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STRONG-MOTION INSTRUMENTATION OF DAMS

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SUMMARY

Strong-motion instrumentation schemes are developed for dams. Emphasis is put on the observation of the free-field motions at the dam sites, of the effective motions at the abutments and of the global dam responses from which the dynamic properties of the dams are also obtained. Array configurations that are compatible with these observation goals are developed for arch, gravity and embankment dams. The associated accelerograph and array specifications are also presented.

1. INTRODUCTION

Fundamentals to the design of earthquake-resistant structures and to the assessment of the seismic safety of existing structures are the consideration of appropriate design earthquakes and the appropriate modelling of all the phenomena that might significantly influence the earthquake response of the structures. The validity of the excitations and of the models of analysis used in the assessment of the earthquake behaviour of structures can only be checked by way of comparison with relevant field observations. The latter are at the present time incomplete and there is a need for field measurements during earthquakes in general and for strong-motion instrumentation in particular. The measurements needed relate to the free-field motions from which information on the earthquake recurrence and characteristics (including wave-propagation aspects) at specific sites can be obtained, and to the structural motions from which selected aspects of the earthquake behaviour of different types of structures can be studied (high-rise buildings, industrial facilities, nuclear power plants, bridges, dams).

The concepts applying to the strong-motion instrumentation of dams are presented in this paper. The observational needs are identified in Section 2 and the array configurations are developed in Section 3. Examples of dam instrumentation are presented in Section 4 and instrument specifications in the Appendix. The paper is intended to bridge the analytical and instrumentation fields. Analysts who need to obtain observation data will be able to devise the appropriate instrumentation schemes and those using observation data will better appreciate their validity and limitations. Instrumentation specialists in charge of maintaining networks will understand why a specific scheme has been selected and what are the possible implications of changing the location of instruments or their parameter settings.

2. OBSERVATIONAL NEEDS

2.1. *Free-field motions*

The prediction of the behaviour of large structures such as dams during future earthquakes generally requires the use of analytical and numerical techniques utilizing a temporal description of a design earthquake (synthetic accelerogram obtained directly or compatible with a design spectrum). The observational basis needed to characterize such earthquakes (amplitudes of motions, strong-motion duration, influence of local geological and soil conditions, attenuation laws and coefficients of wave propagation) is still insufficient. Such observations made in the free field also feed the data bases used when determining the

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seismic hazard at a site and allow the calibration of the design spectra used during preliminary studies, comparison studies and analyses of smaller dams.

2.2. Abutment motions

From the shape and the dimensions of the dam-foundation interface, various aspects of soil–structure interaction can contribute significantly to the earthquake response of a dam. First, the topography of the canyon and the inertial and energy dissipation properties of the foundation rock lead to a non-uniform motion at the interface. This also holds true when it is assumed that the dam is not yet present and that the waves come from a single direction in a synchronised fashion (canyon effects, Figure 1(a)). Second, assuming for a moment that the dam is massless, the motion along the interface is affected by the static resistance offered by the dam to any deformation of its support (kinematic interaction, Figure 1(b)). Third, the seismic excitation originates from waves arriving from several directions (incoherent excitation, Figure 1(c)). Four, the motions at the abutments are affected by the inertial, vibratory response of the dam (inertial interaction, Figure 1(d)). All these effects combine into the total effective input motion along the interface, whose observation is still largely missing. Its observation would contribute to gaining a better understanding of all the phenomena involved, permit calibration of the existing analytical models and the development of new models, and help in specifying design excitations.

2.3. Dynamic responses and characteristics of dams

The synthesis of the response of the individual modes of vibration of a dam to an earthquake determines its global response (linear range). The natural modes of vibration and the associated natural frequencies and levels of energy dissipation can be established relatively easily by way of shaker tests. However, such tests are limited to very low levels of excitation and of response that are not representative of those encountered during large earthquakes. While the mode shapes and the natural frequencies are not expected to vary much with the level of shaking (provided there is no major incursion in the inelastic range), this is not the case of the energy dissipation that needs to be better apprehended.

