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STRONG-MOTION RECORDS AT LARGE DAMS

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SUMMARY

Accelerograph arrays have been installed in the Swiss dams of Grande Dixence, Mauvoisin, Punt dal Gall, Emosson and Mattmark. The apprehension of the overall dam behaviour during earthquakes that leads to the identification of the response patterns and of the governing effects is targeted. Also, data are sought that permit the extraction of information on the dynamic characteristics of the dams, on the effective input motions and on the free-field motions. A further objective is to establish a set of records covering dam excitation and response that can be used to calibrate calculation programs.

Seven earthquakes triggered from 1 to 3 arrays up to mid 1999 (total of 11 array recordings). These records are presented, together with their interpretation. They include those obtained during the Valpelline quake of 1996 at Grande Dixence (6 stations) and Mauvoisin (12 stations), during a local event at Mauvoisin in 1994 and during two earthquakes that occurred near Grande Dixence in 1998. Resonant frequencies are estimated from power spectral density functions and from transfer functions. The resonant frequencies obtained at Mauvoisin are compared to those gathered from 7 series of ambient vibration tests conducted for various water levels.

The motions that have been recorded to date are of low amplitudes. Noise-to-signal ratio thus remains important, what negatively affects the quality of the ensuing interpretations. Still, most sought-after information on the behaviour of dams during earthquakes are obtained and the potential for the arrays to lead to more is documented. It is concluded that more advanced identification techniques than those used need to be applied in order to obtain a comprehensive identification of the dynamic characteristics of the dams.

INTRODUCTION

Accelerograph arrays have been installed in 1992 at Grande Dixence (285 meters high gravity dam, 6 stations), Mauvoisin (250 meters high arch dam, 12 stations), Punt dal Gall (130 meters high arch dam, 7 stations) and Mattmark (120 meters high embankment dam, 4 stations) (Darbre 1995a) and in 1998 at Emosson (180 meters high arch dam, 5 stations). These installations were prompted by the documented need for observational data at dams during earthquakes (NRC 1990). The apprehension of the overall dam behaviour during earthquakes that leads to the identification of the response patterns and of the governing effects was targeted. Also, data were sought that permit the extraction of information on the dynamic characteristics of the dams, on the effective input motions and on the free-field motions (Darbre 1995b). A further objective was to establish a set of records covering dam excitation and response that can be used to calibrate calculation programs.

Complementing this effort, ambient vibration tests were initiated at Mauvoisin in 1995 (de Smet et al. 1998) and forced-vibration tests at Emosson in 1997 (Paultre et al. 1998).

The earthquake records are introduced below, followed by the presentation of the dynamic characteristics of the dams identified from the records. Complementary information on recorded data is found in (Darbre 1998).

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RECORDS

Overview

The events listed in Table 1, none of which induced any damages to the dams, have been recorded up to mid 1999.

Table 1 – Events recorded at the dams up to mid 1999

Date	Name of quake	Magnitude Ml	Focal depth [km]	Dams affected	Epicentral distance [km]
June 14, 1993	Domodossola	4.4	19	Grande Dixence Mauvoisin Mattmark	67 71 24
Nov. 1, 1994	Mauvoisin	Unknown	Unknown	Mauvoisin	~ 0
March 31, 1996	Valpelline	4.2	2	Grande Dixence Mauvoisin Mattmark	18 13 40
July 15, 1996	Meythet	5.2	5	Mauvoisin	100
Dec. 7, 1997	Mattmark	2.0	9	Mattmark	6
May 7, 1998	Dixence	3.5	8	Grande Dixence	2
May 7, 1998	Dixence aftershock	2.3	7	Grande Dixence	4

The Domodossola quake occurred shortly after the accelerographs had been installed and before commissioning of the network. Instruments installed at Grande Dixence, Mauvoisin and Mattmark registered motions up to 1.5 % g (Mattmark). The records were used to assess the functionality of the arrays. Instrumentation shortcomings were identified (Darbre & Studer 1993) and subsequently corrected. These records are not presented here.

