Use of Hydrodemolition To Remove Deteriorated Concrete from Bridge Decks

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Hydrodemolition is a relatively new method of removing select portions of a hardened concrete structure. By using the erosive power of high-velocity water streams, hydrodemolition equipment breaks up concrete by disintegrating the cement matrix between aggregates. The demolishing effect can be tightly controlled to a desired level of removal, ranging from light scarification of the surface to deep penetration of the structural element. The use of the hydrodemolition process has several advantages over conventional concrete removal methods, such as jackhammering. These advantages include a reduction in new damage caused by the removal process; automation, which produces a very consistent level of removal energy over large areas; the ability to seek out and remove weak or deteriorated locations at various depths; and a rough, high-quality bonding surface for repair materials. These characteristics are favorable for construction projects that involve rehabilitation of corrosion-damaged reinforced concrete structures, particularly bridge decks. Details of the hydrodemolition process, equipment operating parameters, and incidental requirements are provided. In addition, appropriate structural conditions that favor the use of hydrodemolition and various methods of specifying work items related to bridge deck rehabilitation are described. The need for comprehensive field evaluations of concrete structures before rehabilitation strategies are developed was found during the course of the work.

An increasing amount of infrastructure construction involves the renewal of existing facilities. Over time the structures within these facilities become inadequate either because of obsolescence or because of degradation caused by continued use and exposure to their environment. At some point in time it becomes necessary or desirable to renovate the structures to restore the functional quality of the facility. In many instances it is beneficial to repair and use selected portions of an existing structure rather than to completely rebuild it. This is often the case with steel-reinforced concrete structures, which are extremely durable by nature but which can be prone to deterioration in isolated areas. Differential deterioration is usually caused by corrosion of reinforcing steel, which creates internal forces sufficient to crack the concrete in locations where tensile stresses are concentrated. As more cracks develop, the process is accelerated and various levels of deterioration occur at different locations throughout the structure. When this situation exists it is desirable to remove the deterioration and place new concrete, which bonds to become part of the structure. The new concrete may be a simple replacement for the deterioration or it may be formed to increase the size of the structural element.

Hydrodemolition is one method used to partially remove selected areas of a concrete element. First developed in Europe in the late 1970s, this method has become a widely used and significant part of concrete rehabilitation. By using the erosive power of high-velocity water streams, hydrodemolition equipment breaks up concrete by disintegrating the cement matrix between aggregates. The disintegration is achieved by the following mechanisms, which occur simultaneously: cavitation, in which rapidly changing pressures in flowing water produce shock waves with magnitudes sufficient to break up the cement matrix; pressurization of cracks and pores, which breaks the concrete in tension; and direct impact of the water jet, which dislodges loosened fragments (*1*). During these processes the aggregates themselves are not fractured. The demolishing effect can be tightly controlled to a desired level of concrete removal, ranging from light scarification of the surface to deep penetration of the structural element.

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ADVANTAGES OF HYDRODEMOLITION

The use of hydrodemolition has several advantages over conventional removal methods, such as jackhammering and rotomilling. A primary advantage of hydrodemolition is its ability to remove concrete around and in between reinforcing bars without inducing additional damage to the surrounding concrete. This advantage is very important because a majority of concrete deterioration occurs adjacent to corroding reinforcing steel. Rotomilling is an effective method, but it is only capable of removing concrete above reinforcing steel. Conventional impact methods, such as jackhammering, are versatile, but they are also slow and labor-intensive for large areas. In addition, jackhammers have been shown to cause new microcracks in concrete because of the intense vibrations in the immediate vicinity of the impact tool (*2,3*). When these tools come into contact with reinforcement and large aggregates, the destructive vibrations are further transferred to sound areas of the concrete that are intended to remain in place.

