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DESIGN FEATURES FOR IMPROVED CONSTRUCTABILITY OF MARINE PIER PROJECTS

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Marine construction projects face significant challenges due to their physical environment as well as safety and environmental regulations. A well-engineered design with constructability in mind is essential for the successful construction of such projects. This study investigated the design features that created significant constructability benefits on the Pier 12 Replacement Project at San Diego, California. The US $82 Million fixed price design-build project involved the construction of a new 1,500-foot pier that could fulfill the utility needs of multiple stationed ships. The following design features were important in improving the constructability of the new pier: (1) Selection of plumb piles; (2) Design of uniform and longer pile spacing; (3) Increased depth of pile dowel tubes; (4) Use of T-headed pile dowels; (5) Avoiding the use of pile caps; (6) Minimizing the fluctuations of deck soffit elevations; (7) Minimizing the expansion joints; (8) Minimizing the variety of rebar sizes; and (9) Increasing the depth of concrete rebar cover.

Keywords: Marine construction, Design-build, Piles, Dowels, Concrete, Deck.

1 INTRODUCTION

Construction efficiency and costs are heavily dependent on the quality of the design. The Construction Industry Institute (CII) defined constructability as “the optimum use of construction knowledge and experience in planning design, procurement, and field operations to achieve overall project objectives” (CII 1993). It is the “potential ‘bridge’ between the design and construction disciplines. Applying constructability concepts at the early stage of construction projects reduces the cost of design and construction and improves the project schedule, design coordination and worker productivity (CII 1993, Jergeas and Van der Put 2001, Pulaski and Horman 2005, Ruby 2008, Song *et al.* 2009, Raviv *et al.* 2012, Kifokeris and Xenidis 2017). According to the CII (1993), constructability efforts save on average, 4.3% on project cost and 7.5% on schedule. These savings have been shown to represent a 10:1 return on investment in the constructability effort.

Marine construction projects take place over and under the water, in order to build structures such as wharves, piers, terminals, bridges, marinas and outfalls. The marine environment, the design requirements, and the strict safety and environmental regulations, create significant challenges for such projects. A well-engineered design with constructability kept in mind is essential for successful construction of such project. The objective of this study was to identify design features that created significant constructability benefits on the Pier 12 Replacement

Project at San Diego, California. This design-built project was performed by the same contractor and designer, who designed and built similar piers (Pier 10 and 11 replacement projects) at the same naval base. As a result of the lessons learned, the design engineers incorporated several changes in the design of the new Pier 12 to improve constructability. This investigation focused on two major operations; pile driving and concrete construction, which included building and setting the formwork, fabricating rebar layouts, and pouring concrete.

2 BACKGROUND

Previous research has identified several constructability principles: (1) Design simplicity, which involves the minimization of the number of materials, sizes and components (Zolfagharian and Irizarry 2017), and the simplification of construction details (Kuo and Wium 2014). (2) Standardization and repetition. The repetition of layout (floor grids, dimensions of elements, and floor height) benefits the learning curve and increases productivity. Standardization of material simplifies procurement and material management and allows volume purchase discounts (O'Connor *et al*. 1987, Zolfagharian and Irizarry 2017). (3) Preassembled components typically improve productivity, parallel sequencing of activities, increase safety, improve quality control, reduce the need for scaffolding (O'Connor *et al*. 1987), and reduced exposure to weather conditions. (4) Consideration of interfaces where joining of materials are difficult (Kuo and Wium 2014). (5) Design solutions that can reduce sensitivity to adverse weather conditions, e.g. by reducing the quality sensitive work conducted outdoors (O'Connor *et al*. 1987). (6) Enhanced accessibility of manpower, materials, and equipment (O'Connor *et al*. 1987, Zolfagharian and Irizarry 2017).

