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Delayed response analysis of dam monitoring data

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ABSTRACT: Long series of monitoring data are obtained during the routine operation of a dam. The Statistical Hydrostatic-Season-Time models which have been widely used for analysing and interpreting these large sets of data are not suitable for hydraulic measurement analysis, as they do not account for the delayed responses of piezometers or cells. This paper describes a model for performing delay analysis on pore pressure measurements. The method is based on Darcy's law and Richard's equation of seepage and involves the use of a linear dynamic system accounting for the contribution of non-ageing factors, i.e., the reservoir level and rainfall events, to the pore-pressure variations.

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1 INTRODUCTION

Quantitative methods of analysis based on statistical models have been used on dam monitoring data for a long time, as reported in particular at the ICOLD Congress.
The Hydrostatic-Season-Time method proposed by Electricité de France for analysing pendulums in 1958 (Ferry & Willm) and in 1967 in a fundamental study (Willm & Beaujoint) has proved to be a powerful tool for interpreting the behaviour of concrete dams in particular (ICOLD 1985, 1989, 2000).

The statistical models involving the use of regression techniques to find correlations between causes and quantified effects account efficiently for mechanical behaviour, but they have several weaknesses :

- theses methods cannot be used to predict variations in the pore pressure rates ;
- they do not include the effects of rainfall because they do not take the history of the loading into account.

The analysis of ageing behaviour requires more accurate methods of non-ageing behaviour analysis.

To understand the long term behaviour of a dam, it is essential to carefully interpret the dissipative effects which tend to occur due to seepage, in order to be able to distinguish between the effects of factors such as drift, irreversible events and the ageing of the dam and the effects of other factors not involving ageing processes.

2 THE HYDROSTATIC-SEASON-TIME MODEL

The main components of the basic Hydrostatic-Season-Time (HST) model are as follows:
- the effect H of the reservoir level Z, which is given by a fourth-degree polynomial,

$$H_n=a_1Z_n+a_2Z_n^2+a_3Z_n^3+a_4Z_n^4 \quad (1)$$

- the seasonnal effect S, represented by the sum of sine functions with one-year and six-month period ($\omega=2\pi/365$)

$$S_n = b_1\sin(\omega t_n)+b_2\cos(\omega t_n)+ b_3\sin^2(\omega t_n)+b_4\sin(\omega t_n)\cos(\omega t_n) \quad (2)$$

- the irreversible effect T (time drift), which is expressed in terms of monotonic time functions.

The HST model is extremely robust and always yields satisfactory results. It gives in a simple, immediately usable form an instantaneous non linear function of the reservoir level H and a periodic function S, which is comparable to a delayed response to the annual and half-yearly cycles in which the total external loads occur.

One of the main gaps in this model is the lack of physical information provided by the parameters.

When the model H is linear ($a_2=a_3=a_4=0$), the coefficient a_1 is equal to the coefficient α :

$$H_n=\alpha Z_n \quad (3)$$

If the value of a is close to zero, this means that the reservoir level will have no instantaneous effect

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on the variations. If a is close to one, this means that the instantaneous variations in the dam monitoring data will be of a similar amplitude to those of the reservoir level.

The three parameters (a_2,a_3,a_4) involved in the explanatory variable H and the four parameters involved in the explanatory variable S are never interpreted in the usual hydraulic data analysis.

The polynomial expression for the effects of the water level (1) was originally based on a mechanical analysis of the effects of the water level on the displacement of an arch dam, based on the resistance of the materials.

This explanatory variable is often used by default in hydraulic data analysis, but a fourth-degree polynomial relationship between a piezometric head and the water level is not mechanically justified.

The only advantage of the previous method is that it provides a means of explaining the readings taken when the explanatory variable is not $Z-Z_0$ but $(Z-Z_0)E(Z-Z_0)$, where $E(Z-Z_0)=1$ if $Z \geq Z_0$ and 0 otherwise, and Z_0 is the threshold piezometric level at which the effect occurs, which depends on the permeability and the slope of the ground and the position of the instrument bottom of the stand pipe piezometer or quotation of pose of the cell.

Seasonal factors are known to affect arch dams : the temperature variations occurring between cold and hot seasons are closely correlated with the downstream drift of the dam, for instance. As it is extremely difficult to use and even to obtain accurate temperature measurements, a periodic seasonal law based on average temperature variations is used.

The hydraulic measurements made at earth dams used for water supply or irrigation purposes also show the effects of the latter factor. The variable S is in fact simply the sum of the two first terms of a Fourier series development (to within the nearest constant):

$$S_n = A_1\sin(\omega(t_n+d_1))+A_2\sin(2\omega(t_n+d_2)) \qquad (4)$$

The rainfall should be taken into account when interpreting the readings obtained with piezometers, which are instruments used on dams of all kinds, especially for foundation monitoring. There exists a simpler method consisting of taking the rainfall during the last ten days (Crépon & al., 1999), but this is a purely statistical approach.

3 AN EXAMPLE OF DELAYED RESPONSE

Figures 1 and 2 give an example of piezometric data obtained on the downstream toe of a homogeneous earthdam.

The variations of piezometric level occurring during the first few years seem at first sight to be in parallel with the water level (fig. 1). This would give a straight line or at least a cloud of aligned points on the graph giving the variations in the piezometric level vs the water level, but it is not in fact the case (fig. 2). Even a high order polynomial would obviously not account for this result.

