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The Impact of Computer Development on the Art of Concrete Dam Displacement Control (a 15 yr, case-history)

Les consequences du developpement des ordinateurs sur l'art du controle des deplacements des barrages (un historique de 15 ans de travail)

Die Folgen der Rechenmaschinenentwicklung hinsichtlich der Dammverschiebungskontrolle (eine fünfzehnjährige Studienarbeit)

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Summary
The joint work carried out by CRIS (Center for Hydraulic and Structural Research) of ENEL - the National Power Board in Italy - and by ISMES (Experimental Institute for Models and Structures) in the field of rational numerical models for dam displacement forecasting provides excellent illustration of a gradual evolution made possible by the progress, over many years, of both hardware and software. The main steps in this development are recalled, with the aim to bring into focus the interplay between the researcher's intuitions, real phenomena as measured in the field and the world of computers.

Résumé
Le travail réalisé en commun par le CRIS (Centre de Recherches d'Hydraulique et de Structures) de l' ENEL (Autorité Nationale pour l'Energie Electrique d'Italie) et par l' ISMES (Institut Expérimental pour les Modèles et les Structures) de Bergamo, dans le domaine des modèles mathématiques rationnels pour la prévision des déplacements des barrages, fournit un example éclatant de l' évolution graduelle qui a été rendue possible par le progrès continu des ordinateurs et du logiciel. On fait l' historique des étapes successives de ce développement, dans le but de mettre en lumière l' interaction entre l'intuition des chercheurs, les phénomènes réels - tels qu' ils sont measurés en nature - et le monde des ordinateurs.

Zusammenfassung
Die gemeinsame Arbeit der CRIS (Center for Hydraulic and Structural Research) der ENEL (the National Power Board of Italy) mit der ISMES (Experimental Institute for Models and Structures) auf dem Gebiet effizienter numerischer Modelle für die Prognose von Staudammwerschiebungen ist ein hervorragendes Beispiel für die über viele Jahre hindurch kontinuierliche Entwicklung von "Hardware" und "Software". Die Hauptschritte dieser Entwicklung werden in Erinnerung gerufen, um die gegenseitige Einwirkung zwischen der Intuition von Forschern, der Realität und der Computerwelt aufzuzeigen.

1. FOREWORD

"In the last years a great widening of the field of use of automatic computational tools has become apparent in every technical application ... the static analysis of arch dam did not escape this general trend". Such words opened an article by FANELLI and CAPOCCHIA written in 1966. Nowadays - 12 years later - these same words still apply. Indeed, the development of "automatic computational tools" proceeded - and will presumably further proceed - at a breakneck pace, reaching higher and higher landmarks.

What only yesterday was almost a science-fiction dream is today a common place and will be tomorrow in the shade of obsolence.

If we keep strictly to the field of structural analysis, which is envisioned by the present Colloquium, we could add that already in the beginning of the Fifties one had forewarning glimpses of those advanced computational methods which were to reach full blossom in the following years, namely only after the introduction of ever more powerful electronic computers.

In this line of development, certain methodological avenues gradually opened up, which were not previously practicable owing to the overwhelming amount of computations to be performed.

A short historical review of the main methods successively used for design and behaviour analysis of arch dams clearly evidences this type of evolution.

Indeed, the first arch dams were analysed by the "independent arches" technique; very simple formules were initially used, such as the "thin pipe", or Mariotte, formula, or the "thick pipe", or Lamé, one. More elaborate "independent arch" formulas, taking into account either rigid or compliant end constraints, were then developed, such as the Guidi [1] and Bresse theory. Some dead-end alleys such as the "active arch" or the "arc plongeant" [2] methods were tried and abandoned, till at last very elaborate statical schemes were conceived: typically, an interconnected arch-cantilever lattice, see the Guidi-Ritter scheme, or a continuous, curved plate or shell (Tölke et al.) [3].

In the same years, a fully codified and organic computational method was put forward by the Bureau of Reclamation: the "Trial Load Method" (TLM) [4], a refinement of the Guidi-Ritter scheme. The TLM lent itself readily to automatic, or semi-automatic, treatment. In fact, at the beginning of the Sixties some "fully" automatic procedures, such as the "Algebraic Load Method" (ALM) [5], [6], the "minimum potential energy method" (CST) [7], [8], the "Modified Ritter method" (MRM) [9], [10] etc., were implemented on the "first generation" of commercially available electronic computers. All of these methods were aimed at taking into account - by means of different approaches - the main structural resources of arch dam, whose shape and size could be varied at will, within limits, by the user. The Vogt theory [11] allowed a simple, albeit approximate, way of representing the foundation compliance. Also the first theoretical developments of the Finite Element Method (F.E.M.), which was to gain such widespread acceptance toward the end of the Sixties, date back to 1956 [12] and to the availability of first-generation computers as well as of first-generation programming languages.

Concurrently with the development of the above-mentioned automatic computational tools, the possibility came to light of endowing each dam with a "tuned" procedure of continuous displacement check-up. The latter was to be based, in principle, upon "a priori" computations giving theoretical estimates of each displacement: these estimates being the sum of a "water level variation" effect and of a "thermal load" effect [13] [14] [15] .

II. CORNERSTONES OF THE CHECK-UP METHOD; FIRST APPLICATIONS BY MANUAL, OR SEMI-AUTOMATIC, MEANS

In 1965 a paper by FANELLI [16] set down the cornerstones of a rational check-up procedure for arch dam displacements. A deterministic correlation was postulated to hold between the external actions (water level variations, thermal variations) and their externally observable structural effects, such as displacements, rotations, unit elongations etc. Basically, the hypothesis of linear-elastic behaviour of the dam material is retained:

$$\varepsilon = \frac{\sigma}{E} + \alpha \, \Delta\vartheta$$

(Hooke's law : E = Young modulus, α = thermal dilatation coefficient, $\Delta\vartheta$= local thermal variation); namely, linear superposition is assumed to hold for separate contributions due to stress level changes and to temperature changes.

The practical implementation of this basic idea needed two main supports:

a) Setting up a proved, automatic computational procedure in order to simulate the structure behaviour under certain loading conditions;
b) a formulation of suitable "unit loading conditions" such that any instantaneous situation could be reasonably well approximated by a linear combination of the unit conditions chosen. In this way, also such external structural effects as the displacements, rotations and so on could be assigned "theoretical" estimates given by linear combinations of "influence coefficients" computed for the corresponding effect under each unit loading condition. These "influence coefficients" would be computed by the automatic computational procedure under a) by using as inputs the unit loading conditions as per b) .

