Development of a Hypertext-Linked Highway Constructability Improvement System

HOSIN LEE, MORGAN K. H. WONG, PAMELA A. CLOVER, AND KEITH W. ANDERSON

The ever-increasing amount of construction problems and unnecessary redesigning work during the construction phase of highway projects with the Washington State Department of Transportation (WSDOT) has made it obvious that investigations must be made in order to improve the constructability of the designs when contract plans are prepared. The Highway Constructability Improvement System (HCIS) was developed and includes information extracted mainly from a critical search of thousands of change orders from 5 years of WSDOT highway construction projects. By using HCIS, engineers at the design office can access a bank of knowledge from past construction experiences and be alerted to the constructability aspects of their designs. This awareness of what has gone wrong in the past allows design engineers to avoid similar errors in preparing future design plans and specifications. This will improve constructability of designs at an early stage of a project. HCIS itself is a complete system, using hypertext technology, for design engineers to get constructability improvement ideas for highway construction projects. The user does not have to refer to other sources for reference while using the system. This system not only eliminates the duplication of information, but also prompts the design engineer of the interrelationship of the different highway construction aspects.

The ever-increasing amount of construction problems and unnecessary redesigning work during the construction phase of highway projects, as evident from the large number of change orders in each project, has made it obvious that investigations must be made in order to improve the constructability of the designs when contract plans are prepared. Although there is no such thing as a perfect set of contract plans, improvements in various aspects of the plans, specifications, and estimate (PS&E) process would certainly result in savings both in time and money. The problem addressed in this project is the concern for the quality of engineering design with regard to its constructability.

Some of the perceived problem areas within the Washington State Department of Transportation (WSDOT) are (a) lack of communication between design and construction engineers, (b) lack of construction expertise of the design engineer, (c) lack of careful review of PS&E before it is finalized as a contract, and (d) lack of postconstruction review to identify items that could be improved through better plans.

H. Lee, M. Wong, and P. Clover, Department of Civil and Environmental Engineering, Washington State University, Pullman, Wash. 99164-2910. K. Anderson, Washington State Department of Transportation, 1655 South Second, QM-21, Tumwater, Wash. 98504.

The objectives of this research are to identify constructability improvement ideas, develop a model constructability review process, and implement a comprehensive constructability improvement program for highway construction projects.

The first phase of this project, the identification of highway constructability ideas and the development of the Highway Constructability Improvement System (HCIS) is described. An extensive literature review was performed to identify constructability concepts and ideas from reported research. Moreover, specific highway constructability ideas were obtained from examining thousands of change orders from 5 years of WSDOT projects. Such a bank of information was used to develop the HCIS.

LITERATURE REVIEW

Reported research in the area of constructability falls into three broad categories: (a) general constructability concepts, (b) effects of applying constructability programs at different stages of a project, and (c) results of specific constructability programs. Although the research in the third category focuses on specific applications, it also demonstrates constructability concepts.

Constructability review of design documents has been an industry practice since the 1960s. The idea of constructability was first published in *Building and Construction Technology Bulletin* and *Constructability—It Works* (*1*,*2*). A study by the National Science Foundation and the American Society of Civil Engineers (*3*) identified constructability, among other topics, as a specific research need for structural engineering. The study pointed out the missing link between design engineers and contractors. For example, problems of constructability of concrete structures occur most often because of the attempt to design slimmer columns. These designs, although satisfying the code of the American Concrete Institute, constrict space for placing concrete and sometimes create difficulty in inserting vibrators.

One of the earlier applications of constructability took the form of evaluation criteria for value engineering incentives. The design and construction of the I-205 Columbia River Bridge near Portland, Oregon, which took this approach, included constructability as one of the evaluation criteria in a type study stipulated in the value engineering incentive clause in the contract documents (*4*). Similarly, using constructability as a criterion, Ramsey (*5*) used constructability as one of the elements in the quality control program of projects, and Lin (*6*) stated that constructability must be considered before creativity can become reality.

Although all these cases used the word "constructability," none provided any rigorous definition of the concept and its specific impacts. It was not until a series of research led by O'Connor (*7–11*) and the Construction Industry Institute (CII) of the University of Texas in Austin was reported that research effort was directed toward providing a more thorough definition of the constructability concept and a clearer picture emerged on the impacts of constructability programs applied on different situations and at various stages of a project.