This example, which we will examine in greater detail below, shows what delayed responses consist of and why neither model (1) nor model (3) can account satisfactorily for these responses.

Delayed effects are due to dissipative behavior (viscoelasticity, seepage ,etc.), and are therefore irreversible. By including the impulse response of a non ageing visco-elastic materials in the statistical analysis, it is possible to analyze the creep deformations occurring in a concrete dam (Dobosz, in ICOLD 1985).

The impulse response of a semi-infinite porous medium given by the Boussinesq equation can also be used to analyze the flow through an earth dam (Brunet 1995, Fabre 1992). At a more general level, one can take the derivative of the loading as the explanatory variable (Crépon & al., 1999).

It can be seen from Figure 2 that a cycle in which the water level rises and falls is a dissipative one (it involves hysteresis) : the path taken as the water level rises (phase 3) and falls (phase 5) is not the same. For this reason, some measurements can indicate that the pore pressure has increased while the water level was decreasing, and *vice-versa*.

This well-known paradox is due to the presence of air trapped inside the body of the dam. This situation has been observed *in situ*, and has also been found to occur under laboratory conditions (Windish & al, 2000).

4 DESCRIPTION BY A STATIONARY LINEAR DYNAMIC SYSTEM

Seepage processes occur in response to continuous reservoir level variations and rainfall events. Richard's equation shows that the pore pressure does not depend on the instantaneous value of the loading, but on the convolution integral of an impulse response (which still remains to be identified) and the loading conditions (reservoir level, rainfall).

In attempting to describe the variations in the pore pressure measured *in situ*, this expression led us to search for a more external description in terms of a stationary linear dynamic system, for the following reasons :

- linear: the class of structure in question is that of dams during a routine period of operation undergoing the specific loading levels for which they were designed; external constraints are therefore assumed to result in reversible deformations which are highly unlikely to be large enough to affect the stability or the resistance of the dam; this justifies the use of a linear approach in the first stage.

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However, a linear approach is obviously more justifiable under saturated or quasi-saturated than under saturated conditions ;

- dynamic: the two main constraints affecting the flow in a hydraulic dam are the variations in the water level and the rainfall; in view of the dissipative nature of the seepage processes, the history of these events has to be taken into account in order to explain the water levels existing at a given instant, and not just the values of these two parameters at the same instant. What is required here is a dynamic description in terms of differential equations ;
- stationary: to be able to quantify the drift with time, i..e , the changes occurring under constant conditions (including the ageing), it is necessary to first quantify the stationary changes, i.e., those resulting from external factors regardless of the time; an invariant stationary system, i.e., one which is independent of the time origin, was therefore adopted. Here the time plays only the kinetic role characteristic of dissipative phenomena (in the sense that the successive events occur at a certain speed), but it has no geological significance (in the sense that the time origin, and hence the age of the system, is not taken into account); here one can refer to the theory of rheology for an exact definition of aging and non ageing behavior.

This approach has already yielded some results.

The response obtained is the sum of a transient term giving the initial conditions, the response to the variations in the water level and the response to the rainfall events.

The term "ageing" seems to be more suitable than the term "irreversible", which is often used to characterize the effects of time (the age of the dam) on hydraulic measurements. Seepage is by nature an irreversible phenomenon.

Accommodation is one of the characteristics of a stationary linear dynamic system, and it renders the use of the explanatory variable S pointless.

In a permanently operating regime, the response to a periodic signal (harmonic test) will also be periodic (definition of accommodation), and the period will be identical, whereas the amplitude will be different and the response will be delayed.

If the input is harmonic

$$Z(\tau)=\sin(\omega\tau) \qquad (5)$$

the response will be

$$h_Z(\xi,\tau,\delta)*Z(\tau)=\alpha g\sin(\omega(\tau+d)) \qquad (6)$$

where α is the static structural decrease in damping of the amplitude, g is the dynamic decrease in the amplitude, and d is the delay. The accommodation is precisely what the seasonal variable S was designed to model (4).

One might naturally expect an explanatory variable expressed in dynamic terms to be an improvement over methods of interpreting hydraulic measurements purely in terms of seasonal effects.

5 AN ORDER ONE DELAY MODEL

The delayed effect H of the water level is proportional to the convolution of the impulse response of the dam structure and the water level Z.

The simplest stationary linear dynamic system is an order one system.

Approximating the impulse response h_Z by taking a system defined by a characteristic time T_{Zx} leads to

$$H(Z,x,t)=\alpha_x Z^*(x,t,Z) \qquad (7)$$

$$Z^*(x,t,Z)=\frac{1}{T_{Zx}}\int_0^t \exp\left(-\frac{t-t'}{T_{Zx}}\right)Z(t')dt' \qquad (8)$$

The coefficient $0\leq\alpha_x\leq 1$ is the static structural damping of the amplitude. It reflects the efficiency of the drainage system or grout curtain, as well as the position of the measuring point in relation to the reservoir level.

A coefficient α_x approximately equal to unity will mean either that the instrument has been placed close to the reservoir level or that the actual drainage outlet is far away, which may constitute a weakness of the drainage system.

