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NEW ASPECTS WHEN ASSESSING UPLIFT PRESSURES UNDER GRAVITY DAMS (*)

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1. INTRODUCTION

The inauguration of the concrete gravity dam Dröda took place in 1971 [1]. The full supply level of the reservoir was achieved for the first time in 1987, thus 16 years later.
This was caused by was the uplift pressures measured during the different stages of the filling control of the reservoir, as every new increase of the reservoir level led to an exceeding of the predicted values and thus to problems proving dam stability.
These are still present in today's dam operation, particularly as water pressure and uplift pressure have to be taken into consideration according to the DIN regulations in case of heading up to the elevation of the crest of the dam. Maximum storage capacity was however only rarely exceeded when measuring values during dam operation.

For the subsequent presentation of this special problem, two facts are of importance:

1. In order to determine the design parameters, full-scale rock mechanic tests were carried out during the process of planning [2].
   - Determination of the vertical deformations $s_v = f(V)$ during the first experimental phase
   - Determination of the horizontal deformations respectively fracture conditions $s_h = f(H)$ (Fig. 2) during the second phase in order to determine the rock-mechanical shear strength parameters

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(*) *Neuves aspectes avec calcul de sous-pressions sous barrages*

$$\tau = \tau_o + \mu . \sigma,$$

with which the proof of safety against shear failure or sliding has to be furnished.

U = uplift pressure
$s_{v, h}$ = vertical or horizontal displacement
V = vertical load
H = horizontal load
τ = shear stress
τ_o = geotechnical cohesion
μ = friction coefficient
σ = normal stress
H_h = reservoir level

2. During construction of the dam a total of 189 stand pipes were installed into its foundation in form of an exhaustive net. Monthly measurements with manometers or tape measures take place.

2. THE DEVELOPMENT OF THE UPLIFT PRESSURE AS A FUNCTION OF THE STORAGE LEVEL

When control filling a reservoir and during the subsequent dam operation, one primarily makes use of the synchronous graph of the reservoir level, hydraulical and geodetic series of measurements.
But already when searching for simple relations, for normal behaviour patterns of the observed object and possible deviations from them, the reservoir level dependant graph and the analysis of these quantities remain the most important tools.
For the control of the reservoir level, the constant interpretation of the interplay between a gravity dam and its rock foundation, as well as the current evaluation and the prognosis of stability, the representation of the uplift pressure as a function of the reservoir level $U = f(H_h)$ is of exceptional importance.

Fig.1 illustrates the development of the uplift pressure at a survey point, which is situated 3 m behind the grout curtain at the heel of the dam in the centre of the valley.

In the initial phase of filling up the reservoir to approx. 430 mNN, a linear behaviour can be made out to a great extent. After that the imaginary curve climbs steeply with a strong curvature when damming up further. In the subsequent phases of drawdown and re-filling (6 - 9) relatively strict linear $U = f(H_h)$ conditions adjust as a function to the amount of the so far not yet dammed levels, which in every higher U-level in hand move towards the boundary condition $U = H_h$. The originally small uplift pressure is not achieved throughout the entire later dam operation again. It becomes apparent that the prognosis of the uplift pressures within the not yet dammed areas can only happen according to the curve, which is formed by assignment of the measured uplift pressure to the first time achieved reservoir level (illustrated in Fig. 1 as fat line o**—**o**---**). This curve also covers all value pairs from the entire dam history at the same time.

Graphically the curve can usually be illustrated as a bent line proceeding upwards; here with a sharp bend and subsequent straight line.

3. COMPARISON WITH THE LOAD-DISPLACEMENT CURVE OF THE FULL-SCALE SHEAR TEST. INTERPRETATION OF THE HYDRAULIC AND GEOMECHANICAL PROCESSES

Fig.2 shows a continuously increasing rate $\Delta s/\Delta H$ by rising horizontal load. Simultaneously it illustrates a constant increase of irreversible (plastic) shift portions in contrast to the reversible (elastic) ones. After initial closing of open joints, fracturing begins to increase. The increasing load spreads over larger areas of the rock mass and these are also implied by the aforementioned consequences.
Finally the covering load-displacement curve asymptoticly approaches the breaking load studied in the test phase.

