Dam surveillance and maintenance - general approach and case studies

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English summary

In the first part of the paper the operational decision - making concerning dam construction is presented from a perspective of the system theory. The decision-making is done in definite conditions with given constrains. The conditions and constrains result from rules and laws of realisation and maintenance of technical structures and reciprocal reaction between structure and its environment. The objective is decision making which could assure the absence of damage from dam failure or breaking, or minimisation of losses resulting from preceding decisions. Another objective is minimisation of dam maintenance costs under the conditions of accepted risk. The system operations are done in a closed-loop. As an application the case studies of three Polish dams are presented.

Résumé français: *Surveillance et entretien des barrages. Approche générale et études de cas*

Dans le présent article, la prise de décisions concernantes des barrages est présenté sous la perspective de la théorie des systèmes. Les structures hydrauliques peuvent être considérées comme des systèmes situés dans une zone dont les caractéristiques plus ou moins sont connues. Ces objets sont sous l'influence de leur environnement et simultanément ils affectent leur environnement. L'identification et l'analyse des phénomènes se produisant dans une structure hydraulique et son environnant agissent en tant qu'opérateur. Les décisions (type et portée des travaux de réparation, paramètres des structures, et mode d'utilisation) agissent en tant qu'entrées. Comme application les trois cas de barrages - réservoirs sont présentés.

Streszczenie polskie: *Pomiary kontrolne i utrzymanie zapór. Ogólna metodyka i wybrane przykłady*

W pracy przedstawiona jest podejmowanie decyzji eksploatacyjnych dotyczących zapory z perspektywy teorii systemów. Decyzje podejmowane są w konkretnych uwarunkowaniach w obecności ograniczeń. Uwarunkowania i ograniczenia wynikają z praw i zasad rządzących realizacją i użytkowaniem struktur technicznych oraz wzajemnych oddziaływań struktury i jej otoczenia. Celem operacji jest wypracowanie decyzji zapewniającej uniknięcie szkód skutkiem awarii lub katastrofy zapory, albo zminimalizowanie nieuniknionych strat jako skutków wcześniejszych decyzji. Celem operacji może być również zminimalizowanie kosztu utrzymania zapory przy akceptowalnym ryzyku. Operacje dokonywane są w układzie zamkniętym. Przykładem zastosowania są trzy polskie zapory.

1. Introduction

Hydraulic structures could by treated as a system situated in a zone of which characteristics are more or less known. Those structures are under environmental influence and they also affect the surrounding. This interaction results in reaction under some constrains. Identification and analysis of those constrains is vital for the decisions quality. In the following paragraph we shall try to present this problem from the perspective of the system theory. The results of physical processes occurring in dams and their foundation create a database for risk analysis and for estimation of structures operation. The proper evaluation of the structure condition depends on the profound study of the processes and their course in space and the local intensity in time. This in turn influences the costs of studies and repair works. The evaluation of structure condition influences the decision making on future dam operation. The decision-making is limited by the certain constrains. The operational conditions result from rules and laws ruling the behaviour of technical structures and reciprocal reaction between structure and its environment. The decision-making should assure the absence of damages resulting from dam failure or breaking during the operational use. The damages also mean the effects of the operational use limitation of the storage reservoir caused by safety conditions violation for dam and terrain being under influence of reservoir failure. The risk could be measured and compared to the socially accepted one. The risk level is determined by product of the failure return period and losses caused by failure or disaster. The measure consists on cost of repair or reconstruction. The cost can be divided into direct ones – reconstruction (disaster) or shortage (failure) and indirect following the event. The acceptable risk level is connected with costs of safe maintenance of a dam. The decision making course is recurrent. The evaluation criteria consist on minimisation of undesirable effects.

2. Analysis of driving forces

Operations (operator F, see Fig.1) include the identification and analysis of events and prevision of their effects resulting from the decisions taken. The decisions belong to the set of inputs (U). In the set of outputs (Y) are effects of decision making. The final decision is made on the basis of outputs set analysis. From that set the subset of acceptable solutions is selected and from that one the most advantageous one is chosen.
A construction situated in the given site is under the influence of different forces and activities. The schematic presentation of these actions and reactions is given in the direction of vertical course (diagram 1). The basic conditions determining the decision space and constrains in decision-making are determined by physical laws and in the legislation. The decisions are influenced by habitual proceedings. These conditions and effects are shown in the upper part of the diagram 1. Reaction intensity could be evaluated in the space of reciprocal influences of a dam and its environment, schematically shown in the bottom of the diagram. The random factor causes that the decisions are made in the conditions of uncertainty. The uncertainty is connected with the time of event and a space distribution of factors characterising this event. It follows the discreet configuration of control measurements network in a dam and its surrounding. The convergence of different processes values, which affects a scale, and scenarios of their course are also random. The existence of the feedback can result in “operational thresholds” leading to failure or disaster. The feedback is shown, in the diagram 1, between the boxes 5 and 4. They are important for static and dynamic decision-making. In the static system the feedback is reduced to the recurrent decision search. In the

