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Design and implementation of strong-motion instrumentation arrays in dams

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ABSTRACT: A dam network of strong-motion instruments is being implemented in Switzerland. The need for strong-motion instrumentation of dams is identified and instrumentation schemes are proposed accordingly. Instrument specifications are also suggested. Among the 4 dams being instrumented are the highest world's concrete dam of 'Grande Dixence' (gravity dam with a maximum height of 285 meters) and the 4th highest world's concrete dam of 'Mauvoisin' (arch dam with a maximum height of 250.5 meters).

1 INTRODUCTION

Fundamentals to the design of earthquake-resistant structures and to the assessment of the seismic safety of existing structures are consideration of appropriate design earthquakes and appropriate modeling of all phenomena which might influence the earthquake response of the structures. That the selected earthquakes and models are appropriate can ultimately only be checked by way of comparison wih observations. The need for observational evidences during large earthquakes led to the creation of a swiss national network of strong-motion instruments which is starting operation in 1992. The national network is subdivided into a free-field network and into a dam network.

The objectives of the free-field network are to gather strong-motion data to be used in determining the characteristics of larger earthquakes occuring in Switzerland (time history, maximum acceleration, frequency content, duration of strong motion, associated response spectrum) for different soil conditions and to validate attenuation relationships and coefficients. 30 accelerographs arranged in 14 clusters of 1 to 4 instruments are being installed in various parts of the country to this end.

The objective of the dam network is to gather data on the earthquake behavior of dams and on the motions they are subjected to. The design and the implementation of the dam network is presented in this paper.

2 NEED FOR OBSERVATIONAL EVIDENCES

Sophisticated mathematical models can be used to analyze the seismic behavior of dams. The application of these models to cases of practical importance presuppose that they are able to reproduce adequately all major phenomena and effects which might influence the behavior of the dams being analyzed, that the material models and characteristics are representative of the in-situ material properties, and that the temporal and spatial variations of the input motions introduced in the analyses are compatible with those of the motions which have occurred or could occur at the dam sites.

As recognized by the panel on earthquake engineering for concrete dams of the US National Research Council (1990), there is a need for field measurements during earthquakes in general and for strong-motion instrumentation in particular. This need is not limited to concrete dams but applies to earth dams as well. Such measurements should provide enough observational evidences so as to be able to assess the extent to which the models, parameters and input motions used in analyses are adequate, provide direct informations on the parameters and input motions to be used in the analyses, and identify possibly unsuspected phenomena which might affect the earthquake response of dams.

2.1 Site motion

The earthquake excitation must be viewed in the context of wave propagation. Instruments should be installed at various elevations and at different fictitious cross sections of the canyon. If in any way possible, these instruments should be supplemented by instruments located in the foundation rock thus enabling to better study wave propagation mechanisms.

In particular, there is a great interest in obtaining informations on the spatial variation of earthquake motions along dam abutments. This is especially important for dams whose length of the dam/foundation interface is similar to the significant wave lengths of the earthquake motions expected at the site.

2.2 Linear dam behavior

In an analysis, the linear dam response is most conveniently captured as the combined response of the normal modes of vibration. The modal properties can be viewed as an integral representation of the geometry of the dam, of its material characteristics including mass and energy dissipation, and of its support conditions. In-situ modal properties can be obtained by shaker tests or ambient vibration tests with less effort than with strong-motion instrumentation. However, such tests are limited to very low levels of shaking. While it may be expected that the natural frequencies and mode shapes at higher levels of shaking will not be much different from those obtained in such tests, this is not necessarily the case for what modal damping is concerned and there is a specific need for informations on modal damping in dams during larger earthquakes.

The linear dam response is also affected by the hydrodynamic pressure which acts on the upstream face of the dam. This pressure depends on the geometry of the reservoir, on the motion of the upstream dam face, on the motion of the reservoir bottom and sides and on the absorption of the water pressure waves in the sediment layer at the bottom (and sides) of the reservoir. Strong-motion instruments placed at regular intervals along the reservoir bottom and sides complemented by pressure transducers placed at the same locations as well as on the upstream dam face will lead to informations on the energy dissipation in the sediment layer and on the hydrodynamic pressure.

2.3 Nonlinear dam behavior

Nonlinear behavior may occur in dams and in their foundation during large earthquakes and can lead to permanent deformations and displacements (permanent settlements in earth dams), cracks and opening of joints (in concrete dams). Nonlinearities are usually highly localized and their precise locations are hardly predictable (with the exception of known weak zones such as existing cracks or joints). An integral measure of the level of nonlinear behavior may be obtained from the data gathered by the instruments installed to monitor the linear dam behavior. Complementary laboratory material tests (mass concrete / fill material and foundation rock) are then necessary.