The characteristic time T_{Zx} integrates several items of information about the zone situated between the reservoir surface and the drainage point : the efficiency of the drainage system or the grout curtain, and the diffusive properties of the materials, which depend on the permeability and the state of saturation of the ground and the compressibility of the water.

A very large characteristic response time indicates either that the ground is not saturated (S<85%), the degree of permeability is very low or the drainage distance is very long.

When the characteristic response time is very short, the process is taken to be an instantaneous one corresponding to (3).

The delayed effect P of the rainfall is proportional to the convolution of the impulse response of the dam structure and the rainfall Q.

Approximating the impulse response in terms of an order one dynamic system defined by a characteristic time T_{Qx} gives

$$P(Q,x,t)=T_{kx}Q^*(Q,x,t) \qquad (9)$$

$$Q^*(Q,x,t)=\frac{1}{T_{Qx}}\int_0^t \exp\left(-\frac{t-t'}{T_{Qx}}\right)Q(t')dt' \qquad (10)$$

The coefficient T_{kx} is the drainage time in the part of the dam in which piezometers have been installed. The characteristic time T_{Qx} integrates several kinds of information about the zone situated between the surface of the ground and the actual drainage outlet point, such as the efficiency of the drainage system and the diffusive properties of the materials.

The following are suitable expressions for the discrete convolutions involved here :

$$Z^*_{n+1} = Z^*_n + \Delta Z_{n+1} + (Z_n - H_n - \Delta Z_{n+1}\frac{T_{Zx}}{\Delta t_n})(1-e^{-\Delta t_n/T_{Zx}}) \qquad (11)$$

$$Q^*_{n+1} = Q^*_n + (Q_{n+1} - Q^*_n)(1-e^{-\Delta t_n/T_{Qx}}) \qquad (12)$$

where $\Delta Z_{n+1} = Z_{n+1} - Z_n$ and $\Delta t_{n+1} = t_{n+1} - t_n$.

6 VALIDATION

An example confirming the validity of the model (11) as compared to an exact solution (Carslaw & al., 1959) of the diffusion problem is given in figures 3, 4, 5 and 6.

Figures 3 and 4 show the response to a stepwise increase in the reservoir level. Figure 3 gives the spatial profile of the response to one stepwise increase in the water level at several successive instants. Figure 4 gives the pattern of response with time. These two figures show the static damping of the amplitude.

Figures 5 and 6 give the responses to a harmonic variation of loading imposed by the reservoir level. They show: 1) the delayed effect and the dynamic and static decrease in the amplitude, 2) the fact that the delayed response model (11) accounts efficiently for periodic loading.

Similar results have been obtained with this delayed response model (12) in a flow loading situation (Bonelli, 2000).

By studying the exact solution, it is possible to specify T_{Zx} and α_x , given what is known about the characteristics of the dam :

$$\alpha_x = 1-\frac{x}{L} \quad , \quad T_{Zx} = T_Z\frac{1-\alpha_x^2}{6} \quad , \quad T_Z = \frac{L^2}{D} \qquad (11)$$

where x is the distance between the measuring instrument and the upstream face, L is the distance between the drainage system and the upstream face (the length of the drainage path), T_{Zx} is the characteristic response time of the measuring instrument, T_Z is the characteristic response time in the region to be instrumented and D is the diffusion coefficient characteristic of the region to be instrumented (fig. 7).

It is now possible to assess the consistency of the responses recorded by the instruments placed within the same zone. The permeability can also be assessed by quantifying the capacity coefficient**,** based on the amount of trapped air present.

7 APPLICATION TO DETERMINING THE EFFECTS OF THE WATER LEVEL ON PORE-PRESSURE CELLS RESPONSE

The analysis of the readings obtained with a pore pressure cell placed in the body of an earth dam (location CV13 in fig. 10) makes it possible to account accurately for the behavior of the dam (figs. 8 and 9). Figure 8 shows the delay in the responses. Figure 9 shows the hysteretic characteristic of the dissipative, and therefore delayed, behavior observed. The static HST model cannot account for behavior of this kind.

Measurements obtained with the six cells placed inside the structure of the Alzitone earthdam (France) (fig. 10) were analyzed and interpreted (table 1).

The permeability of the region within which the water level fluctuates (10^{-8} m/s) was found to be one order of magnitude lower than that of the permanently saturated zones (10^{-7} m/s).

The permeabilities deduced from laboratory tests, *in situ* Lefranc tests and finite element simulations range between 10^{-6} and 10^{-7} m/ s.

Table 1. Effects of the water level, results of delayed response analysis of data obtained with cells (Alzitone dam)

Cell	α_x	T_{Zx} (days)	T_Z (days)	L (m)	D (10^{-5} m^2/s)	k (10^{-8} m/s)
Elevation 52, unsaturated zone (water level fluctuation)						
CV33	0.27	33	211	27	4	1.5
CV23	0.38	33	228	32	5	2.3
CV13	0.39	23	160	33	8	2.7
Elevation 40, saturated zone						
CV32	0.47	25	191	103	60	14
CV22	0.49	33	260	106	50	13
CV12	0.38	10	73	88	100	21
Foundation						
CV31	0.43	28	210	141	100	24
CV21	0.43	56	409	140	60	11
CV11	0.51	32	259	163	100	14

Measurements obtained with six cells set within the structure of the Chamboux earthdam (France) (fig. 11) were analyzed and interpreted (table 2). The effects of the water level were instantaneous on the three cells located at the interface with the foundations, giving a permeability value greater than 10^{-8} m/s, whereas the three cells located inside the structure of the dam detected a delayed effect. Since these

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cells were placed within the water level fluctuation zone, the permeability in the permanently saturated region can be taken to have been one order of magnitude less, namely 10^{-7} m/s.