An event of unknown magnitude occurred in the close vicinity of Mauvoisin on November 1, 1994. 3 accelerographs were disconnected at that time for maintenance reasons. Thus, only 9 stations out of the 12 installed at the dam recorded the event.

The Valpelline quake triggered all stations at Grande Dixence and at Mauvoisin, as well as the station at the crest of the crown section at Mattmark.

The Meythet quake triggered only the station at the crest of the crown section at Mauvoisin. The corresponding station at Mattmark was also the only one to register a motion due to an earthquake that occurred in its vicinity in 1997.

The earthquake which occurred in the immediate vicinity of Grande Dixence in 1998 was followed by an aftershock on that same day. All stations of the Grande Dixence's array triggered on both occasions.

Data processing

Correction and alignment

The original data are subjected to a constant base-line correction, minimizing the integral of the square of the velocities over the duration of the records. No correction for instrument response is performed because of the nature of the sensors and of the filter (Smit 1996).

The three components of the records are rearranged to coincide with the following directions: x- and y-directions in the horizontal plane, with x pointing downstream perpendicular to the plane of the dam and y pointing towards the left abutment, z-direction vertical. For the stations located away from the dam (free-field), the x-direction is that perpendicular to the plane of the dam at the crown section.

Interpretation

The response spectra of the signals are computed for various levels of critical damping. None are presented here as they do not show any particularities.

The power spectral densities (*PSD*) and the relative transfer functions (*TF*) from a station along the abutment, in the foundation rock or in the free field to a station in the dam are calculated. Resonant frequencies are identified, noting that those stemming from the *PSD* refer to the dam-foundation-reservoir system and that those stemming from the *TF* ideally refer to the dam-reservoir system alone (without foundation).

DAM OF GRANDE DIXENCE

Dam

The dam is sketched in Figure 1. Three accelerographs are located at the crown section (one at the crest and two on either side of the base), and two additional ones at the crest one block away from the central block (on either side). The free-field station is located in an access tunnel 290 meters downstream from the dam.

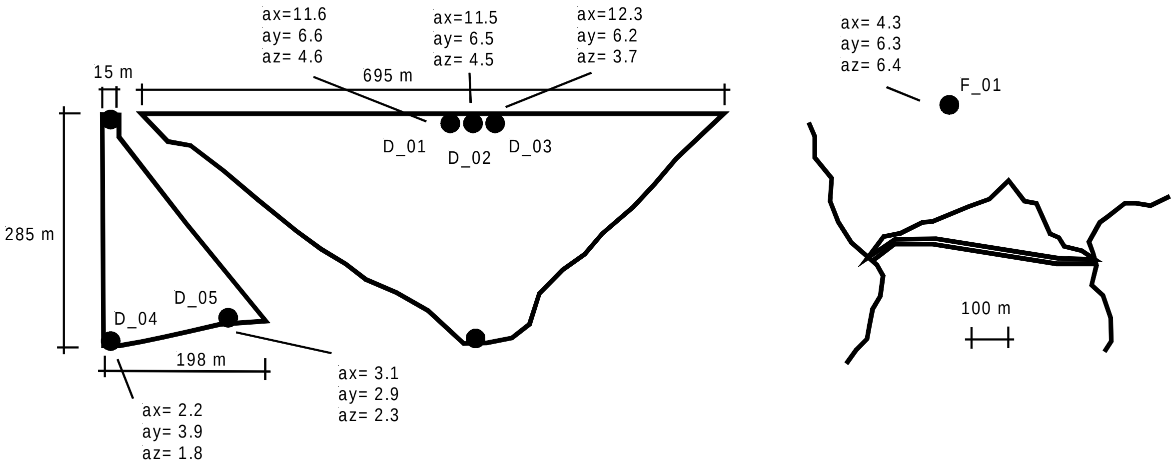

Figure 1 - Grande Dixence: Sketch and peak accelerations during the Valpelline quake [cm/sec2]**

Records

The peak accelerations recorded during the Valpelline quake are also reported in Figure 1. The water level reached 160 meters above the base at the time of the event, i.e. slightly more than mid-height. The peak accelerations recorded during the earthquakes of May 7, 1998 are reported in Figure 2. The water level reached 128 meters at the time, i.e. slightly less than mid-height. The time histories of the stream (x-) component of acceleration that prevailed during the Valpelline quake and during the main shock on May 7, 1998 are reported in Figure 3.