dynamic systems it leads to taking into a consideration the consequence of effects. The connection of the box 3 with box 2.2. shows a necessity of legislation, execution rules or operational instructions change. It should follow the experience obtained from work of many hydraulic structures. There could exists a need to complete the information concerning a dam construction and processes occurring in it and in its surrounding. Box 6 situated between operator 1 and decision set 4 includes archives of prior works, studies and previous decision-making.

Tools for decision assistance and methodology of use are included in the operator F. The operator encompasses all operational instructions starting from - location studies, designing, starting up, and operating with repair works and eventual reconstruction - to structure removal. According to the above scope the methodology is divided and adapted to the object status. Every stage of the object should be properly recorded. It is evident that the quality of archives is invaluable for decision quality. That was often underestimated in the engineering practice, what increased the uncertainty in decision-making. The introduction of the proper legislation should help in documentation collection and storage. History of decision-making is, along with the measurement and observation results, a basis for the consecutive supervision. The additive effects of the processes in the structure and its foundation determine the technical state of the entire structure. The structure durability depends on the conditions of the individual elements and, in particular, of the state of its weakest point. It can be situated in a dam or in the foundation. The location of that point and recognition of the degree of an unfavourable process development depend on the proper interpretation of the available data. When the standard observation data are not sufficient for phenomena explanation, the decision to perform the additional measurements could be taken. Because of the costs, such a decision should be taken when the decision making assistant methods are exploited. The prior experiences are important in following that process; the scope and costs of additional studies depend on them. The examples of such operations are as follows:

- Decisions concerning the kind and scope of studies
  - → Standard studies – described by instruction of use
  - → Special studies – adapted to the concrete needs
- Decisions concerning the works in a dam
  - → Maintenance according to the instruction
  - → Periodical repair works
  - → Major repair
  - → Special works dictated by a given situation
- Defining of design parameters
  - → According to the design plan
  - → Change of the parameters (periodical, durable) – for example: reduction of water head
- Decisions concerning the use of an object
  - → According to design plan
  - → Change of the use
  - → Periodical exclusion from operational use
  - → Emptying of the reservoir
  - → Proclamation of disaster

The above decisions are undertaken under influence of:

- Conditions determined by regulations and standards that may be:
  - → Invariable during the realisation and operation
  - → Variable in time
- Conditions of use determined by design
- Constrains following dam impact on its surrounding such as:
  - → Stresses in structure substratum
  - → Deformation of substratum
  - → Aquifers levels or pressures
- Influence of the surrounding:
  - → Action of useful load
  - → Consequence of atmospheric phenomena
  - → Exceptional loads (for example caused by uneven settlements)
- Faults and accidents
  - → Deterministic:
    - Disadvantageous location of dam axis,
    - Insufficient recognition of substratum
  - → Random
    - Local changes in a structure which are unforeseen, or impossible to foresee by standard methods
    - The same as above in substratum
    - Human errors

Cost of repair and protection works could be one of the measures of the above impacts and the constrains caused by them. Some of those impacts, especially the ones causing disasters, are very costly for the society. Such cases, very often provokes changes in legislation or design standards (loop 3-2.2.)

The presented criteria of the decision evaluation, which are shown in the set Y (box 5 in the diagram), admit limitation in the use of a dam. The optimal decision would be to maintain the safety without disturbing the reservoir operation.

Below the examples of consecutive operational decision-making are presented:

- Identification of points and causes internal pressures and leaks in a dam and foundation. Determination of time depending factors in seepage processes (water head action on surface water and aquifer, pressure gradients, intensity and location of leaks, piping effects etc.)
- Identification of strains (plastic, elastic…), progress and forecast of irreversible dislocations; spatial and time depending deformations and their relation to dam loading and seepage in a dam and foundation.

Other processes in a dam and foundations are treated in the same way, as follows:

- External deformation of the structure caused by the changes of atmospheric and water movements (water level, waves…); chemical reactions in the constructions materials; living organisms.
- External destruction caused by internal processes (local settlements, piping effect), washing out and deposition of chemicals, structure cracking, drainage system silting up…

- Special tests for identification of physical-mechanical processes taking place in the structure, for example tests ”in situ”, exploratory cores drilling, water absorption.