The projected permeability (laboratory tests) yielded a vertical permeability of 10^{-8} m/s.

In both cases studied here, the accuracy of the results obtained with the delayed response model was all the more impressive as this was not actually the purpose for which the model was designed.

Table 2. Effects of the water level, results of delayed response analysis of data obtained with cells (Chamboux dam)

Cell	α_x	T_x (days)	T (days)	L (m)	D (10^{-5} m^2/s)	k (10^{-8} m/s)
Elevation 488.50, dam/foundation interface						
C1	0.44	0	-	80	-	-
C2	0.28	0	-	78	-	-
C3	0.07	0	-	75	-	-
Elevation 497, body of the dam						
C4	0.25	35	225	17	1.5	0.9
C5	0.21	35	215	19	2.0	1.3
C6	0.06	43	256	20	1.8	1.2

8 APPLICATION TO DETERMINING THE EFFECTS OF THE WATER LEVEL ON PIEZOMETERS RESPONSE

The piezometer mentioned above was analyzed in two phases (piezometer P1 placed on the downstream toe of the Alzitone earth dam, evolution figs. 1 and 2, situation fig. 16).

During the filling of the dam, 120 measurements were carried out during a period of 150 days. The water level chart included 212 measurements recorded during a period of 329 days, including 179 days during which measurements were possible before the start-up. After adjustment of the model (9), we obtained T_{Zx}=83 days, α_x=0.44 and T_Z=613 days (figs. 12 and 13).

During the operating phase, 570 measurements were carried out during a period of 2280 days. This gave T_{Zx}=159 days, α_x=0.22 and T_Z=1000 days (figs. 14 and 15).

The simulation obtained with the dynamic model is remarkably accurate, given the extreme simplicity of the model. The results were compared with those obtained with the static HST model (3) (which was found to be ineffective) and with the measured data.

The results of the analysis of the readings obtained with the piezometers located in the body of the Alzitone dam (fig. 16) are summarized in table 3. The results of the cell reading analyses are also included in this table, and the great consistency of these results is worth noting.

Table 3. Effects of the water level, results of delayed response analysis of the piezometer data and some of the data obtained with cells (Alzitone dam)

Instruments	α_x	T_{Zx} (days)	T_Z (days)	L (m)	D (10^{-5} m^2/s)	k (10^{-8} m/s)
Left side						
CV33	0.27	33	211	27	4	1.5
CV32	0.47	25	191	103	60	14
PID9	0.42	45	325	111	40	14
PID10	0.23	45	285	100	40	17
Middle						
CV23	0.38	33	228	32	5	2.3
CV22	0.49	33	260	106	50	13
PID8	0.29	30	200	76	30	63
PID3	0.21	31	193	90	50	2.4
Right side						
CV13	0.39	23	160	33	8	2.7
CV12	0.38	10	73	88	100	21
PID7	0.28	18	119	75	50	14
PID6	0.53	22	183	150	100	37
PID5	0.16	91	558	107	20	8.9

9 APPLICATION TO DETERMINING THE EFFECTS OF RAINFALL ON PIEZOMETERS RESPONSE

The data obtained with four piezometers located in abutments of La Verne earthdam (France) were analyzed in order to assess the rainfall effect model (12). Two of the instruments were placed on the right bank (PZ17 and PZ14) and two on the left bank (PZ18 and PA4).

The effect of the water level was found to be instantaneous ($T_z \approx 0$). This finding still remains to be interpreted in the light of the structural and operational data available about this dam.

The model used accounted only satisfactorily for the variations observed (figs. 17 and 19). Since the drainage path was not known, it was impossible to interpret the parameters reflecting the effects of the rainfall.

When only the effects of the water level was considered, peaks were observed in the piezometric level corresponding to rainfall events (fig. 19). The graph on which corrected water level values were plotted shows that the rainfall model needs to be improved, since it showed only some of the peaks and hollows which occurred (fig. 20).

Although the delayed model (12) for the effects of the rainfall is still an improvement over the previously available models, the results are not as outstanding as those obtained in the case of the water level.

There are two possible reasons for this difference in the efficiency of the model between the two cases tested here: 1) the rain-water is not entirely infiltrated: the quantities of infiltrated and streaming rain-water depend the amount of rainfall, and on the slope and the permeability of the ground; 2) the path

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taken by the infiltrated water begins at the surface, and crosses an unsaturated zone, which it is difficult to account for using a linear model with a constant diffusivity coefficient.