2.4. Other aspects

A strong-motion instrumentation permits the comparison of the behaviour of a dam during an earthquake with the one predicted in the design phase, and the prediction of its behaviour during future earthquakes. It

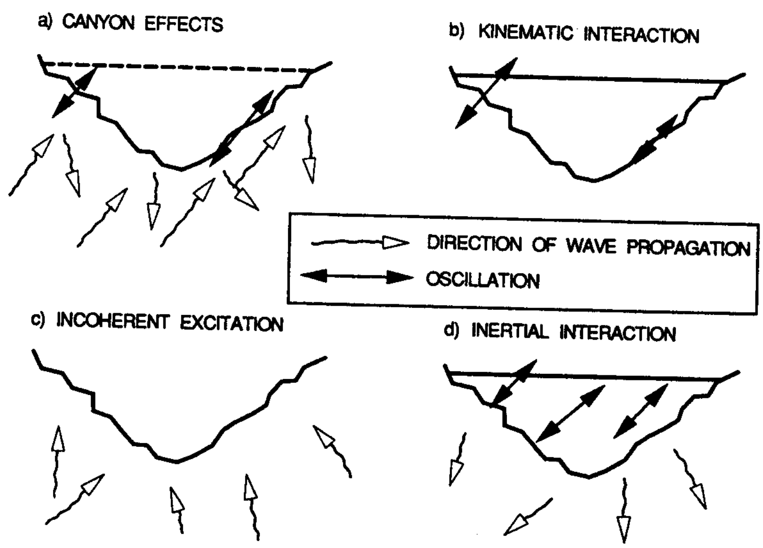


Figure 1. Soil–structure interaction for arch dams: (a) canyon effects; (b) kinematic interaction; (c) incoherent excitation; (d) inertial interaction

can also guide the search for possible damages and support the establishment of rehabilitation measures.[1,2]

Accelerographs placed in the dam and in its immediate vicinity address the observational needs presented above. The observation of other phenomena would require a more involved instrumentation, such as for the following (see also References 3 and 4).

Cracks: The locations at which cracks develop can hardly be predicted with precision, with the possible exception of joints and other structural singularities. The observation of the development of cracks during an earthquake is thus difficult.

Reservoir–dam interaction: The reciprocal influence exerted by the dam and the water contained in the reservoir also depends on the compressibility of the water, on the dissipation of the water pressure waves at the reservoir bottom and sides, on the extent of the reservoir and on the exciting motions and on their frequency contents. A complete observation that would allow the calibration of the analytical models and the assessment of the practical importance of the compressibility of the water in the interaction process is still largely missing. This would require the additional installation of pressure gages along the upstream face of the dam and at the bottom and sides of the reservoir, together with that of accelerographs across the reservoir (at regularly spaced cross sections).

Canyon effects: Canyon effects could be observed directly by a free-field instrumentation perpendicular to the canyon axis.

Embankment dams: Acquiring a good understanding of the earthquake response of embankment dams also necessitates the observation of the variations in pore water pressures during and after the earthquake.

3. ARRAY CONFIGURATIONS

The observational needs established above lead to the following array configurations for arch, gravity and embankment dams. They are developed while assuming that three-component accelerometers are installed. In the figures, a circle identifies an accelerograph location and the letter inside the circle refers to the instrumentation scheme.

3.1. Arch dams

Free-field instrument (Figure 2(a)): The free-field instrument must be located far enough from the dam and from the appurtenant structures so as not to be affected by their presence and vibrations. At the same time, it must be close enough to measure the motions that are representative of those at the site. Considering the studies of Reference 5, a distance equal to twice the dam height is appropriate for concrete dams. It can be reduced to once the dam height when the modulus of elasticity of the foundation is equal to or higher than the modulus of the dam concrete.

Abutment instruments (Figure 2(b)): The total effective input motion at the abutments is measured by instruments located along the dam–foundation interface. When they are placed in sufficient number, the deformation of the interface can be observed in addition to the rigid-body motions (translations and rotations).

Foundation instruments (Figure 2(c)): Wave propagation in the foundation can be apprehended by instruments installed in exploratory and grouting galleries.

In-structure instruments (Figure 2(d)): The response of the dam can be assessed globally by taking advantage of a modal decomposition (linear range). The instruments at the crest of the dam are located at points of maximal modal deflections (middle and quarter points for a dam that is essentially symmetrical). In this way, the responses of the lower modes of vibration are well captured.

Instrumentation schemes: The resulting instrumentation schemes are shown in Figure 3. A minimum observation of the excitation and of the response is made through scheme A, complemented by schemes B and E for a more detailed observation. The effective input motion is captured by schemes D and G (complementary to schemes A and B). Galleries in the foundation may allow observation of wave propagation (scheme F) while scheme C provides for the free-field motion.

