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UNITED STATES GENERAL ACCOUNTING OFFICE

WASHINGTON, D.C. 20548

RESOURCES, COMMUNITY,
AND ECONOMIC DEVELOPMENT
DIVISION

B-214229

FEBRUARY 17, 1984

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The Honorable John O. Marsh, Jr.
The Secretary of the Army

Dear Mr. Secretary:

Subject: Thermal Analysis of Mass Concrete Structures: Lock & Dam No. 26 (Replacement) Project (GAO/RCED-84-87)

During our survey of the U.S. Army Corps of Engineers Lock & Dam No. 26 (Replacement) Project, we noted that Corps design engineers were using outdated thermal analysis techniques in attempting to predict temperature distribution and resulting thermal stresses in the mass concrete to be used in this project. The thermal analysis techniques being used are based on methodology and programs developed about 15 years ago. State-of-the-art finite element computer programs which aid in predicting the potential location of cracks from thermal stresses in mass concrete structures are currently used by large consulting engineering firms and federal agencies, such as the Nuclear Regulatory Commission and the Bureau of Reclamation, U.S. Department of the Interior, in designing concrete structures. Corps officials acknowledged that the Corps lacks experience in the use of state-of-the-art thermal analysis programs.

Dr. Manohar Singh of our office brought these observations (details are included in enclosure I) to the attention of Corps officials in the Office of the Chief of Engineers, the Directorate of Research and Development, the Waterways Experimentation Station, and various division and district offices. The officials contacted acknowledged their lack of experience in the use of state-of-the-art thermal analysis programs. As a result the Corps, in September 1983, began consultations with Bureau of Reclamation officials on their experiences with finite element programs for thermal analysis of concrete structures. Also, Corps officials advised us that based on our observations, a 4-year (fiscal years 1984-87) research and development program has been initiated for the study of concrete cracking. The estimated cost for this program is about $510,000.

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Corps officials stated that it would not be practical to use state-of-the-art programs on the first stage of the Lock & Dam No. 26 (Replacement) Project because it is about 85 percent complete. The Corps will, however, examine the feasibility of using state-of-the-art programs in predicting temperature and strain-stress distributions in the project's second stage. Further, we were advised that the Corps acknowledges that an expanded manual is needed to provide guidance on thermal analysis and that, overall, the Corps needs to reassess its capability to provide direction to its district offices on thermal analysis of mass concrete. Because of actions taken and planned by the Corps as a result of our work, we are not making any recommendations.

Our purpose is to bring to your attention the actions taken and promised by the Corps. We would appreciate being advised of any Corps actions and the Corps' progress in applying state-of-the-art thermal analysis programs to future mass concrete structures.

Copies of this report are being sent to the Director, Office of Management and Budget, and to appropriate congressional committees having oversight responsibilities for Corps activities.

Sincerely yours,

J. Dexter Peach
Director

Enclosure

THERMAL ANALYSIS OF MASS CONCRETE STRUCTURES:

LOCK & DAM NO. 26 (REPLACEMENT) PROJECT

BACKGROUND

Lock and Dam No. 26 (Replacement) Project was authorized by Public Law 95-502. The project is located on the Mississippi River, 200.78 miles upstream from the confluence of the Mississippi and Ohio Rivers and about 2 miles downstream from the existing Locks and Dam No. 26. The Corps has stated that the existing structures needed to be replaced because they (1) were not large enough to handle anticipated traffic on the Mississippi River and (2) had a history of structural problems.

The dam, including a navigation lock, will have a total length of about 1,350 feet. The concrete structure will be founded on steel H-piles driven into bedrock. The navigation lock will be 1,200 feet long and 110 feet wide and have a design depth of 9 feet. The lock will be located on the Illinois side of the river and have a maximum lift of 24 feet. The lock will have a lift gate on the upstream side and a miter gate downstream. Construction of the Lock and Dam No. 26 (Replacement) Project will extend until 1989. The project is in various stages of design and construction. As of October 1, 1983, the Corps had estimated the project's construction cost to be $833 million.