The load-displacement curve s = f(H) and the reservoir level dependant uplift pressure curve $U = f(H_h)$ do not only resemble to each other on the surface, they are also related to each other in a physical sense.
In strongly jointed, water-permeable rock masses, the behavior of the uplift pressure corresponds to the relation of loose rock (known from soil mechanics) to a large extent; the uplift pressure decreases from the headwater to the tailwater level in a linear manner. If only limited jointed rock mass and unfavorable geological structural characters are present at the downstream toe of the dam and if the existing joints are filled with cohesive material, so that only a weak or no drainage is possible ("hydraulic barrier"), then this can result in a building-up of high uplift pressures in combination with changing characteristics of the grout curtain, whereby the uplift pressure often only decreases on a long-term basis.

In this present case such type of conditions exist:

- The phyllitical clay schist shows substantial quality differences in all areas of the rock foundation and towards its depth
- Strong dispersion of the geological structural parameters
- Compact and little jointed rock mass almost in the middle third between the upstream and downstream face of the dam; contact-metamorphic hardened schist, very strong and compact
- Towards the upstream face, jointed and structurally wrecked; with broken and partly sealed rock; accumulation of joints filled with loam and quartz

So if the reduction of water-pressure within the joints is thus obstructed, the water will try to spread into areas wherever it finds the possibility to do so.
A reduction of the compressive stress resulting from dead load will occur at the same time as an increase of water and uplift pressure within the area at the heel of the dam, and the density of the latently existant, but previously pressed joints (by the dam load) will diminish.
Under the conditions of varying deformation characteristics in the building-grout curtain-subsoil system, overturning, displacement and deformations may occur.