Selective Removal

Another advantage of hydrodemolition is its consistent execution of the removal operation because of the automated nature of the equipment. Once operating parameters have been established for a particular structure they are held constant to deliver a uniform level of removal energy throughout the process. This consistency produces the unique advantage of selective removal. Areas of a structure that contain weaker or more deteriorated concrete will break up faster, allowing time for the demolition to penetrate deeper, where it is needed. By maintaining stable control of the water stream's dispersion characteristics, hydrodemolition equipment has the ability to remove only low-strength or deteriorated concrete, whereas it leaves sound concrete intact. The penetration depth of the removal process varies to match the depth to which the lower strength or

FIGURE 1 Hydrodemolished bridge deck surface.

deterioration has progressed (*1*). Figure 1 shows a hydrodemolished bridge deck surface with various penetration depths.

Bonding Surface Quality

Additional advantages of hydrodemolition are related to the quality of the surface left behind after the removal operation. Of the many factors that affect the bond quality between new and old concrete, the condition of the scarified surface is among the most important. To provide long-term repairs through the use of concrete patching or overlays, the bonding surface of the original concrete must be clean, rough, and free of microcracks. It has been demonstrated that the concrete remaining after partial removal with impact hammers contains microcracking in approximately the upper 9 mm (0.35 in.) of the exposed surface (*2*). Depending on their sizes and densities, these cracks have been shown to dramatically reduce bond strengths and are very likely to contribute to the premature delamination of patch materials. Conversely, the surfaces remaining after the use of hydrodemolition contain significantly fewer microcracks. Tests have shown that the magnitude of surface roughness after hydrodemolition is approximately 50 percent higher than that after scarification with impact hammers. This rougher profile provides a greater bonding surface area, inhibits the formation of local shear planes, and can result in a doubling of the tensile bond strength of the overlay material (*2,3*).

Lastly, the hydrodemolition operation simultaneously blast cleans any exposed reinforcing steel as the removal is taking place. This promotes a good bond of the new concrete to the reinforcement and reduces the need for additional blast cleaning of the steel. However, precautions should be taken to inhibit new corrosion of the reinforcing steel, both while it is exposed to the atmosphere and after new concrete is placed.

DESCRIPTION OF EQUIPMENT

A typical hydrodemolition apparatus is composed of two distinct parts: a power unit that filters, pressurizes, and delivers the water supply and a demolishing unit that directs the flow of water to the concrete surface in a precisely controlled manner. The power unit, usually housed in a semitrailer, is versatile for many applications of the hydrodemolition method. The demolishing unit is designed for particular uses, such as on horizontal, vertical, or overhead surfaces. The majority of hydrodemolition work is performed on flat, essentially horizontal concrete elements such as bridge and parking garage decks. For this application the demolishing unit is usually mounted on the rear of a tractor-like vehicle, which travels over the deck's surface in a controlled manner.

The demolishing unit consists of a screedlike housing in which the high-pressure water jet is directed toward the concrete surface from a moving nozzle. The movement is produced by mounting the nozzle in a rotating head, off center of the axis of rotation. The head is attached to a cross-feed carriage that moves laterally in both directions across the full width of the demolishing unit. The combined motion of the rotating head and the cross-feed carriage produces a spiral path of the water jet. As the water jet passes over the concrete surface the removal is accomplished by the mechanisms described earlier. After a programmed number of lateral carriage passes the entire tractor advances forward a set distance and the cycle is repeated. All of these preprogrammed movements create an automated progression of the demolishing jet over the work area, allowing the removal to be performed in a consistent manner. Figure 2 shows a typical demolishing unit for horizontal applications.

Equipment Operating Parameters

Several operating parameters of the hydrodemolition equipment are adjusted to strike a balance between obtaining top-quality results for the specific project and maximizing production and efficiency. The basic equipment operating parameters are as follows: water pressure, flow rate, nozzle rotation rate, transverse carriage speed, and the tractor advance rate. Variations in any of these parameters affect the amount of energy delivered by the system per unit area of concrete traversed. Generally, the water pressure and flow rate are variables set by the operating contractor on the basis of the capabilities of the system. The water pressure and flow rate are inversely proportional for a fixed amount of removal energy. Some equipment models can develop water pressure as high as 241 MPa (35,000 lb/in.^{2}), allowing a relatively low flow rate of about 120 L/min (32 gal/min) for typical bridge deck removal. Equipment models that develop a lower maximum pressure will require a greater flow rate