Table 4. Effects of the rainfall: results of delayed response analysis of piezometer data. The effects of the water level were instantaneous (La Verne dam)

Piezometer	Water level effect	Rainfall effect	α	T_{Zx} (days)	T_{Kx} (days)	T_{Qx} (days)
PZ 17	60%	24%	0.32	0	273	38
PZ 14	54%	23%	0.14	0	147	53
PZ 18	62%	19%	1.00	0	815	39
PA 4	21%	52%	0.46	0	1016	32

10 APPLICATION TO DETERMINING THE EFFECTS OF THE WATER LEVEL AND THE RAINFALL ON PIEZOMETERS RESPONSE

The results of the analysis of the piezometer data obtained beneath the Chamboux dam (fig. 20) are summarized in table 5. Since the drainage path was not known, it was impossible to interpret the parameters.

This table gives some orders of magnitude. The rainfall certainly affected the readings obtained on some of the instruments. The response times to the rainfall were distinctly longer than the response times to variations in the water level.

Table 5. Effects of the water level and rainfall: results of delayed response analysis of piezometer data (Chamboux dam)

Piezometers	Water level effect	Rainfall effect	α_x	T_{Zx} (days)	T_{Kx} (days)	T_{Qx} (days)
PD1	87%	6%	0.77	5	77	39
PD2	53%	6%	0.33	4	33	19
PD3	21%	6%	0.21	3	24	13
PD4	17%	45%	0.04	0	54	52
PD5	12%	54%	0.05	3	76	34
PD6	24%	46%	0.09	0	106	54
PD7	86%	10%	0.85	7	156	66
PD8	21%	49%	0.20	30	198	65
PG1	88%	6%	1.00	3	109	63
PG2	73%	9%	0.30	5	34	16
PG3	23%	36%	0.07	3	39	22
PG4	16%	49%	0.05	11	54	40
PG5	32%	31%	0.71	3	608	83

11 CONCLUSION

Some important conclusions can be drawn from the results presented above.

The delayed response model accounted satisfactorily for seasonal effects on all the piezometric and pore pressure data analyzed. The delayed response model always yielded greater static damping of the amplitude α_x than the static HST model. This is consistent with the previous comment, since the present model takes the variations in the water level into account, whereas the seasonal variations in the piezometric and pore pressure data are not attributed to the variations in the water level in the HST analysis.

Underestimating α_x is not conducive to safety, and the use of the delay model is therefore a must from this point of view.

All instrument readings, whether they are obtained using cells set inside the structure of the dam or piezometers sounding the outside of the dam, the foundation, the abutments and the banks, are liable to exhibit delayed response effects.

The results obtained with the delayed response model were found to constitute an improvement over the previously available methods as far as the effects of the rainfall were concerned, but the results obtained on the effects of the water level were even more satisfactory.

The delayed response model can therefore be used to perform mechanical analyses of the data obtained using instruments set inside the structure of dams where the drainage path can be determined and where the rainfall has negligible effects.

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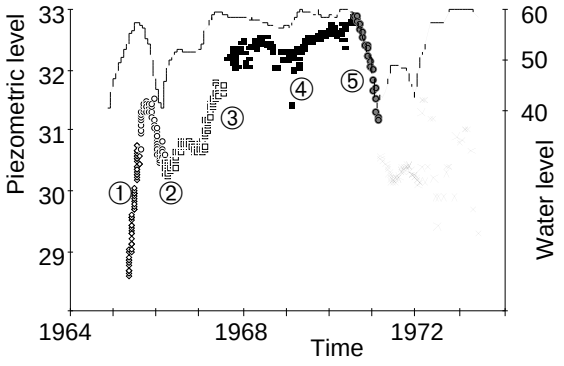


Figure 1. Example of piezometer data.

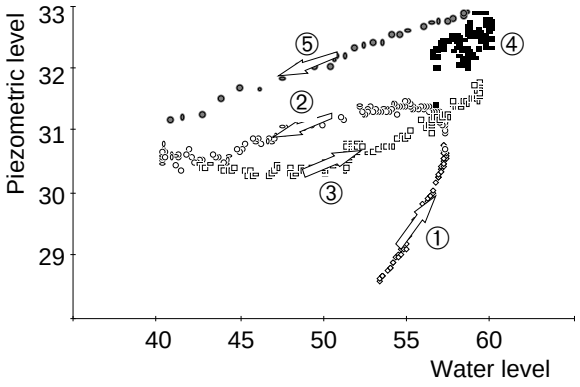


Figure 2. Piezometric head v.s. water level. The path taken as the water level rises and is not the same.

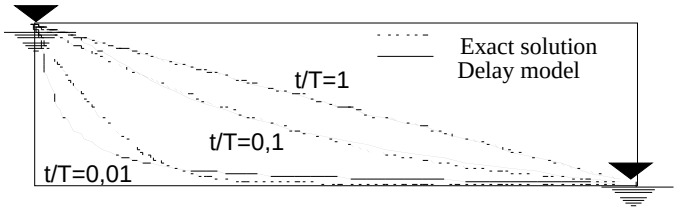


Figure 3. Validation of the delay model as compared to an exact solution, spatial profile of the response at several instants.