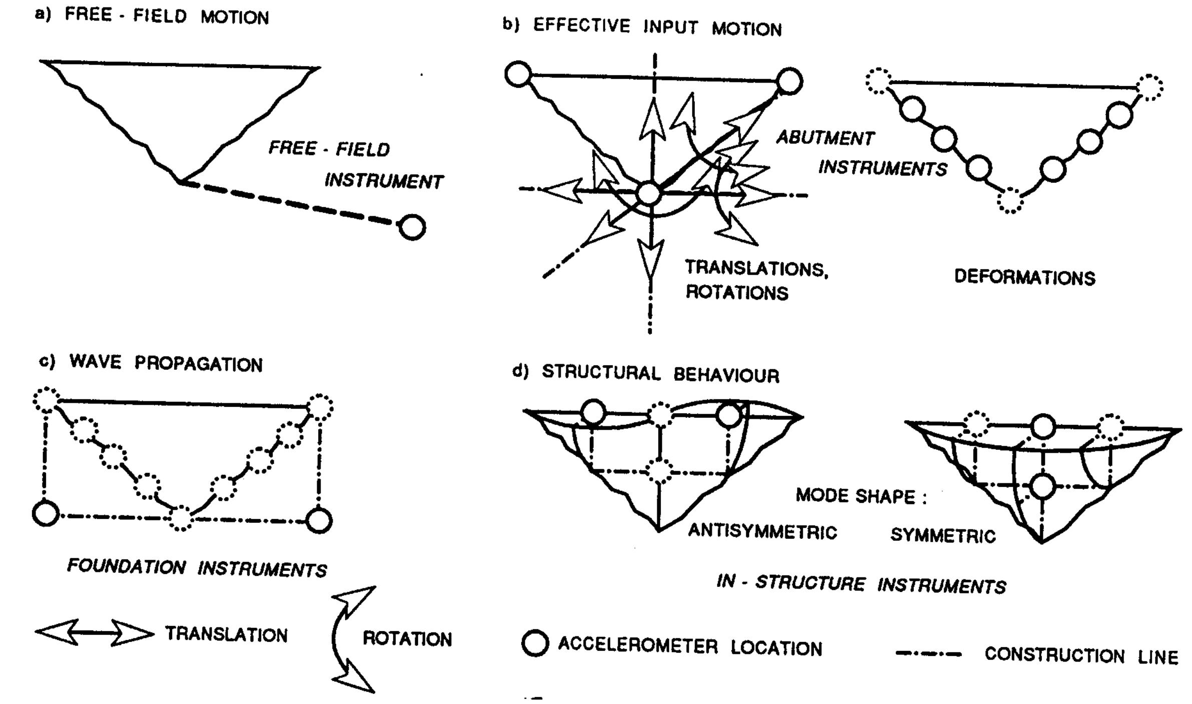


Figure 2. Observational goals and instrument locations in arch dams: (a) free-field motion; (b) effective input motion; (c) wave propagation; (d) structural motion

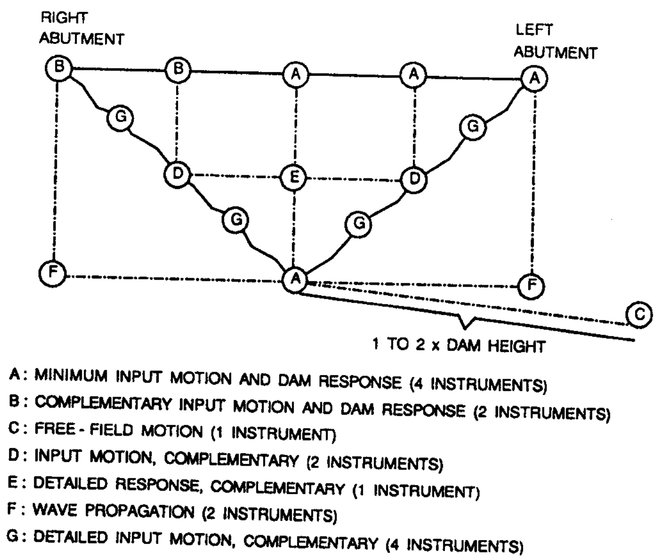


Figure 3. Accelerograph arrays for arch dams (downstream view)

The instruments are positioned with respect to a fictitious rectangular grid (dashed-dotted lines in the figure), thus allowing easier correlation between the recordings made at different stations of the array.

3.2. Gravity dams

Gravity dams are generally designed and analysed by assuming that the blocks (monoliths) behave independently from one another (bidimensional behaviour). The instrumentation is consequently concentrated to the middle/highest block. Three observational objectives are more particularly relevant to gravity dams, in addition to those of free-field and in-structure responses identified for arch dams:

Base input motion: The variation of the motion across the base can possibly be substantial in a large dam (base thickness comparable to a predominant wave length). The associated effective base input motion should be observed.

Tridimensional response: A tridimensional response is expected due to longitudinal excitations, when the dam is built in a narrow canyon and due to transverse excitations in a dam with shear keys.

Independent behaviour of blocks: The extent to which the blocks have an independent behaviour can be appreciated from the comparison of their individual motions.

