Design for the rehabilitation of Ancipa dam

G. Giuseppetti and G. Mazzà, ENEL-DSR-CRIS, Italy
G. Lombardi and A. Piazza, Lombardi Engineering Ltd, Switzerland
M. Cadeddu, ENEL-DP, Italy

Severe cracking occurred at the 111 m-high Ancipa gravity dam in Italy, from the time of its construction. The design of remedial measures, now under consideration, is described here, with particular reference to the dynamic investigations and advanced numerical modelling techniques used to support the design.

Ancipa dam, on the island of Sicily in the South of Italy, is formed by nine hollow buttresses of the so-called Marcello type and two small gravity wings [Anidel, 1953[1]]. The maximum height is 111 m and the length of the rectilinear crest is about 250 m (see Fig. 1).

During construction between 1949 and 1952, many cracks, mainly sub-vertical, were detected in the webs and on the downstream face of all the elements. The structural behaviour was kept under careful observation from the time of initial operation [Marcello, 1955[2]; and Spagnoletti, 1962[3]], and a special commission was appointed by the authorities to monitor the behaviour of the dam [Arredi, 1982[4]].

In spite of the reasonably good behaviour of the structure over the years, it was decided in 1975 to reduce the operating level of the reservoir. In fact, systematic observation of the cracks had revealed that some of them were tending to widen and also to propagate. This was considered to be reducing the safety margins, mainly in view of the seismic level of the zone in which the dam is located (seismic effects were only introduced into the Italian Regulations in 1959 and they had therefore not been considered among the design loads). Hence, a detailed site investigation and a study were carried out in the 1980s. The main results of this can be summarized as follows:

- Investigation of the bedrock eliminated the possibility that foundation and abutment deformation had had an effect on the activation and evolution of the cracks.
- Additional minor cracks, both vertical and horizontal, became evident.