By analyzing the construction resource utilization tradeoffs, which result from constructability improvements, in a large industrial construction project, O'Connor (*7*) presented some constructability stategies and methods for achieving the more cost-beneficial impacts. His findings point to the need for additional engineering effort for any constuctability improvements and the importance of the designer in ensuring economical construction.

Further research by O'Connor and Tucker (*8*) pointed to the requirement of integration between designers and contractors for constructability improvements. An analysis of the constructability problems existing on a large refinery expansion project indicated that designers and contractors possess equal potential for improving project constructability.

With the constructability improvements in mind, techniques to collect data and improvement ideas were addressed (*9*). The experience with a contructability study at a large refinery expansion concluded that the most effective program of constructability data collection uses many data collection techniques and involves many project participants. Techniques to collect project constructability improvement data (including voluntary survey, questionnaires, interviews, preconstruction meeting notes, and final project reports) were discussed and analyzed.

As the research on the concept and application of constructability progressed, the effects of constructability improvements at different stages of a project were addressed. From the earlier application at the project conceptual stage, addressed in the research already mentioned and by Tatum (*12*), focus was turned to the engineering and procurement stage (*10*), and then to the field operations stage (*11*). Different specific examples of application were presented in these reports.

Although the literature showed the development of formalizing the constructability concept, the most comprehensive aggregate of the research in this area is recorded in three CII publications (*13–15*).

The awareness of issues connected to constructability and the application of constructability improvement ideas is evident from some recent publications. Two examples of constructability improvement application in concrete construction include a precast concrete stay-in-place forming system for lock wall rehabilitation, where a constructability demonstration phase was included after the design phase (*16*), and a redesigning of large 100-ton concrete panels into smaller panels for better constructability through contractor involvement in the design stage (*17*).

A demonstration of a designer-contractor interaction is seen in a water-injection facilities project with full involvement of the owner's and the contractor's construction expertise to simplify construction methods, reduce the number of interdependencies in various field operations, and consider the limited resource capabilities of the local contractors (*18*).

Further examples involve a constructability issue in pavement construction—providing adequate support for construction equipment by the base material (*19*)—and the construction of complex structures that require considerable engineering input from the design office to back up the construction staff on site (*20,21*).

COLLECTION OF CONSTRUCTABILITY IMPROVEMENT IDEAS

The literature review shows that two very important aspects of constructability improvement are realized: implementation of constructability improvements at an early stage of the project, and the collection of constructability improvement ideas. The latter aspect is the focus of this section.

Although a list of data collection ideas is suggested by O'Connor et al. (*9*), the literature review led to a new direction that had not been attempted previously. The specific examples seen in the literature review indicated that constructability improvements are to some extent site-specific and quite definitely unique in each type of construction. In order to develop a pool of constructability improvement ideas for highway construction in the state of Washington, the change orders of various highway construction projects done by the WSDOT were examined. This direction was based on a rather obvious assumption that change orders are issued during the construction stage because of problems encountered in construction. Although many problems are related to field conditions not apparent during the design process, a significant number of change orders could have been prevented.

From the few thousand change orders available from WSDOT, issued in different projects during the past 5 years, about 400 that applied specifically to highway construction were critically examined. The construction problems, causes of the problems, and solutions to the problems in terms of a change in material, construction methods, or design, were recorded and summarized to be included in a highway constructability ideas bank.

Although the majority of the information was derived from the change orders, other sources, such as the relevant results of a statewide WSDOT survey on plans improvements, can be also incorporated in the system. These improvement ideas have been collected from various sections and different levels of personnel of all six WSDOT districts, thus providing a good prospective from the views of both design and construction engineers.

RESEARCH APPROACH AND SOFTWARE SELECTION

Hypertext

With a mass of constructability ideas extracted from the change orders, the next task was to present these ideas so that the design engineer can efficiently search through change order summaries and get constructability improvement ideas related to highway construction projects. This access allows the design engineers to see what had gone wrong in the past and avoid repeating similar errors in preparing future design plans and specifications. This planning will improve constructability of designs at an early stage of a project.