The development of a "unit load conditions" definition technique such as under b) was made necessary, in particular, for thermal effects estimation. Otherwise, any particular thermal situation would need a long series of manual operations, at the end of which a corresponding particular thermal load would have obtained; and this, in turn, would still have to be introduced as input in the procedure under a) in order to get the corresponding structural effect estimate. Such an approach, of course, would have been intolerably money - and time - consuming, to the point of making a continuous check-up practically unfeasible. On the other hand, this "unit thermal load conditions" definition technique (referred to hereafter , for brevity sake , as the "monothermometric technique") achieved the goal of a substantial reduction in the amount of the computations required by each particular thermal situation only at the expense of introducing certain simplifying assumptions (these were later largely relaxed, see further on) . Among these simplifying assumptions were the linearization of thermal distribution inside the arch thickness (fig. 1) (°) as well as the Navier-Stokes hypotesis of plane-section conservation.

(°) Each "unit loading condition" at the arch level had to be transformed in an equivalent linear temperature diagram, which had to conserve the same average ($\bar{\tau}$) as the diagram of the unit thermal load as well as the same barycentric abscissa (this latter condition allowing one to deduce the linearized thermal jump, $\Delta\tau$).

With this "monothermometric technique" many sets of unit loading conditions had still to be introduced into the numerical model; but all of these computations were carried out only once, before actual beginning of the check-up process, which was then reduced to the very simple form of a linear combination of the influence coefficients which were the model output under the different "unit loading" conditions.

The above-defined logical scheme needed a powerful, easy-to-use structural analysis program, in order to allow the building-up of the corresponding unit influence coefficients. Of course, such a program could also be used as a general tool for the static analysis of arch dams subjected to any set of loads.

Around 1958-1960 we had no general-purpose structural analysis program. The decision was taken to develop a specialized code, restricted to arch dam analysis. The outcome of such a decision was the so-called "CST" program, implemented on a UNIVAC USS/90 computer system. The latter consisted of three I/O peripheral units (card reader, card puncher, printer) and a central unit with a magnetic-drum core of 5000 words capacity (each word having 10 characters plus algebraic sign). No auxiliarystorage was available; half of the above-mentioned central memory was taken up by the interpretative program, so that working storage capacity was severely restricted. Because of this, the overall computation was subdivided into 16 successive steps (fig. 2), the punched card being used as the physical support of data and program. Each successive program segment performed a single computation step, after checking and storing the segment instructions as well as the necessary data; at the end of each step the results were printed and card-punched in order to be fed (as an input) to the successive step. (fig. 3). This program was written using "advanced" programming techniques (as compared to the state-of-the-art prevailing at the time) in order to impart to it the greatest flexibility: none of the program steps had to be modified when the shape of the dam to be analysed was changed.

The limitations of the system conditioned the choice of the method of analysis. In fact, linear algebraic systems could be solved by UNIVAC USS 90 only if the number of unknowns was less than 64 (with symmetric matrix of coefficients) or 48 (with unsymmetric matrix). Given this limitation, the method develop (based on the principle of minimum potential energy as already stated) used special "degrees of freedom" which allowed such a reduction in the number of unknowns, at the expense of rather heavy preliminary computations. (°)

The whole program was made up by 12, 000 instructions in interpretative language, that were punched on 4, 000 cards. In addition to this, about 2, 000 cards were needed to record the input data for a medium-size arch/cantilever grid (about 7 arches and 7 cantilevers for half of the dam, which was supposed to be symmetrical).

(°) One may observe in passing that the "modern" approach can take the opposite choice (many unknowns, very simple "degrees of freedom" and scanty preliminary computations) thanks to the enormously increased capacity and speed of present-day computers.

During the period of use of CST program, which covered several years, about 120 hours of computer time were used for 34 complete analysis of arch dams.

By way of example, some results are presented concerning the displacement check-up for a crown target of Isolato arch dam. Fig. 4 shows the chronologic diagram of computed and measured displacements for years 1954-1964; also shown are discrepancies between "forecast" and "observed" values and their frequency distribution. Fig. 5 exemplifies a chart, embodying the influence coefficients computed with CST in the above-described way, by means of which the synthesis of the "theoretical" displacement could be effected graphically, once the water level and the thermometric readings were known.

Till 1969 this early type of displacement check-up was used for only six italian dams, owing to limitations in computer time availability and to the necessity of validating the basic conceptions of this methodology through a suitable period of experimentation.

III. COMING OF AGE OF F.E.M. AND THIRD-GENERATION COMPUTERS

At the beginning of the Seventies, larger and faster computers were made commercially available by IBM, Honeywell, CDC, UNIVAC etc. The capacity of automatic computations was so increased as to change radically working methods in every engineering field. The main innovations brought on by these so-called third-generation machines concerned the hardware as well as the software. The new developments of hardware can be summarized as follows:

a) a fast memory by far exceeding in capacity any previous possibility and having almost limitless expansion potential;
b) several direct-access peripheral units such as : mag -tape, disk, fast paper tape or card reader/puncher, fast printer etc. ;
c) possibility of long-distance access to large "remote" computers by means of "terminals" ;
d) indirect-access units such as interactive graphical systems, plotters, "pencil-follower" tables for coordinate reading, etc.

In the same time the available software became ever more flexible and comprehensive, so as to allow development of computational codes using "programming languages" both simple and accessible to non-specialists. In other words, a deep knowledge of the machine and of its internal language was no longer necessary in order to write a reasonably efficient program.

In this period many computer codes were indeed developed, addressed specifically to the solution of important engineering problems. In particular for the analysis of static and dynamic behaviour of structures, big programs or even "systems" of programs were written based on the F.E.M.

It would be beyond the scope of the present paper to dwell at length on such a widely known method [17] ; suffice it to say that it was and is often used - since the beginnings - also to study the behaviour of dams of the most various types: arch, arch-gravity, gravity (massive or hollow), buttress etc. This new general tool allowed, indeed, a better schematization not only of the structure itself, but also of its foundations; besides, also the effects of local details or singularities could be more faithfully simulated.

Also the implementation of displacement check-up methodology found in these new developments a natural vehicle for advances in basic model approximation flexibility and scope of applications. The starting assumptions were mantained, namely the superposition of separately computed effects for hydrostatic load and for thermal loads, but the techniques for building up "influence functions" was considerably refined, especially so for the "monothermometric coefficients", whose computation was made not only fully automatic, but remarkably more accurate at the same time.

Fig. 6 illustrates the logical flow-chart of the present version of our deterministic displacement-forecasting method [18] [19].