Construction researchers have developed guidelines for the constructability of reinforced concrete structures (Fischer 1991), steel structures (Ruby 2008), façades (Horn 2015), formwork (Jarkas 2010, Jiang *et al*. 2015), and commercial buildings (Zolfagharian and Irizarry 2017). With regards to constructability of marine pier structures, the use of large precast components has been used to accelerate pier construction, saving time on formwork and concrete curing (Rosner *et. al* 2010, Jaradat 2013).

3 METHOD

This investigation used the case study method at the project level. Data were collected through interviews with the project personnel (design engineers, project manager, estimator, quality control and field personnel) and extensive field observations. One of the authors was working as a project engineer on the project and had access to the personnel and operations. The design engineers and project management staff had worked previously on several similar piers (original Pier 12, Pier 10, etc.). The engineers and contractor discussed the lessons learned from previous pier projects and explained the construction advantages of the selected design features. Interviews with craft employees (laborers, pile drivers, surveyors, and foremen) discussed the difficulties and problems that field encountered. Finally, extensive observations and documentation of the construction activities recorded the details of the operations examined.

4 PROJECT DESCRIPTION

The Pier 12 Replacement project involved the construction of a new pier 1,500 feet long, and 117 feet wide that could fulfill the utility needs of multiple stationed ships. The cost was US $82 Million, and the schedule was 25 months. The delivery method was design-build with fixed price contract. The major operations included: (1) Dredging of approximately 130,000 cubic yards around the pier area; (2) Demolition of the existing 1,460-foot Pier 12, (3) Driving 512 24-inch octagonal precast prestressed concrete piles configured into 64 bents (rows) of piles that contain eight piles; (4) Construction of the new Pier 12; (5) Construction of one guard tower; and (6) Installation of 56 100-ton mooring bollards; and (7) Driving 204 concrete fender piles. The construction of the new pier required (1) Construction of the 24 inch thick main deck surrounded by a 22.5-foot utility trench making the entire pier deck approximately 175,000 square feet and 15,000 cubic yards of concrete; (2) Construction of a utility system consisting of a plumbing network that fulfills the ship's needs for fresh water, oily waste, and sewage; and (3) Installation of the electrical package. The investigation focused on the pile driving and concrete operations.

The pile driving operation included the following activities: (1) Receive and stack the concrete piles; (2) Load the piles onto a 7,500 square foot flat barge using a derrick barge crane; (3) Drive the piles in the bay floor using the derrick barge crane, and a D-80 hammer; (5) Cut the top of the piles at the proper elevation (or pour additional length if needed), and (6) set the dowels. The formwork and rebar operation included the following activities: (1) Set friction collars onto concrete piles; (2) Set I-beams on top of the friction collars; (3) Set prefabricated formwork panels and parallam beams on top of I-beams to elevation; (4) Set sidewall formwork panels and lateral supports; and (5) Install reinforcement bars and electrical conduits. Concrete placing included the primary pour for the 72-foot long deck section over four center piles, and secondary pour for the utility trench sections over the outer four piles. Finally, the formwork panels were stripped by removing the friction collars while the I-beams and formwork panels were secured to the concrete deck with stripping cables, and then cutting the stripping cables, dropping the I-beams and panels into the water.

5 RESULTS: CONSTRUCTABILITY OPPORTUNITIES

The design-build contractor identified nine design decisions that were significant for the constructability of Pier 12.