A primary concern relating to mass concrete construction is the control of thermal cracking. During construction, heat is produced by concrete during the critical days after the concrete is placed. Subsequent thermal gradients occur due to cooling at rates depending especially on external temperature. Concrete temperature change causes proportional volume change that, if restrained, either externally or internally by the mass concrete itself, will result in cracking. Such cracking is of concern because it can occur at any time during or after construction.

Cracking in mass concrete structures is undesirable as it affects the water tightness, durability, appearance, and internal stresses of the structures. Cracks vary from extremely small, or hairline, surface cracks which penetrate only a few inches into the mass, to irregular structural cracks of varying width which completely cross construction blocks, to the regular contraction joint with a relatively uniform opening which separates the construction blocks in a concrete monolith. These cracks have economic impacts because of the cost of rehabilitating navigation and flood control structures. According to the Corps' Walla Walla District officials, the Corps has spent about $500,000 thus far in attempting to repair a single extensive crack resulting from thermal stresses in the Dworshak Dam in Idaho.

Officials of the Portland Cement Association advised that various techniques to reduce the potential for thermal cracking have been developed. These include reducing the potential temperature rise by limiting the heat of hydration[1] of cements used, minimizing cement content, or replacing part of the cement with fly ash. Other measures include precooling the aggregate to reduce placement temperature of insulating surfaces to control thermal absorption or loss, or postcooling the concrete mass with cooling pipes to reduce peak temperatures or thermal gradients. According to a professor of engineering at Ohio State University, since the 1930's, numerical methods have been developed to predict temperature distribution and resulting thermal stresses in mass concrete structures. These approaches permit the evaluation of various ways of controlling temperature during dam construction. The professor advised that the finite element method (FEM) of analysis has superseded other numerical methods of investigating thermal analysis.

The finite element method was initially developed to analyze problems in structural mechanics. FEM involves replacing the actual continuum by a finite number of discrete subregions called elements. For the purposes of structural analysis, a structure is defined as a system of nodal points (joints) interconnected by discrete elements. Using FEM of analysis, joint displacements and the internal stresses in the structural elements can be determined given (1) the joint loading, (2) the geometry of the structure (location of joints), and (3) the stiffness properties of the structural elements.

The development of FEM as an analysis tool began with the advent of the electronic digital computer. For the numerical solution of a structural or continuum problem, it is necessary to establish and solve algebraic equations that govern the response of the system. During the past 2 decades, FEM of analysis has become a popular and effective technique for the computer solution of the governing equations for complex problems in engineering.

OBJECTIVES, SCOPE, AND METHODOLOGY

Our review objectives were to (1) examine the effectiveness of the U.S. Army Corps of Engineers' programs to predict temperature distributions and resulting thermal strain-stress distributions in mass concrete, (2) examine the state-of-the-art finite element computer programs for thermal analysis that are being used

[1]Newly placed concrete undergoes a rise in temperature due to the exothermic reaction of the cementing materials. The amount of heat of hydration generated will depend on the amount and type of cementitious materials in the concrete.

by major consulting engineering firms and other federal agencies such as the Bureau of Reclamation, U.S. Department of the Interior, (3) determine whether such state-of-the-art programs can be modified and applied to perform thermal analysis of the Lock & Dam No. 26 (Replacement) Project, and (4) examine the Corps' capability to use state-of-the-art programs to perform thermal analysis of mass concrete structures. Manohar Singh, a Doctor of Science, was the project manager of this review.