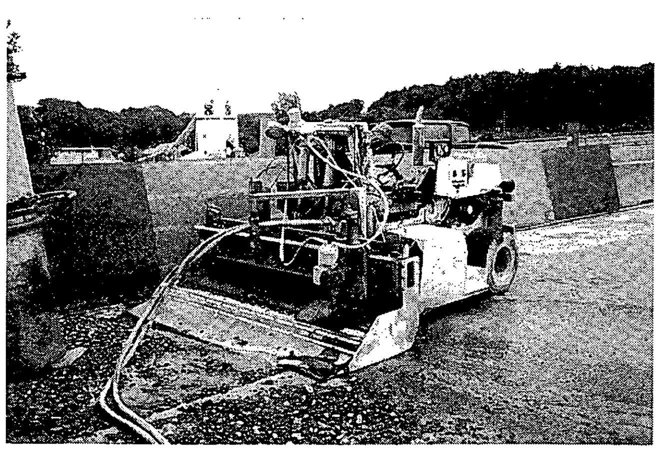

FIGURE 2 Hydrodemolishing unit.

to deliver the equivalent removal energy. In addition to these parameters, the optimum nozzle rotation rate is established by the hydrodemolition contractor on the basis of experience and is not routinely changed on a project-by-project basis.

The two main parameters that are routinely adjusted for each individual project or structure are the transverse carriage speed and the tractor advance rate. These adjustments work on the principle that the longer a fixed-energy water jet stays in one place the deeper it will penetrate. Therefore, the slower the nozzle traverses the concrete surface the more removal energy will be delivered per unit area. A typical bridge deck demolishing unit has a carriage width of approximately 2150 mm (7 ft). Depending on numerous structure-specific variables described later, the carriage speed is set and quantified by the amount of time that it takes to make one pass across the width of the screed. A typical setting is on the order of 400 mm/sec (1.31 ft/sec), or 5.4 sec/pass. Then, the entire tractor is programmed to advance forward after a set number of carriage passes, typically one to four passes per advance increment. The distance that the tractor advances each time [usually about 30 mm (1.18 in.)] can also be adjusted and must be monitored to ensure that the removal depth and production rate remain consistent.

For example, the desired removal on a typical bridge deck is achieved when the carriage speed is 5.0 sec-pass, and the tractor advances 30 mm after three passes. This means that an area of 2150 mm by 30 mm (7 ft by 0.1 ft) or 64,500 mm^2 (0.7 ft^2) is removed every 15 sec. This gives a production rate of 15.6 m^2/hr (168 ft^2/hr). This example shows that small changes in these equipment settings can greatly affect the amount of time that it takes to demolish a fixed-size bridge deck. Also, actual production rates can be significantly influenced by unforeseen problems such as downtime because of equipment failure and poor coordination of project activities. Maintaining a profitable production rate is primarily a concern of the hydrodemolition contractor. However, it is beneficial for bridge engineers to understand these relationships when they are involved in a hydrodemolition project.

Equipment Calibration Procedure

Because every structure and application is unique it is necessary to calibrate the hydrodemolition equipment before each use. The objective of the calibration is to balance the removal energy such that all deteriorated concrete will be removed without excess penetration of the sound areas. The procedure used to strike this balance involves adjusting the operating parameters mentioned earlier to produce the desired results.

Usually, an extensive evaluation of project goals and structure-specific variables is used to specify a minimum mean depth of removal for the entire demolition area. Since deeper removal will occur in weak and deteriorated areas, verification of the depth is performed at locations known to be sound and with strength characteristics typical of those of the original structure. For a bridge deck it is desirable to locate a sound area that is at least 2 m^2 (21.5 ft^2) for the calibration. Then, using past experience, the hydrodemolition equipment operator sets initial adjustments that are anticipated to achieve the minimum removal depth in the sound area. After several advances of the demolishing unit the operation is stopped and a depth measurement is taken. Depending on whether the penetration is too deep or too shallow, the transverse carriage speed is changed appropriately until the proper removal depth is accomplished. As stated, these adjustments may reduce the production rate of the unit, but achieving the proper removal depth is essential for high-quality results.

