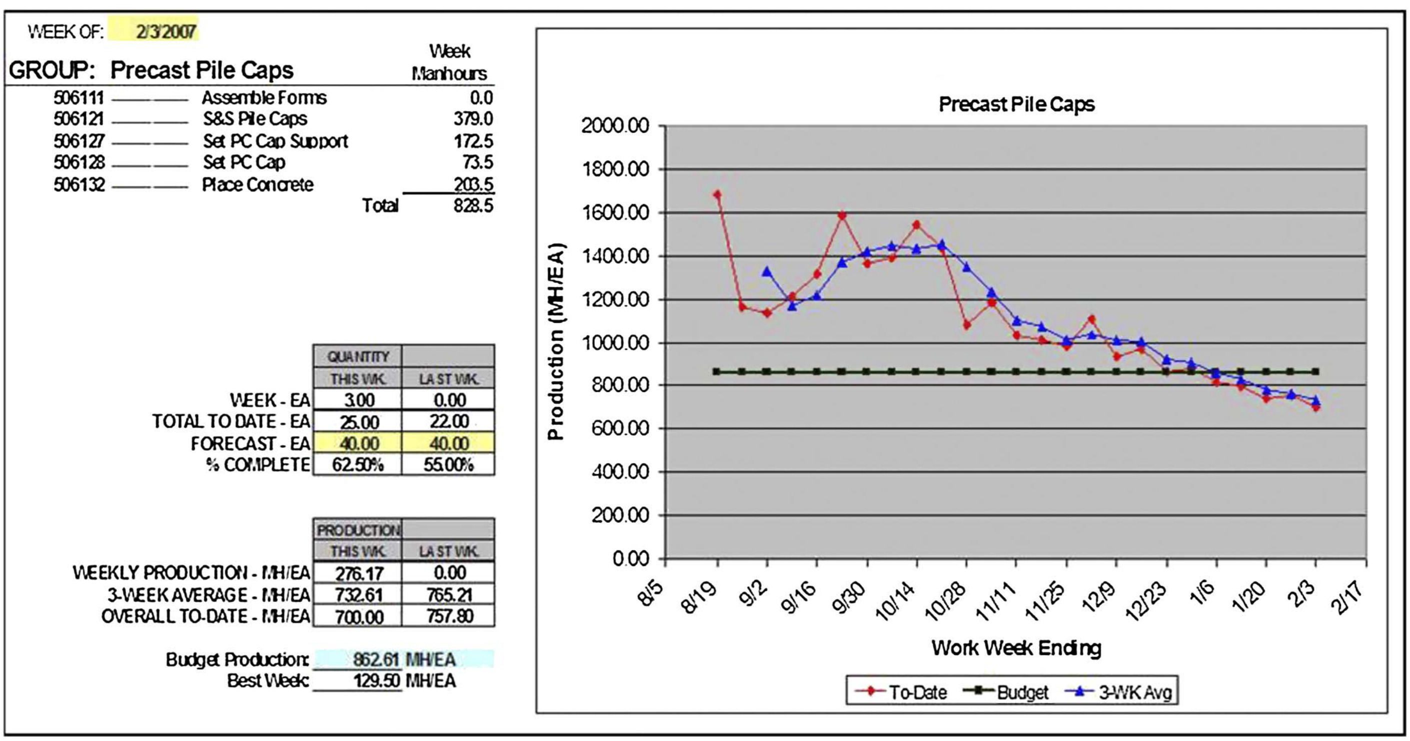

Fig. 3. Precast cap metrics

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cutting off five piles in a shift, and stripping/cleaning/resetting the closure forms for a cap in a shift.

For the weekly metric, a composite productivity measurement was used, as shown in Fig. 3. The tabular data on the left of the figure provided a summary of the cost accounts with activity during the week, a quantity status, and a production overview for the week. The graph provides an overall look at the weekly productions. A 3 week moving average is used in lieu of individual weeks because the overall duration of the activity makes weekly productions highly variable. As seen in the graph for the 3 week moving average, initial productions were highly variable during the startup period, followed by significant gains in productivity during the learning curve, and then slower gains as improvements to the operation were implemented. Overall progress on the caps was tracked using the number of completed caps as the metric.