As far as the computation of "monothermometric coefficients" is concerned, the present methodology is based on a F.E.-oriented solution ("TERFUN" program) of the heat-conduction equation :

$$a \nabla^2 \vartheta = \frac{\partial \vartheta}{\partial t}$$

[a = thermal diffusivity coefficient, $\vartheta = \vartheta(x, y, z, t)$ = temperature inside the dam],

with limit conditions $\vartheta = T_j$ at thermometer n° "j" (which can be located either on a dam facing or in the interior), under the simplifying assumption of periodic, sinusoidal variations of ϑ (the period is usually assumed a yearly one). Since a synthesis of the overall temperature distribution is needed starting only from the known thermometric readings, the estimate of the temperature at the generic point (x, y, z) at general time t is assumed to depend on these readings through a relationship of the type:

$$\vartheta(x, y, z, t) = \Sigma_j b_j T_j(t) + \Sigma_j c_j \frac{\partial T_j}{\partial t}$$

which is consistent with the hypothesis of sinusoidal time-variations of T_j ($1 \leq j \leq M$, if M is the total number of installed thermometers).

In this expression, b_j and c_j are spatial distribution coefficients $b_j = b_j(x, y, z)$; $c_j = c_j(x, y, z)$ respectively for unit temperature variation at T_j (and zero variation at any other thermometer) and for unit thermal time-gradient at T_j. Such distribution coefficients are automatically computed by the "TERFUN" program. The thermal diffusivity coefficient a, whose knowledge is necessary as an input data to TERFUN, can be estimated from the thermal time-history of the inner control thermometers using another special F.E. program, named "TERDIF".

Spatial-distributions embodied, for each unit thermometric variation, by coefficient b_j, c_j make up a thermal input for the structural analysis F.E. program "TRITEN"; the output being the above-mentioned "monothermometric" influence coefficients for displacements (or any other structural quantity).

The heavier part of this present version of our methodology is tied to the creation of a 3-D F.E. mesh for the geometric input to TRITEN: this requires a considerable expenditure of man-hours. A possible improvement in this direction lies in the development of new types of F.E., such as the "hyerarchic" family, which can yield very high-precision results, even with relatively coarse meshes, so that the time required for their geometric definition can be substantially reduced.

Fig. 8 shows some results of displacements check-up for the Talvacchia arch-dam crown plumb-line (obtained with this more recent methodology).

The advent of general-purpose F.E. methods allowed us to extend the same check-up methodology also to other dam structural types, e.g. gravity dams. The first results were of particular interest, insofar as they evidenced some, hitherto neglected, components of structural behaviour. Indeed, the study of displacement behaviour of Barbellino gravity dam showed that not only the dam and foundation deformability had to be accounted for, but also the whole "regional tilting" of the impoundment basin under the reservoir water level variations affected the overall observed displacements and had therefore to be included in the theoretical model. Figs.9, 10 show the forecast displacements obtained with, respectively without, such regional tilting effect. It is evident that these methodologies offer a valuable means of assessing possible trends of time - evolutions in the mechanical characteristics either of the concrete or of the foundation rock; such information is of outstanding importance to follow the current state of safety of the dam.

IV. CONCLUSIONS

The dam displacement check-up, which can be taken as a signal instance of in-depth structural analysis - even under its present limitations to the linear - elastic field - underwent, in 15 years time, a remarkable evolution, for which the spectacular improvements in capacity, speed and flexibility of computers (and their ancillary equipment), as well as in software power, were largely the prerequisites. On the other hand, such an influence only made possible operations never before attempted because of their complexity, but could not by itself produce new concepts or lines of approach: the latter are still firmly in the hands of the research people, who were ready to take advantage of the "amplifier" effect brought around by computers in terms of number-crunching power.

If sometimes the sheer availability of such computing power fostered serious consideration of "new" types of analyses never before attempted, this availability was always a necessary, not a sufficient, condition.

Every new approach in the particular field here illustrated was checked against the actual behaviour of real-size structures. This allowed a balanced development and the eventual formulation of an organic proposal for the design of an on-line, real-time, continuous check-up system, based on present - day capabilities of computers (big ones as well as micro) and harmonically integrated in the public utility management . (°)

It would, however, be unfair to leave unmentioned some outstanding unsolved problems :

- management problems : which operative decisions should be taken when the check-up system shows an "abnormal" event? In this field the computer could help in making possible a rational (optimal) choice between the existing alternatives: a very complex problem of optimal strategy choice should in this case be posed, taking into account many parameters (width of tolerance bands, risks etc.) . Unfortunately, many of the quantities involved (e. g. estimates of the economic consequences of accidents) are very difficult to define quantitatively.
- responsibility problems : where should the responsibility for taking operative decisions reside? Public utilities local and top management, public Authorities, public opinion are all involved; in this area, however, the computer cannot give much help (save perhaps in the field of automatic classification, storage and retrieval of information about past experiences).

(°) Let us recall in this context the efforts being deployed within the ENEL organization toward remote power-plant operation.

- technical and organizational problems, such as data archive updating, mathematical model updating; maintenance and updating of check-up systems; links with research organizations, etc.); these could all profit from present-day computer capabilities.
- economic problems (cost and cost/benefit analysis of system features and specifications; evaluation of possible alternatives etc.) Here the computer could help in performing lengthy and complex analyses, but only under condition that all the terms of the question were quantitatively known (or could be parametrized within reasonably limited ranges), which is not always the case.

These problems must be clearly focussed and a serious effort is needed to solve them. Otherwise, the almost limitless possibilities offered by computers cannot be fully exploited: worse than that, a risk is run of creating a delusory sense of safety and/or a conflict of competences and loyalties, leading to greater confusion.

The organizational structure of our technical world and, more generally, of our society is not yet prepared to cope with the impact of computers. Let us take a clear conscience of this "fact of life" and start looking for means and procedures by which these new, powerful allies can be made "compatible" with old, but always worthwhile, goals such as greater safety and well-being for everybody.