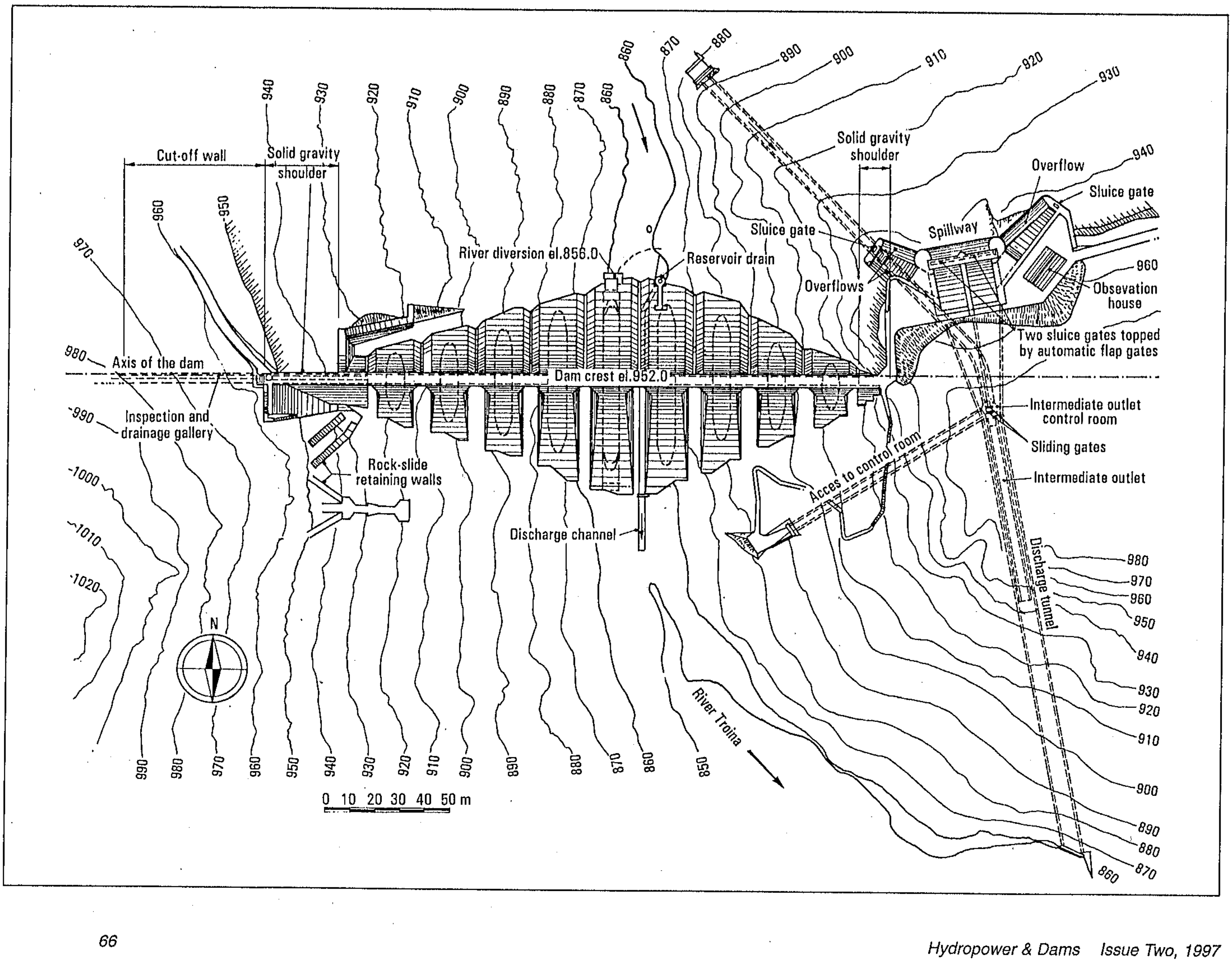


Fig. 1. Plan view of the Ancipa dam.

- Borings drilled in the webs, to investigate the depth of the the cracks, showed the presence of widespread honeycombing in the interior of the walls.
- Studies carried out using mathematical modelling confirmed that the most probable causes of the cracking were shrinkage and cooling of the concrete; furthermore, the model showed that the seasonal temperature variations may have played a significant role in the cracking process. The downstream face of the dam is exposed to south, and the elevation of the structure (about el. 1000) and its geographical location give rise to quite a severe thermal regime.

On the basis of this study, a first rehabilitation design was proposed [Appendino et al, 1991[5]] which mainly comprised the following measures.

- Construction of thick concrete walls to close the open gaps between the buttresses on the downstream dam face and to connect the various dam elements in the cross-valley direction, which were considered to be the most critical from the seismic point of view; in addition, the closing of the cavities reduces the temperature variations in the concrete mass.
- Consolidation by cement grouting of the honeycombing and cracks in the webs.
- Filling of the hollow cavities in the elements with cast-in concrete, to increase the safety of the dam against sliding.

Technical problems associated with the rehabilitation works (which were aimed at restoring the maximum storage) and financial problems related to the sharing of the costs between ENEL SpA (the owner) and the reservoir users (for drinking water and irrigation) delayed any further activity for some years. The dam has been operating since then with a reduced water level.

Recently the various problems have been overcome, and ENEL SpA has reconsidered the possibility of rehabilitating the dam.

1. Main features of the rehabilitation design

The two main concerns as far as the stability of the dam is concerned are:

- the sub-vertical fissures in the webs of the buttresses, which affect the upstream-downstream stability of the whole structure; and,
- the sensivity of the buttresses to a cross-valley seismic acceleration.

This last problem is clearly related to the vertical cracks which split the downstream faces of the buttresses almost exactly along their centreline.

1.1 Thermal loads

There is no doubt that the cracks were originally caused by the cooling and shrinkage of the concrete and that they propagated from the foundation upwards, where the rock mass represents a strong constraint for the relatively thin webs.

It is also clear that the cracks were deepened and extended by deformations induced by thermal loads. At present there are a number of cracks running right through the dam, connecting the internal and the external faces of the structure.

For this reason it was necessary to carry out detailed studies to confirm the effect of temperature on the cracks and to seek ways of reducing the thermal loads.

Fig. 2 gives an impression of the crack pattern in the walls, which obviously varies from buttress to buttress. It should also be taken into account that, with few exceptions, the buttresses are founded on the valley flanks, so their two webs are of different heights.