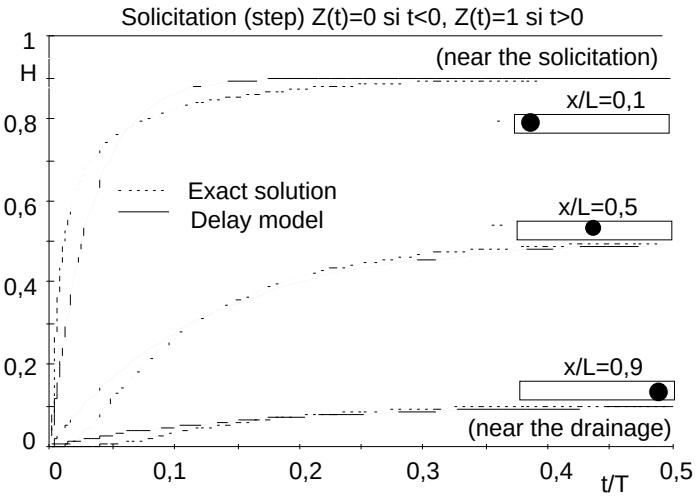


Figure 4. Validation of the delay model as compared to an exact solution, pattern of response with time.

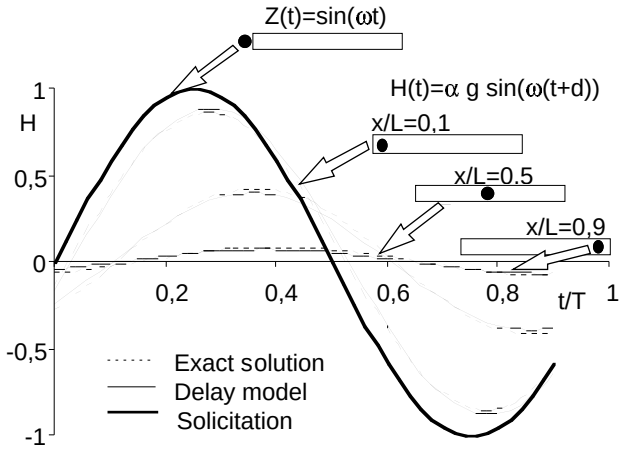


Figure 5. Validation of the delay model as compared to an exact solution, pattern of response to a harmonic variation of loading imposed by the reservoir level.

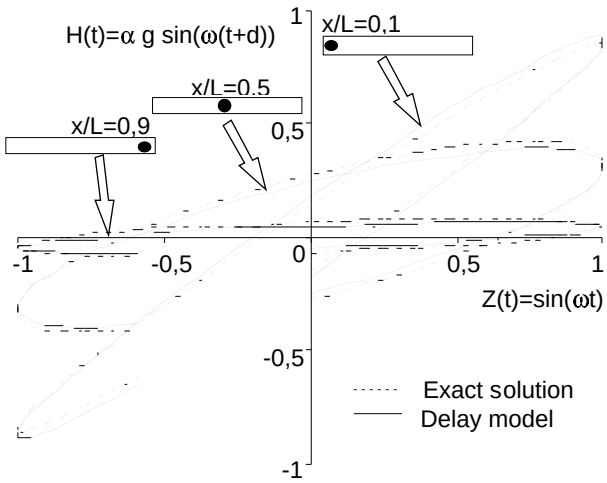


Figure 6. Validation of the delay model as compared to an exact solution, harmonic test, response v.s. solicitation.

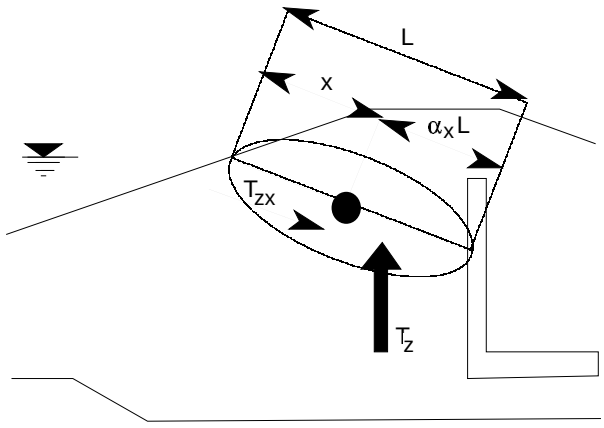


Figure 7. The parameters T_{Zx} and α_x can be specified for an instrument placed in the body of the dam.

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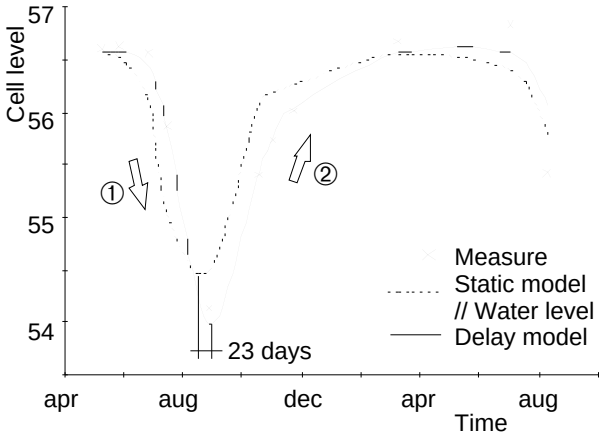


Figure 8. Example of data for a cell located in the body of the dam, cell level v.s. time. The delay is about 23 days.