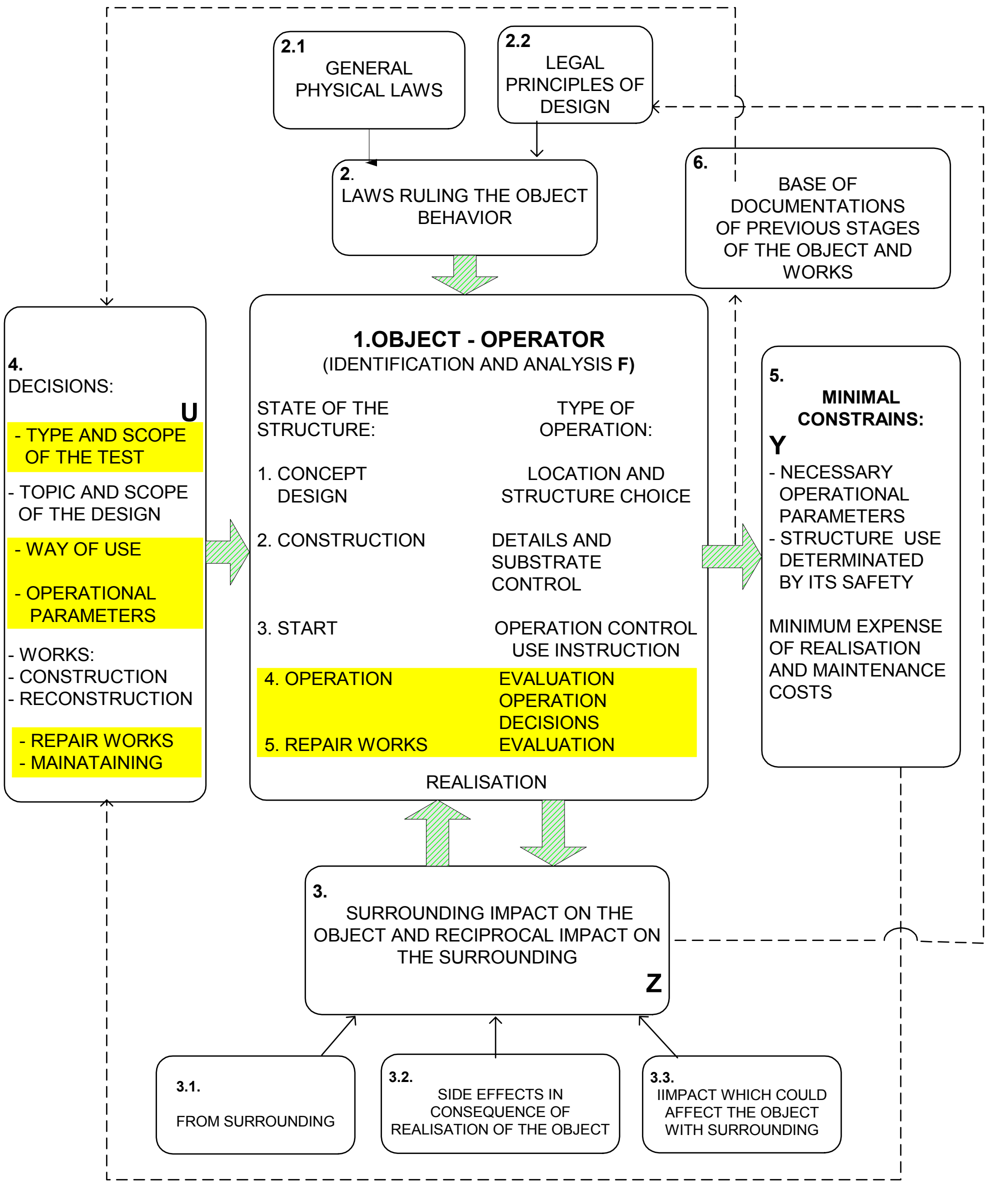

DIAGRAM 1. DECISION - MAKING IN DAM SURVEILLANCE

Furthermore during the decision-making preparation procedure are carried out:

- Test made for recognition of leakage preferential routes inside the structure, for example: tracer tests, chemical analysis, geophysical tests
- Analysis of above mentioned processes and their interactions inside the structure, scenarios for possible developments, computer simulations, risk analysis, decision making methods (Bayes) etc.

CASE STUDIES

We have chosen three dams Goczałkowice, Klimkówka and Wapienica to show the different problems of dam safety.