To fulfill our objectives, we examined the latest engineering guidance on thermal analysis. In addition, we discussed the state-of-the-art finite element computer programs on thermal analysis with (1) large consulting engineering firms that apply these programs in their engineering projects, (2) a nonprofit organization, the Portland Cement Association, Chicago, Illinois, (3) academicians at the University of California in Berkeley, California; Massachusetts Institute of Technology in Cambridge, Massachusetts; and the Ohio State University in Columbus, Ohio, who developed the first finite element method of analysis for temperature distributions and thermal stress analysis of mass concrete, (4) engineers at the Nuclear Regulatory Commission and the Bureau of Reclamation, and (5) Corps officials at Washington, D.C., the St. Louis and Walla Walla Districts, the North Pacific and Lower Mississippi Valley Divisions, and the Waterways Experimentation Station (WES), Vicksburg, Mississippi.

The review was performed in accordance with generally accepted government auditing standards.

THE CORPS' APPROACH TO CONDUCTING THERMAL ANALYSIS OF MASS CONCRETE

Our review showed that the Corps' Engineering Manual EM 1110-2-2000 (dated Sept. 1982), Engineering and Design, Standard Practice for Concrete, gives minimal treatment to thermal analysis of mass concrete structures when compared with the Engineering Monograph No. 34 (dated 1981), Control of Cracking in Mass Concrete Structures, of the Bureau of Reclamation.

Elements discussed in the Corps' manual include design studies and reports, preparation of contract plans and specifications, construction preparation, and concrete construction inspection. The manual discusses the thermal analysis of mass concrete in a very general way. The Bureau's monograph is a comprehensive treatment of temperature control studies; design consideration; construction requirements; thermal properties of concrete for various dams; temperature variations of flat concrete slabs exposed to yearly, bimonthly, and daily temperature variations on both surfaces; the range of actual reservoir temperatures under operating conditions; the increase of temperature due to solar radiation; and the effect of initial temperature on heat of hydration.

In 1967, a graduate student[2] at the University of California, Berkeley, California, developed a finite element computer program called 2-Dimensional (2-D) Stress Analysis with Incremental Construction & Creep[3] to predict thermal strain-stress distribution for the Dworshak Dam. The Corps' Walla Walla District funded the development of the program as a part of its design and construction of Dworshak Dam. The temperature distribution histories for input to this program were generated by the finite difference method.[4] In 1968, Dr. Edward L. Wilson of the same university developed another finite element computer program called Determination of Temperatures Within Mass Concrete Structures (DTMCS) for the Corps' Walla Walla District to predict the temperature distribution during and after construction of Dworshak Dam. The output from the DTMCS program was used as input to the Stress Analysis with Incremental Construction & Creep program. Program inputs included concrete placement schedules, ambient air condition, material properties of concrete, geometry of the structure, and insulation considered necessary for thermal strain control. While these programs were deemed to be a major advance in state-of-the-art thermal analysis, according to a Corps official at the Waterway Experimental Station, they were not effective in helping the Corps to avoid thermal cracking at the Dworshak Dam. The Corps still uses the programs developed at the University of California in 1967 and 1968.

STATE-OF-THE-ART THERMAL ANALYSIS FINITE ELEMENT PROGRAMS

In discussions with major consulting engineering firms and academicians, we found that these firms use some modifications of

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[2]Dr. Ranbir Singh Sandhu, currently a professor of engineering at the Ohio State University, Columbus, Ohio.

[3]The Portland Cement Association defines creep as the slow increase of deformation due to sustained load and shrinkage in a stress-independent, long-time deformation caused by drying. In concrete, creep deformation exceeds several times the instantaneous elastic deformation. Shrinkage is of similar magnitude as the elastic deformation. Creep properties change with the age of the concrete. Accordingly, the effects of creep in structures can be very significant.

[4]This is another alternative to replacing differential equations by a set of algebraic equations. This method was popular before the finite element method of analysis came into being.

the Structural Analysis Program (SAP)[5] of the University of California. Executives of these firms confirmed that the state-of-the-art finite element programs are the ADINAT (temperature), ADINA (strain-stress), and the SAP-83 (strain-stress) programs. The SAP-83 program was developed by Dr. Wilson of the University of California. The SAP-83 program has nonlinear analysis capability in 2 dimensions and 3 dimensions. Thermal analysis experts at one of the major consulting engineering firms consider SAP-83 to be a very efficient program.

