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ARCH EFFECT OF CURVED GRAVITY DAMS (*)

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1. INTRODUCTION

Since 1890 more than 80 gravity dams have been constructed in Germany. The oldest dams are massive masonry structures built of quarry stones. However beginning in the 1930s, concrete was chosen over masonry as the preferred method of construction. Gravity dams resist external loads by virtue of their own weight, and are often designed with a slight bend. In Germany, one safety requirement for existing dams is that they are subject to so-called "In-Depth Hydraulic Structure Examinations" at regular intervals. The examinations include stability analysis for cases in which input parameters have changed, or if the former calculation methods applied are no longer considered state of the art. These computations require a wide range of load cases with different combinations of impacts and resistance conditions.

Today it is common to use the finite element method (FEM) to investigate dam stability. The question arises as to which extend 2-D models deliver adequate results, or whether 3-D modelling is necessary to model slightly bended gravity dams to considering the arch effect and lateral load transfer into the valley

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* *Effet de voûte aux barrages-poids*

walls. 2-D models have the advantage that it is easier to represent the dam geometry because detailed information about the topology of the foundation is often not available. Furthermore, the computational effort for 2-D models is significantly less compared to 3-D approaches, which can be decisive when calibrations of the model or sensitivity analysis are additionally required. This article investigates the effect of curved gravity dams on the structural safety. A case study is curried out with the FEM program ANSYS to compare the results of 2D and 3D simulations for different dam sizes and valley shapes.

2. MODEL DEVELPMENT

2.1 GEOMETRY

The model geometry of the dam and the foundation is shown in Fig. 1. The dimension of the considered structures is geared to typical German gravity dams. Dam heights vary from 30 m to 110 m and the radius of the dam curvature ranges between ∞ (straight-lined crest) and 100 m for small dams. Fixed dimensions were also assigned: the crest width at 6 m, the slope of the upstream face of 0.03:1 and the slope of the downstream face of 0.70:1. The ground curtain has a length of H/5 and a width of 2.5 m. To avoid boundary condition effects, an adequate expansion of the foundation depending on the dam height H according to Fig. 1 is selected.

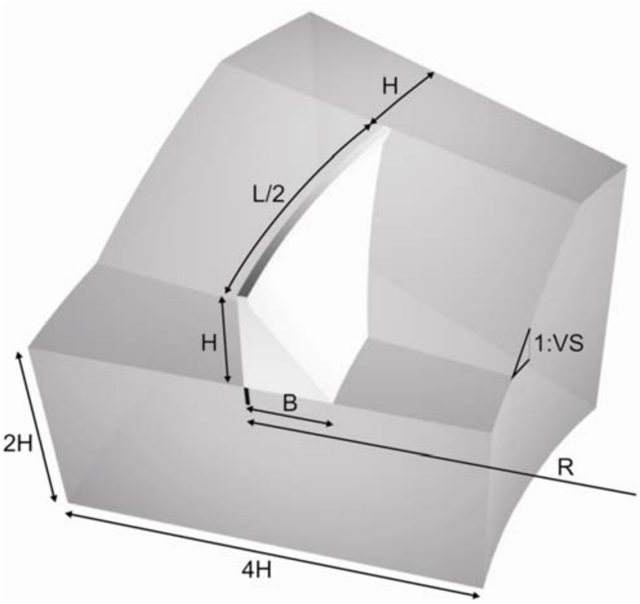

Fig. 1
Model geometry: H dam height, L crest length, R radius of curvature, VS valley slope

Géométrie du modèle, H hauteur du barrage, L longueur de la crête, R radius de la courbure horizontale du barrage-poids, VS pente de la vallée

2.2 DISCRETIZATION

To define the required quantity of elements, reference simulations with different element sizes are carried out. Fig. 2 shows the final mesh. The disctretization of the foundation is courser, to achieve improved computing times. For the same reason the axial symmetry of the structure is used as a boundary condition and only the half geometry is modelled. The older gravity dams in Germany do not have temperature joints so they are not implemented in the model. Permanent deformation joints would impact the spatial structural performance of the dam.