3 STRONG-MOTION INSTRUMENTATION SCHEMES

Only that part of the instrumentation which deals with strong-motion instruments placed in the dam and at its immediate vicinity is addressed here. No mention is made of additional instruments necessary to obtain a full description of wave propagation mechanisms, reservoir motion and hydrodynamic pressures as well as of specialized instruments required to monitor nonlinear behavior.

The schemes are presented for the individual dam types (gravity, arch and earth) presuming the use of 3-components transducers.

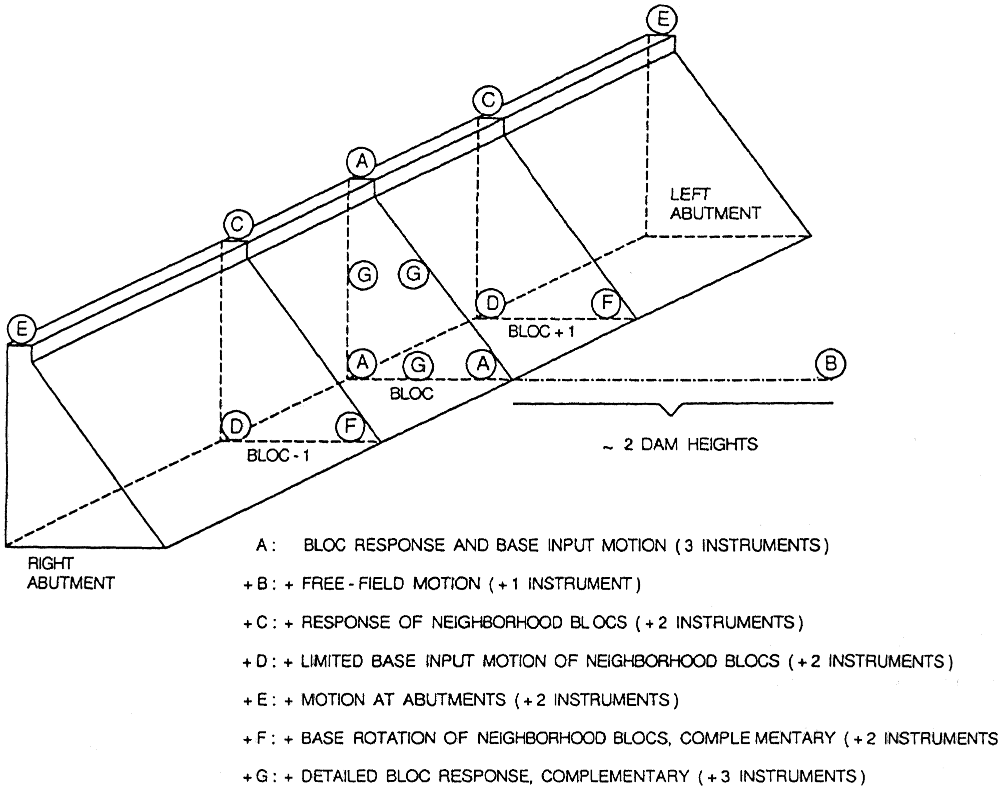


Figure 1. Strong-motion instrumentation of gravity dams.

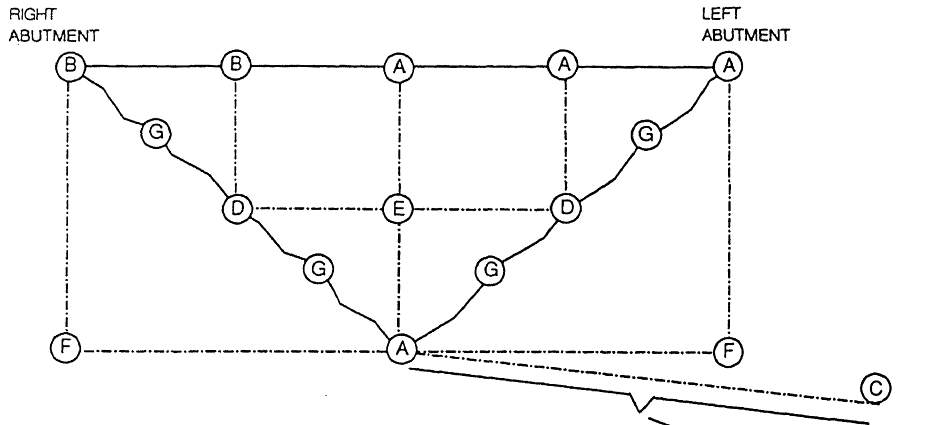
Installation of a free-field instrument is proposed for each dam type. It must be viewed as an instrument which records the motion at the site, undisturbed by the presence of the dam. It should be placed far enough from the dam such that the motion measured is effectively not influenced by the dam, but at the same time close enough such that this motion is representative of the free-field motion at the dam site. This instrument should be founded on the same rock as the dam.