Instrumentation schemes: A minimal observation of the excitation and of the response of the dam is obtained through scheme A of Figure 4, complemented by scheme G for a more detailed observation. The independent behaviour of neighbouring blocks is investigated through schemes C, D and F while the variation of the motion across the canyon is addressed by scheme E. The tridimensional response of the dam is captured by scheme H (crest instruments at the quarter points) while scheme B provides for the free-field motion.

3.3. Embankment dams

Embankment dams are generally designed and analysed assuming a bidimensional behaviour, as in gravity dams. A similar instrumentation concept thus applies (instruments for free-field motion, effective base input motion and tridimensional response), the following issues being of further relevance to embankment dams.

Settlements: Settlements can induce an unacceptable reduction of the free-board (Figure 5(a)). Observation of their temporal development is of interest.

Cracks: Longitudinal cracks (associated with strong lateral vibrations, Figure 5(b)), transverse cracks (associated with strong longitudinal oscillations or with a transverse asynchron excitation, Figure 5(c)) and cracks in the dam body (Figure 5(d)) can occur during an earthquake. All cracks can lead to an internal erosion (piping). Their direct, simple observation is not possible although it would be of value.

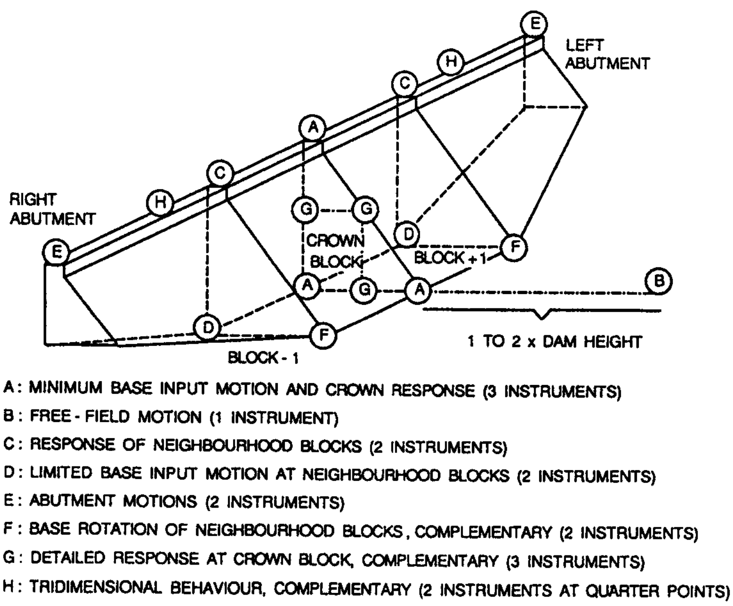


Figure 4. Accelerograph arrays for gravity dams

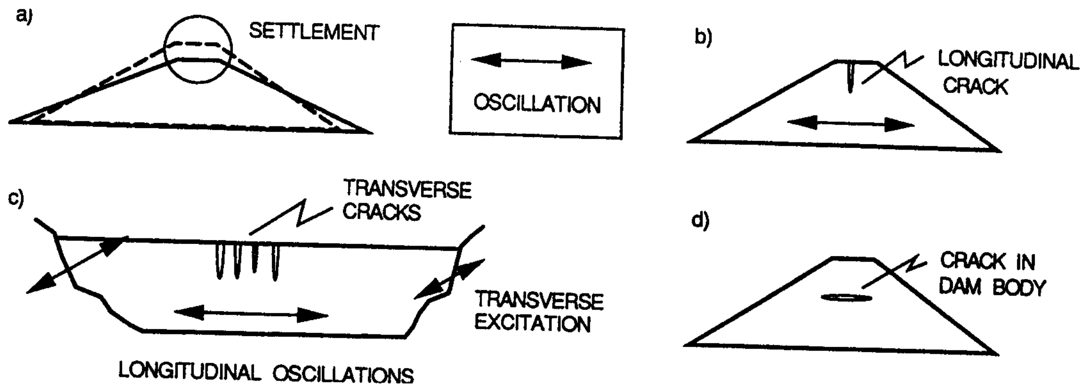
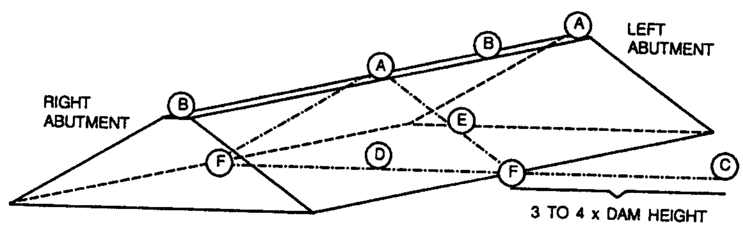