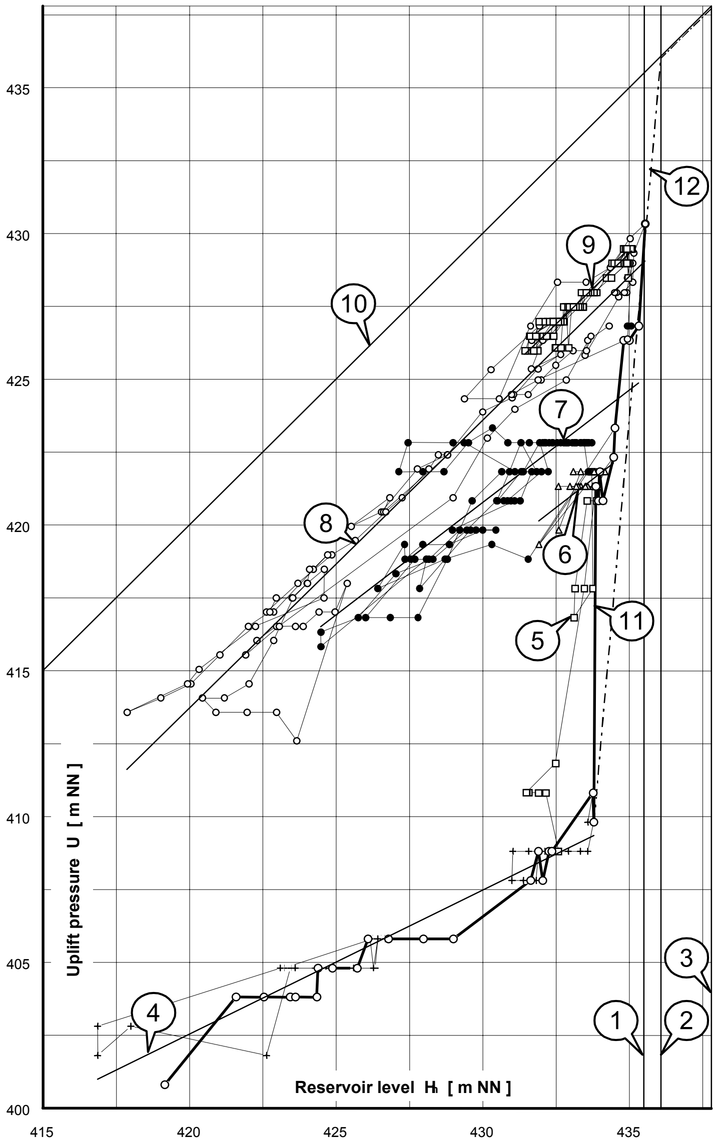

Fig.1
Gravity dam Dröda - Development of uplift pressure dependent on water level
Barrage-poids Dröda - Développement de la sous-pression dépendant de niveau du lac

1	Full supply level	435,50 m NN	
2	Maximum water level (1000 year flood)	436,08 m NN	
3	Elevation of top water level	437,80 m NN	
4-9	Measuring sequences H_h/U with trending lines for chronologically water level phases (of it 6-9 phases of drawdown and re-filling)		
4	02/72 - 08/76	$U = 0{,}494 \cdot H_h + 195{,}2$	R=0,96
5	08/76 - 11/77 (Phase first loading)		
6	12/77 - 12/79	$U = 0{,}778 \cdot H_h + 84{,}3$	R = 0,71
7	01/80 - 09/87	$U = 0{,}771 \cdot H_h + 89{,}2$	R = 0,85
8	10/87 - 01/96	$U = 0{,}987 \cdot H_h - 0{,}7$	R = 0,98
9	02/96 - 07/99	$U = 0{,}968 \cdot H_h + 8{,}1$	R = 0,97
10		$U = H_h$	
11	Sequence H_h/U for reservoir levels H_h achieved for the first time		
12	Line for extrapolation on maximum water level (upwards limited by $U=H_h$)		

1 *Retenue normale (RN)*
2 *Niveau maximal (crue millennale)*
3 *Cote du couronnement*
4-9 *Suites de mesures H_h/U avec lignes de équasion de regression pour phases H_h/U chronologiquement suivantes (en 6-9 phases de creux et reremplissage)*
5 *(Phase première poids)*
11 *Suite H_h/U pour la première fois observé H_h*
12 *Ligne pronostique pour niveau maximal (haute limite par $U=H_h$)*