3.1 Gravity dams

Gravity dams are routinely designed and analyzed under the assumption that the individual blocs behave idependently from one another. A minimum instrumentation scheme will thus concentrate on the behavior of a single bloc (central bloc / highest bloc). A minimum information on bloc input motion and linear behavior is given by scheme 'A' of Figure 1, complemented by scheme 'G' for a more detailed monitoring. The extent to which the blocs behave independently from one another is addressed by schemes 'C', 'D' and 'F' while the variation of the motion across the canyon is addressed in a simple way by scheme 'E'. Scheme 'B' provides for the recording of the reference free-field motion.

3.2 Arch dams

Similar instrumentation schemes are presented in Figure 2 for arch dams. The instruments at the crest are located at points of maximum modal deflections (mid- and quarter points of developed crest in "regular" dams). Other instruments are located at the corner points of a fictitious rectangular grid. This concept ensures that the responses of the lower modes of vibration are well captured and that the motions recorded at all locations can be correlated with one another in a straightforward manner.



A : MINIMUM DAM RESPONSE AND INPUT MOTION (4 INSTRUMENTS)

+B : + COMPLEMENTARY DAM RESPONSE AND INPUT MOTION (+2 INSTRUMENTS)

+C : + FREE-FIELD MOTION (+1 INSTRUMENT)

+D : + EFFECTIVE INPUT MOTION, COMPLEMENTARY (+2 INSTRUMENTS)

+E : + DETAILED DAM RESPONSE, COMPLEMENTARY (+1 INSTRUMENT)

+F : + WAVE PROPAGATION (+2 INSTRUMENTS)

+G : + DETAILED EFFECTIVE INPUT MOTION, COMPLEMENTARY (+4 INSTRUMENTS)

Figure 2. Strong-motion instrumentation of arch dams.

A minimum monitoring of dam input motion and response is given by scheme 'A', complemented by schemes 'B' and 'E' for a more detailed monitoring. The issue of effective input motion is addressed by schemes 'D' and 'G' (as complements to schemes 'A' and 'B'). The presence of galleries in the foundation rock may permit instrumentation according to scheme 'F', thus leading to informations on wave propagation mechanisms. Scheme 'C' provides for the recording of the reference free-field motion.

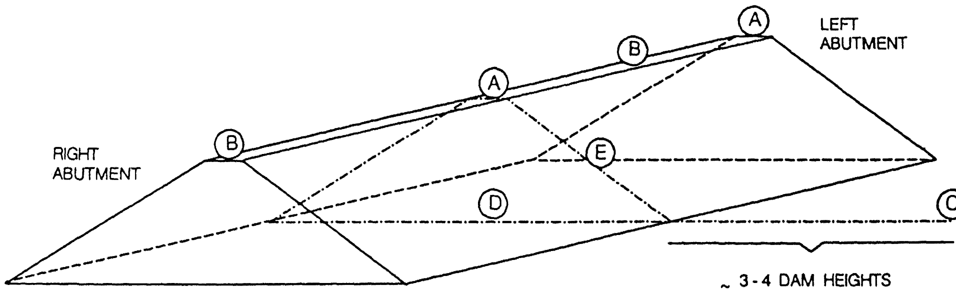
3.3 Earth dams

Strong-motion instrumentation of earth dams has been studied by Fedock (1982). The resulting schemes, shown in an adapted form in Figure 3, are similar to the ones presented above. An absolute minimum instrumentation consists in locating instruments at one abutment and at the center of the dam, thus capturing basic informations on excitation and response. This instrumentation can be complemented by the one of scheme 'B' from which the variation of input motion from one abutment to the other and the difference in response from one section to the other can be studied. More detailed informations on input and response are obtained by instrumentating according to schemes 'D' and 'E', respectively. Scheme 'C' provides for the recording of the reference free-field input motion. This instrumentation can be complemented by borehole instruments placed within the dam body, primarily at the mid section.

4 INSTRUMENT SPECIFICATIONS

The specifications of the instruments must be compatible with the instrumentation objectives and with the environmental conditions prevailing at the instrument locations (see also Bolt & Hudson, 1975).