Although these pieces of information extracted from the change orders seem scattered and fragmented, they are interrelated in many cases and in different ways. However, the interrelationships are mostly nonlinear and hard to organize into a practical structured manner. This led to the decision to use the technology called hypertext.

The name "hypertext" was given to mean nonsequential writing by Theodore Nelson about 25 years ago; the concept was envisioned in 1945 by Vannevar Bush, President Franklin Roosevelt's science advisor and overseer of all wartime research. Recently, because of the advancement of computer technology, it has become more popularly used in the artificial intelligence and expert system areas. At its most basic level, hypertext is a data base management system (DBMS) that lets the user connect screens of information using associative links. At its most sophisticated level, hypertext is a software environment for collaborative work, communication, and knowledge acquisition. Hypertext products mimic the brain's ability to store and retrieve information by referential links for quick and intuitive access (*22*).

KnowledgePro

The software chosen for this project is KnowledgePro. KnowledgePro is uniquely appropriate for our application because it is a marriage of hypertext and expert system technologies. It is a development environment, a programming language, and an information management tool (*23*). It is described by Rasmus (*24*) as "a knowledge-based systems development environment that incorporates rules, graphics, hypertext, and database access."

In expert system terms, KnowledgePro uses production rules with an inference-engine usually available in an expert system shell. However, its interaction of hypertext and expert systems brings some unique advantages to an application in knowledge representation. On one hand, hypertext gives the user flexibility to choose any path through the knowledge base, to examine areas of interest and skip others. On the other hand, the expert system tends to steer the user down a path that is determined by the user's responses to a set of questions preset by the developer. By combining the features of both systems, KnowledgePro allows two-way communication. The developer can present the user with information and guidance in a way that his or her expertise dictates will be most helpful. The user can arbitrarily explore or learn more about specific pieces of knowledge along the way (*23*).

These unique features of KnowledgePro are very appropriate for the presentation of knowledge such as that extracted from change orders. The design engineer can be guided through the change order summaries in the areas relevent to a specific project and get additional explanation via hypertext whenever needed. This additional information can be in the form of graphic displays because the software is compatable with external programs such as PC Paintbrush, Lotus 1-2-3, and dBase III (*25*).

HIGHWAY CONSTRUCTABILITY IMPROVEMENT SYSTEM

To develop the HCIS structure, the relationship among the different constructability improvement ideas was established. The system structure is similar to that of a semantic net, with general nodes (e.g., roads, traffic, earthwork) branching off into a hierarchy of increasingly more specific nodes (e.g., road shoulders, signals, excavation). These nodes are linked by hypertext. A simplified schematic of categorizing constructability improvement ideas is shown in Figure 1.

The main areas of construction included in this system are roads, bridge structures, earthwork, drainage structures, and traffic. Because the structure of this system is primarily driven by the information extracted from the change orders, the main areas mentioned are actually different major categories for the change orders. Although all aspects of highway construction could not be included, the categories in the system represent the areas where problems have been frequently encountered.

Because the summaries of the change orders refer to various sections of the WSDOT standard specifications and standard plans, the AASHTO standards, and the ASTM standards, relevant parts of these sections were extracted and incorporated in the system. They are linked to the change order summaries by hypertext so that the design engineer can efficiently access these references to get a good understanding of the context of the change order summaries.

With such a system, the design engineers can choose the facet of highway construction relevant to the projects, be guided through the system to look at subtopics associated with that facet, and obtain experiences from previous projects. Specific terminology and technical jargon, WSDOT standard specifications and plans, and other standards are linked by hypertext to explanation screens, with summaries of the specifications or graphics, for the user's quick reference. Therefore, the HCIS itself is a complete system for design engineers to get constructability improvement ideas for highway construction projects. Unless detailed standards and specifications are needed, the user does not have to refer to other sources in order to understand these constructability improvement ideas.

Demonstration of HCIS

A sample run of the HCIS is shown in the following figures. This example demonstrates the use of hypertext to link up different interrelated information such as change order summaries, technical jargon explanation, WSDOT standard specifications and standard plans, and specific drawings related to the change order. The hypertext, which is highlighted in the program, is underscored on the screen samples of the demonstration.