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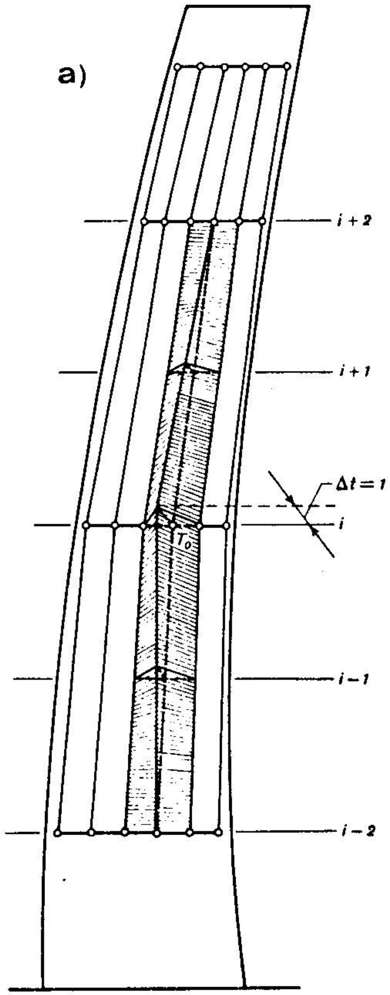
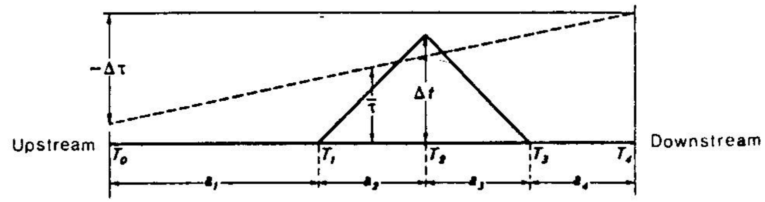
a)



b)



a) Thermal distribution in the crown-cantilever for the unit temperature variation in the thermometer T_o.

b) Average temperature ($\bar{\bar{T}}$) and linear thermal difference between upstream and downstream (ΔT) for a variation $\Delta T = 1^oC$ affecting only the thermometer T_2.

Fig. 1

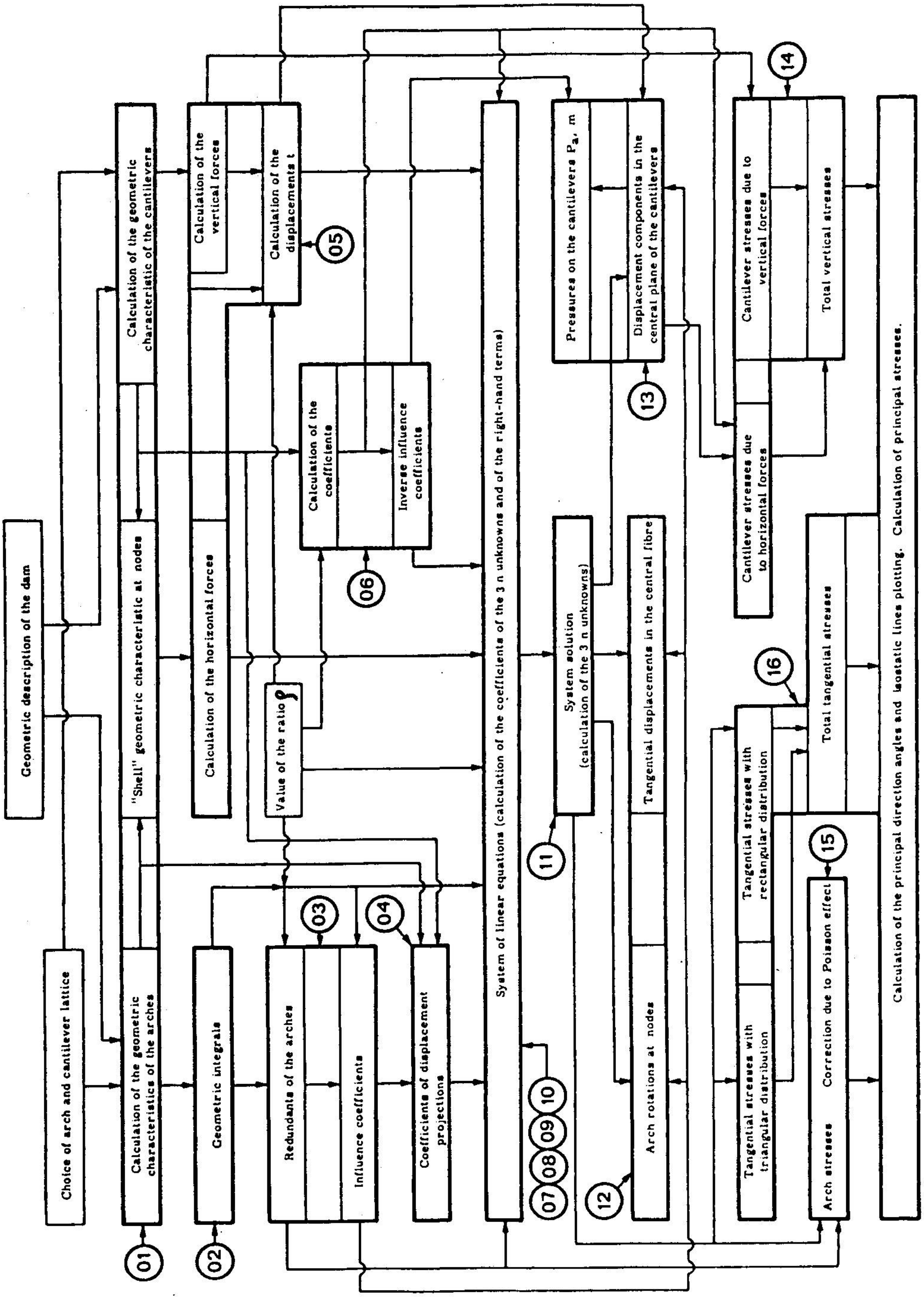


Fig.2 FLOW CHART OF THE PROGRAM (16 STEPS)