Process Improvement

The initial work plan becomes the baseline for process improvement once the operation begins. Changes to the operation are made on a systematic basis, metrics are tracked so the impact of the change can be assessed, and the work plan is updated to incorporate the successful changes. For ongoing operations such as the precast caps, the weekly cost and schedule meetings were used to solicit and implement improvements to the overall operation. Action items are identified and tracked with the responsible individuals identified. At U.S. 90, several improvements were made to the precast cap operation. For example, the access platforms were simplified to improve overall access and improvements were made to the methods for setting the friction collars, which reduced the manhours required for this step in the operation. Crew sizing was also optimized.

Once the operation is completed, lessons learned and actual outcomes are documented for each of the work plans as part of the project final report. The final reports and work plans are archived as reference material with the intent that they will be used as the basis for future operations.

Key Aspects of the Work Plan

The key aspects of a successful work plan are
- Involvement of field personnel in its development,
- Communication of the plan on an ongoing basis,
- Selection and communication of metrics, and
- Disciplined but open approach to change.

If the personnel that are required to execute the plan are not involved in its development, it is difficult to get buy-in and commitment to it. The personnel executing the plan also become more accountable for its success or failure. The involvement of field personnel adds their expertise gained from hands-on experience to the plan.

The work plan is useless if it is not effectively communicated. This is particularly difficult if the plan is complex and has a large number of steps. To be effectively communicated, the plan has to be summarized on a single page that provides the key information for that day's activities. This includes the details for that day's steps, what the highest risks are, quality concerns, environmental issues, and productivity expectations. In addition, language and education barriers must be taken into consideration when disseminating the information.

Selection of the metrics that accurately reflect the overall economics of an operation is critical. Selecting metrics that only provide a partial picture rather than an overall measure of the success or failure of an operation can be detrimental to the overall success of the project. An example of this would be to measure the setting and stripping of the friction collars that support the precast cap as a separate metric. Optimizing the cost of setting the friction collars might result in a higher overall cost if the changes to the setting of the friction collars adversely impacted the setting of the precast segments. If metrics are selected that are too broad, the metric does not provide meaningful information. If the metric for the precast cap operation at U.S. 90 included pile driving, which is typically performed independently with no shared resources, the information provided would not allow meaningful measurements for changes to either operation.

As part of the ongoing communication of the work plan, the metrics need to be shared with the personnel performing the operation. This continues the buy-in and commitment that was initially started by involving the field personnel in developing the plan. Without this information, it is difficult to effectively involve the field personnel in process-improvement initiatives.

The work plan is an evolving plan that is improved as operations continue. To do this efficiently, a disciplined approach is required—one that makes changes in a proactive rather than reactive manner, measures the impact of the changes, and reacts accordingly. Although the approach needs to be disciplined, there also needs to be a willingness to experiment with alternate solutions until the optimal solution is determined.

Construction Engineering Education

The work plan process is a means of performing the planning and technical analysis required as part of the construction engineer's role as part of the overall project delivery process. The work plan process utilizes basic problem-solving skills that are fundamental to an engineering education. These skills remain the same regardless of the technology and/or tools used. Problem-solving skills are also applied in essentially the same manner regardless of the technical, environmental, economical, or community considerations surrounding the problem.

Given the increasing rate of change in both tools and technology and the increasing complexity of the factors considered in construction engineering, education of a construction engineer must emphasize fundamental problem-solving skills. These skills include problem definition, identification of constraints and their relative importance, analysis techniques, and, solution validation. These skills need to be taught using basic tools so that the skills are learned rather than software being learned.

Finally, no engineering solution, no matter how elegant, can be effective if it is not communicated. The construction engineer does not need to only be taught how to solve a problem, but also how to communicate the solution across any educational, cultural, and/or language barriers that may exist.

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