After showing an introduction screen listing the functions of the system, the system proceeds directly to the main menu

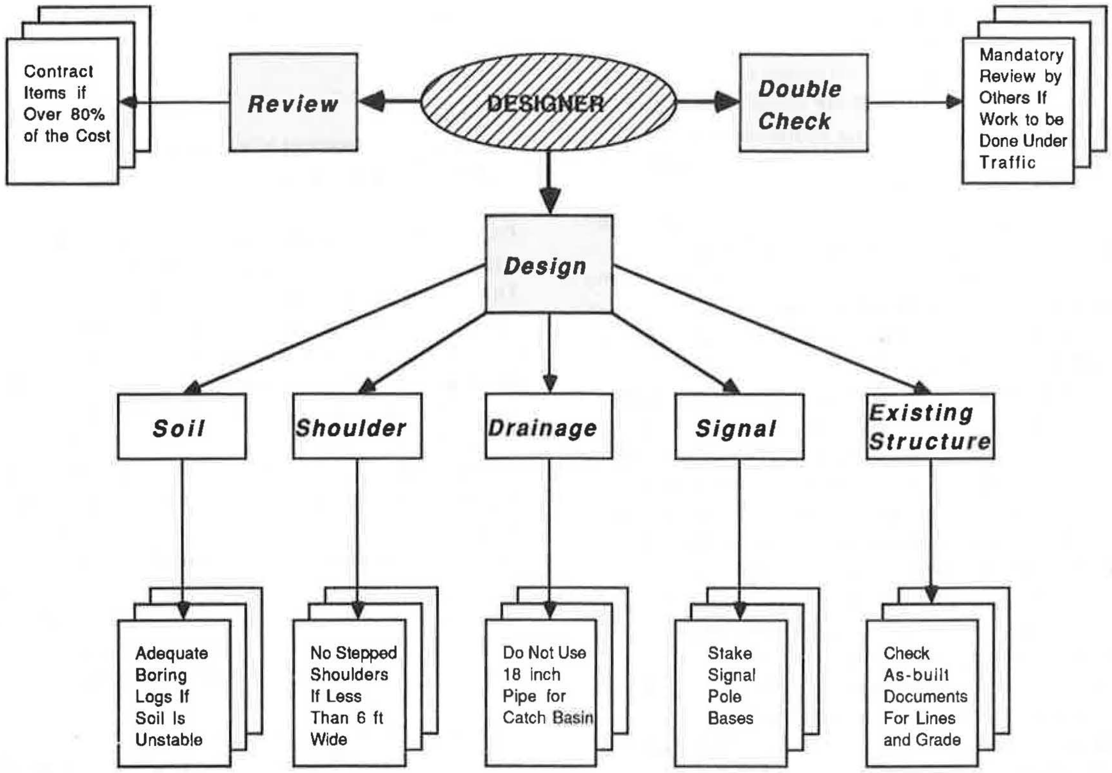

FIGURE 1 Schematic diagram of categorizing constructability improvement ideas for designer.

containing the major categories of highway construction presented in the system (Figure 2).

For example, design engineers designing the various elements of a highway and wanting to check for constructability improvement ideas regarding the drainage systems of that roadway would choose the drainage system hypertext. This choice would lead the designers to a screen with more specific areas of drainage systems in highway construction. One of these areas, also in hypertext, is linked to a specific change order that deals with the installation of concrete inlets (Figure 3). In this change order summary, the reason for such a change is given so that the design engineers can compare whether such a need is relevant to their projects. It tells the engineers that in low-lying sections of a roadway, at regions where winter snow conditions exist, care should be taken to ensure that proper drainage, such as concrete inlets, is provided along

The different aspects of highway construction considered in this program for constructability improvement include:

* Roads,

* Bridges,

* Drainage Structures and Water Distribution, and

* Earthwork.

In order to proceed further for constructability improvement ideas regarding the above aspects, press F3 (or use the mouse) to move the cursor to choose the topic, and F4 to view the information.

FIGURE 2 Main menu.

Install Concrete Inlets and 8" diameter Drain Pipe at locations staked by the Engineer. Materials and construction shall be in accordance with Standard Specifications, Section 8-04.3(3), Standard Plan B-4a, and with the attached drawing.