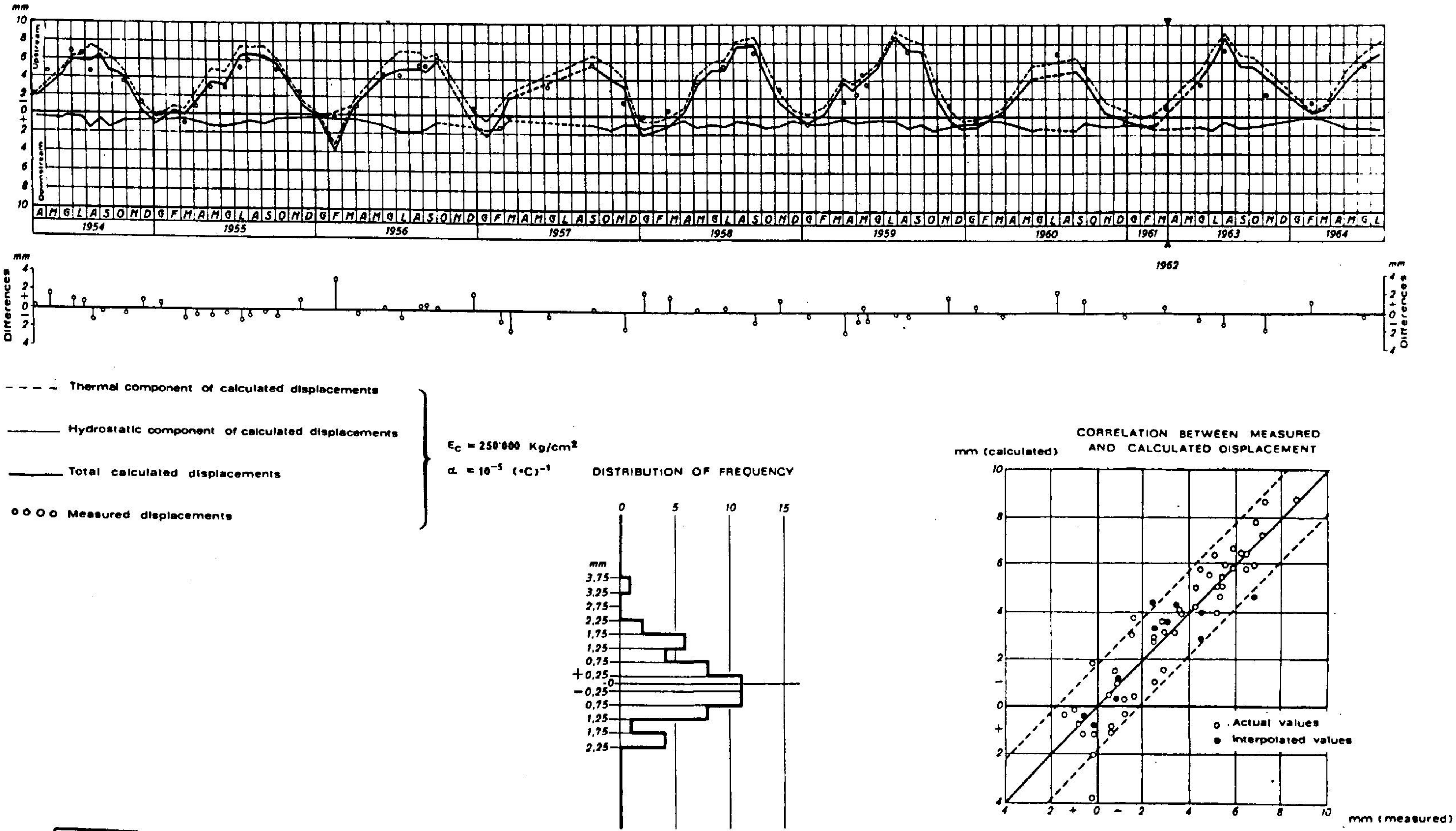
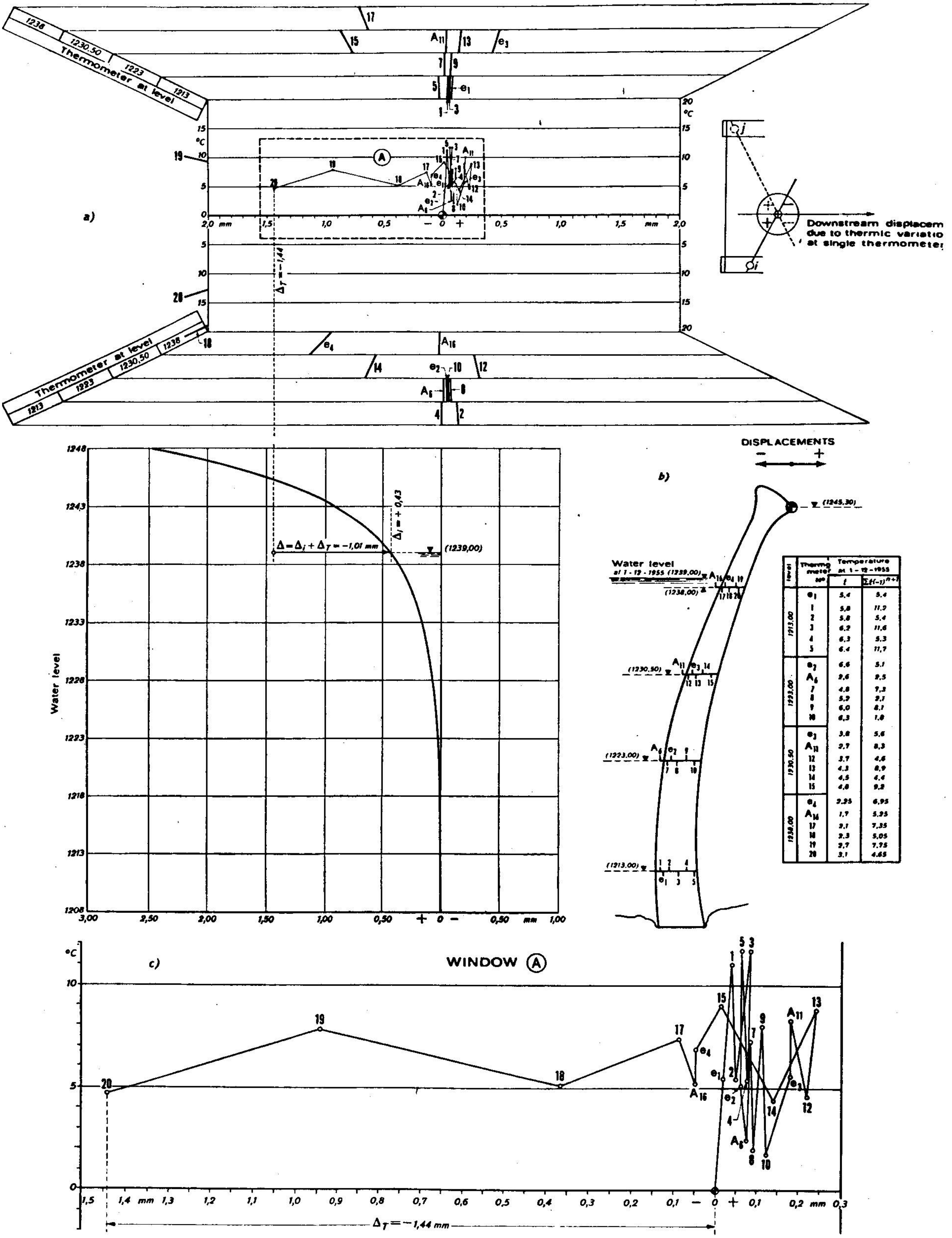


Fig. 3 Isolato arch-dam. Comparison between measured and calculated displacements for the movable staff at the level 1245.30 m. slm (yrs 1954 - 1964).



level	Thermometer n°	Temperature at 1-12-1955 t	$\Sigma t(-1)^{n+1}$
1213,00	e_1	5,4	5,4
	1	5,8	11,2
	2	5,8	5,4
	3	6,2	11,6
	4	6,3	5,3
	5	6,4	11,7
1223,00	e_2	6,6	5,1
	A_6	2,6	2,5
	7	4,8	7,3
	8	5,2	2,1
	9	6,0	8,1
	10	6,3	1,8
1230,50	e_3	3,8	5,6
	A_{11}	2,7	8,3
	12	3,7	4,6
	13	4,3	8,9
	14	4,5	4,4
	15	4,8	9,2
1238,00	e_4	2,25	6,95
	A_{16}	1,7	5,25
	17	2,1	7,35
	18	2,3	5,05
	19	2,7	7,75
	20	3,1	4,65

Fig. 4
a) Graphic calculation of the theoretic displacement at 1. 12. 1955
b) Crown-cantilever of the Isolato arch-dam and thermal situation at 1. 12. 1955
c) Window A - Graphic calculation of the thermal displacement at 1. 12. 1955.