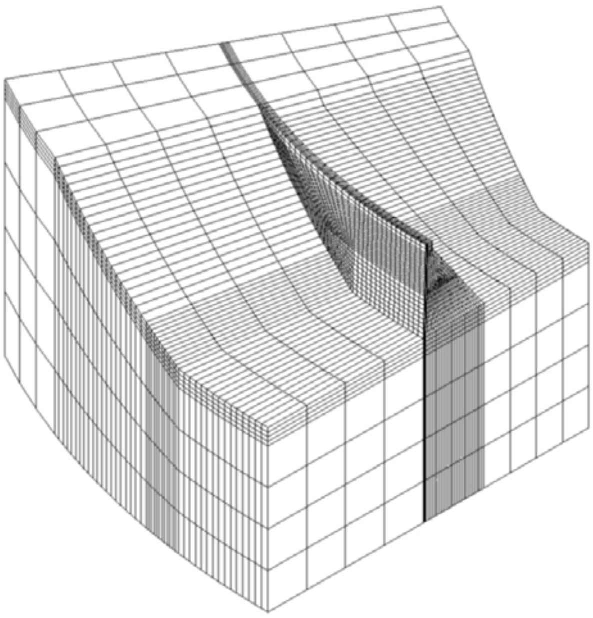

Fig. 2
3D Model showing finite elements
Représentation du maillage des éléments finis du modèle

2.3 MATERIAL PROPERTIES

Table 1 lists the specific values of the materials applied in the model. Here the assumption is made that the dam and the foundation have the same properties, excepting the permeability.

Table 1
Material properties
Propriétés des matériaux

Density ζ [kg/m³]	2400
Elasticity module E [N/mm²]	26000
Poisson's ratio υ [-]	0.2
Compressive strength σ_C [N/mm²]	15
Cohesion c_i [N/mm²]	2.5
Friction angel φ_i [°]	45
Thermal conductivity λ [W/(mK)]	2.1
Thermal capacity c [J/(kgK)]	1100
Coefficient of thermal expansion α_V [K^{-1}]	$6 \cdot 10^{-6}$
Permeability Rock k_R [m/s]	10^{-6}
Permeability ground curtain k_G [m/s]	10^{-7}

2.4 LOAD EFFECTS

The water level is applied equal to the crest level of the dam.

To simulate the underground flow with ANSYS, the heat analogy is used. The water level above grade evaluation equates to the temperature and the permeability is equivalent to the thermal conductivity. It is assumed that the sealing and drainage system of the dam is operational so there is no seepage inside of the dam body. The results of this computation step deliver flow forces in the foundation and uplift pressure on the dam basement.

Beside water loads, the ambient temperature affects the dam structure. To get the resultant temperature development inside the dam, a thermal analysis with a total calculation time of 12 years with a time increment of one month is executed. The used monthly air values and the water temperature dependent on depth is plotted in Fig. 3. In July occur low temperatures in the interior of the dam and high temperatures on the surface. This difference leads to the high compressive strength at external zones of the contact area, so the temperature development of July is used for further analysis.