Purpose of change is to improve drainage of low spots during winter snow conditions. The ridge of snow under the guard rail and along the shoulders prevents the water from draining off of the roadway, this creates a ponding situation which freezes when the temperature drops.

Ref: Contract 2908 Change Order No. 11

Return to Main Menu

FIGURE 3 Change order summary sample.

WSDOT Standard Specifications
Section 8-04.3(3) Inlets

Inlets shall be securely connected to the gutter and to the spillway forming a water tight connection.

Concrete inlets shall be constructed in accordance with the Standard Plan and may be precast or cast in place. Concrete shall conform to the requirements of Section 6-02.

Metal inlets shall be constructed in accordance with the Standard Plan.

Return to Main Menu

FIGURE 4 Standard specifications.

the guard rails. The section numbers of the WSDOT standard specifications and standard plans are in hypertext. They can be accessed by the click of a button. The hypertext "Section 8-04.3(3)" is linked to the screen shown in Figure 4, and the hypertext "Standard Plan B-4a" is linked to the graphics screen shown in Figure 5.

Because a specific drawing is attached to the change order, it is also included in the system and linked by hypertext, shown in Figure 6. Hypertext is not limited to linking text to text and text to graphics; it can also link keywords on a graphics screen to a text screen with the explanation of the word. The example shows the keyword "Riprap" on Figure 6 being linked to the text screen shown in Figure 7.

The system allows the user to get back to the previous node from any node of the network. As seen in Figures 3, 4, and 7, the user can also get back to the main menu from any point of the network by clicking the hypertext "Main Menu."

Moreover, because the hypertext links are formed in a non-linear network, the user may get to the same information from different routes. For example, the screen shown in Figure 4 can be obtained from hypertext keys, "inlets," "metal

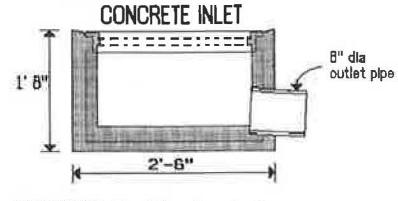

FIGURE 5 Standard plans.

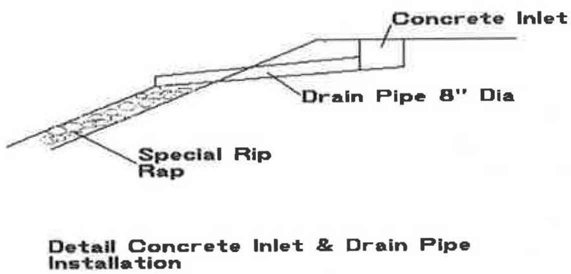

FIGURE 6 Specific drawings associated with the change order.

inlets," "concrete inlets," and Standard Specification "Section 8-04.3(3)." This not only eliminates the duplication of information, but also prompts the design engineer of the interrelationship of the different highway construction aspects.

Furthermore, the hypertext can bring the design engineers to any point on the network as needed. For example, while the engineers are looking at the "concrete inlet" change order summary, they may be reminded of the guard rails that are required in the project by the hypertexted word "guard rail." By clicking this hypertext, the system will bring the engineers to a description of different types of guard rails. Realizing that the project has Type I guard rails, the design engineers continue to pursue the hypertext links, which finally bring them to a change order summary as shown in Figure 8. It describes a past constructability problem with Type I guard rails. When a structure, such as a retaining wall, is too close to the pavement, it is impossible to install the standard Type I guard rails. As a result, the configuration of guard rails must be modified. In the case of this change order, a modified guard rail, consisting of a thrie-beam element and a W-beam element attached directly to the post without a block, was used. Of course, in conjunction with this change order, the necessary standard plans (Figure 9) and specific drawings (Figures 10 and 11) are linked by hypertext as shown.

WSDOT Standard Specifications
Section 8-15 RIPRAP

Section 8-15.3(1)	Excavation of Riprap
Section 8-15.3(2)	Loose Riprap
Section 8-15.3(3)	Hand Placed Riprap
Section 8-15.3(4)	Sack Riprap
Section 8-15.3(5)	Concrete Slab Riprap
Section 8-15.3(6)	Quarry Spalls
Section 8-15.3(7)	Filter Blanket

Return to Main Menu

FIGURE 7 Keyword explanation.