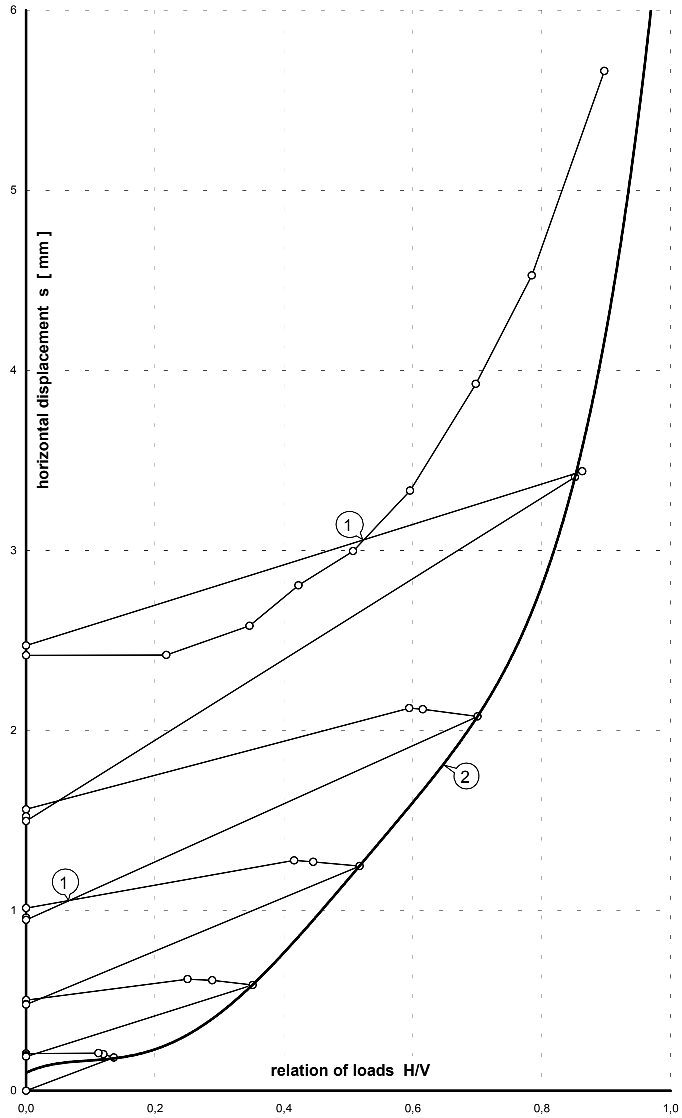

Fig.2
Gravity dam Dröda - Rock mechanic full-scale shear test – Diagram
Barrage-poids Dröda - Mécanique des roches essai de cisaillement in situ - Diagramme poids/déplacement

1 Loading cycles in the test
2 Sequence H/V / sh for relation loading H/V achieved for the first time

1 Cycles du relation du poids dans le test
2 Suite H/V / s_h pour la première fois observé relation du poids H/V

Locally this can lead to cracking and possibly to breaking of material links between the rock fragments and finally -as in the present case- to failures in the grout curtain.

The entirety of these processes correspond to fracturing in the $U=f(H_h)$ curve, which cause the progressive displacements in the load-displacement-curve of the full-scale test.

The so-called "gaping joint" according to the regulations for stability calculation (e.g. DIN 1054) may ensue as a final state from this, which then has to take up the full uplift pressure according to the reservoir level ($U = H_h$) to its theoretical end. That way an uplift pressure can amount, which lies over the linear connecting line between reservoir and tailwater level.

4. ADVICES FOR FURTHER ANALYSIS AND MONITORING OF THE UPLIFT PRESSURE

Due to the possible very different qualitative and quantitative $U=f(H_h)$ relations, the covering curve represented in Fig. 1 should be deduced separately for each individual survey point. Looking at the question of proving stability, an extrapolation to the reservoir level according to the prevailing standard (in Germany top water level, maximum water level, maximum water level plus freeboard) can be made at every single curve. The complex analysis of all measurement results of a dam profile or section of the dam results in the load picture for the uplift pressure (Fig. 3), which is integrated into the computational proof of stability.

In the special case of the Dröda dam the complex evaluation of the entire dam proved no serious stability problems to be present.

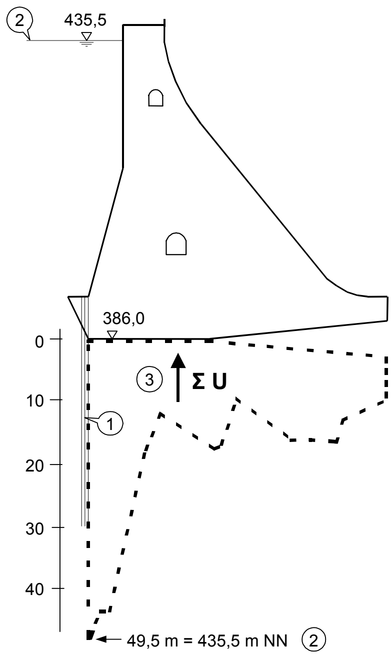

Fig.3
Gravity dam Dröda - Cross-section at valley with uplift pressure distribution (load picture) at full supply level
Barrage-poids Dröda - Profil en vallée avec distribution des sous-pression (image du poids) à retenue normale

1 Grout curtain
2 Full supply level
3 Load picture uplift pressure

1 *Écran d´injektion*
2 *Retenue normale (RN)*
3 *Image du poids sous-pression*

In order to avoid uncontrollable structural and hydraulic redistributions of stress causing critical situations for the stability during the first reservoir filling and during dam operation, intensified monitoring measures should be initiated with every increase beyond an achieved reservoir level (measurements of the uplift pressure and selected measurements of geometrical dimensions in quick succession, as continuously as possible with immediate analysis; visual observations).
A rapid reservoir filling within the area of the highest upstream water level so far should be carried out with care.