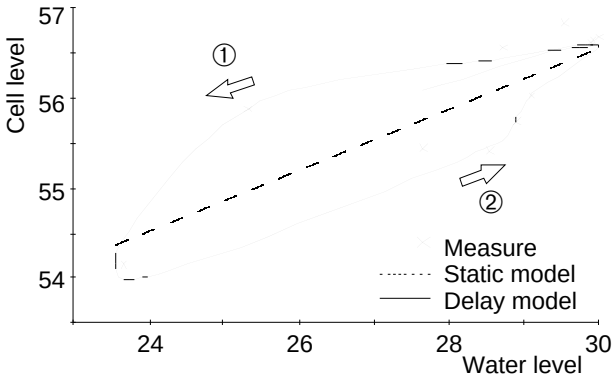


Figure 9. Example of data for a cell located in the body of the dam, cell level v.s. water level. The path taken as the water level rises (phase 2) and falls (phase 1) is not the same.

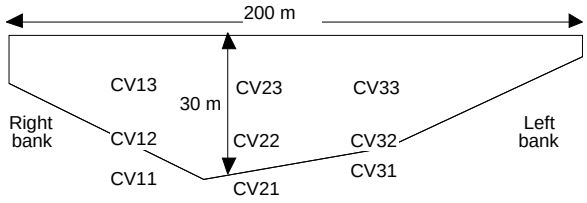


Figure 10. Location map of the cells, longitudinal profil from downstream (Alzitone dam).

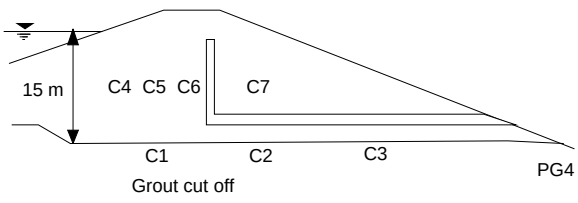


Figure 11. Location map of the cells, cross section (Chamboux dam)

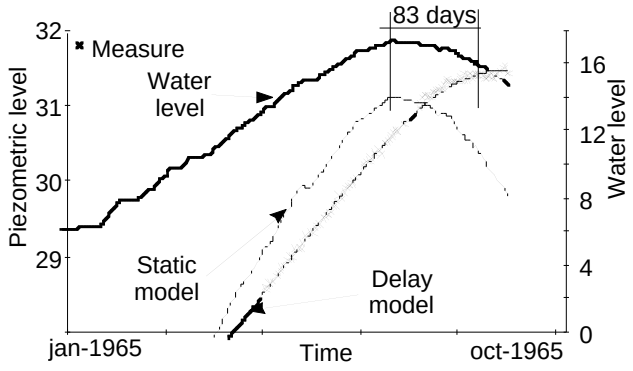


Figure 12. Delay analysis of P1 piezometer during the impounding phase, piezometric head v.s. time. The delay is about 83 days.

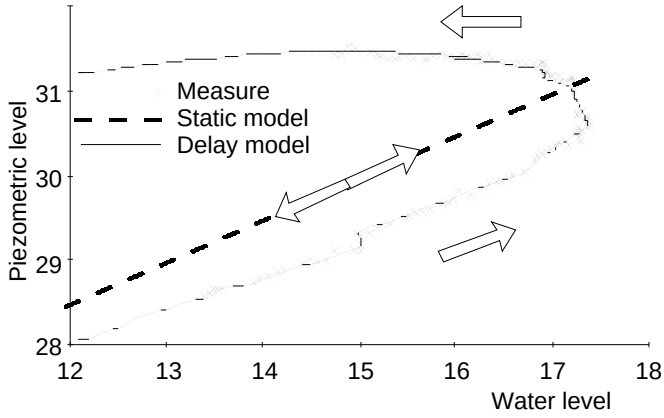


Figure 13. Delay analysis of P1 piezometer during the impounding phase, piezometric head v.s. water level. The path taken as the water level rises and falls is not the same.

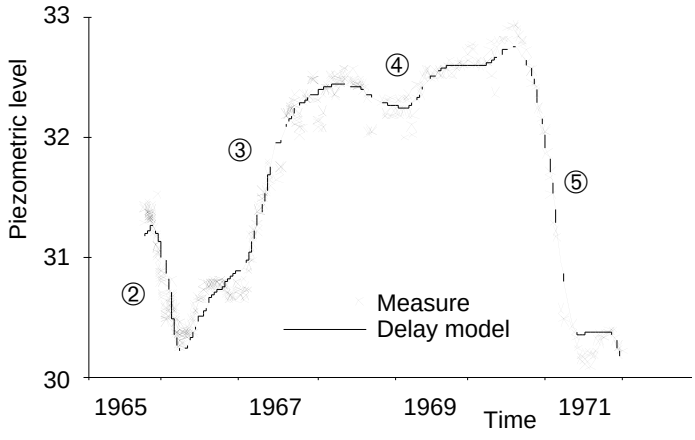


Figure 14. Delay analysis of P1 piezometer during the exploitation phase, piezometric head v.s. time.