CONCLUSION

Constructability concepts identify ways in which construction knowledge and expertise can be more effectively used at various phases of a project (planning, engineering, procurement, and field operations) to optimize construction. Although these concepts have been around for decades, improvement ideas and techniques have just recently begun to be collected and categorized.

The development of the HCIS is presented. It is concluded that in order to avoid similar highway constructability problems, a postconstruction review of the project, such as reviewing the change orders, is very useful and important. The results of such reviews should be available at the design office

Furnish and install "Modified Beam Guard Rail" in lieu of the "Beam Guard Rail Type I". Modified Beam Guard Rail will consist of thrie beam rail elements and W beam rail elements mounted on posts without blocks. All work should be per Section 8-11 of the Standard Specifications, and attached drawings. Measurement will be in Linear foot.

This change is required because an existing retaining wall is located too closed to the edge of pavement to place Type I Beam Guard Rail. The guard rail posts would hit the retaining wall.

Ref: Contract 2980 Change Order No. 11

Return to Main Menu

FIGURE 8 Change order summary for modified beam guard rails.

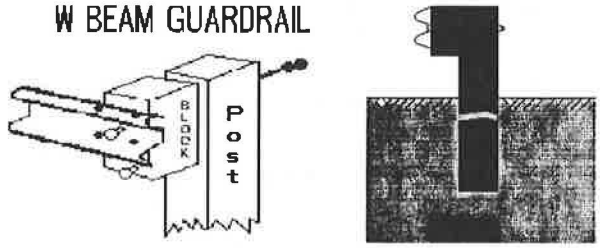

FIGURE 9 **Standard plan (Type I guard rail).**

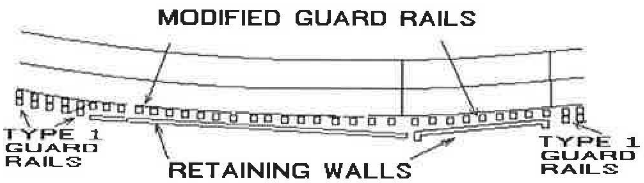

FIGURE 10 **Specific drawings associated with the change order.**

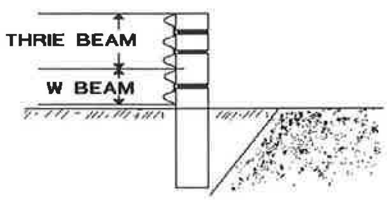

FIGURE 11 **Modified guard rail.**

in the form of a system like HCIS. In addition, the experience from developing the HCIS showed that hypertext is a very powerful tool for representing a large amount of unstructured but interrelated pieces of information.

Through the HCIS, engineers at the design office can have access to a bank of knowledge from past construction experiences and be alerted to various constructability aspects of their designs. This allows the design engineers to be aware of what had gone wrong in the past and avoid repeating similar errors in preparing future design plans and specifications. This knowledge will improve constructability of designs at an early stage of a project.

The HCIS itself can be a complete system for design engineers to get constructability improvement ideas for highway construction projects. Unless detailed standards and specifications are needed, the users does not have to refer to other sources for reference in order to understand these constructability improvement ideas. This system not only eliminates the duplication of information, but also prompts the design engineer of the interrelationship of the different highway construction aspects.

However, the HCIS can never be a panacea for all constructability problems. It cannot replace the thorough constructability review process currently used in many organizations including WSDOT. The HCIS is a tool to help improve the quality of the design, increase awareness of design engineers to constructability concerns, and promote the coordination of design details in different areas; for example, guard rail design coordinated with retaining wall design as illustrated. Again, the HCIS should not be looked upon as a replacement for review of design, but as a tool to help determine whether the design is constructable.

ACKNOWLEDGMENTS

The authors acknowledge the combined efforts and support of the Washington State Transportation Center at the University of Washington and Washington State University, and the Washington State Department of Transportation in cooperation with FHWA.