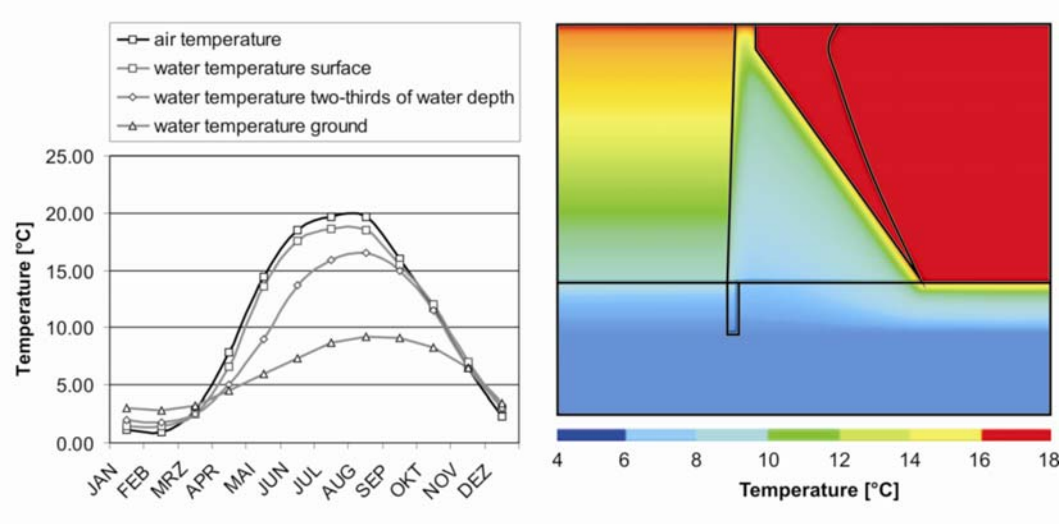

Fig. 3
left: Seasonal ambient temperature; right: temperature development July
Gauche: température ambiante saisonnière droite: développement de température en juillet

2.5 STABILITY CRITERIA

For all individual simulations, the dam safety is analysed with the following three criteria at the base area.

2.5.1 Principal Compressive Stress

The safety factor for permissible principal compressive stress is defined as the quotient of the compressive strength σ_C and the calculated maximum principal compressive stress σ_3:

$$FS\ compressive\ stress = \frac{\sigma_C}{\sigma_3} \quad [1]$$

2.5.2 Sliding

The acceptable safety in relation to sliding valuated with the shearing strength properties. The permissible shear stress is estimated by Coulomb's friction law, defined by the cohesion c_i and the tangent of friction angle φ_i multiplied with the averaged normal stress σ_a:

$$FS\ sliding = \frac{c + \sigma_a \cdot \tan(\varphi)}{\tau_a} \quad [2]$$

2.5.3 Overturning

The dam is considered to be safe against overturning, when the eccentric resulting e does not exceed the middle point of the base by a value of 1/6 of the base length B. The safety against overturning is described with the following criteria:

$$CS\ overturning = \frac{B/6}{e} \qquad [3]$$

3. SIMULATION RESULTS

3.1 IMPACT OF THE VALLEY SIDE

The influence of the valley side on the structural behaviour of dams with a straight-lined crest is investigated first (β = 1, compare section 3.2). Fig. 4 shows the vertical compressive stress along a path at the dam foundation for a 70 m high dam. The black line indicates the results of the 2D-Simulation. Due to the temperature development of the summer, external zones upstream and downstream at the base area have increased compression stress. The other curves shows the outcome of the 3 D simulations with varying ratio α between crest length L and dam height H (α = L/H) and a valley slope of 1:0.6. Dams with a relatively short crest length transfer the loads not only in the foundation, but in some extend lateral into the valley. That leads to lesser contact pressure especially at the downstream part.

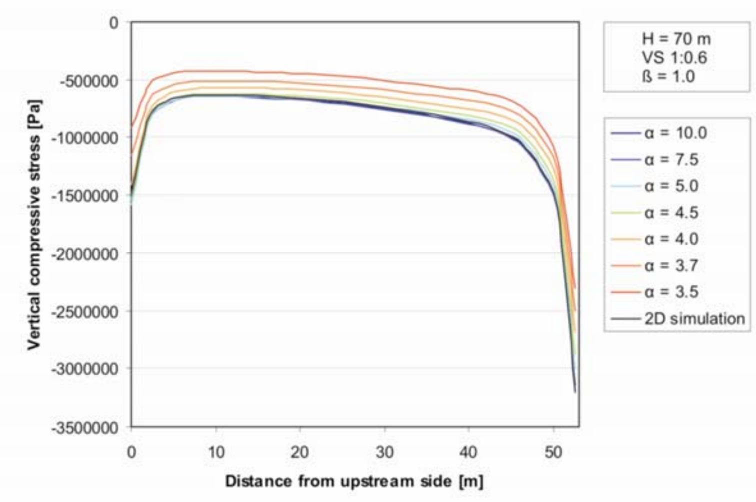

Fig.4
Vertical compressive stress for 70 m height dams with a valley slope of 1:0.6 and a variegated ratio α = L/H