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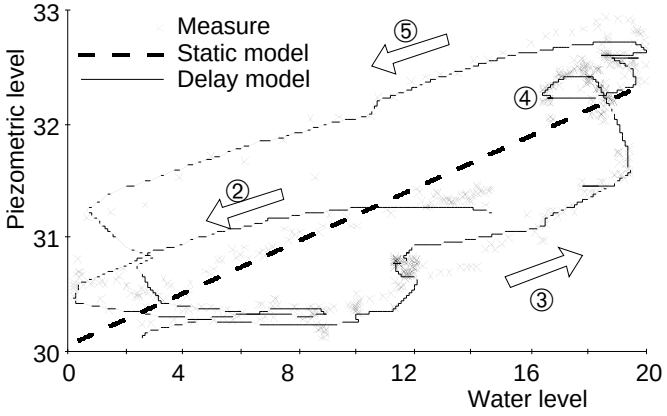


Figure 15. Delay analysis of P1 piezometer during the exploitation phase, piezometric head v.s.water level. The path taken as the water level rises and falls is not the same.

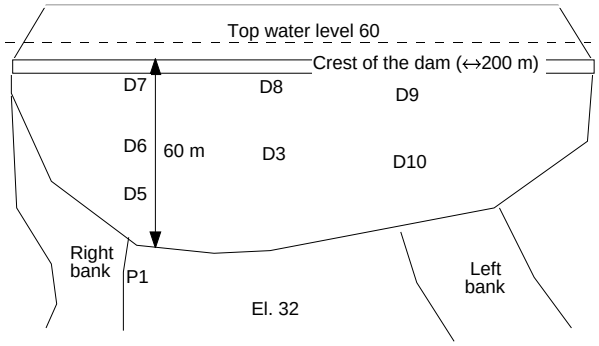


Figure 16. Location map of piezometers in the plan of the dam site (Alzitone dam).

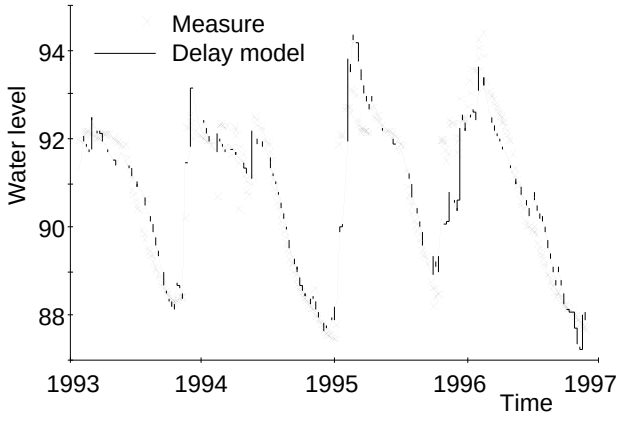


Figure 17. Delay analysis of PZ17 piezometer during exploitation, piezometric head v.s. water level (La Verne dam).

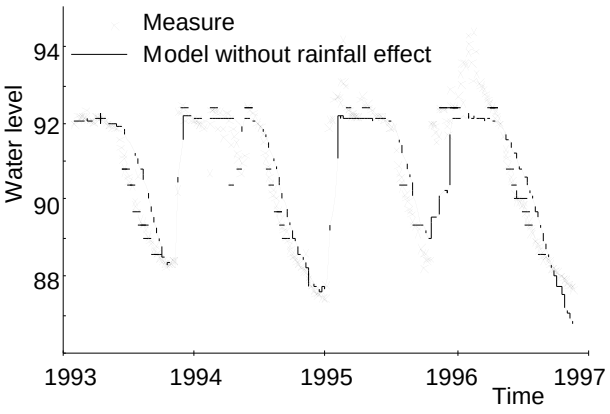


Figure 18. Delay analysis of PZ17 piezometer during exploitation without rainfall effect, piezometric head v.s. water level. Peaks were observed in the piezometric level corresponding to rainfall events.

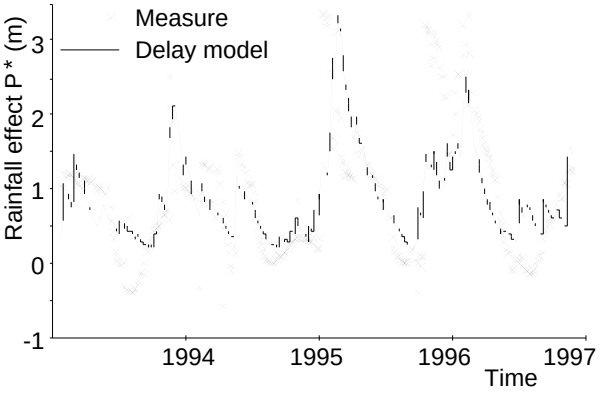


Figure 19. Delay analysis of PZ17 piezometer during exploitation, rainfall effect v.s. time

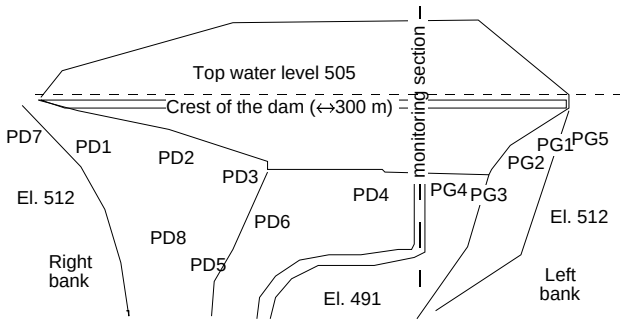


Figure 20. Location map of piezometers in the plan of the dam site (Chamboux dam).