Inspection of the time histories confirms that, for the three events, the records of the stations at the crest (D_01 to D_03) are essentially identical. This is not the case of the records at the base stations (D_04 and D_05), that show distinctive features. Also, it is noted that the motion in the free-field is larger than at the base (for all three components) and that the crest motion is amplified with respect to that of the base (4 to 5 times for the stream component during the Valpelline quake and during the main shock of May 7, 1998).

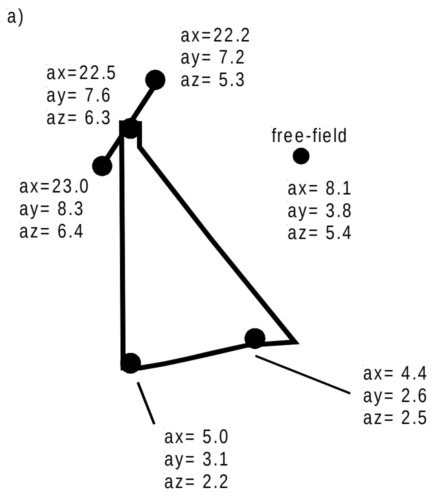

Figure 2 - Grande Dixence: Peak accelerations [cm/sec2] during local quakes of May 7, 1998:**
a) Main shock **b) Aftershock**