Fig.2. Location of the chosen case studies

Table 1. Dams and Reservoirs -Basic Data

Dam and reservoir	Goczałkowice	Klimkówka	Wapienica
Construction year	1956	1995	1932
River	Vistula	Ropa	Wapienica
Catchment surface	523 km^2	210 km^2	10 km^2
Height H	16 m	36 m	29 m
Length L	3000 m	210 m	290 m
Dam Volume V	1.04×10^6 m^3	0.4×10^6 m^3	0.65×10^6 m^3
Reservoir storage	168.40×10^6 m^3	43.50×10^6 m^3	1.1×10^6 m^3
Reservoir surface	32×10^6 m^3	3.06×10^6 m^3	$0,3\times10^6$ m^3
Dam type	Gravity - earth	Gravity - earth	Gravity -concrete
Use	Water supply, flood protection	Water supply, flood protection, tourism	Water supply

Geological structure of the dam site

The first recognition of the dam site was done in years 1948-1950. As it is seen in the fig.4 the dam is located on alluvium of very diverse layers granulation. There is a tectonic fault below the Miocene layers.

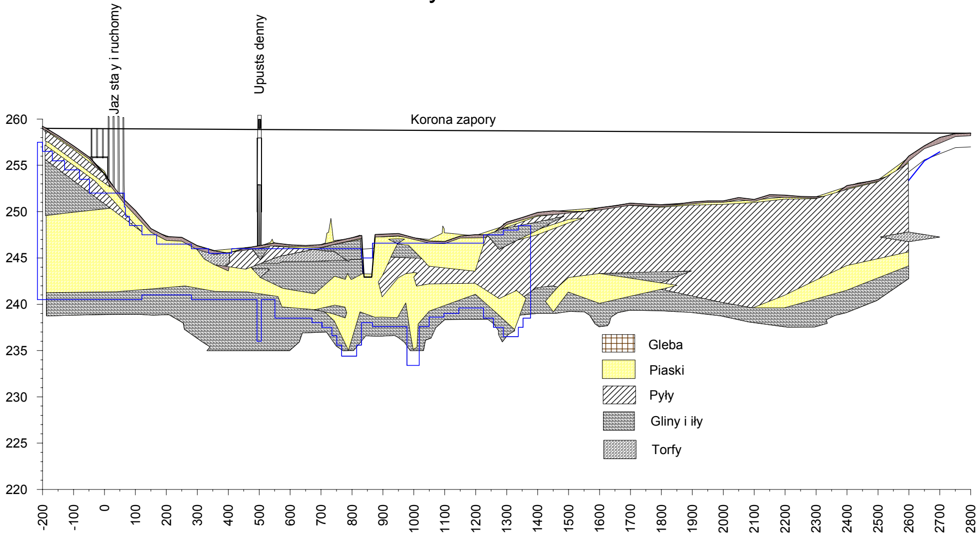

Fig.3. Geological structure of the dam site with one aquifer

The three ancient Vistula ox-bows (ancient riverbed) can be distinguished. According to this geological profile the sheet-pall wall was designed – steel one Larsen type. The sheet–pile wall reaching the quaternary silts and clays was supposed to close the first aquifer. In 1965-1990 the field investigations determined the position of the second aquifer (the artesian pressure in it is 3m higher than in the first one) which was very close to the ox-bows.