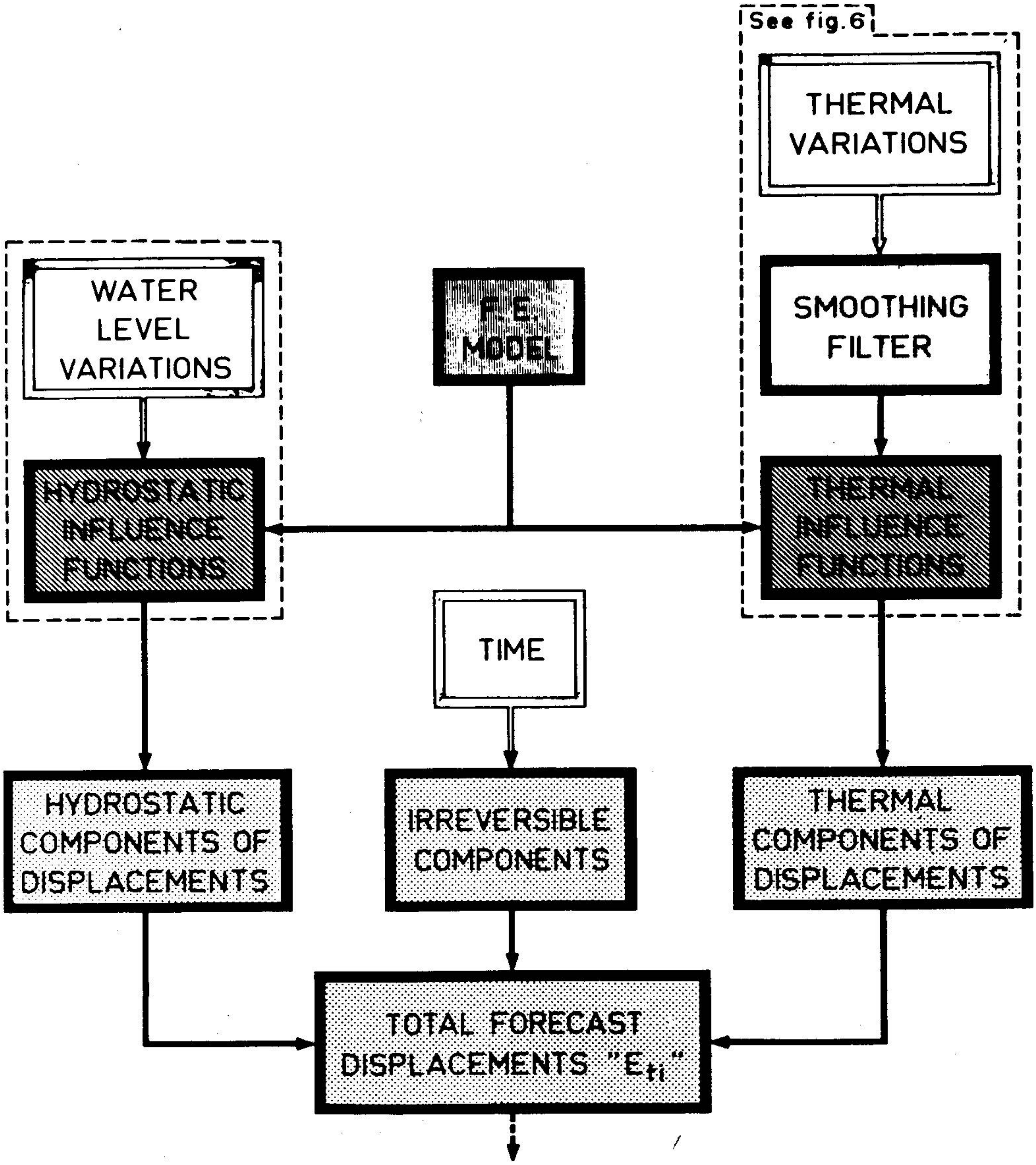
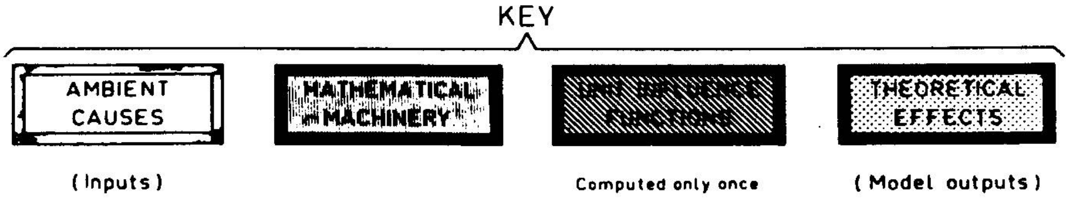