The ADINAT and ADINA programs are proprietary. They were developed by Dr. Klaus-Jurgen Bathe of the Massachusetts Institute of Technology. ADINAT is a heat transfer program compatible with ADINA. Both ADINAT and ADINA have 2-D and 3-D capabilities. The programs can be used in linear and nonlinear, steady-state, and transient heat transfer analysis. Nonlinear conduction and boundary convection and radiation conditions can be taken into account. According to Dr. Bathe, ADINAT with 9 nodes/element has been used on an experimental basis, and ADINAT can be modified in approximately 2 days to introduce 9 nodes/element instead of the current 8 nodes/element for predicting temperature distributions in mass concrete. Both the SAP-83 and ADINA programs can perform analysis for incremental construction, creep, thermal expansion, and cracking.

In 1976, another computer program called Determination of Temperatures in Construction (DETECT) was developed by Dr. Wilson and a graduate student at the University of California, Berkeley, to predict temperature distributions in mass concrete with 8 nodes/element. It is a linear finite element program. According to experts in a major consulting firm, this program with the 8 nodes/element capability did not provide accurate results of temperature distributions in mass concrete of a large dam. This program is being enhanced with a 9 nodes/element capability to provide accurate temperature distributions. These experts believe that when the DETECT program of predicting temperature distribution is modified with 9 nodes/element, SAP-83 will provide highly accurate results of strain-stress distribution in mass concrete.

An official of the Nuclear Regulatory Commission advises that the Commission uses the University of California-developed SAP IV[6] and SAP V finite element programs to determine the thermal

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[5]In 1969, the development of the series of programs SAP-I to SAP-IV was initiated.

[6]This program was developed by Drs. Wilson, Bathe, and Peterson at the University of California in June 1973 and revised in April 1974.

strain-stress distributions in mass concrete of nuclear-related structures. The Bureau of Reclamation has been using the Heat Flow finite element program to determine temperature distribution in mass concrete structures for the last 10 years. This program was also developed at the University of California. It is a 2-D, nonlinear program. Bureau officials stated that they used this program on the Upper Stillwater Dam, which is in the construction bid stage. Temperatures in the test sections (in-situ conditions) correlated with the temperatures predicted by the Heat Flow program. Also, the Bureau developed a finite element program called the Arch Dam Stress Analysis System (ADSAS) to determine strain-stress distribution in arch dams only. It is a 3-D, linear program in which creep is factored indirectly. For stress distribution in arch and gravity dams, the Bureau uses the 3-D SAP-IV program. Recently, the Bureau used the ADINA program to determine strain-stress distributions in the Upper Stillwater Dam. We noted that the Bureau is satisfied with the performance of the Heat Flow program and the ADINAT program for temperature distributions and the ADSAS, SAP-IV, and ADINA finite element programs for strain-stress distribution in mass concrete structures.

Corps officials acknowledged that they lack experience in using the state-of-the-art programs on thermal analysis of mass concrete that are being used by major engineering firms and by the Bureau of Reclamation. Furthermore, the capability of Corps headquarters and WES to provide direction on thermal analysis to the numerous district offices is severly limited. Only two staff engineers and one research physicist are available for this effort.

EFFECT OF NOT USING STATE-OF-THE-ART THERMAL ANALYSIS PROGRAMS ON THE PROJECTS'S FIRST STAGE

In 1981, for the first stage of the concrete dam construction at the Lock and Dam No. 26 (Replacement) Project, WES used the 1968 DTMCS program after some modification to predict temperature distributions, and the Stress Analysis with Incremental Construction & Creep program to determine strain-stress distribution as functions of time, incremental construction, materials, and construction parameters. Not using state-of-the-art finite element programs for thermal analysis of mass concrete in the design of the project could lead to the development of deep cracks during and after construction; this could lead to safety, engineering, and economic problems. According to an academician, state-of-the-art finite element programs can predict whether cracking in mass concrete will occur and the location of cracking.