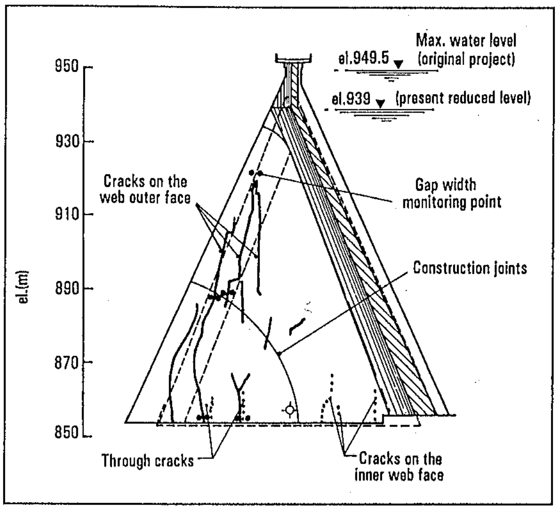


Fig. 2. Typical crack pattern in a web.

Additional stresses and strains are thus induced in the structure even under symmetrical loads such as hydrostatic pressure.

As mentioned, because of the orientation of the downstream face of the buttresses, they are exposed to the south, that is, to full solar radiation, so their temperature is likely to increase strongly. The lateral walls, on the other hand, are generally protected from solar radiation, and the upstream dam face (at least its lower part) is kept at a fairly constant temperature by the impounded water.

Another very important factor is the thermal gradient between the outside ambient temperature and the temperature in the cavity or of the hollow buttresses.

Fig. 3 shows the computed deformations in a horizontal section of an element at about half elevation, for extreme winter and summer temperatures.

As the thermal gradient reverses from season to season, the movements correspond and thus also the opening of the cracks. It can be observed that the worst conditions occur on the downstream face. The upstream face is much better, and the lateral walls are in an intermediate state.

The crack openings shown seem to be concentrated in a single section, but they actually comprise several finer cracks.

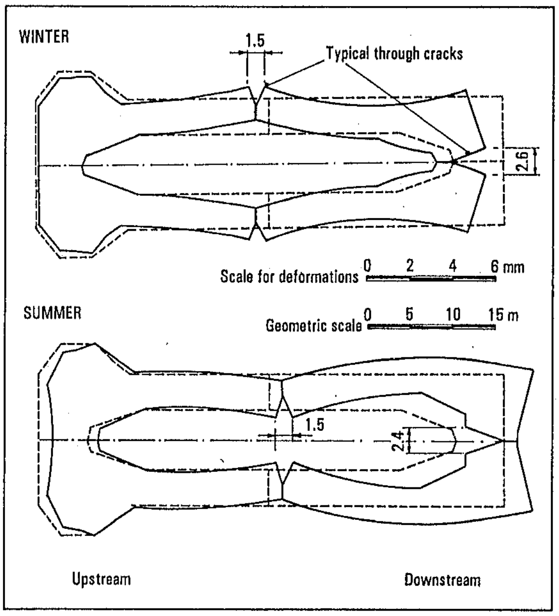
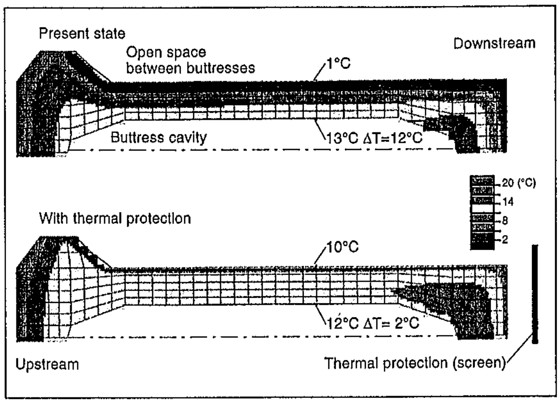


Fig. 3. Computed temperature induced deformations in a horizontal section of a buttress.

Fig. 4. Thermal field at low winter temperature with and without the protective downstream screen.



This is not the case for the downstream cracks because of the shape of the cross section which more clearly defines the position of the crack.