Fig. 5 GENERAL LAYOUT OF THE DETERMINISTIC, F.E. MODEL



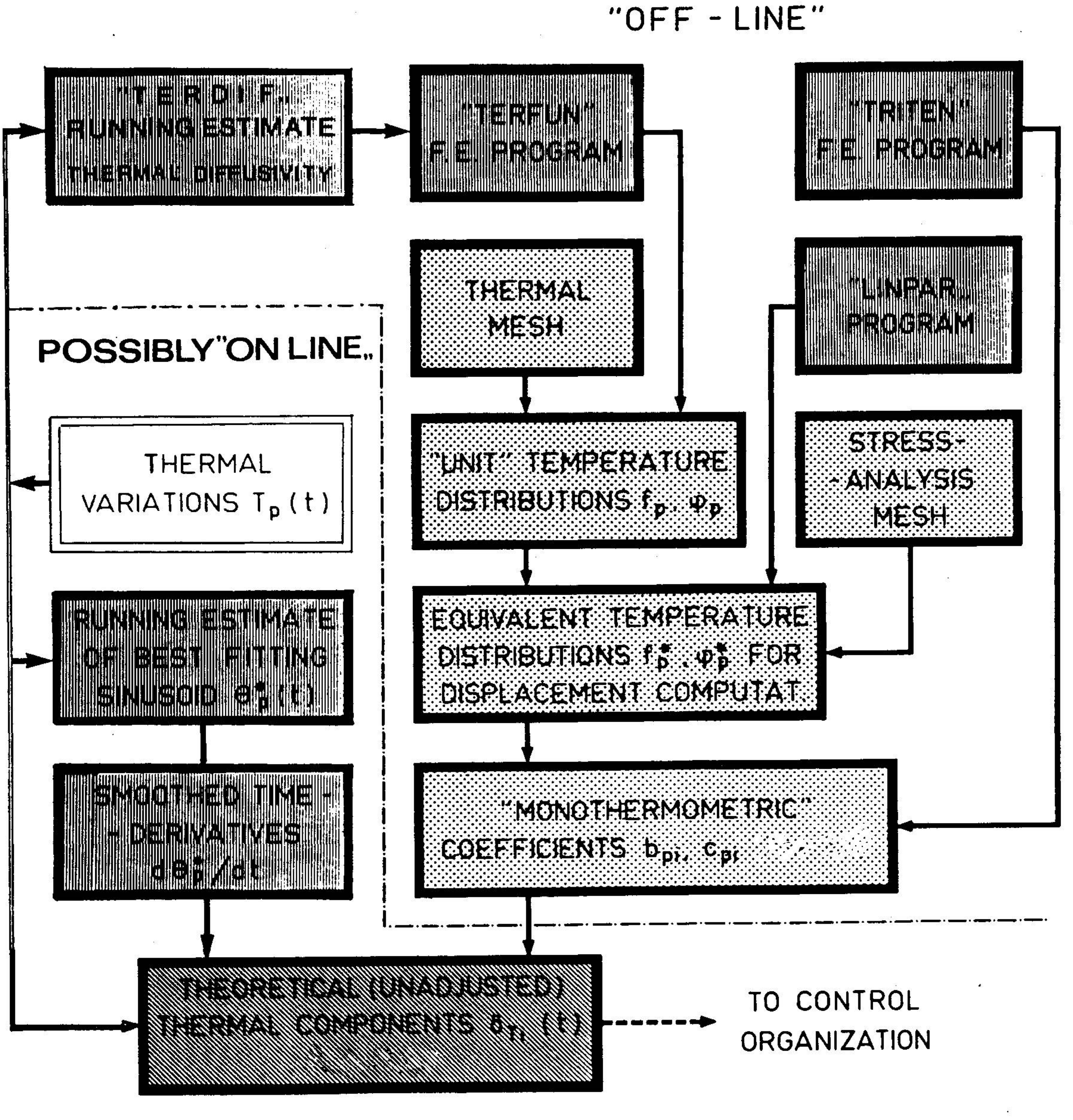


Fig. 6 FLOW-CHART FOR COMPUTATION OF "MONOTHERMOMETRIC COEFFICIENTS"

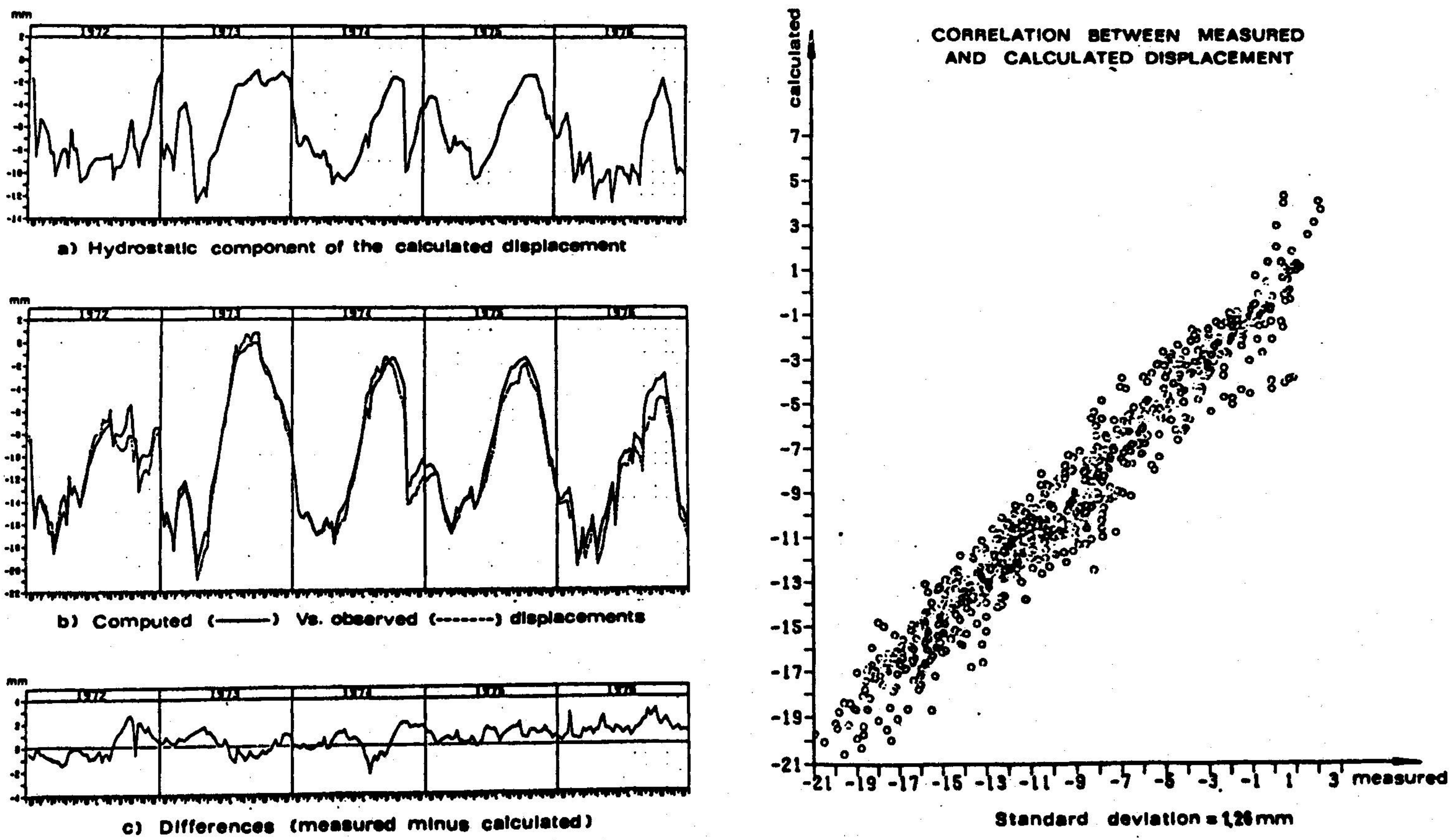
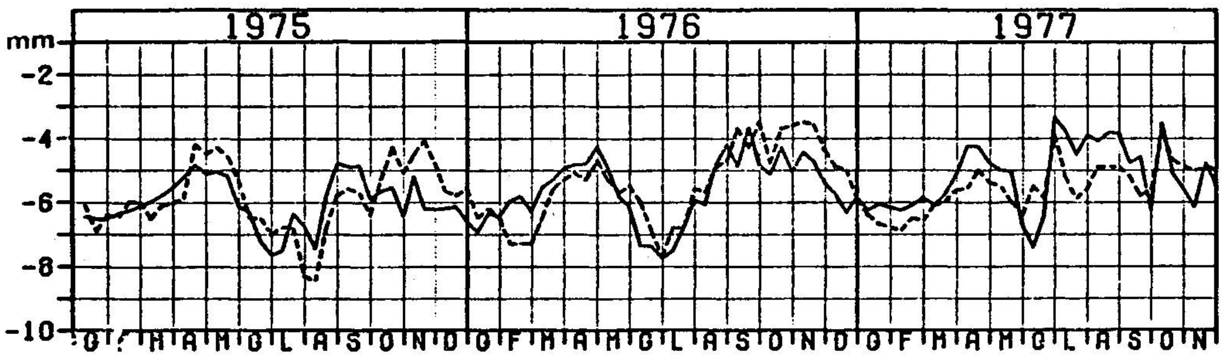
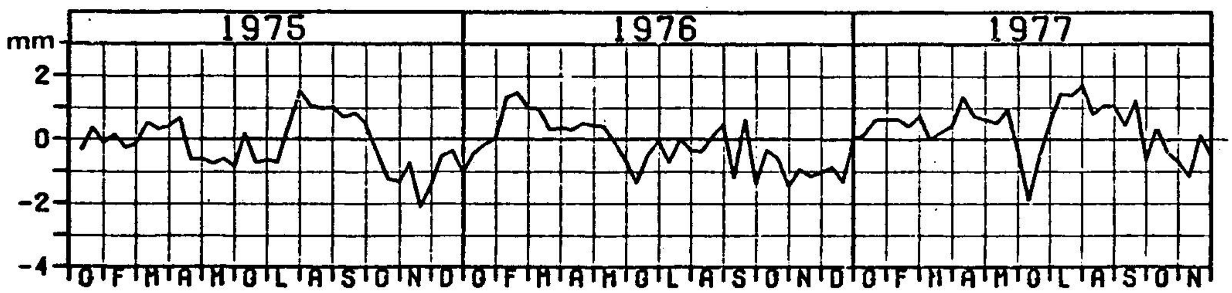