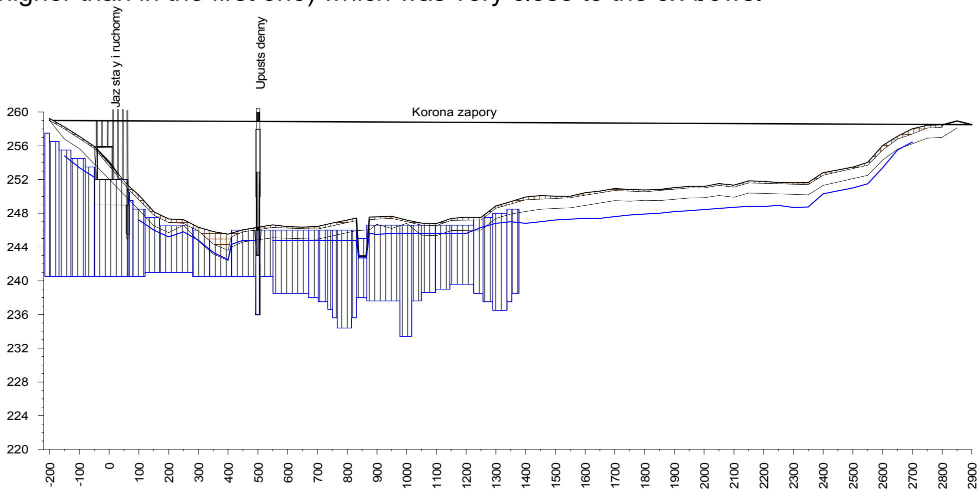

Fig. 4. Geological structure of the dam site with two aquifers

The dam structure

Goczałkowice Gravity Dam typical cross-section is shown in the figure 5

- The dam embankment is built from sand, to assure leakproof condition, in the northern part, by concrete screen (to the ox-bows) and in the rest by clay screen. On the whole lengths are filters and concrete slabs cover the surface. The sheet–pile wall exists only 1.390m along the dam.
- Water evacuation is performed by bottom outlets and spillway
- Downstream of the spillway are two weirs built after the dam construction.

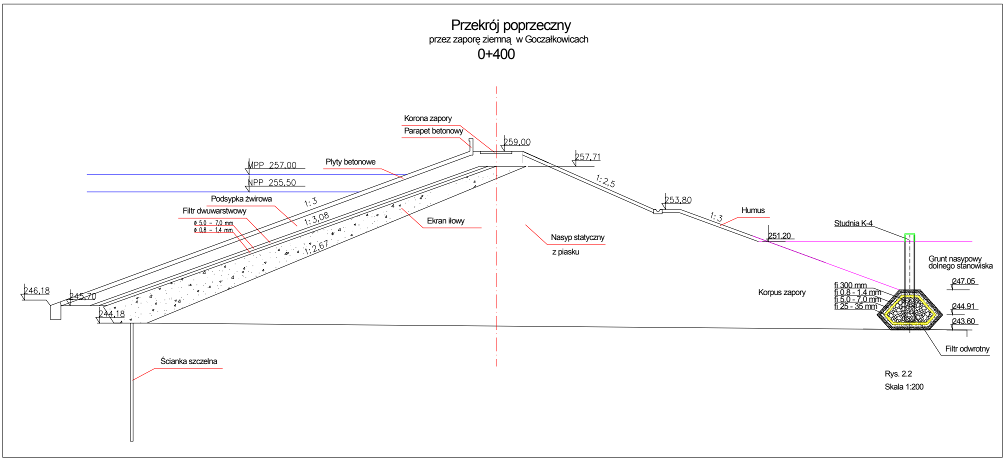

Fig. 5. Dam cross-section with clay screen

Problems existing in Goczałkowice dam and reservoir

- Local piping between the ox-bows and outlet downstream region;
- Stability of downstream region and river bed;
- Diversity in settlements;
- Reaction to the mining works in the vicinity;
- Limited stability of bench marks (extensometers)
- Local piping effect near pumping-over stations Podgrobel and Zarzecze and in trenches of side dikes.

Location of surveillance instruments

The structure and its surroundings are equipped with: bench-marks (extensometers) in the dam embankment; bench-marks in the vicinity of abutments and downstream region; cross-section with piezometers situated in the dam embankment; piezometers along the downstream side of the dam.

Field measurements results

The dam was surveyed from the beginning of the construction, surveillance covered:

- Routine inspection twice a year
- Inspection of the dam integrity and evaluation every 5 years.

The results of measurement analysis from the years 2000-2001 are herewith presented against the background of the previous data. The analysis was done for readings of piezometers in the dam embankment reaching the first aquifer and downstream reaching the first and the second aquifer.