It can be seen that sizes of the crack openings are quite significant, in some cases reaching as much as 2.6 mm.

In view of these conditions, it was obviously important to carry out a detailed thermal study of the buttresses. At same time, the idea of installing a protective thermal 'screen' along the whole length of the downstream face of the dam began to take shape.

The aim of the screen would be to protect the dam from direct insolation and to reduce the temperature gradients in the concrete mass.

Fig. 4 shows, as one example of many, the thermal field in a wall at extremely low winter ambient temperatures.

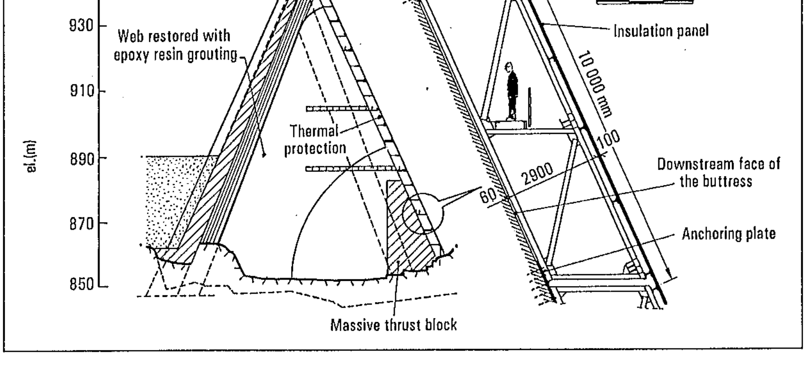
The gradient across the wall of 12°C, in the present state, would be reduced to little more than 2°C if thermal protection were provided along the dam. This is certainly a very significant reduction in the loads acting on the buttresses.

For the average temperatures, the screen is obviously not effective to the same extent, but for the progression of the cracks the extreme temperature peaks are evidently the ones which have the greatest influence.

The average monthly temperature over a 25 year period on the external face varies from about 7° to 20°C with no protective screen, but the variation would only be from 13° to 20°C with such a screen. The amplitude thus reduces to half its original value.

On the inner surface, the amplitude remains about the same (in the order of 4°C), but there is a significant increase of the average, by about 4°C. This can be regarded as a kind of 'greenhouse effect' in spite of some circulation of air which would exist in any case.

Fig. 5. General layout of the rehabilitation design.



Most significant, however, is the fact that the temperature increase from one side of the wall to the other is reduced to a quite insignificant value of less than 2°C.

It can thus be said that the effect of the thermal screen is extremely significant.

1.2 Structural considerations

It follows from these thermal conditions that the cracks in the walls could now be grouted and the monolithic behaviour of the buttresses restored. There would be no further risk of the cracks re-opening for thermal reasons.

The structural conditions in the upstream-downstream direction would thus correspond again to the original design, and would no longer seem to be of any concern, regardless of whether or not the vertical cracks in the axis of the downstream face of each buttress are grouted or not.

In fact this question is not very easy to solve for various reasons.

The lateral stability of the buttresses in the case of a cross-valley earthquake has been mentioned. However, the different elevations of the foundation of two of the webs of the same buttress means that there will be relative movements of these even with normal loads acting on the axis of the buttresses.

To avoid, at least as far as possible, stresses being induced by this asymmetry, it was finally decided not to grout these cracks and to allow the two halves of the buttress to act more or less independently of each other.

Consequently, their lateral stability had to be achieved by the design of a concrete block which would act as a strut from one side of the valley to the other; this block would be placed at the downstream heel of the buttresses. As already mentioned, the structural analyses had shown that the behaviour of the buttresses under seismic loading would be satisfactorily solved in this way. In addition, such a massive strut will increase the stability of the dam elements founded on the steep valley flanks [Lombardi, 1993[8]].

1.3 Rehabilitation design

In summary, the rehabilitation work will comprise three main elements:

- the provision of a downstream thermal screen to reduce significantly the thermally induced movements and stresses in the dam elements;
- grouting of the cracks in the buttress webs and the filling in of the honeycombing detected in the central part of the walls; and,
- provision of a downstream heel concrete block crossing the valley to stabilize the buttresses and their foundation in the transverse direction.