Figure 5. Settlements and cracks in embankment dams: (a) settlement; (b) longitudinal crack; (c) transverse cracks; (d) crack in dam body



A: ABSOLUTE MINIMUM ABUTMENT MOTIONS AND DAM RESPONSE (2 INSTRUMENTS)
A+B: MINIMUM ABUTMENT MOTIONS AND DAM RESPONSE (4 INSTRUMENTS)
C: FREE-FIELD MOTION (1 INSTRUMENT)
D: BASE MOTION (1 INSTRUMENT)
E: COMPLEMENTARY DAM RESPONSE (1 INSTRUMENT AT MID-HEIGHT)
F: DETAILED BASE INPUT MOTION (2 INSTRUMENTS, REPLACE 'D')

Figure 6. Accelerograph arrays for embankment dams

Instrumentation schemes: The instrumentation schemes for embankment dams, Figure 6, are adapted in part from Reference 6. An absolutely minimal instrumentation consists in placing instruments at one abutment and at the middle of the dam (crest level), thus obtaining information on the excitation and on the dam response (scheme A). The development of settlements can also be followed by the instrument at the crest. This instrumentation can be complemented by the one of scheme B to observe the variation of the excitation from one abutment to the other and the tridimensional response (instrument at a quarter point). A more detailed information on the excitation and on the response is obtained through schemes D and E, respectively, and on the effective base input motion through scheme F (middle section). Scheme C provides for the free-field motion, at a distance of 3–4 times the dam height (a distance equal to the period of the first mode of vibration of the dam multiplied by the shear wave velocity of the foundation is also suggested in Reference 6).

This instrumentation can be complemented by bore-hole instruments in the dam, in priority at the middle section.

3.4. Remark

A more basic instrumentation can be performed when economical or other constraints prevent the installation of arrays as shown in Figures 3, 4 and 6. It includes the observation of the free-field motions (one free-field instrument), of the total motions at the foundation–dam interface (one instrument at the base or at an abutment) and of the dam responses (one instrument at the crest of the crown section) (see references 7).

4. EXAMPLES OF DAM INSTRUMENTATION

The concepts presented in the paper were developed during the course of a project culminating in 1992 and 1993 in the instrumentation of four large Swiss dams as summarized below.

Dams instrumented: The arch dam of Mauvoisin is the 4th highest concrete dam in the world. It has a height of 250·5 m, a crest length of 520 m, a base thickness of 54 m and a crest thickness of 12 m (Figure 7). It has been instrumented with a star-like array of 12 three-component accelerographs. The array is meant primarily to observe the total effective input motions (including wave propagation) with five instruments installed at the abutments and two in the foundation rock (in exploratory galleries). Other objectives are the observation of the global dam responses and in particular the dissipation of energy (three instruments in the upper gallery placed at location of maximum modal deflections and one in an intermediate gallery), and of the free-field motions with an accelerograph placed at the entry of a winter gallery 600 m downstream of the dam. The accelerographs are connected to the central unit located in a cavern at the right abutment (crest level) through a total of 6494 m of fibre-optic cables.

The world's highest concrete dam of Grande Dixence (gravity dam of 285 m and base thickness of 198 m) has been instrumented with a similar array of six accelerographs, Figure 8(a). An array of seven accelerographs has been installed in the 130 m high arch dam of Punt dal Gall, Figure 8(b), and an array of four accelerographs in the embankment dam of Mattmark (120 m high), Figure 8(c).

First data collected: The arrays of Mattmark and Grande Dixence were triggered on 14 June 1993 by a magnitude 4·4 earthquake that occurred at epicentral distances of 25 and 69 km, respectively. The peak accelerations at Mattmark reached 0·7% g at the base and 1·5% g at the crest (stream direction). In Grande Dixence, the base acceleration in the stream direction reached 0·1% g and that at the crest reached 0·5% g; a fundamental frequency of 2·2 Hz with associated damping of 1% of critical were tentatively identified from the records.