The strong-motion instruments must be able to accomodate the maximum acceleration expected. This value depends primarily on the seismicity of the site, the target measurement return period and the location of the instruments (in-structure response is usually larger



A: ABSOLUTE MINIMUM DAM RESPONSE AND ABUTMENT MOTION (2 INSTRUMENTS)

A+B: MINIMUM DAM RESPONSE AND ABUTMENT MOTION (4 INSTRUMENTS)

+C: + FREE-FIELD MOTION (+1 INSTRUMENT)

+D: + BASE MOTION (+1 INSTRUMENT)

+E: + COMPLEMENTARY DAM RESPONSE (+1 INSTRUMENT)

Figure 3. Strong-motion instrumentation of earth dams (adapted from Fedock, 1982).

than free-field response). Bolt & Hudson suggest to use a full-scale acceleration of 1g. A value of 0.5g is used in the swiss dam network because of the rather limited level of seismicity prevailing at the selected dam sites. An acceleration resolution of at least 0.001g seems necessary with instrument noise remaining below acceleration resolution.

In order to be able to investigate the possible occurence of permanent displacements (settlements in earth dams), very accurate measurement should be possible from 0 Hz (DC) to a frequency value which is well above the natural frequency of the highest dam mode contributing to the response as well as above the highest significant frequency expected to be contained in the earthquake acceleration traces. A value of at least 30 Hz is suggested, whereby a value of 50 Hz is used in the swiss dam network. It is also recommended to use digital instruments to facilitate data processing.

Studies on effective input motion and on wave propagation require that all instruments record in a synchronized fashion. Interconnection of the instruments with enforcement of common triggering and common sampling is thus necessary. When interconnecting the instruments, care must be taken to minimize possibilities for malfunctions and damages due to differences in electric potential between the individual instruments and due to lightning striking in the vicinity of the interconnection cables. The instruments must further be adequately protected against power surges (possibly also due to lightning).

The SYSCOM accelerograph MR2002 (recorder and separate sensor) is being installed in the swiss dam network. The accelerograph is very compact and is mounted on gallery walls directly (concrete or rock). No preparatory constructions are necessary (e.g. no pedestals) and the instruments can be placed in locations where limited space is available. Recording occurs at the accelerographs directly (memory modules) with each recorder in a dam array being connected to a motion control center which ensures common triggering and common sampling of all instruments. The interconnection occurs through fiber optic cables thus eliminating completely the problems associated with differences in electric potential and with lightning striking in the vicinity of the interconnection cables. A time code receiver is connected to the motion control center and an exact time signal is sent to the individual recorders. All recorders can be accessed from the motion control center through a personal computer connected to it or through a modem. Easy data retrieval, setting of recorder parameters and verification of the results of built-in functional tests are thus possible.

5 IMPLEMENTATIONS

The swiss dam network is being implemented with the primary objective of gathering informations on linear dam response, on effective input motion and on relative bloc displacements (gravity dams). The dams instrumented have been selected considering that they are representative of the diversity of the dam types encountered in the country (mostly concrete dams), are typical in terms of foundation and geometric characteristics and are at sites of high enough seismicity so that actual measurements may be expected within a reasonable lapse of time.

A difficulty which was encountered at all sites was to find an appropriate location for the free-field instrument and the distances from the dam suggested in Figures 1 to 3 could not always be satisfied.

5.1 Gravity dam of 'Grande Dixence'

'Grande Dixence' is the highest concrete dam in the world (285 meters) and is located in the south-western part of Switzerland. Referring to Figure 1, instrumentation schemes 'A+B+C' are being implemented thus putting emphasis on obtaining the response of the central bloc and the corresponding input motion, and on evaluating possible occurence of relative bloc displacements. 6 accelerographs are thus installed with the free-field accelerograph being located at a distance of 300 meters from the dam.

5.2 Arch dams of 'Punt dal Gall' and 'Mauvoisin'

'Punt dal Gall' is an arch dam of 130 meters in height located in the south-eastern part of Switzerland. There, the emphasis is placed on obtaining dam response and input motion according to instrumentation schemes 'A+B+C' of Figure 2. 7 accelerographs are thus installed with the free-field accelerograph being located at a distance of 300 meters from the dam.

'Mauvoisin' is the 4th highest concrete dam in the world with a height of 250.5 meters. It is located in the south-western part of Switzerland and instrumentation emphasis is put on effective input motion, dam response and wave propagation according to instrumentation schemes 'A+B+C+D+E+F' of Figure 2. This results in installing 12 accelerographs with the free-field instrument being located at a distance of 550 meters from the dam.

5.3 Earth dam of 'Mattmark'

The earth dam of 'Mattmark' is 120 meters high. It is the 2nd highest embankment dam in the country and is located in its south-western part. Instrumentation schemes 'A+C+D' (Figure 3) have been selected, thus putting emphasis on a minimum instrumentation from which informations on the general behavior of the dam can be obtained. This results in installing 4 accelerographs including a free-field instrument located at a distance of 1'000 meters from the dam.

ACKNOWLEDGMENTS

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