Fig. 5 gives an overview of the proposed rehabilitation works. Obviously a number of construction details have also been studied, for example, the exact procedure for grouting with cement and epoxy resin in relation to the actual concrete temperatures, the connection of the thrust block to the buttresses, the design of the thermal protection screen, the openings for air circulation, and so on.

In particular the thermal screen is designed in such a way as to allow for a complete inspection of the concrete surfaces at any time and, if necessary, to carry out any additional grouting work which may be required in future. For this a number of walkways along the walls have been designed.

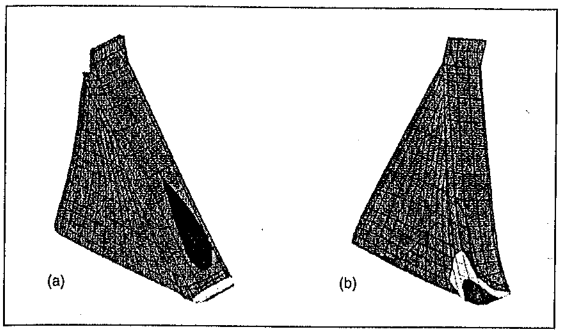


Fig. 6. Contour plot of the maximum (red) principal stresses relevant to element 5 for a loading condition including dead weight, hydrostatic pressure, and seismic actions; (a) is the head of the element constrained along the joint surfaces in the cross-valley direction and (b) is the head of the element which is free in the same direction.

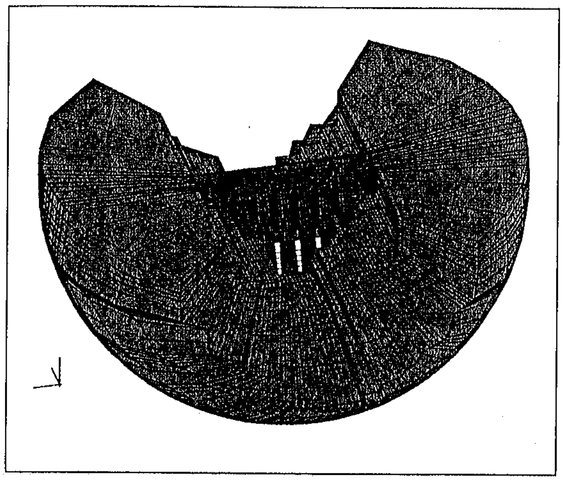


Fig. 7. Finite element mesh of the Ancipa dam.

2. Studies to support the rehabilitation design

Based on the main features of the new design for the rehabilitation of Ancipa, a series of studies, both experimental and numerical, were carried out.

The first complex aspect to be analysed was related to the choice of the most realistic structural scheme to be considered in the analyses. Usually, mathematical models developed for this kind of dam refer to a single buttress, generally the highest, for which extreme constraint and loading conditions are assumed. In particular, for cross-valley seismic loads, the single element is considered to be both completely free (the only constraint being at the dam-foundation interface) and fully clamped along the joints between adjacent elements (assuming, again, that the element is constrained at its base).

Such schemes, even if rather basic, are usually considered to be acceptable for relatively small buttresses. In this case, however, the height of the dam is significant and the two different schemes mentioned give rise to considerably different results (see Fig. 6). Moreover, many of the highest elements (with the exception of element 5) are extremely asymmetrical including in the cross-valley direction, because of the steepness of the valley sides. Therefore it was decided to investigate this aspect in more detail, so that a mathematical model could be developed which would be capable of describing the actual behaviour in the dam more precisely.