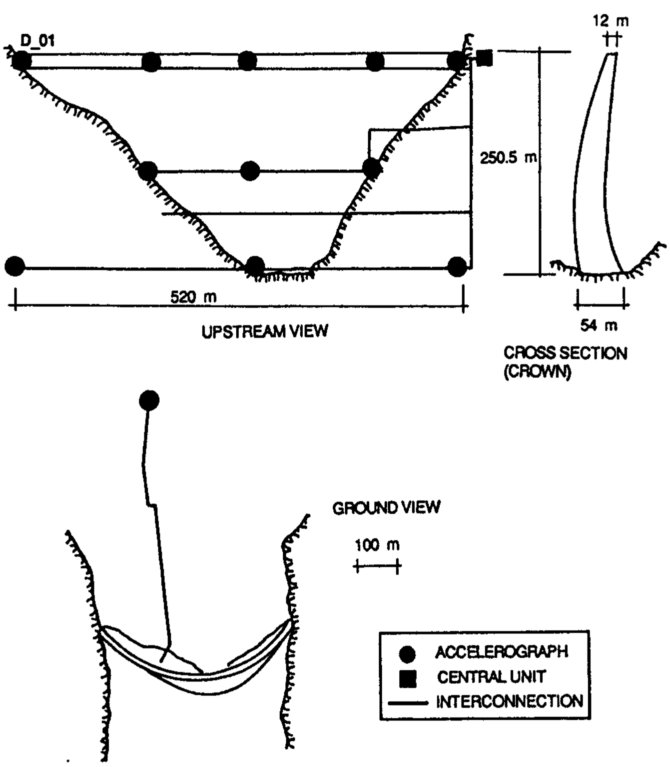


Figure 7. Strong-motion array at the arch dam of Mauvoisin

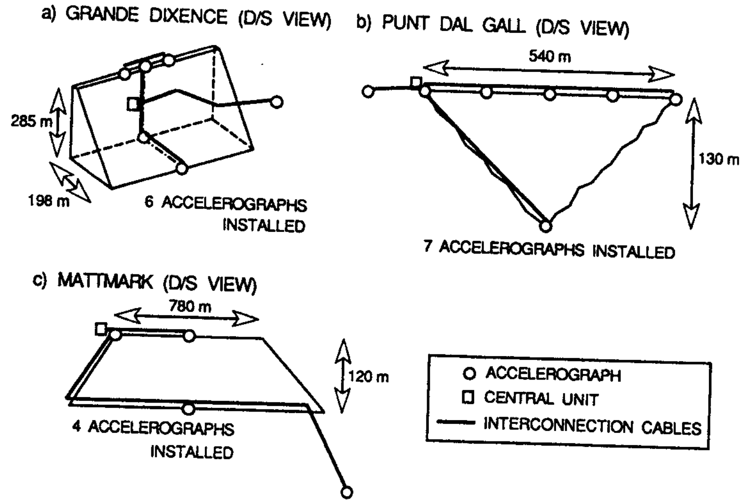


Figure 8. Strong motion arrays at the dams of: (a) Grande Dixence; (b) Punt dal Gall; (c) Mattmark

5. FINAL REMARKS

The basic principles developed in the paper are applicable to the instrumentation of all types of large civil engineering structures. The driving idea is to perform an instrumentation that is consistent with clearly defined observation goals. The detailed instrumentation that results may be in contradiction with the views of owners and public agencies that usually prefer to instrument a large number of structures at the expense of thoroughness.

The instrumentation schemes presented here are more particularly directed to covering research needs. The basic instrumentation of Section 3·4 can be implemented when only an earthquake warning system is needed.

An array of accelerographs can also be used for warning purposes, a signal being generated as soon as oscillations of pre-set amplitudes occur at the dam (trigger criterion similar to the ones for recording). This signal is transmitted to an operating room staffed 24 h a day (usually at the power station), from where the appropriate safety checks of the dam can be initiated.

Finally, the interpretation of the data and their dissemination to appropriate institutions must be carefully planned as data gathering alone does not warrant a strong-motion instrumentation.

APPENDIX: SPECIFICATIONS

The instrument specifications depend on the environmental conditions that prevail at the instrument locations and on the observational objectives.[1,3,8,9] It is necessary that the instruments function in an utmost reliable fashion because of the scarcity of severe earthquakes. Thus, only instruments of simple design and construction that have been thoroughly tested under field conditions should be installed. It is also necessary that the earthquake or structural engineer in charge works closely with an electrical technician specialized in instrumentation.

Accelerographs

Recording: The installation of digital recording instruments is recommended as data treatment is facilitated. The lack of moving parts also enhance the reliability of the accelerographs.[3]

Maximum acceleration: The maximum recording acceleration a_{max} must be higher than the peak acceleration corresponding to the seismic hazard at the site associated with a target return period (a return period of 100 years is appropriate); the peak acceleration may be that of the mean or of the mean plus one to several standard deviations. The vibration amplification occurring in a dam and thus at an accelerograph station must thereby be considered. As an example, the base-to-crest amplification in the stream direction of an arch dam can theoretically reach a value of the order of six at the crown section (of the order of three at a quarter section).

Resolution: The acceleration resolution Δa is related to the resolution D in data bits through the relation $\Delta a = 2a_{max}/2^D$. It is recommended to use a resolution of 12 data bits or more; the acceleration resolution should simultaneously reach at least 0·001 g. The recording of moderate events should further be guaranteed with a resolution that is sufficient when compared to the amplitudes of motion that are expected.