Contraintes de compression verticales d´un barrage de 70 m d´hauteur avec une inclination de pente de la vallée de 1:0.6 et un rapport α = L/H variable

The impact of the valley width on the stability criteria is illustrated in Fig. 5. The 2-D simulations show that higher dams have a lower safety factor in relation to principal compressive stress and sliding. The location of the resulting force relating to the base length however is similar independent from the dam height. 3D computations with a ratio α greater than 7.5 deliver comparable results to the 2D simulations. The altered stress distribution of dams with smaller α lead to minor principal compressive stress and a better safety against sliding. The safety against overturning in contrast can be lesser especially for dams with a smaller height.

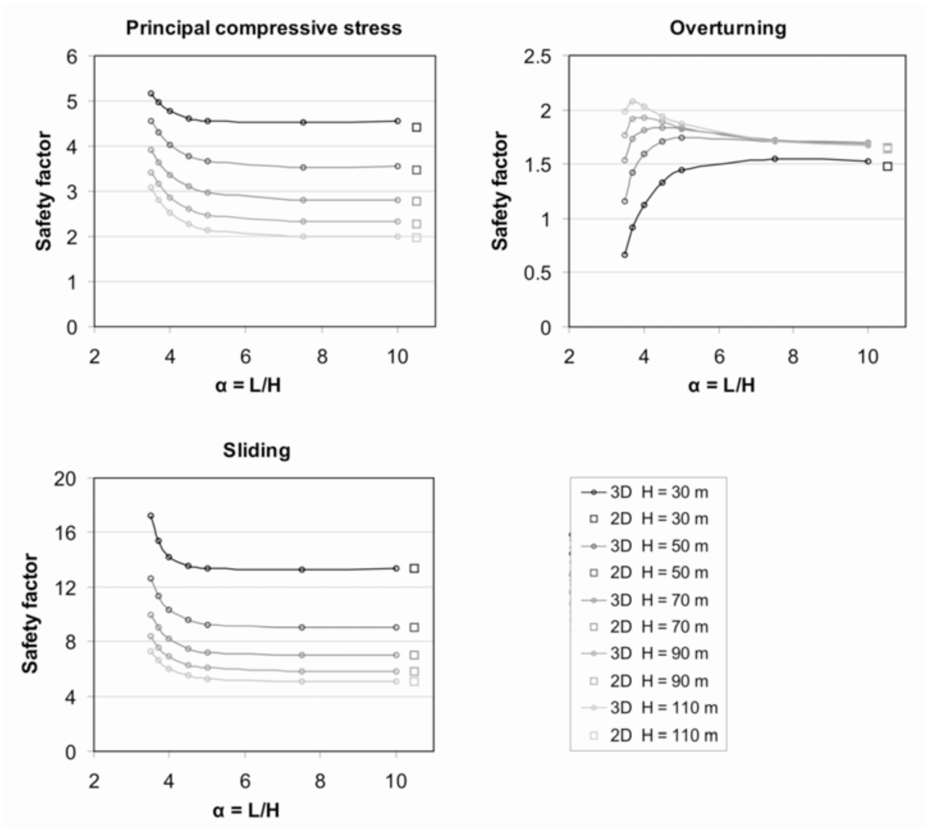

Fig.5

Factors of safety for straight-lined dams with different heights and a variegated α = L/H. The valley slope is set at 1:0.6

Facteurs de sécurité pour des barrages aux crêtes droites avec des hauteurs H et des rapports α = L/H variables. L'inclination de pente de la vallée a été fixé à 1:0.6

Fig 6 shows the influence of varying valley slops from 1:0.6 to 1:1.4 on the distribution of stress at the dam foundation for a 70 m height dam with a α value of 4. The steeper the valley, the smaller influence it has on the structural dam performance. A two-dimensional load-bearing behaviour can hence occur for dams with α smaller than 7.5 on condition that the valley is steep.