REFERENCES

1. *Building and Construction Technology Bulletin.* Proctor and Gamble, Cincinnati, Ohio, 1976.
2. *Constructability—It Works.* Proctor and Gamble, Cincinnati, Ohio, 1977.
3. Structural Engineering Research Needs. *Civil Engineering*, ASCE, Vol. 49, No. 12, Dec. 1979, pp. 61–65.
4. F. P. Blanchard. I-205 Columbia River Bridge: Design and Construction. *Transportation Engineering Journal*, ASCE, Vol. 107, No. 6, 1981, pp. 625–633.
5. T. S. Ramsey. Quality Control—A Necessity, Not An Option. *Journal of Construction Engineering and Management*, Vol. 110, No. 4, 1984, pp. 513–517.
6. T. Y. Lin. Creativity and Constructability in Structural Engineering. *Civil Engineering for Practicing and Design Engineers*, Vol. 3, No. 9, Sept. 1984, pp. 907–930.
7. J. T. O'Connor. Impacts of Constructability Improvement. *Journal of Construction Engineering and Management*, ASCE, Vol. 111, No. 4, 1985, pp. 404–410.
8. J. T. O'Connor and R. L. Tucker. Industrial Project Constructability Improvement. *Journal of Construction Engineering and Management*, ASCE, Vol. 112, No. 1, 1986, pp. 69–82.
9. J. T. O'Connor, M. A. Larimore, and R. L. Tucker. Collecting Constructability Improvement Ideas. *Journal of Construction Engineering and Management*, ASCE, Vol. 112, No. 4, 1986, pp. 463–475.
10. J. T. O'Connor, S. E. Rusch, and M. J. Schultz. Constructability Concepts for Engineering and Procurement. *Journal of Construction Engineering and Management*, ASCE, Vol. 113, No. 2, 1987, pp. 235–248.
11. J. T. O'Connor and V. S. Davis. Constructability Improvement During Field Operations. *Journal of Construction Engineering and Management*, ASCE, Vol. 114, No. 4, 1988, pp. 548–564.
12. C. B. Tatum. Improving Constructability During Conceptual Planning. *Journal of Construction Engineering and Management*, ASCE, Vol. 113, No. 2, 1987, pp. 191–207.
13. *Constructability (A Primer).* Publication 3-1. The Construction Industry Institute, University of Texas, Austin, 1986.
14. *Guidelines for Implementing a Constructability Program.* Publication 3-2. The Construction Industry Institute, University of Texas, Austin, 1987.
15. *Constructability Concepts File.* Publication 3-3. The Construction Industry Institute, University of Texas, Austin, 1987.
16. *A Demonstration of the Constructability of a Precast Concrete Stay-in-Place Forming System for Lock Wall Rehabilitation.* Technical Report REMR-CS-14, U.S. Army Corps of Engineers, 1987.
17. M. Wallace. Redesign Improves Constructability: Attention to Details Enhances Appearance. *Concrete Construction*, Vol. 32, No. 4, April, 1987, pp. 357–364.
18. N. N. Eldin. Constructability Improvement of Project Designs. *Journal of Construction Engineering and Management*, ASCE, Vol. 114, No. 4, 1988, pp. 631–640.
19. K. L. Highlands and G. L. Hoffman. Subbase Permeability and Pavement Performance. In *Transportation Research Record 1159*, TRB, National Research Council, Washington, D.C., 1988, pp. 7–20.

20. A. F. Gee. Constructability of Bridges—A Construction Engineer's View. *Concrete International: Design and Construction*, May, 1989, pp. 48–52.
21. R. I. Pearson. Washington State's Mammoth I-90 Project. *Concrete International: Design and Construction*, Feb. 1989, pp. 23–53.
22. J. Fiderio. A Grand Vision. *BYTE*, Oct. 1988, pp. 237–244.
23. D. Shafer (ed). Hypertext and AI Merge. *Intelligent Systems Analyst*, Vol. 1, No. 9, 1988.
24. D. Rasmus. KnowledgePro—A Complete Applications Development Environment. *PC AI*, Vol. 3, No. 5, Sept./Oct. 1989, pp. 47–57.
25. B. Thompson and B. Thompson. *KnowledgePro User Manual*. Knowledge Garden, Inc., 1988.

Publication of this paper sponsored by Committee on Construction Management.