RESEARCH AND DEVELOPMENT OF REINFORCED CONCRETE COOLING TOWERS

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1. Introduction

In 1977 the *Electric Power Research Institute* (VEIKI) commissioned the *Department of Reinforced Concrete Structures, Technical University, Budapest* to make "Theoretical Research on Engineering Mechanical Problems of Constructing Large-Size Cooling Towers, Structural Safety Problems." At the same time the *Section of Technical Development* of the *Ministry for Building and Urban Development* commissioned this Department through the *Design Office for Civil Engineering* to elaborate building codes for the construction of cooling towers, involving the slip-form building method. The main trends of research based on these two commissions were:

— Establishment of forces and reactions in the shell structure, the bracing rings, the columns and the annular base, theoretical investigation of static and dynamic stability and elaboration of methods of use for the design practice.
— Analysis of effects of transversal excitation by wind eddies, methods to determine natural frequency.
— A comprehensive geotechnical study of cooling tower foundations.
— Safety of the structure during construction and in final state.

The detailed investigation of the scope was the responsibility of the Department of Reinforced Concrete Structures with the co-operation of the *Department of Civil Engineering Mechanics* and of the *Department of Geotechnique.* In addition, *Department of Surveying* made subsidence measurements on erected cooling towers and investigated movements due to unilateral insolation.

The research work was essentially intended to develop — based on the analysis of Hungarian and foreign experience — possibly simple but reliable and relatively rapid procedures for the design practice.

The question arises whether a research work of this kind and to this scale is altogether necessary when international experience is available, besides

Hungarian design and construction practice proved to be able to internationally interesting achievements.

The research work had the following motivations:

— cooling tower dimensions go growing;
— the uncertain design values of wind load acting on tall structures affect the safety of the structure;
— theoretical calculation methods are developing; beside use of computers, demands arise for checking computer results and for approximation methods applicable without computers;
— continuously improving construction technologies, dimensional accuracy permit to reduce dimensions. On the other hand, reduced dimensions, e.g. wall thicknesses, raise new theoretical and construction problems (e.g. effect of geometry errors on forces and reactions);
— last but not least, catastrophes in the recent years hinted to the necessity of deepgoing analyses.

Dynamic analyses were urged also by the fact that calculation of shells of reinforced concrete cooling towers as hyperboloids of revolution was elaborated only for the case where the rotation axis coincided with the axis of the hyperboloid. There was a single calculation method for the so-called displaced-axis hyperboloid and this had also to do with the membrane theory and was not of a form for direct practical use. References offer no method for the application of the flexural theory in general cases.

2. Research results

Research work started by surveying and processing the special literature of several hundred studies and books presented in a report of nearly four hundred pages, enumerating data involved in the design of cooling tower shapes, design wind loads and temperature stresses as well as published methods to determine loads, fundamentals of dynamic analyses and stability calculations known so far.

Study of the published matter pointed out the absence of expedient methods for static or dynamic loads or for stability analysis directly applicable in our general problem. For the calculation by the membrane theory of a hyperboloid of revolution with a displaced axis only the computer-oriented procedure by *Krätzig* was found, but no flexural theory proper was developed for this case.

Also an integer theoretical method reckoning with the interaction between soil, annular foundation, columns and shell — i.e. of the entire structure — was missing. Computation methods referred to separate structural members and only allusions were found of them as an integer system.

2.1 *Static analyses*

The following statements are based on published data and on our investigations.

2.11 *Forces and reactions in the shell*

Static analyses involved in detail:

— exact membrane theory,

— approximate flexural theory

for the general case where the axis of the directrix did not coincide with the rotation axis of the hyperboloid of revolution. Elaboration of the computation procedure is due to the late Dr. *János Szalai*, scientific consultant.

2.12 *Temperature effects*

Temperature effects and our suggestions to their consideration in design have been recapitulated in a separate report, involving, beside permanent heat flow, the intermittent warming up of structural members and the alternating heat flow. Both international publications and Hungarian measurement results on unilateral insolation stated the shell deformations to be relatively small and the temperature changes along the circumference to be negligible, it being sufficient to investigate the case of circular symmetry. Temperature differences across the shell were lower than expected, measured deformations due to solar heat were small, so it was decided to neglect the effect of unilateral insolation on the shell. The stiffening effect of edge rings was, however, apparent also in measurements, thus edge disturbances have to be taken into consideration but assumption of circular symmetry as an approximation is permissible. Suggestions have been made for the approximate computation of swelling due to soaking of wet-process cooling tower walls. In conclusion, the temperature effects can be stated to be primarily important for the shell edge disturbances, a problem deserving attention.

2.13 *Investigation of the columns*

There are two possibilities to calculate columns supporting the shell. The first and more general one is a complex integer model comprising all the structural parts, thus also the elastic half-space of bedding, yielding the stresses in the columns supporting the shell as part results. The other is a mathematical model centered on the column and ranking the other structural parts according to their effect on it.

For want of a big-capacity computer system required by the first — rather intricate — method, the second one was chosen, leading to the development of a practically useful design method, the essentials of which will be discussed by its author, Dr. *Béla Kovács*.

2.14. *Investigation of the foundation ring*

A new method relying on the interaction between annular foundation and soil considering the foundation ring of sloping base plane as the primary case has been developed, described in detail by Dr. *István Hegedűs.*

Testing the effect of support displacements has led to the following statements:

— in certain cases the unequal subsidence causes an important deformation of the entire shell;
— support displacement over a short section of the foundation ring — such as failure of one or two adjacent columns — is a kind of edge disturbance and affects only the bottom part of the shell;
— in case of failure of one column, most of the forces in the column are taken over by the adjacent columns;
— application of a top edge ring is advantageous by reducing top edge deformations even in the event of support displacement, thus it is also favourable from no-strain deformation and stability aspects.