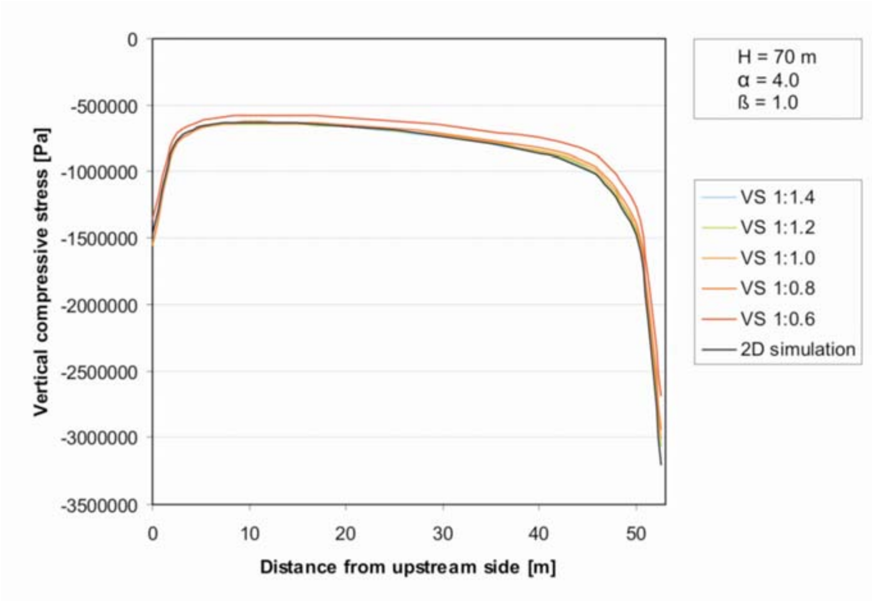

Fig.6

Vertical compressive stress for 70 m height straight-lined dams varying the valley slopes VS

Contraintes de compression verticales d´un barrage de 70 m d´hauteur à crête droite ayant des inclinations de pente de vallée variables VS

3.2 IMPACT OF A CURVED CREST

To rate the curve of the dams the variable β is established that describes the ratio between the radius of curvature and the radius minus the width of bottom: β = R/(R-B) (cp. Fig. 1). The β-value of German gravity dams are in range between 1.02 and 1.27. The distribution of vertical stress for different curved 70 m high dams with a constant ratio α = 4.0 is shown in Fig 7. A β value of 1.0 applies to straight-lined dams and a value of 1.3 results in this case for a dam with a crest radius of about 225 m. It is obvious that the curved shape has only a minor effect on the distribution of stress at the dam foundation. The vertical pressure at the upstream side of curved dams is however slightly higher. This is due to the horizontal water load being oriented at the middle of the dam, concentrating the load transfer there. Comparative simulations with other dam heights arrive at the same conclusion. Load cases with an empty reservoir but with thermal loads show that the distribution of stress at the dam foundation is independent from the curvature of the dam.

Fig. 8 points out that only curved dams situated in narrow valleys (α = 4.0) have reduced vertical compressive stress at the downstream side and the ratio β influences the results of the safety criteria. The safety factor in relation to principal compressive stress and sliding is slightly higher for dams with β values exceeding 1.2 (Fig. 9). The location of the resulting force is affected by the bending and located nearer to the middle point of the base with a rising dam curvature. That applies for dams with a long crest length in relation to the dam height as well. In summary, the arch form has compared to the valley shape only a minor influence to the load-bearing behaviour of the dam.