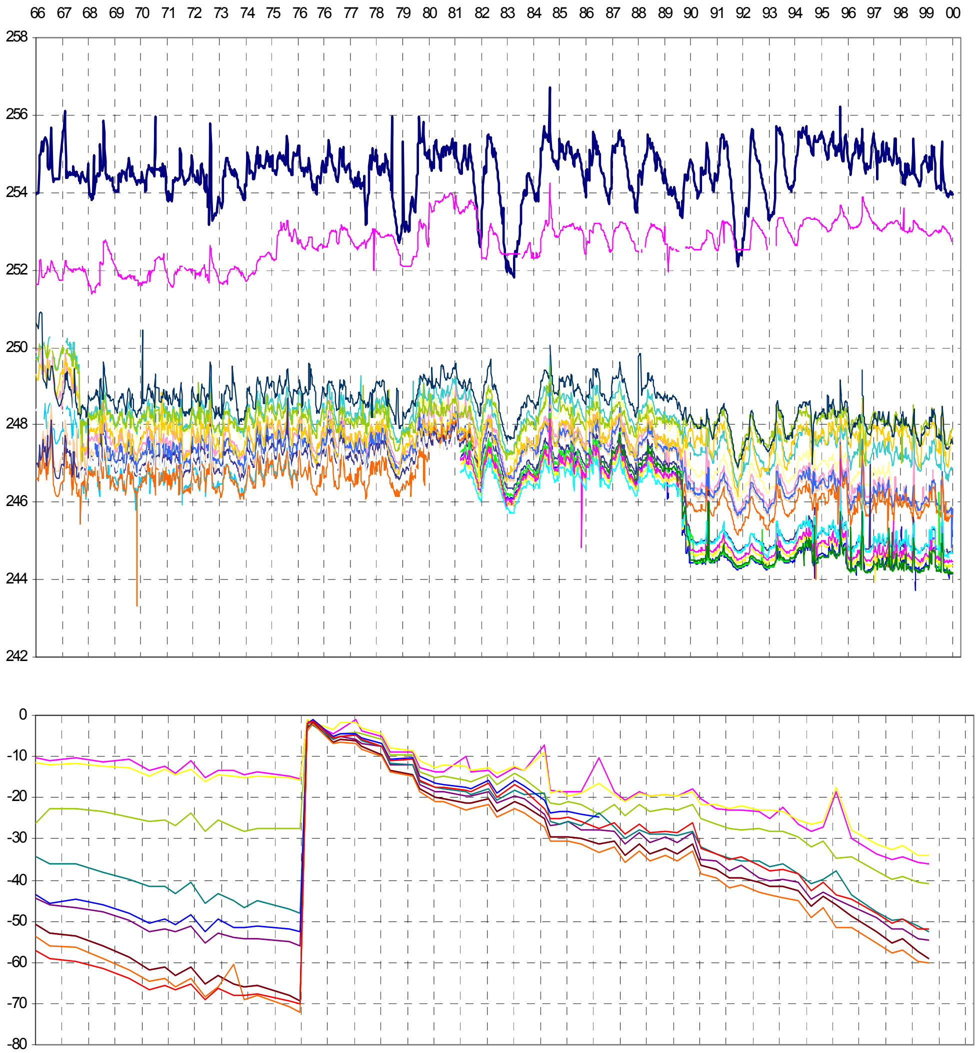

Fig.6 Reservoir level versus piezometric levels in years 1966 to 2001

A significant difference of the readings for the five cross-sections, where piezometers were placed in the embankment, was observed. An interaction between reservoir water level and piezometric levels in years 1966 to 2001 is shown in Fig.6. It could be seen, that in the year 1974 a rapid change appeared:

- The readings from piezometers situated in cross-section of the dam embankment and in the southern downstream side, showed high correlation between changes of reservoir levels and all piezometric levels. Therefore, it indicates a quick transfer of water head to both aquifers, where the pressures are rather high. For this reason we presumed that water from lower aquifer got inside the dam embankment. The stability was preserved owing to the relatively high altitude of downstream area.
- A completely different situation occurred in the piezometers located at bottom outlet where the piezometers' readings did not follow the changes of reservoir water head. The fluctuations were unexpected; it could be explain by the effect of downstream water on piezometric level. The piezometers downstream did not show unexpected fluctuations (fluctuations are corresponding to the reservoir water level). Therefore there is no piping between lower and upper level aquifers.

For the cross-section situated in the emplacement of the ox-bow the piezometric readings showed a close correlation to the water head in the reservoir. However, it is puzzling why these fluctuations are so big, while in the neighbouring cross-sections deviations are small.

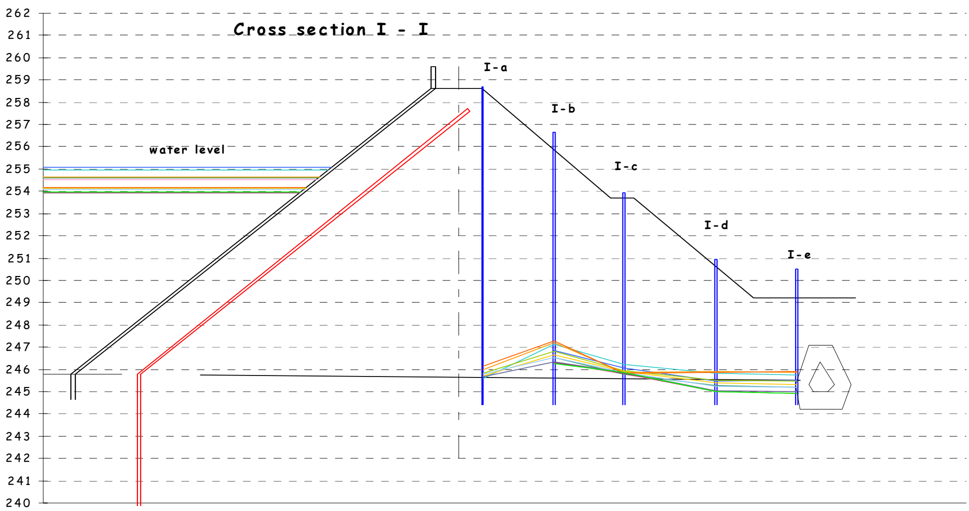

Fig. 7. Piezometric level fluctuations in I cross-section

Does exist piping from the lower aquifer? - That is a question:

In order to answer this question in the years 2000 and 2001 the additional studies were done, that resulted in a strong supposition of piping existence. However in order to affirm the existence of piping we need more precise measurements, that is the daily ones with simultaneous observations of precipitation and ground water levels. The daily observations and the knowledge of seepage routes would permit to use the French model of retarded reaction.

Settlements

Both these processes - the settlements and the seepage are closely linked, because of their influence on the stresses in the dam foundation (Fig.6).

In the graph we can observe the following increase of the benchmarks settlements in the dam crest:

- From March 2000 to August 2001 the settlements are weak;
- From March 1998 to August 1999 the settlements were 4 mm and were evenly distributed along the crest except the spillway area;

The sums of settlements calculated from the year 1974 gave maximum value of 65mm for benchmark 18 and 72mm for benchmark 20 (situated above the ox-bows) and for benchmark 13 (situated in the northern embankment near the bottom outlet shaft) as well. Generally the southern part (1,000m from the southern abutment) is characterised by bigger settlements (from 45mm to 72mm) than northern one (around 40mm)

Mathematical model

The results of the simulation of the internal porewater pressure development in time, shown in Fig.8., indicate the rapid increase of the pressures, it is confirmed by development of piezometric pressures which is followed by the deformation of the dam embankment (Fig.9).

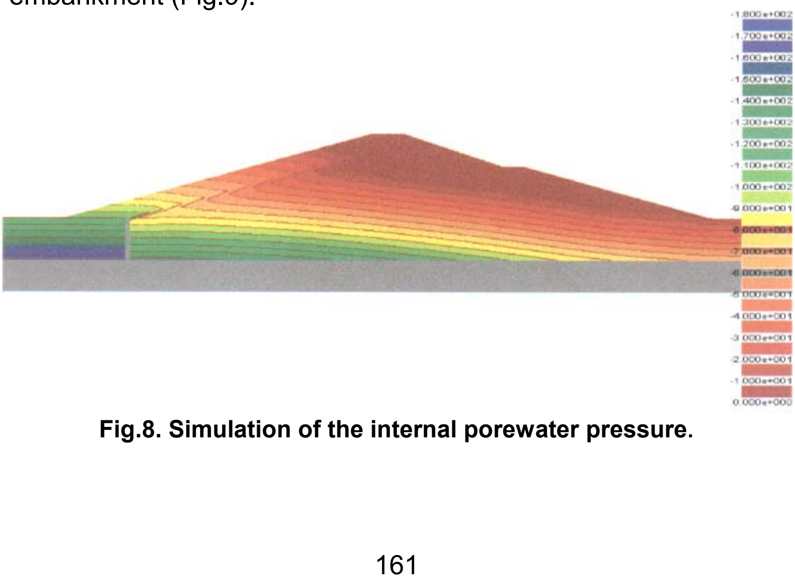

Fig.8. Simulation of the internal porewater pressure.

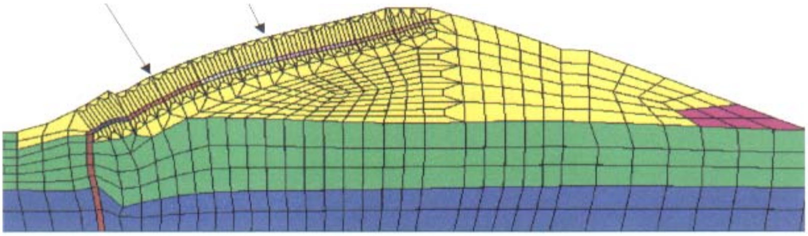

Fig.9. Deformation of the embankment

Conclusions

In order to identify the complicated system of two aquifers with the possibility of piping and high ground water pressures, it would be necessary:

- To design and install a piezometric network in side dikes and their vicinity;
- To perform daily observations of piezometers readings as well as precipitation and ground water levels
- To use more advanced mathematical models, which need the acquisition of broaden data base.