Once the equipment settings are established on a sound area of the deck, it is beneficial to check the level of removal on a weak or delaminated section. This secondary calibration is not performed for further adjustment of the machine settings but rather to ensure that the equipment will seek out and selectively remove all deterioration with the current settings. Chain dragging or other sounding methods are generally used to determine whether or not all deterioration has been removed. It is the responsibility of the project engineer to determine if additional adjustments are necessary. Once the calibration is complete the equipment settings should not be modified during the production removal.

PROJECT-SPECIFIC VARIABLES

Each hydrodemolition project contains an array of unique circumstances that make it necessary to assess goals and plan operations accordingly. Before the start of any construction work it is assumed that an extensive structure evaluation survey that led to a design calling for partial removal of the concrete structure and subsequent repair was performed. The condition surveys should include a delamination survey of all exposed surfaces; concrete strength tests by various methods; chloride ion concentration tests at various depths within the structure; half-cell potential survey at as many locations as possible; depth of cover over reinforcement survey; and an assessment of cracking, airvoids, and related characteristics of the hardened concrete (*4*). Additional test methods, now available for more detailed evaluations, have been developed as follows: measurement of reinforcing steel corrosion rates, automated flaw detection equipment that operates on both bare and asphalt-covered bridge decks, and various methods of evaluating the condition of existing corrosion-reducing techniques (*5*). The completeness and accuracy of the preconstruction condition survey of a concrete structure is fundamental to the success of the hydrodemolition and the overall rehabilitation strategy.

Structure Variables

If the results of the condition survey support the use of hydrodemolition for partial removal and repair, additional factors must be addressed. One factor is the amount of removal area that is accessible to the hydrodemolition equipment. Hydrodemolition is the preferred removal method and should be used wherever possible on a bridge deck. Certain areas around parapets, expansion joints, and other obstacles will require the use of impact hammers. It must also be determined whether the entire surface or only specific delineated areas showing deterioration will be subjected to removal. This type of spot removal and patching can be effective and economical, provided that all deterioration is found and removed.

Mean Depth of Removal

Depending on the findings of the condition survey the desired mean depth of removal must be specified such that all deteriorated and weak concrete is completely removed but that excessive concrete from sound areas is not removed. The automated, consistent energy characteristics of hydrodemolition increase the need for comprehensive and accurate data related to the existing condition of the concrete. Specifically, the total area and average depth of deterioration (delamination, microcracks, etc.) will greatly affect the volume of concrete removed by the hydrodemolisher. It has been estimated that when the anticipated amount of full-depth deck removal approaches 25 to 30 percent of the total area it is not cost-effective to pursue partial removal and repair. In these cases complete replacement of the bridge deck is probably warranted. If a high percentage of the deck's area is delaminated but it is predominantly limited to the top mat of reinforcement, partial removal down to a sound level is still a viable strategy. It is only large areas of full-depth deterioration that escalate the cost of rehabilitation, rendering it less economical to salvage any of the old deck. When the condition survey accurately quantifies the amount of full-depth deterioration, strategy decisions are more easily justified. Another consideration is the possibility that the length of time between the condition survey and the actual demolition may be long enough for additional corrosion and loading to significantly increase the amount of deterioration, and hence the quantity of removal.

Uniformity

Another structural variable unique for each bridge deck is the uniformity of the concrete slab. Decks that have not been altered since their original construction generally have uniform concrete strength or hardness with various levels of deterioration. When this is the case the hydrodemolisher will selectively remove deteriorated areas as described earlier. However, many times a bridge deck has undergone minor patching and repairs over its life. These patches usually have different strength characteristics than the original surrounding concrete because of the use of different materials, such as fast-setting or high-early-strength cements. When the hydrodemolisher reaches a patch significant changes in the depth of removal may occur. Usually, less removal takes place on the patch itself, and deeper removal occurs around the perimeter of the patch. The causes of this phenomenon include differential chloride ion concentrations that tend to passivate reinforcement corrosion within the patch material and accelerate corrosion in the older concrete and the possibility that jackhammering for the patches induced microcracking. Both of these situations promote further deterioration around the perimeter of the patch. When the presence of past patching is encountered while designing a rehabilitation strategy, special provisions for dealing with variable removal depths may require consideration. Figure 3 shows the presence of past patching on a hydrodemolished bridge deck.