Fig.7 Talvacchia arch-dam. Comparison between measured and calculated displacements at the plumb-line (yrs 1972-1976).

Plumb - line



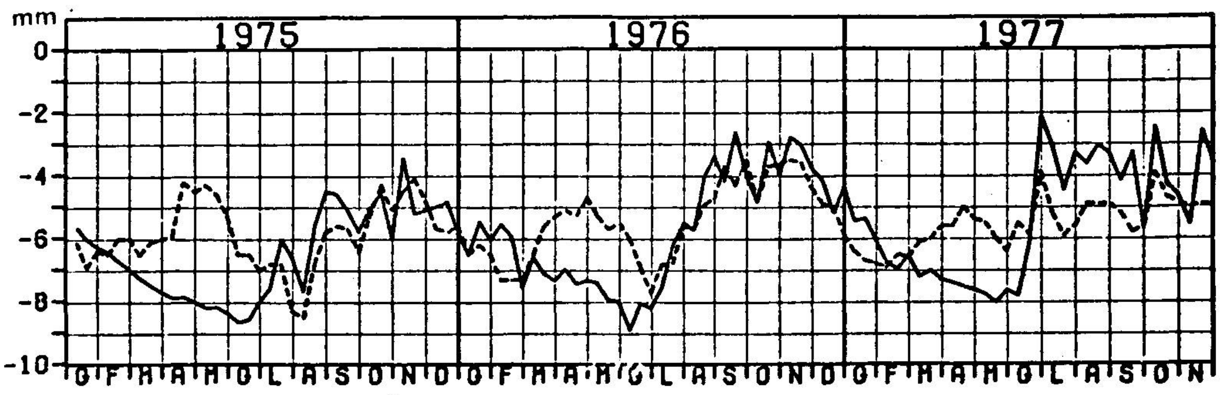
a) Computed (———) vs. observed (------) displacements



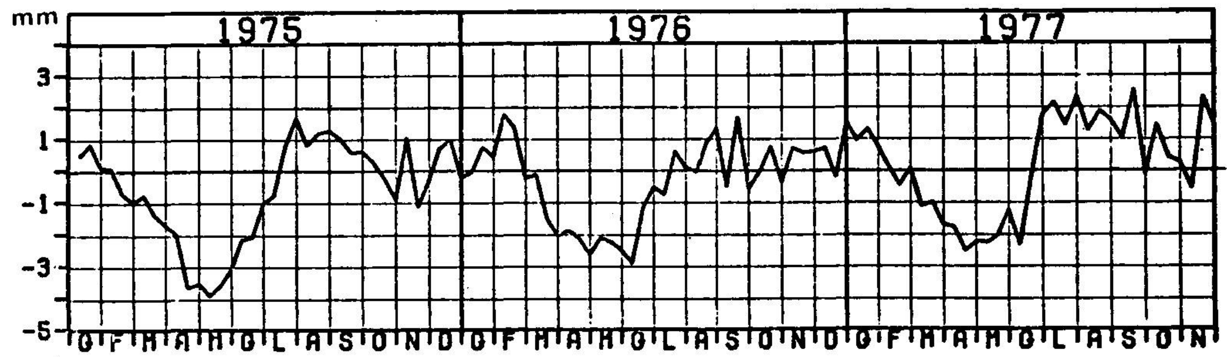
b) Differences

Fig. 8 Displacement forecasting for Barbellino gravity dam with Boussinesq regional tilting included.

Plumb - line



a) Computed (———) vs. observed (------) displacements



b) Differences

Fig.9 Displacement forecasting for Barbellino gravity dam without Boussinesq component.

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