We do not know the prehistory of uplift pressure with older gravity dams. It is only in recent time that supplementary measuring instruments are being installed. Very often they are not surface covering, but just in a few cross sections of the dam. Graphic or computational extrapolation of the unknown reservoir level area is then substantially made more difficult and the editor is left to apply the experiences won at other dams to an appropriate estimation.

5. ADVICES FOR SANITATION TO REDUCE HIGH UPLIFT PRESSURES

The fact that fracturing caused by reservoir elevation may also affect an existing grout curtain, requires suitable sanitation measures should the occasion arise.
The crossing point of the grout curtain of the dam into the rock mass is to be regarded as the particularly endangered area. Secondary groutings within the pressure loaded joints and cracks could be carried out with a soft-elastic sealant in such cases. These should not only include the small area of the curtain base, but a broader transition area (e.g. by fan-shaped borings starting from the inspection gallery). This should make it possible to put the grout curtain, which probably is still intact in the direction of the depth, back into working order again for further decades.

We regard the upstream grout curtain to be an appropriate method in order to reduce high uplift pressures. Drainages arranged behind the grout curtain can be a useful supplementation. An exclusive arrangement of drainages, particularly with high potential gradients and thus provoked strong flow, is not advisable due to the danger of negative effects on the structure of the rock mass in approach and during dam operation.

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SUMMARY

The technical status of the monitoring equipment as well as the computational and graphic computer analysis allow us to gain an insight into the connections and interrelations between a dam and its foundation rock, which -for all questions of stability- are of great importance.
The experiences derived from monitoring results of many years and of particular dams can also be used for monitoring and operation of others dams.

After several phases of premier and repeated reservoir filling, the direct linear relations between reservoir level and uplift pressure expected at first did not show up at the observed object, but apart from reversible uplift pressure increases also very high irreversible portions, which made initial prognosis of further developments substantially more difficult.

Following is to be noted as result of the analyses: Prognoses of reservoir level areas which up to now have not been damed up require a curve, which results from the sequence of reservoir levels achieved for the first time together with the appropriate measured uplift pressure. It indirectly reflects the hydraulic situation in the rock foundation and can have very different qualitatively and quantitatively appearances from survey point to survey point already within distances of a few meters.

The method is universally applicable, particularly as the "normal case" of an unaffected uplift pressure reduction is included as borderline case.

RÉSUMÉ

Le niveau technique des instruments de la surveillance et de l´analyse de l´ordinateur par voie de calcul et graphique permit des connaisances des connexions et des interactions entre une barrage et leur rocher de fondation. Ces ont une grande importance pour toutes questions de la stabilité.
Les expériences avec la surveillance pendant beaucoup des années sont utile pour la surveillance et l´exploitation d´autres barrages.

Après plusieurs phases de la remplissage et baisse de niveau les relations direct entre niveau du lac et sous-pression n´étaient pas observés. Mais des intensifications réversibles et permanent de la sous-pression rennent plus difficile les pronotices du developpement.

Il s´ensuit qu´une courbe est valable jusqu´à la zone sur le niveau du lac.
Cet courbe est le resultat des interactions entre chaqun niveau du lac pour la première fois observé et la sous-pression.
Elle indirect reflète la situation hydraulique dans le rocher de fondation.

La methode est universellement valable et elle aussi content le „cas normal“ de la sous-decompression tranquille comme le cas limite.