Aggregate and Reinforcement Characteristics

Lastly, the size and density of the deck materials are structure-specific variables that affect the mean depth of removal and production rate of the hydrodemolition operation. The composition of the original concrete mix determines such variables as the gradation and maximum size of the aggregates and, hence, the ratio of large aggregate volume to cement matrix volume. Since the demolishing water jet erodes only the cement matrix of the concrete, the aggregates remain essentially intact. More energy and time may be required to demolish with the water jet concrete mixes that have more large aggregate by volume, indicating a lower volume of cement matrix. This condition exists under the assumption that the volume of cement matrix is not so low that the overall compressive strength is lower than a normal level. The vast number of combinations of aggregate sizes and mortar characteristics are interrelated variables that determine the strength and hardness of the concrete. Coring or other sampling techniques are good ways to identify the composition of the deck to better estimate removal quantities and production rates.

FIGURE 3 Existing patches on a hydrodemolished bridge deck.

The size, spacing, and vertical placement of the reinforcement also vary from structure to structure, affecting the removal operation. The predominant variable regarding reinforcement is its depth of cover. Many bridge decks do not have the same top mat reinforcement cover as shown in the original design plans. Shallow cover is one of the primary reasons for premature delaminations and spalling. Sometimes, the amount of cover varies considerably over a deck's area. Although not often performed, an accurate depth-of-cover survey is valuable in developing rehabilitation strategies. For example, if a deck has at least 60 mm (2.36 in.) of cover over its entire area, it may be beneficial to rotomill down to the top mat before hydrodemolition. If they are done under the right conditions, this combination of removal methods can be more economical than hydrodemolition alone (*6*). However, if hydrodemolition is chosen and unanticipated areas of lower cover are encountered, the quality and cost-effectiveness of the job may be reduced. Consideration of these variables shows that a comprehensive and accurate evaluation of a structure before the design and construction of a rehabilitation strategy is extremely important for obtaining high-quality and cost-effective results.

Other Project-Specific Requirements

In addition to a detailed assessment of the physical condition of the bridge deck to be hydrodemolished, other aspects of the removal operation should be assessed before work begins. One requirement is a method of controlling the runoff water. As stated, water is dispensed during removal at a rate of approximately 120 L/min/nozzle (32 gal/min/nozzle). Once out on the deck this water must be routed, filtered, and disposed of in a manner compliant with environmental regulations. Usually, this is accomplished by either vacuuming the water immediately after its release or routing it to a sedimentation basin. Each structure has an unique geometry that will affect the water drainage and collection setup.

Also to be considered is the cleanup of the debris generated during hydrodemolition. As the unit progresses over the deck it leaves behind a wet mixture of concrete slurry and solid fragments. It is extremely important that this debris be washed off and removed from the scarified surface before it has a chance to dry up and rehydrate. If it is allowed to occur, rehydration will cause the slurry and rubble to rebond to the surface, making a poor bonding surface for repair materials. Pressure washing of the surface along with vacuuming of the rubble behind the hydrodemolition unit is effective in removing the debris in a timely manner. If the slurry is allowed to bond to the surface or the surface is contaminated because of prolonged exposure, sandblasting may be necessary to restore the high-quality bonding surface.

Lastly, safety precautions are very important aspects of the hydrodemolition operation. There is always a possibility that a weak area of the deck will blow out, causing pieces of concrete to fall below. This can be extremely dangerous because it usually occurs unexpectedly. Appropriate precautionary measures must be used to avoid blowout accidents. Also, flying debris can be expected near the demolishing unit. These units are equipped with protective shrouds around the nozzle area, but flying fragments still find their way out and can cause injury or property damage. This is of special concern at locations where traffic is present near the demolition area. In some cases it is necessary to set up plywood shields around the immediate work area. Safety glasses and face shields should also be worn by all personnel in the vicinity of the demolition unit.