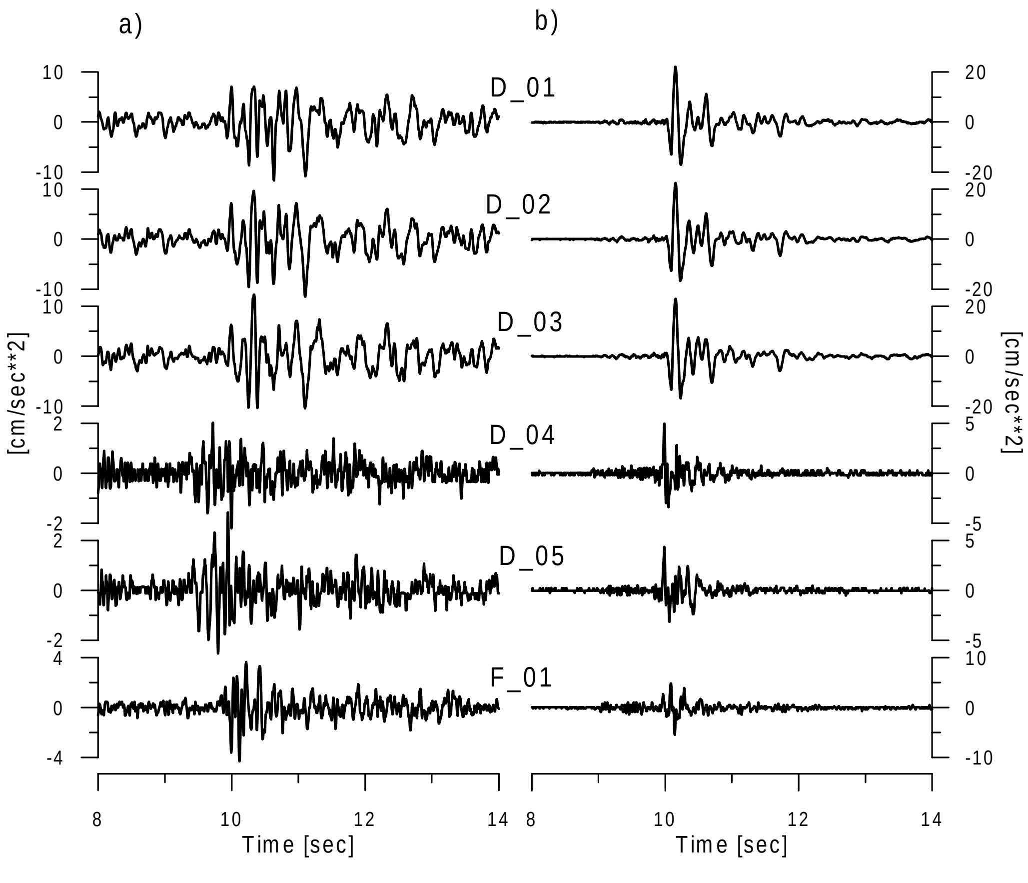

Figure 3 – Stream component of acceleration time histories during:
a) Valpelline quake **b) Main shock May 7, 1998**

Resonant frequencies

The lowest resonant frequencies identified both from the *PSD* and from the *TF* of the records of the Valpelline quake and of the main local quake are reported in Table 2. They are indicated in parenthesis whenever their identification is uncertain. It has been attempted to relate the resonant frequencies obtained from the 4 sets of functions to one another in the Table. It is reminded that the water level was similar, in relative terms, during both events (56% of full reservoir vs. 45%), although it decisively differed in absolute terms (32 meters difference). Good correspondence exists between the sets of results, although a frequency may be identified with confidence in one set and not in another.

Table 2 – Grande Dixence: Resonant frequencies

Valpelline quake (WL 160)		Local quake (main shock, WL 128)			Valpelline quake (WL 160)		Local quake (main shock, WL 128)	
PSD	*TF*	*PSD*	*TF*		*PSD*	*TF*	*PSD*	*TF*
2.05	2.00	2.07	2.09, ζ=0.9%		(4.38)	4.45	(4.31)	4.29, ζ=1.0%
2.23	(2.30)	2.27	(2.21)				4.63	(4.61)
(2.52)	(2.55)		(2.53)		(4.67)	(4.79)		4.70
		(2.62)	(2.64)				4.84	
		2.79	(2.79)		(5.00)			(5.11)
3.02	3.10	3.00			(5.22)	5.20		(5.21)
			(3.28)				5.30	
	3.44	3.45			5.56	5.61		
(3.67)	3.67	3.57			(5.73)			
		3.85			(6.00)		6.09	
(4.05)					(6.28)	(6.17)	(6. 36)	
(4.21)	4.16	4.13			6.70	(6.68)	(6.71)	6.71, ζ=0.2%

Damping levels could be identified from the records of the main shock of May 7, 1998 (half-power method). They reached on the order of 1% of critical at 2.09 Hz and at 4.29 Hz (0.2% at 6.71Hz).

It is interesting to note that the resonant frequencies are visible in the *PSD* of the free-field records of the Valpelline quake, although the station is located 290 meters away from the dam (for a dam height of 285 meters).

DAM OF MAUVOISIN

Dam

The dam is sketched in Figure 4. Four accelerographs are located in the dam (D_02 to D_04 at the crest and D_07 at mid-height), five along the abutments (D_01, D_06, D_10, D_08 and D_05), two in the foundation rock (D_09 and D_11) and one in the free-field (F_01 in an access tunnel 600 meters downstream from the dam).