2.15 *Stability analyses*

The survey of publications concluded to that available procedures and relationships are of no direct use in our problem.

Dr. *Endre Dulácska* has developed a new method of stability analysis, taking the cracked condition of the shell and the resulting rigidity changes into account. By this he contributed greatly to the theoretical solution of the problem and his method, simple in handling, can be considered of a high practical importance. This method, submitted to the IASS Conference in Madrid, has been promoted by IASS to an international recommendation.

2.16 *Structural safety*

This study made at the Department of Reinforced Concrete Structures has led to the conclusion that safety parameters valid to usual structures may be adopted in the design of cooling towers, there is no need of specific safety factors. Relevant examination results have been presented in the paper by Prof. Dr. *Kálmán Szalai.*

2.2 *Geotechnical analyses*

The *Department of Geotechnique* prepared a concise study giving a detailed analysis of foundation problems of cooling towers involving general design problems, soil strength tests, determination of soil stresses and displacements, stability problems, and gave suggestions for field tests.

It must be mentioned that the analysis of interaction of soil and structure needs further research since a great part of the basic data resulted from field measurements.

2.3 Vibration analyses

Vibration analyses were made by Dr. *György Vértes*, *Department of Civil Engineering Mechanics*, who presented methods for testing the top edge ring and for determining the natural frequency of the cooling tower.

2.4 Design and construction directives

No specification or codes specially for cooling towers have been issued so far in this country. Already at the beginning of the work the idea emerged to collect special demands for, and observations made on, these structures and to confront them with specifications and codes valid in Hungary. Results of this work are contained in the tentative building code prepared at the *Department of Reinforced Concrete Structures* and assembled by Dr. *Ferenc Sebők*. In Hungary this is the first directive of this kind, summarizing also recent international experiences.

3. Long-range tasks, suggestions for further research

In every research work, further problems arise, thus no such thing as to completely finish a subject exists in practice.

During the one and a half year that could be spent on research, progress could be achieved in some problems while some questions remained unanswered. Major problems still facing Hungarian and international research are:

a) Classification and pathogenesis of damages in existing cooling towers.

b) Field measurements to determine geometrical and structural errors due to building technologies.

c) Experimental and theoretical establishment of methods for following the hardening process of concrete placed according to different technologies, for a more reliable control of forces and reactions during the construction.

d) Measurements to obtain more reliable and accurate data of wind loads acting on tall structures of 100 m and over.

Theoretical research is expected to deal with the following problems:

— Effects of rigidity changes due to cracking on forces and reactions in the shell structure.

— A calculation method taking the interaction between soil, foundation ring, supports and shell into account. This is naturally a very complicated problem and can only be solved in a computer but programming would take years. It has to be mentioned that an eventual program in operation — less general than that — lasted about ten years to develop.

— Interaction between the structure and the foundation has to be analysed in particular, for a realistic determination of expected subsidence values. Actually, in general, subsidence is calculated from loads acting on the soil, omitting the reaction of the structure, leading to higher than real subsidence values.
— Development of methods and structural solutions for counteracting no-strain deformations, in particular, application, emplacement and dimensions of bracing rings, partly because of their effect on the stability. Building technology problems of applying bracing rings have to be considered.
— Theoretical elaboration of a method for demonstrating the force effects due to geometrical inaccuracies arisen in the construction of cooling towers, precondition of a detailed analysis of existing structures, of the stress state during construction, and of the establishment of tolerances.
— Experimental investigation of the effect of surface roughness of the shell and building technology possibilities of a solution. Difficulty of this problem resides in that reliable results can hardly be expected from model tests in a wind tunnel.

These problems picked out at random — without aiming at completeness — are just illustrating how important questions have been left unanswered by the performed research work.

The *Department of Reinforced Concrete Structures* described research results in 21 reports totalling about 1100 pages. Of them 2 reports — about 50 pages — are due to the *Department of Civil Engineering Mechanics* and about 200 pages to the *Department of Geotechnique.*

4. Conclusions

In 1965 three cooling towers of the *Ferrybridge Power Station* collapsed. Catastrophes occurring ever since and the increase in cooling tower dimensions induced to start an intensified research and development work, chiefly in European countries. This is the first time that a comprehensive study was carried out in this scope in Hungary.

Of course, results obtained by research work of hardly more than a year are not comparable to those in other countries with ten to fifteen years of research experience. Nevertheless some important problems concerning towers of hyperbolic directrix seem to be cleared and the results are likely of direct use in design.

It can be stated that up-to-date, economical and safe methods are available for the design and construction of big cooling towers.

Research on thermal effects, on foundations, on the stability of shell supports and on forces and reactions of the foundation ring resulted in savings in building materials and in expenses compared to earlier, known solutions.

In the short survey of the research results, development possibilities were pointed out. For the further analysis of almost all problems, computer methods seem essential in evaluating the theoretical results, in further investigations as well as in up-to-date, economical design. In possession of computer methods some effects will be accessible to analysis; research can be started on e.g. shell form optimization. This research would require, however, the same volume of intellectual and financial expenditure as that described above.

There is a real possibility to develop a practical method for the theoretical analysis of the dynamic behaviour of shells and to check it experimentally on an erected structure, further, to develop computer subroutines for separate structural members.

Summary

Scope and major achievements of research on large cooling towers at the Department of Reinforced Concrete Structures, Technical University, Budapest, are reported on. Design methods for the shell, the columns, the foundation ring, problems of stability analysis and temperature effects are presented. Further research problems including interaction between structural members, and the imperative of integer analysis of the structure are pointed out.

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