5.1 Plumb Instead of Battered Piles

The use of plumb piles provided several benefits: (1) *Fewer piles*. Pier 12 required 512 plumb piles, as opposed to same size Pier 10 that called out for 362 battered piles and 334 plumb piles totaling 696 piles. This was 184 fewer piles to be transported, handled and driven. (2) *Reduced cycle time*. When driving the battered piles of Pier 10, the crane had to relocate and re-anchor up to eight times for every two bents of piles it drove. In contrast, for plum piles of Pier 12, the crane had to relocate and re-anchor five times for every two bents of piles driven. This decrease in the number of moves drastically reduced the cycle time and increased productivity. On Pier 10, an average of 8 battered piles were driven per day, while on Pier 12 an average 11 plumb piles were driven per day. (3) *Lower pile driving cost*. Considering the cost for materials, labor and equipment, using plumb pile over battered piles saved the project about $4,500 per pile and a total of $828,000. (4) *Faster installation of friction collars*. Since battered piles are set at an angle, the workers must carefully set the friction collars and then use an alignment collar in order to evenly set the I-beams above it. The use of plumb piles eliminated the need for alignment collars and made installation of squeeze collars faster. This change saved money with equipment and labor cost adding up to about $125,000. (5) *Improved safety*. Installing battered piles involved higher safety risk due to chipping off, rubbing on gate, and risk of ears on hammer breaking.

5.2 Pile Spacing

The spacing between pile bents determines the length of the deck panels. Larger spacing increases the length of formwork and makes formwork easier to set, but it increases the concrete load on the form, which is in turn requires more reinforcement bars, as well as more friction collars. Thus, to determine an economical length of the panels, the contractor considered the trade-off between efficiency of formwork installation against the increased friction collars and rebar required. For Pier 12, the designer considered three spacing options and selected a standard bent-to-bent span distance of 24 feet except for the last two spans (10 and 16 feet). A longer and a shorter span were found to be less economical. The uniform distance resulted in uniform size deck panels (48 feet long). This reduces potential mistakes due to a variety of panel sizes. Standard spacing also allows reuse of formwork panels down the pier, which reduces waste of formwork material.

5.3 Depth of Pile Dowel Tubes

Each precast pile required eight rebar dowels to tie into the reinforcement bars in the deck of the pier. The spec required that these dowels were embedded 6 feet in the pile. For this, each pile had at the top eight corrugated metal tubes of 2 inch diameter for the dowels to be embedded and grouted into place. On the Pier 12 project, the contractor ordered the piles with dowel tubes of 16 feet. This way, a pile could be cut up to 10 feet (in order to be at the correct elevation) without requiring extra drilling to embed the dowels. This “lesson” was learned on a previous project, where the contractor used dowel tubes 10 feet deep. However, a large portion of the piles had to be cut by more than 4 feet, and the contractor had to perform extensive drilling to achieve embedment of 6 feet. The labor and equipment time and cost to drill more embedment depth Is much greater than just filling the extra embedment tube length with more grout. The 16 feet depth increased the tolerance for the variation in pile depth.

5.4 T-headed Instead of Angled Pile Dowels

The original design called for 90-degree angled pile dowels. However, because the piles are not at the perfect location, the angled dowels were often out of position and did not meet the required minimum cover depth of three inches. This led to numerous rebar dowels needing to be bent to make the needed 3-inch cover. Bending these rebar dowels out in the field was not an easy task and cost the crew great deal of time. Other dowels had to be cut and retrofitted with a T-head using a lenton rebar splice. After the contractor identified the problem, they changed the design to T- headed dowels. These dowels were more expensive and needed a three-week lead-time but drastically reduced the need to rework the dowels, as they provided larger tolerance to meet the rebar cover requirements.

5.5 Deck Design Without Pile Caps

Pile caps and pile cap beams are needed when a thinner deck is thinner, or a precast deck is used. In those cases, the pile caps are formed and poured before the deck, adding another step to the operation. Pile caps are also labor intensive and require extensive formwork, thus increasing material and production costs. Pile caps also pose an easy target for deterioration and corrosion. In Pier 12, there were no separate pile caps; the required reinforcement was part of the thick deck. The main deck was 24 inches thick, but at the along the sides of the pier the utility trench the depth of the trench reached 4. 5 feet. With the thick deck, the pile cap was incorporated in the deck soffit, which eliminated the need for separate formwork and pouring.