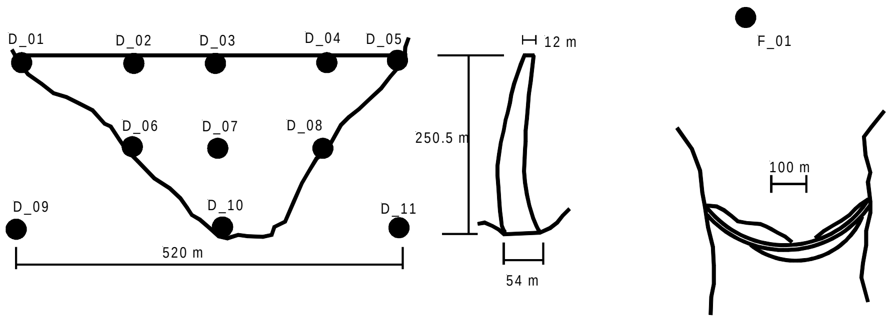

Figure 4 - Sketch of Mauvoisin

Records

The peak accelerations recorded during the local event of November 1, 1994, and during the Valpelline quake are reported in Figures 5a and 5b, respectively. In the first case no amplification of motion in the dam is observed. Inspection of the records and of the *PSD* reveal that the motions are of high frequency content, larger than the resonant frequencies of the dam (it is in fact not certain that the event is an earthquake; although unlikely, an explosion or rock fall near the site is not excluded). On the other hand, an amplification clearly occurs during the Valpelline quake (of up to a factor 5 in the stream direction).

The peak accelerations recorded at the crest (station D_03) during the Meythet earthquake are 5.3, 1.5 and 1.8 [cm/sec**2] in the x-, y- and z- directions, respectively.

The water level was at 234 meters during the local event (reservoir almost full) and at 138 meters at the time of the Valpelline quake (slightly over mid-height). It was at 183 meters during the Meythet quake (more than two thirds full).

It is interesting to note that the vertical component of the Valpelline record at the station D_05 at the right abutment (crest) contains almost no trace of structural response and characteristics (not shown). This is consistent with the construction details, a joint existing over the upper 15 meters of the dam-rock interface at this location.

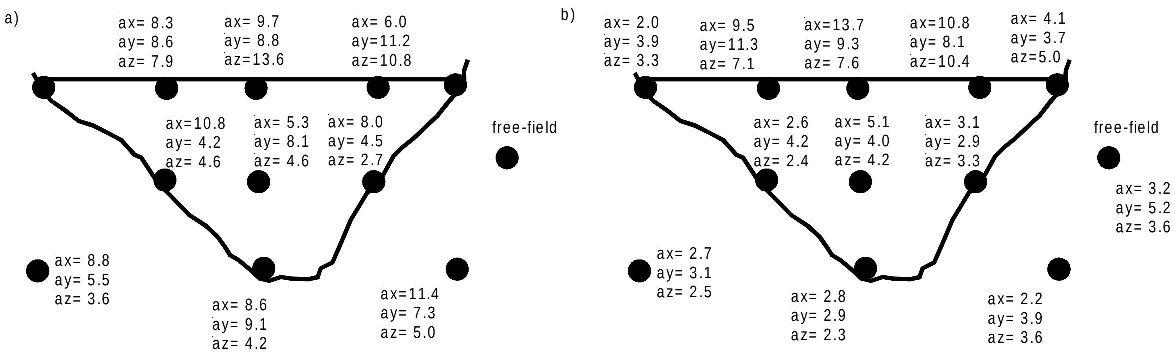

Figure 5 - Mauvoisin: Peak accelerations [cm/sec2] during:**
(a) Local event of November 1, 1994 (b) Valpelline quake

The resonant frequencies listed in Table 3 are identified from the *PSD* and from the *TF*. Again, the frequencies are in parenthesis whenever doubts on the correctness of the identification remain. The water level is reported in the second row of the Table.

Table 3 – Mauvoisin: Resonant frequencies

T1	Valpelline		Meythet	T5	T2	T3	Local	T7	T6	T4
124	138	138	183	187	199	231	234	234	237	238
	PSD	*TF*	*PSD*				*PSD*			
2.18	2.10	2.10	(2.24)	2.28	2.21	1.92		1.93	1.89	1.88
2.35	2.30	2.31	(2.39)	2.40	2.36	2.16	(2.13)	2.15	2.13	2.12
			(2.47)							
		(2.66)		2.76	2.68	(2.37)	2.36	2.37	2.36	(2.36)
			(2.98)	2.86	(2.80)	2.55	(2.59)		(2.52)	(2.49)
	3.28	3.29	(3.33)	3.27	(3.20)		(2.87)		2.71	(2.70)
3.36		(3.49)	3.53	3.55	3.53	3.28	3.20	3.21	3.20	3.18