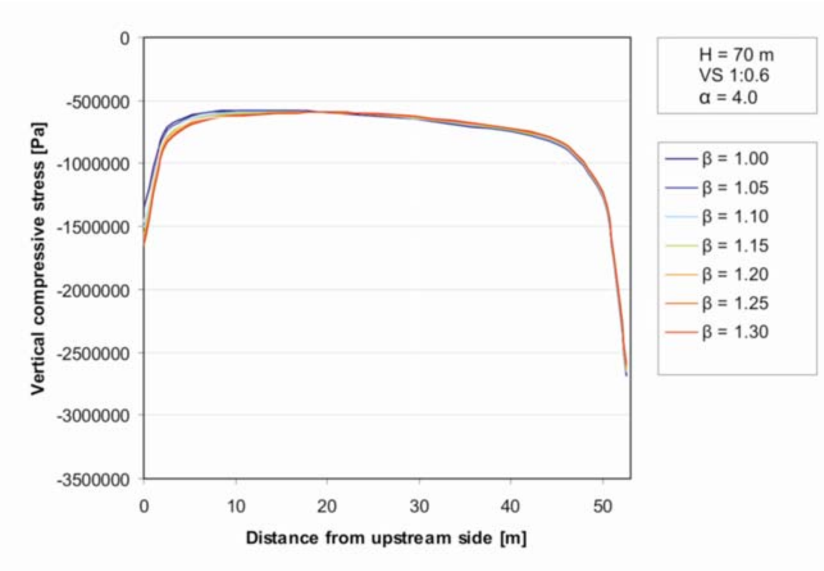

Fig.7
Vertical compressive stress for 70 m height dams with a ratio α = 4.0, varying β = R/(R-B)
Contraintes de compression verticales d´un barrage de 70 m d´hauteur avec un rapport α = 4.0 fixe et un facteur β = R/(R-B) variable

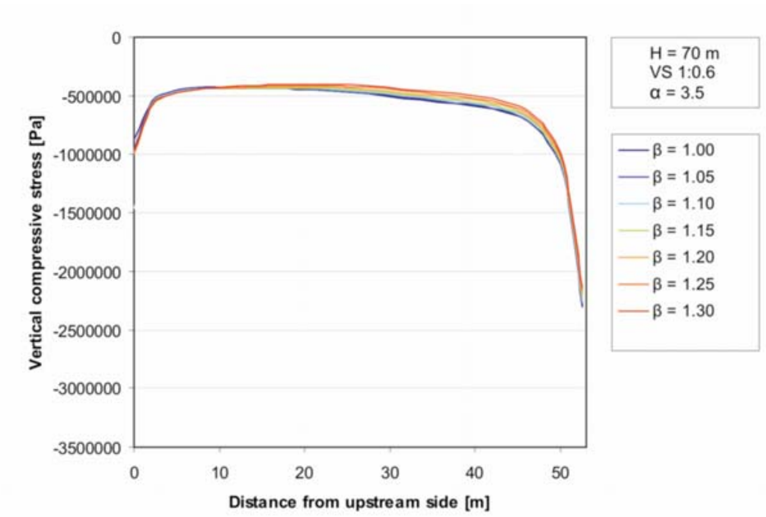

Fig.8
Vertical compressive stress for 70 m height dams with a ratio α = 3.5, varying β = R/(R-B)

Contraintes de compression verticales d´un barrage de 70 m d´hauteur avec un rapport α = 3.5 fixe et un facteur β = R/(R-B) variable