Bandwidth: The lowest frequency that is measured should be less than 10% of the fundamental natural frequency of the dam (amplification factor of 1·01 for no damping) and simultaneously less than the predominant excitation frequencies of the earthquakes. Recording from 0 Hz is recommended: the calibration of the sensors can then be verified more easily (with a portable tilt table) and data interpretation is simplified[10] (base-line correction, double integration). Similarly, the upper frequency that is measured should be higher than the frequency of the highest natural mode of variation that contributes to the dam response and simultaneously higher than the predominant excitation frequencies of the earthquakes. This upper frequency should be at least 30 Hz (special studies may require higher values).

Recording trigger: The recording trigger levels should be set based on three factors. To avoid that motions of lower amplitudes that would be of limited use are recorded, the trigger levels should be of at least 10 times the resolution Δa. Also, numerous recordings that could quickly saturate the recording memory in a high-seismicity region should be avoided by increasing the trigger levels accordingly. Finally, the amplification of the motions that takes place in the dam should be considered and the trigger levels of the in-structure accelerographs should be increased accordingly.

Some accelerographs offer the possibility to start recording only after the trigger level is reached simultaneously in two or three directions. This option should be activated only if *simultaneously* means a time window of at least a few seconds to ensure that the criterion is satisfied during low-amplitudes vibrations (of the same order of magnitude as the trigger levels).

Pre- and post-event recording: The duration of the pre-event recording should be set based on the trigger level (longer duration for a higher level) and on the distance to a possible earthquake source (recording of the motions associated with the compression waves that arrive before the shear waves when the former do not trigger the recording).

The duration of the post-event recording (after the acceleration has returned below the trigger level) should also be set based on the trigger level, as well as on the periods and damping values of the natural modes of vibration of the dam that contribute to the dynamic response (recording of the free vibration until such time as the amplitudes return below the recording resolution). It is possible to determine the zero deviation at the end of the event when the post-event duration is long enough and an instable recording behaviour can be identified by comparison with the zero deviation prevailing at the beginning of the record.

Recording stability: The sensors must remain stable over the expected duration of a record (short-term stability). This also applies to the long-term stability associated with the acceleration as a function of the output signal.

The zero deviation of records obtained from an instrument recording from 0 Hz is affected by changes in the inclination of the support of the accelerometer; such changes are mainly due to variations in the reservoir level (static deformation). The long-term stability of the zero deviation can then not be achieved; this is of no major adverse consequence when pre- and post-event traces are available as the records can then be corrected easily.

Noise: The recording noise originating from the sensor and from the electronic components combined must remain below the recording resolution (ideally less than half this value). This applies to the peak noise rather than to a root-mean-square or other weighted average value.

Time marks: It is necessary to have precise time marks on all the records of the same event made at different locations (this requirement can be relaxed when common sampling is enforced in the array). Only then can precise correlations be performed.

Autonomy: The power needed during interruptions of the main power supply must be provided by internal batteries (caution: cases of gasses corroding electronic equipment and of exploding batteries have reportedly been observed). Their autonomy should be set based on the characteristics of the electrical installation and on the time usually needed to re-establish power. An additional external power source should be available when power shortages of duration that can not be covered by internal batteries can occur (external batteries, solar panels, connection to an emergency power unit).

Electromagnetic compatibility: Electromagnetic fields originating from medium and high voltage cables can negatively affect the performance of the accelerographs whose electromagnetic compatibility is inadequate.

Power-surge protection: Small perturbations of the power supply should not affect an accelerograph. Large power surges may however occur in locations that are particularly exposed to lightning. The instruments must then be mounted on supports that are electrically isolated and all the metallic cables connected to an accelerograph must go through a power-surge protection placed in the immediate vicinity. The cable segments that are protected should not touch nor cross non-protected segments. They should further be fixed a few centimetres away from the wall and from the ground or placed in isolated tubes.

Grounding: Differences in electrical potential can lead to ground loops that perturb the functioning of an accelerograph.[11] This can be prevented by connecting all the electrical components to an unique grounding point. The metallic cases must also be grounded for reasons of protection of persons.

Instrument cases: A very high level of humidity generally prevails in dam galleries. The instrument cases thus must be non-corroding and water proof, and desiccant packets placed inside the instruments. Water should be allowed to flow freely behind the instruments mounted on walls (a space of a few millimetres should be left between the mounting plate and the wall).

Mounting: The accelerographs must be installed away from all vibratory sources and such as to be fairly protected from possible accidental shocks. Their mounting should be simple and requiring few or no preparatory works. Wall-mounted, compact instruments with an external accelerometer are well adapted to an installation in dams.