5.6 Flush Deck Soffit

In Pier 12 Replacement, the design of the deck soffit was flush. Eliminating fluctuations in the elevation of the deck soffit greatly simplified the formwork fabrication and rebar installation. This was a change from the old Pier 12, which had four different soffit profiles. The changing elevations across the bent as well as from bent to bent have a substantial impact on the labor costs for formwork and rebar fabrication and installation. Having the experience of the old pier 12, the designer and contractor simplified the design of the deck soffit for the new pier 12. Minimizing the fluctuations of the deck soffit elevations at Pier 12 created significant savings, as the fabrication of the deck formwork was a lot simpler and faster. The saving in labor and time (without accounting for potential errors and rework) exceeded the additional cost of material.

5.7 Minimum Number of Expansion Joints

The installation of expansion joints is very labor intensive and requires extensive formwork. The Pier 10 replacement project required three construction joints with base isolators along the structure. The installation of the expansion joint and base isolators required a total of 650 man-hours and 6 weeks duration. In addition, the expansion joints in the middle of the pier also prevent the reuse of the deck panels and formwork. After considering the lessons from Pier 10, the designer and contractor decided to install at Pier 12 only one construction joint with base isolator at the base of the pier since the use of plumb piles gave the structure more flexibility from internal and external forces.

5.8 Low Variety of Rebar Sizes

In Pier 12, the designer also tried to keep the complexity of rebar configurations at minimum, by standardizing rebar sizes for each work area of the pier and using few rebar sizes at each area. The majority of the concrete deck used #6 and #8 size rebar, the utility trenches used #5 and #10 rebar, the precast electrical vaults used #4 and #5 rebar, the precast trench lids used #4 and #9 rebar. The simplicity and standardization of the rebar resulted in faster installation and fewer mistakes when installing rebar cages.

5.9 Depth of Rebar Cover

On the Pier 12 project, the design specified 3 ½ -inch concrete cover with a DCI corrosion-inhibiting admixture to inhibit rebar corrosion. The reason was to avoid the difficulties faced on Pier 10, which used epoxy- coated rebar and a standard 3-inch concrete cover. Since the reinforcement bars in Pier 10 had a cover less than 3 ½ -inches, all bars had to be coated with epoxy due to the corrosive marine environment. The epoxy coat was applied by the manufacturer prior to shipping. The contractor identified the following disadvantages of the coated rebar: (1) it was about $1 per pound more expensive than non-epoxied rebar; (2) it required very careful handling - if the epoxy was chipped or damaged, the bars had to be patched with epoxy; (3) the crew found it difficult walking on the rebar due to the slippery conditions. The crew also reported difficulties clearing debris from the rebar when working with a 3 inches cover.

On Pier 12, the design specified 3-½ inch cover with a corrosion inhibiting concrete admixture. This required more concrete but eliminated the need for epoxied rebar and all the associated difficulties. It also allowed the ironworkers to bend any rebar on site if needed, since damaging the epoxy was not an issue and made easier to clear out debris in the rebar.

6 CONCLUSIONS

The study identified nine constructability improvements that the designer and builder incorporated in the design of Pier 12 replacement project based on their experience with previous similar piers. Most of these practices aimed at creating a simple and standardized deck design. The *pile spacing*, the *flush soffit*, the *avoidance of pile caps*, and the *minimum use of expansion joints* reduced the variety of formwork panels, simplified formwork fabrication and installation and increased the reuse of the panels. The trade-off was increased quantity of concrete.

The *rebar design*, and the 3 ½ inch *rebar cover* reduced the difficulties of the rebar activity. The trade-off was again increased quantity of concrete. The *plumb piles* and *pile spacing* reduced the scope, complexity and difficulties of piling driving and friction collar installation. The trade-off was an increased flexibility of the structure, which in this case was a desired attribute. Finally, two other features—the increased *depth of dowel embedment*, and the use of *T-headed dowels*, demonstrate the importance of design details that provide adequate tolerance and minimize the costs of adjustments to the variability of field conditions, such as extra drilling, and modifying the dowels, which generate significant additional costs.

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