Due to several reasons cited by thermal analysis experts, we have concerns regarding the adequacy of the program the Corps used in conducting thermal strain-stress analysis of the Lock & Dam No. 26 (Replacement) Project's first stage. The Corps' current thermal analysis program is inadequate because the finite element methodology used limits the program to linear analysis only. The program also

--allows changes in temperature but assumes that the properties of concrete will not change, i.e., the specific heat[7] and conductivity[8] of concrete will remain constant;

--does not allow for radiation from concrete surfaces;

--predicts temperature distribution in mass concrete with only 4 nodes/element; and

--predicts temperature distribution in 2 dimensions only, therefore lacking the 3-D capability of predicting all-encompassing temperature distribution in mass concrete.

THERMAL ANALYSIS OF THE PROJECT'S SECOND STAGE

In March 1983, WES submitted a proposal to the St. Louis District Office (STLD) to perform thermal strain-stress analysis of the second stage of the Lock & Dam No. 26 (Replacement) Project. The work was scheduled to be done in fiscal year 1984 at a cost of $100,000. A minimal 3-D analysis was also part of the proposal so that WES could compare both the results with the 2-D analysis.

Experts from major design and engineering consulting firms having direct field experience in designing and constructing large concrete dams and academicians accredited with developing the state-of-the-art thermal analysis programs have told us that the computer program in the WES proposal will be inefficient. The program will be inefficient because it (1) does not factor in realistic properties of materials, such as temperature dependence of specific heat and conductivity of concrete and incremental construction, and (2) factors in creep in concrete in only a rudimentary manner.

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[7]Specific heat is the ratio of the amount of heat required to raise a unit weight of the material 1 degree to the amount of heat required to raise the same weight of water 1 degree.

[8]Thermal conductivity is a measure of the ability of the material to conduct heat and is defined as the ratio of the rate of heat flow to the temperature gradient.

As a result of our advising WES officials of the inefficiencies in the program proposed, in June 1983 WES sent another proposal to the STLD to perform thermal analysis of the project using a state-of-the-art finite element program. In October 1983, STLD sent a letter to the Lower Mississippi Valley Division with a recommendation that this latest WES proposal be accepted. Further, STLD recommends instrumentation of the lock during construction so that temperature distribution in the lock structure can be determined.

VIEWS OF RESPONSIBLE OFFICIALS

Office of the Chief of Engineers

Officials of the Corps' Office of the Chief of Engineers stated that they recognized the need for the Corps to become more familiar with the improvements that have taken place in the area of thermal analysis of concrete structures. The Corps has begun consultations with the Bureau of Reclamation on its experience with the state-of-the-art finite element programs on thermal analysis of mass concrete. Based on our observations, the Corps has initiated a 4-year research and development program for the study of concrete cracking (estimated to cost $510,000). For fiscal year 1984, WES will spend $110,000 to examine the state-of-the-art finite element programs on thermal analysis and to examine analytical models of concrete cracking.

Corps officials stated that it would not be practical to use the programs on the first stage of the Lock & Dam No. 26 (Replacement) Project since it is about 85 percent complete. However, in fiscal year 1984, the Corps will examine the state-of-the-art finite element programs such as Heat Flow, DETECT, and ADINAT for temperature distribution and SAP-83 and ADINA programs for strain-stress distribution in the second stage of the project.

We were further advised that the Corps acknowledges that an expanded manual is needed to provide guidance on thermal analysis and that the Corps needs to reassess its capability to provide direction to its district offices on thermal analysis of mass concrete structures.

Directorate of Research & Development

Officials of the Corps' Directorate of Research and Development believe that research and development aspects of thermal analysis need to be strengthened.