2.1 Experimental in situ investigations

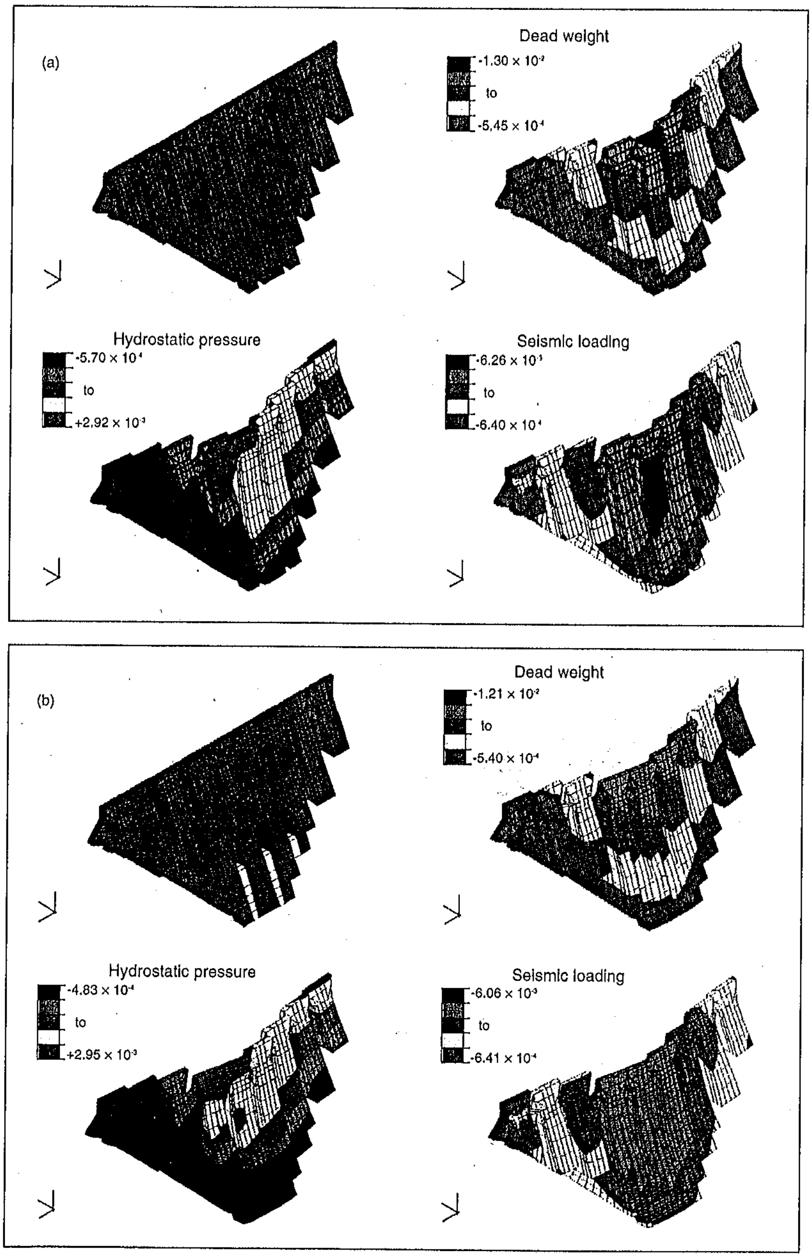
In December 1995 a dynamic in situ investigation was carried out with two dynamic exciters (vibrodynes) which were able to emit sinusoidal unidirectional forces. The first vibrodyne was used to investigate the frequency field between 0 and 5 Hz; the second was used for the field between 5 and 16 Hz. The forces applied to the structure (as a function of the frequency) ranged from 4 to 47 kN for the first exciter, and from 25 to 78 kN for the second. The water level in the reservoir was kept almost constant during the tests.

The response of the structure was measured by 41 seismometers and 10 displacement transducers installed on elements 5, 6 and 7. The vibrodynes were applied at the top of element 6.

The main results of the experimental investigations can be summarized as follows:

- The first two resonant frequencies of the structure were found to be 5.3 Hz and 5.98 Hz.
- The modal shapes clearly prove that the vibrations induced by the exciters in element 6 are only partially transmitted to the adjacent elements 5 and 7 as regards the upstream-downstream component; on the other

Fig. 8. Contour plots of the dam displacements for the conditions which include dead weight, hydrostatic pressure, and seismic loading; (a) is the dam assumed to be completely sound (no cracks) and (b) represents the actual condition of the dam including concrete blocks (height 30 m).



hand, the overall response of the dam can be observed in the cross-valley direction.