External accelerometer: The specifications above must be adapted accordingly when the accelerometer is external to the recording unit (electromagnetic compatibility, power-surge protection, grounding, instrument cases). The cable connecting the accelerometer to the recorder, through which analogue signals of low voltage are transmitted, should not cross nor touch other electric cables so as to avoid any perturbations.

Array

Interconnection: The main objective sought in installing an array is to record an earthquake simultaneously in different locations. This presupposes an interconnection of all the instruments by cables as it is usually not possible to establish radio links in large dams.

Metallic and fibre-optic cables can be used for the interconnection. The installation of the metallic cables is simple; however, they can be utilized only over short distances and may necessitate grounding and power-surge protection measures. The advantages of the fibre-optic cables lie in the possibility of transmitting signals over large distances and in the absence of any problems of electric origin; their installation is however more complicated than that of metallic cables.

Power-surge protection: The metallic interconnection cables must be connected to power-surge protections in exposed areas. A central server unit, such as it exists in a star-like array configuration, must be installed and protected as an accelerograph.

Common trigger: A single accelerograph should not be allowed to trigger simultaneous array recording by itself in order to avoid frequent accidental triggering due to local disturbances.

The accelerographs should function as stand-alone instruments during malfunctions of the interconnection. Local recording is preferred over centralized recording to prevent a possible loss of data in such a situation.

Common sampling: It is recommended to enforce common sampling of all the accelerographs in the array. The absence of a precise time mark on the records is then of limited adverse consequence.

Operation

Orientation: Orienting all the accelerometers in a similar way facilitates the first interpretation of the data (e.g. oriented tangential and normal to the dam as well as vertical).

Self-tests: The operation of an array is simplified when instruments that perform automatic internal checks at regular intervals and keep the corresponding results in memory are used.

Remote communication: Remote communication is not only a necessity when quick access to the records is wanted after an earthquake; it is also of value in day-to-day operation: the current working state of the instruments can be checked, the operational parameters can be changed, the results of the self-tests and the records can be retrieved at any time and the memory can be cleared. It is then sufficient to perform a site visit once a year for the purpose of visual check and of calibration of the sensors.

Communication software: A user-friendly and complete modem and direct communication software must be available. A quick visualization of the acceleration time histories and of their Fourier transforms must be included.

REFERENCES

1. B. A. Bolt and D. E. Hudson, 'Seismic instrumentation of dams', *J. geotech. eng. div. ASCE* **101**, 1095–1104 (1975).
2. U.S. National Research Council—Committee on the Safety of Existing Dams, *Safety of Existing Dams: Evaluation and Improvement*, National Academy Press, Washington, DC, 1983.
3. U.S. Committee on Large Dams, Strong Motion Instruments at Dams: Guidelines for their Selection, Installation, Operation and Maintenance, U.S. COLD, Denver, CO, 1989.
4. U.S. National Research Council—Panel on Earthquake Engineering for Concrete Dams, *Earthquake Engineering for Concrete Dams: Design, Performance and Research Needs*, National Academy Press, Washington, DC, 1990.
5. K.-L. Fok and A. K. Chopra, 'Earthquake analysis and response of concrete arch dams', *Report No. UCB/EERC-85/07*, Earthquake Engineering Research Center, University of California, Berkeley, 1985.
6. J. J. Fedock, 'Strong-motion instrumentation of earth dams', *Open-File Report 82-469* (*preliminary*), U.S. Department of the Interior, Geological Survey, 1982.
7. R. W. Clough and Y. Ghanaat, 'Concrete dams: evaluation for seismic loading', *Proc. int. workshop on dam safety evaluation*, Grindelwald, Vol. 4, pp. 137–169, 1993.
8. W. D. Iwan, 'Instrument arrays for strong motion studies', in *Lifeline earthquake engineering—buried pipelines, seismic risk and instrumentation, Proc. 3rd national congress on pressure vessels and piping*. San Francisco, California, ASME, PVP-34, 1979.
9. W. D. Iwan, 'Strong-motion earthquake measurement: past accomplishments and future directions', *Proc. 9th world conf. earthquake eng.*, Tokyo-Kyoto, **8**, 97–104, 1988.
10. J. D. Deal, 'Strong-motion accelerograph selection guide', *Kinemetrics Application Note 20*, Pasadena, CA, 1991.
11. E. E. Eller and R. W. Conrad, 'Introduction to shock and vibration measurements', in C. M. Haris and C. E. Crede (eds), *Shock and Vibration Handbook*, 2nd edn., McGraw Hill, New York, 1976.