KLIMKÓWKA DAM AND RESERVOIR

Fig. 10. Klimkówka Dam General view.

Results of the field measurements

From the beginning the surveillance of the dam covered the following procedures:

- Routine inspection twice a year,
- Inspection of the dam integrity and evaluation every 5 years,
- The piezometric pressure measurements have been registered for the last 8 years (from 1994).

In 1997 the field test with the use of tracers was done. Only one piezometer near the right abutment showed the existence of the tracer. That allowed to calculated the seepage velocity =30m/day. In the following years, smaller amount of drained water was observed It was connected with the increase of the pressure in PRM-5 and PRM-11.

Problems existing in Klimkówka Dam

- Periodic increase of piezometric pressures is not connected with reservoir water level fluctuations.
- Seepage

The results of mathematical models for seepage and stability obtained by consulting engineers from Hydroprojekt

In order to analyse the seepage the Z-SOIL FLOW 2D model was used. The soil parameters – Darcy coefficient, were taken from the laboratory tests done during the construction of the dam. The computations were done for two cases of the downstream drainage. The influence of runoff from the slopes was not taken under the consideration. The results are shown in the fig. 12.

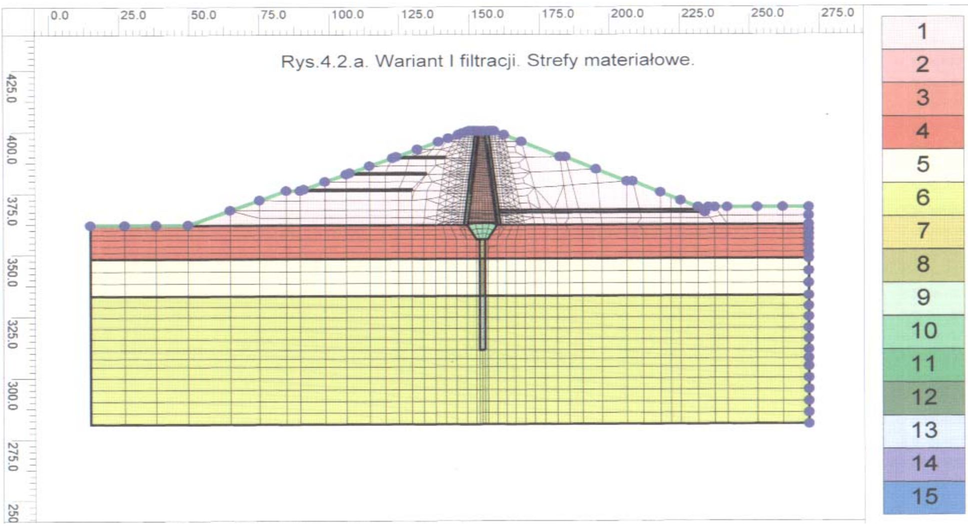

Fig.12. Seepage simulation

The dam stability computation was done with use of the GALENA model for two cross-sections. The soil parameters were taken from the laboratory tests done during the construction. For both cases the failure surfaces were the same and the stability coefficients n =2.21. The calculated coefficients are higher than the required ones for the construction of Ist class n= 1.67.

Conclusions

As a result of field investigations two different opinions were formulated, the first proposed additional injections, the second did not excluded the necessity of grouting but that decision should be preceded by additional measurements and observations.

Grouting curtain should not endangered the stability of the dam

1) Some problems could appear from the underground flow from slopes, which could saturated the dam embankment during the storm rainfalls.
2) Investigation should be continued in order to get information on the seepage routing

WAPIENICA DAM AND RESERVOIR

The old concrete gravity dam presents many problems, connected with the leakage through the dam and foundation - washing out of cement injection components (soft water). There were three series of injections during the last 70 years, every time the results are different. It is caused by changes of preferential seepage ways. The last series are done with slag binder better for alkali environment.

Problems existing in Wapiennica Dam

1. General view of the dam downstream side, which was already covered two times by cement revetment, we can observe the leakage of two colours – white resulting from washing out the cement sealing injections, the reddish-brown from the foundation. From the dam slope the calcium hydrocarbonate is washout causing the damages, also the surface corrosion is provoked by wet surface (seepage effect) and frost,
2. The spillway surface serious damages, the brownish-red traces are coming from the foundation bedrock (shiest with iron components), se can see that the water pressure uplift is very important.
3. The same effect in another place
4. Bore hole sample showing the badly chosen concrete granulometry (during the construction)
5. Expansion joint showing the leakage damages
6. Expansion joint showing the leakage damages coming from foundation.

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See the photographs following pages ⇨

WAPIENICA