CONTRACTING PRACTICES

When it is determined that hydrodemolition will be used a contract to complete the work must be developed such that quality is achieved at the lowest possible cost. When considering the content and format of a contract, it is important to identify all project tasks that are related to or affected by the removal operation. The relationships of these tasks can then be analyzed to determine the most cost-effective method of specifying contract items to complete the work. The quantities of some work items will be fixed, whereas the quantities of others may vary as construction progresses. If the design engineer has a good understanding of the variables mentioned earlier contract terms can be adjusted accordingly to obtain the best possible results.

Interrelated Work Items and Contractor Relationships

The facility owner awards most construction contracts to a single corporation, identified as the prime or general contractor. Often, when some of the construction items are highly specialized, requiring unique equipment and procedures, the general contractor will hire a specialty subcontractor to do those tasks. Usually, the general contractor is ultimately responsible for meeting all of the terms of the contract, regardless of who performs the work. Because of the expense of the equipment hydrodemolition is almost always subcontracted to a specialty firm. The responsibilities of the hydrodemolition subcontractor are usually limited to two basic tasks: mobilizing to the site in a timely manner and performing the removal operation on a fixed-size deck area to the specified minimum depth. Although very closely related to hydrodemolition, tasks such as cleanup of debris, runoff control, and final surface preparation are routinely done by the general contractor. The costs associated with the subcontractor's tasks are almost purely time dependent. Once the equipment is calibrated, which dictates the time required to cover the entire deck surface, variations in the volume of material removed do not affect the cost of the pure removal operation. The primary variable for the hydrodemolition subcontractor is the speed at which the equipment can achieve the minimum depth of removal in the sound areas of the deck. Because of the size of the equipment and its capital-intensive nature, hydrodemolition is most economical when large, continuous areas are accessible for removal with few mobilizations. When the removal area is approximately 500 m^2 (5,400 ft^2) or greater, the cost of the pure removal, excluding all incidentals, is about \$65/m^2 (\$6/ft^2) (*6*). Although higher costs may occur for a variety of reasons, this is a good initial estimate for typical circumstances.

In contrast, the general contractor is usually responsible for a multitude of removal-related tasks that are dependent on many variables. Before the hydrodemolition subcontractor mobilizes to the site the general contractor must do some preparation work, such as clear space and optimize accessibility for the equipment; set up traffic control systems; set up the water routing, filtration, and disposal system; and make safety precautions for flying debris and blowout areas. During the removal operation the general contractor is usually responsible for the cleanup and removal of the debris, which are dependent on the speed of the machine and the volume of material removed. Also, the general contractor is responsible for the ultimate quality of the prepared surface, which may require extra work such as power washing, sandblasting, and replacing damaged bars. In addition, placement of the new concrete in the form of patches and overlays is usually performed by the general contractor. These items are all related to or affected by the hydrodemolition operation, and the efforts required to perform most of them are affected by the volume of material removed. Because of these relationships it is beneficial to manipulate contract items on the basis of project-specific variables to obtain high-quality repairs at the lowest possible cost.

Methods of Specification

When developing special provisions for a bridge deck rehabilitation contract, all of the equipment operating characteristics, project goals, and structure condition information need to be considered. The detailed tasks required to complete the repair can be grouped into three major activities, as follows: the removal operation, including mobilization, preparation work, and efforts to provide the final surface quality; the cleanup and disposal of demolition debris; and the supply and placement of new material. These activities can be quantified together or separately to establish the work items that will be put out to bid. These bid items provide the basis for payment when the construction contract is awarded and the work is completed.

Items Combined

One specification strategy is to combine the three activities listed earlier into one contract item and to quantify it by volume. The volume is usually measured by the amount of new concrete placed, and the hydrodemolition is included in the work item as a surface preparation activity. This method is based on the premise that the volume of concrete placed will equal the volume of concrete removed, provided that there are to be no changes in the deck's geometry. Therefore, if the removal and replacement volumes are equal, they can be combined into a single item, resulting in fewer items to be measured. The disadvantages of this strategy become apparent when the quantity of concrete removed by the hydrodemolisher is greater than that originally estimated. When this occurs the costs of non-volume-dependent work activities, such as the pure removal operation, increase. The converse situation reduces costs: however, quantity overruns are more likely to occur. The practice of combining these activities into a single bid item can be beneficial if deterioration assessments, and hence, quantity estimates, are presented with a high level of confidence. Also, the single-item method may be appropriate for spot removal and patching situations, in which case the removal volumes are more easily estimated.