- These results have proved that the faces of adjacent elements along the joints are in contact and, hence, cross-valley loads can be transmitted along the dam axis, while only limited shear forces can act between them.
- Further resonance frequencies have been measured; in particular, the third was found to be at 7.86 Hz and the fourth at 10.38 Hz.
- Measurements carried out on the cracks on the downstream face showed that significant displacements can be observed only for the frequency of 10.38 Hz.

The dynamic campaign was repeated in June 1996, so that any possible variations in the dynamic behaviour of the dam caused by different environmental conditions could be detected. The results obtained from this second investigation completely confirmed those of the first.

2.2 Mathematical modelling

Based on the choices made by the designer and the results of the experimental dynamic investigations, it was decided to develop the mathematical model shown in Fig. 7 (see p69). The whole dam and a large portion of the rock foundation were considered. Moreover, all the joints between adjacent elements, the cracks on the downstream face of elements 4 and 5, and two different solutions for the concrete massive blocks to be built at the downstream heel (to connect the tallest elements of the dam in the cross-valley direction) were included in the simulation.

This quite complex numerical simulation provided a structural model which was much more realistic than a single element scheme. Various different hypothetical solutions were analysed in collaboration with the designer.

The main aspects and results of the analyses can be summarized briefly as follows:

- Various sets of parameters for the joints (friction, cohesion, hypothetical gap between the faces) were investigated, keeping in mind the results of the dynamic testing.
- Detailed information about the stress field in the webs of the elements was provided to the designers, to allow them to make the best choice of materials to be used for the grouting to restore the continuity of the structure.
- A great deal of effort was also devoted to studying the dimensions of the concrete blocks at the downstream heel in relation to the presence of the cracks along the downstream element faces; in fact, for the reasons described earlier it was decided not to grout these cracks. The optimal height of the blocks was found to be 30 m. The stiffness of the restored dam was found to be comparable with that of the dam when assumed to be completely sound, see Fig. 8 (p69).
- As regards the various sets of loads, the stress-strain fields were computed for all the elements of the dam, including their foundations, so that an accurate safety assessment could be carried out in accordance with Italian Regulations.

3. Conclusions

The case history which has been described shows that a combination of many factors (such as monitoring, frequent visual inspections, on-site and laboratory investigations for materials, special tests including dynamic ones, and so on) forms the basis for establishing a reliable design for the rehabilitation of existing structures such as Ancipa dam. In this context, the use of advanced mathematical modelling is fully justified. The high cost of these methods of analysis and their sensitivity to the variations of the parameters is compensated by the extensive knowledge of structural behaviour that is generally obtained. Moreover, close collaboration between the designer and the specialist of numerical methods can enable them to achieve good results, avoiding mistakes and a waste of resources.

The design for the rehabilitation of Ancipa dam is now being examined by the authorities. The comprehensive monitoring system installed at the dam, capable of recording both static behaviour during normal operation and dynamic behaviour during possible seismic events, will verify the appropriateness of the proposed solution. In addition, the mathematical model which has been developed could also be used if more detailed knowledge is required for further specific structural analyses (for example, to set up a forecasting model for the dam behaviour to be adopted during and after the rehabilitation works) or for studies which could take into account the site response spectrum. The experimental dynamic investigations could be repeated after the rehabilitation work, to verify their effects on the seismic behaviour of the dam.

The proposed rehabilitation scheme for Ancipa in fact consists of a combination of reducing thermal loads and structural strengthening of the dam [Fanelli, 1989[6]; Lombardi, 1989[7]; and, Lombardi, 1993[8]]. ◊

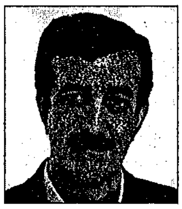
Acknowledgements

The authors wish to express their gratitude to Dr. Bertola of Lombardi Enginnering Ltd and Dr. Meghella, Mr. Galimberti and Dr Chillè of ENEL-CRIS for their contributions. The work of ISMES SpA in carrying out the experimental in situ investigations is also particularly appreciated.