	(3.77)	(3.78)	(3.94)							
	3.95	(3.96)					(3.64)			
		(4.08)								
4.22	(4.17)	(4.29)		4.30	4.20	(4.00)			(3.98)	
(4.39)	4.52	4.54	(4.52)	4.45	4.39	(4.14)	4.14		(4.09)	4.11
(4.62)				4.70	4.58	(4.22)		4.17	4.14	(4.19)
	(4.79)	(4.98)					4.47			
							(4.71)			
							(4.80)			
(5.03)	(5.06)	(5.31)		5.51	5.46					5.04
5.11			(5.90)	5.87	5.89		(5.12)		(5.09)	(5.08)
(5.22)				6.27	6.22					
	(5.76)	5.65					5.77			
		5.81								
	(6.09)	(6.10)	(6.57)				(6.10)			
6.23	(6.24)			6.77	6.71		6.32		(6.25)	(6.25)
	6.56	6.52					(6.72)			
	(6.78)	(6.76)					(7.29)			
		(6.90)								
	(7.35)	7.28		8.01	8.03		7.53			
7.29	(7.50)	(7.54)			(8.22)					(7.77)
	(7.79)									
8.43				9.48	9.56					9.44

The *TF* of the set of records of the local event could not be used in the identification process as they are close to white noise (none can be calculated for the Meythet quake as only one station triggered).

The differences in readings from one set of records to an other do not only stem from the interpretation made by the analyst (complicated by the occurrence of closed-space frequencies), but also from the differences in water level and in temperature conditions. An attempt has been made in the Table to associate the frequencies that correspond to one another. This was done by comparing the frequencies identified to those allocated during ambient vibration tests (see below).

Ambient vibration tests

A series of ambient vibration tests was initiated in 1995 (de Smet et al. 1998). The resonant frequencies that have been identified are also indicated in Table 3. The influence of the water level is clearly visible (all tests were performed from late spring to fall). The excellent agreement between the two sets of resonant frequencies obtained for the water elevation of 234 meters (local quake and ambient measurement T7) is also noted.

DAM OF MATTMARK

Records

The embankment dam of Mattmark is 780 meters long, 9 meters wide at the crest, 373 meters wide at the base and 120 meters high. The accelerations recorded at the crest of the crown section during the Valpelline quake and during the local event of December 7, 1997 reached 6.5, 6.0 and 6.6 [cm/sec**2] for the former and 4.7, 5.6 and 2.9 [cm/sec**2] for the latter in the x-, y- and z-direction, respectively.

The resonant frequencies of Table 4 are identified form the PSD. The water level was at 41 meters during the Valpelline quake (reservoir one third full) and 95 meters during the local event (four fifths full).

Table 4 – Mattmark: Resonant frequencies

Valpelline (WL 41)	(2.52)		3.11			(4.41)	4.96	(5.35)
Local event (WL 95)	(2.53)	2.83	(3.07)	3.46	(3.86)			5.27
Valpelline (WL 41)	5.77		(6.70)	(7.14)	7.46	(7.75)		
Local event (WL 95)	(5.94)	(6.41)	6.90	7.16	(7.41)	(7.70)	(7.88)	

COMMENTS

The motions recorded to date are of low amplitudes. This negatively affects the quality of the interpretations as the noise remains comparatively important. Still, it clearly appears that the arrays have the potential of providing most useful and sought-after information on the behavior of dams during earthquakes.

The differences in resonant frequencies as obtained from the *PSD* and the *TF* as well as the large number of frequencies identified with uncertainty show that the simple identification techniques used are not well suited to a comprehensive identification of the dynamic characteristics of dams. More advanced techniques have to be used (e.g. Loh & Wu 1996, Safak 1999), further addressing more thoroughly energy dissipation and mode shapes.

No attempt has been made to interpret the records in terms of effective input (uniformity of the abutment motion or lack thereof) nor of wave propagation. These aspects were also targeted when designing the arrays. There is some evidence that the non-uniform input might have adverse consequences that have not been sufficiently looked into in the past (Mojtahedi & Fenves 1996).

ACKNOWLEDGMENTS

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