Items Separated

An alternate specification strategy is to present multiple contract items for the activities related to hydrodemolition. The two major items are the removal of the old concrete and the supply and placement of the new material. It is appropriate to quantify the removal item on the basis of the surface area of the deck, which is fixed and known for each structure. The costs associated with the supply and placement of new concrete vary with its volume, which is estimated before construction but which is not known exactly. Because of possible variations the placement item should be measured by volume, with subprovisions for full and partial depth placement. The activity that is difficult to clearly place in either of these two major items is the cleanup and disposal of demolition debris. This work is removal related but is also volume dependent. Since it is undesir-

TABLE 1 Theoretical Cost Analysis of Specification Methods

Bridge Deck Area: 2000 m^2 (21,528 ft^2)
Minimum Depth of Removal: 60 mm (2.4 in)
Estimated Removal and Replacement Volume: 150 m^3 (196 yd^3)
(including identified deterioration)

	Contract Pay Items			
	Combined		Separated	
Description	SI Units	US Customary Units	SI Units	US Customary Units
Unit price for hydro removal and placement of new concrete	$1500/$m^3$	$1148/$yd^3$	-	-
Unit price for hydro removal, only	-	-	$85.00/$m^2$	$7.90/$ft^2$
Unit price for placement of new concrete, only	-	-	$367/$m^3$	$281/$yd^3$
0% Removal overrun				
Total price for hydro removal	-	-	$170,000	$170,000
Total price for new concrete	-	-	$ 55,000	$ 55,000
Total price for hydro removal and placement of new concrete	$225,000	$225,000	$225,000	$225,000
20% Removal overrun				
Actual removal and replacement quantity	180 m^3	235 yd^3	180 m^3	235 yd^3
Total price for hydro removal	-	-	$170,000	$170,000
Total price for new concrete	-	-	$ 66,000	$ 66,000
Total price for hydro removal and placement of new concrete	$270,000	$270,000	$236,000	$236,000
Total cost overrun	$ 45,000 (20%)	$ 45,000 (20%)	$ 11,000 (4.9%)	$ 11,000 (4.9%)

- Indicates data not applicable.

able to create too many pay items the debris work should be considered part of the hydrodemolition operation and should be included with the removal item.

The advantages of separating the items are most established when more concrete is removed than was originally estimated. With the two-item setup, the cost of hydrodemolition remains constant, whereas the volume of replacement concrete varies with the volume removed. In addition, owners are better able to keep track of which deck repair items are the most costly. This information can then be used for future decisions regarding rehabilitation strategies. Although single-item specification can be appropriate when deterioration assessments are very accurate, it may significantly raise the cost of the hydrodemolition operation when overruns in the volume of concrete placed are incurred. Table 1 provides a simple example.

CONCLUSIONS

Several conclusions can be drawn from the analysis of the use of hydrodemolition to remove deteriorated concrete from bridge decks. First, it is important to identify the advantages associated with using hydrodemolition over using conventional impact removal methods. A top-quality bonding surface free of cracking is essential to the long-term success of any concrete repair effort. Second, it can be concluded that knowledge of the hydrodemolition operating parameters is beneficial for obtaining the best possible results. The equipment calibration procedure is key to the process of ensuring the removal of all deteriorated concrete at the most efficient operating speed. In addition, a comprehensive and accurate evaluation of an existing bridge deck's condition is essential for developing an appropriate rehabilitation strategy. Many project- and structure-specific variables must be considered during the design process to provide an appropriate solution to the needs of the particular situation. When the design is complete it is beneficial to analyze all related activities so that contract items can then be quantified and manipulated to maximize the quality and cost-effectiveness of the whole effort.

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