References

1. **ANIDEL**, "Le dighe di ritenuta in Italia", in: 'Diga di Ancipa', Vol. VII; 1953.
2. **Marcello, C.**, "Notices préliminaires concernantes les observations sur le barrage d'Ancipa", *Proceedings*, 5th ICOLD Congress, Paris, France; 1955.
3. **Spagnoletti, S.**, "Sul comportamento della diga a gravità a elementi cavi tipo Marcello"L'Energia Elettrica; Nos. 3 and 4, 1962.
4. **Arredi, F.**, "Commissione per lo studio del comportamento della diga di Ancipa", General Report; September 1982.
5. **Appendino, M., Di Monaco, F., Garino, A., Manzo, F., and Scarinci, S.**, ENEL-DCO Turin, "Specific and General Trends of the Ageing of Buttress Dams as Revealed by Investigations carried out on the Ancipa Dam" 17th ICOLD Congress, Vienna, Austria; 1991.
6. **Fanelli, M.**, "Theme A: Concrete Dams - Fracture Problems. General Report", ICOLD Symposium on Analytical Evaluation of Dam Related Safety Problems, Copenhagen, Denmark; 1989.
7. **Lombardi, G.**, "Opening remarks and Closing of Session", ICOLD Symposium on Analytical Evaluation of Dam Related Safety Problems, Copenhagen, Denmark; 1989.
8. **Lombardi, G.**, "Concrete Dams and Foundations - Evaluation for Static Loading", International Workshop on Dam Safety Evaluation, Grindelwald, Switzerland; 1993.

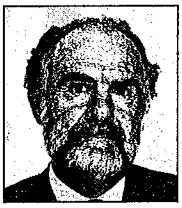
G. Giuseppetti



G. Mazzà

G. Lombardi

A. Piazza



M. Caddedu

Gabriella Giuseppetti graduated as a civil engineer from Bologna University, Italy, in 1969. She joined the Hydraulic and Structural Research Centre of ENEL in 1971, where she was involved in studying problems related to dam safety assessment. In 1988 she became responsible for the Theoretical Analysis Service of the Centre. In 1993 she changed her position, becoming responsible for a Specialist Unit at the Research and Development Department. In 1995 she was appointed Director of the Hydraulic and Structural Research Centre. Since 1994 she has chaired the ICOLD Committee on Computational Aspects of Analysis and Design of Dams.

Guido Mazzà graduated as a civil engineer from the Politecnico of Milan, Italy, in 1976. He began his career as a consultant engineer and designer of civil structures. He joined the Hydraulic and Structural Research Centre of ENEL in 1978. Since 1991 he has been Head of the Theoretical Analysis Unit of the Centre. He has devoted most of his activities to the safety evaluation of large dams, and research in the field of numerical modelling.

ENEL SpA - Hydraulic and Structural Research Centre, Via L. Ornato 90/14, 20162 Milan, Italy.

Dr Giovanni Lombardi graduated from ETH Zurich, and subsequently received a doctorate for his dissertation on the subject of thin arch dams. He is a consulting engineer specializing in design, construction and research in the field of large dams, underground works and hydro plants. In addition to work for his own company and the computing centre he set up in 1966, he is now independently involved as an expert on many projects worldwide. He was President of ICOLD from 1985 to 1988, and is now Honorary President.

Alberto Piazza was awarded an MSc in civil engineering at the Institute of Technology in Milan in 1985. He has been working at Lombardi Engineering Ltd since 1989, in the field of dams and hydraulic structures. As Design Engineer he has been involved in various rehabilitation projects for concrete dams as well as in the design and construction supervision of hydroelectric schemes.

Lombardi Engineering Ltd, CH-6648 Minusio-Locarno, Via R. Simen 19, Switzerland.

Massimo Caddedu is Vice President of ICOLD, and of the Italian Committee on Large Dams. He is also Deputy Director of ENEL's Division of Power Production. His Directorate at ENEL is responsible for the operation and maintenance of more than 600 hydro plants and 270 large dams. The powerplants have a total capacity of 16 000 MW, and an average annual production of 35 TWh.

ENEL Divisione Produzione, Via G.B. Martini 3, 00198 Rome, Italy.