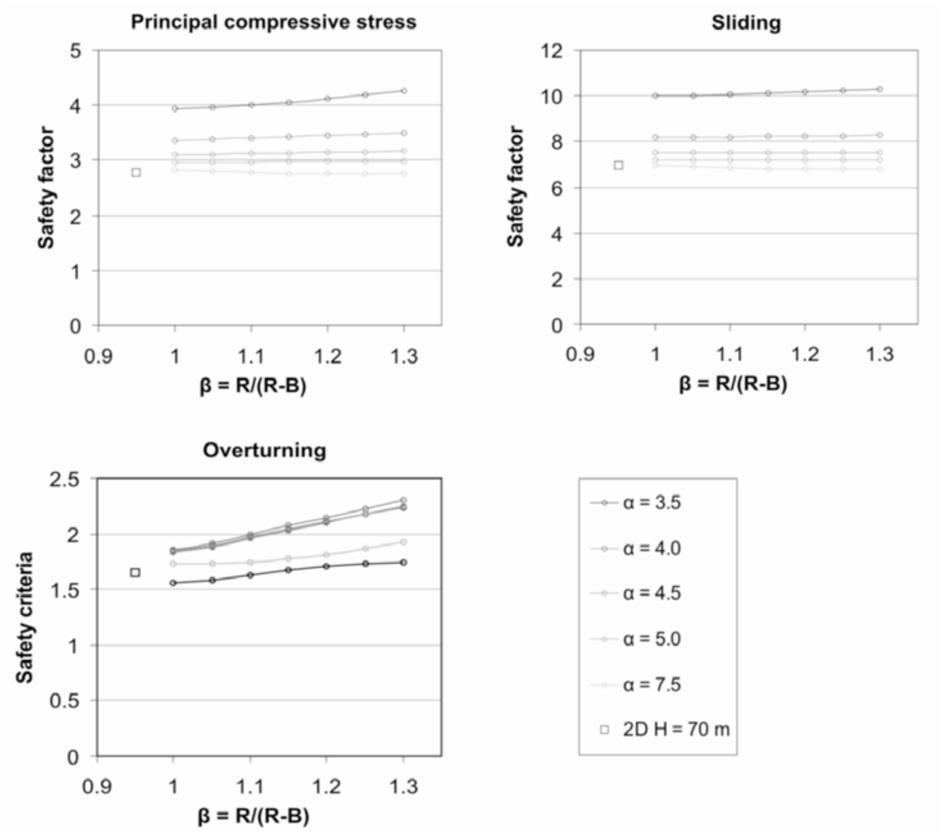

Fig.9

Factors of safety for 70 m height curved dams with a valley slope of 1:0.6 and a variegated ratio α = L/H and β = R/(R-B)

Facteurs de sécurité pour des barrages curvilignes ayants une inclination de pente de vallée fixé `a 1:0.6 et des rapports α = L/H et β = R/(R-B) variables

4. CONCLUSIONS

30 percent of the gravity dams in Germany have a ratio α greater than 7.5. The study came to the conclusion that in this case a two-dimensional FE simulation is sufficient. The α-value of further 50 percent of the dams is in between 4.5 and 7.5. The load transfer is slightly influenced by the valley side. The remaining 20% of the structures should be analysed by means of three-dimensional computations on condition that lateral load transfer is not disturbed by vertical joints or openings like spillways.

About half of the gravity dams in Germany have a curved dam crest. Due to the bending the compressive stress at the upstream side is slightly greater. A reduction of the base pressure does only determinable for dams with a α smaller than 4.0 and β greater than 1.2. This applies only to 10% of the curved gravity dams. Hence the impact of the valley shape is more significant than the curvature of the dam.

SUMMARY

This study investigates the stability of gravity dams subject to the valley shape and bending of the dam crest. The results of the 2-D and 3-D finite element computations are compared to investigate to which extent 3-D modelling is necessary to perform stability analyses of existing dams in the framework "In-Depth Hydraulic Structure Examinations" in Germany. Simulations of straight-lined dams with a varying ratio of crest length to dam height show that up to a value smaller than 7.5, a lateral load transfer to the valley side appears, where two-dimensional simulations show varying results. Next, the influence oft the curvature of the dam was investigated. The computations point out that the bending of the crest has only a minor influence to the stability of gravity dams. Only in the case of narrow valleys are the compressive stresses at the dam foundation reduced. The study arrives at the conclusion that for about 20% of the German gravity dams, stability analysis with three-dimensional calculations would be reasonable.

RÉSUMÉ

Dans cette étude la stabilité des barrages-poids, qui dépend de la forme de la vallée ainsi que de la courbure de sa crête, est analysée. Les résultats des calculs à l´aide des modèles d´éléments finis 2D et 3D sont comparés pour montrer à quel degré une modélisation 3D soit nécessaire dans le cadre des "analyses approfondies" concernant la stabilité des vieux barrages en Allemagne. Les simulations 2D montrent pour des barrages aux crêtes droites, ayant un rapport de longueur de crête à hauteur du barrage variable, que jusqu' à une valeur en dessous de 7,5 les charges sont partiellement transférées vers les pentes de la vallée tandisque les calcules 2D produisent des variabilités. Ensuite, l´influence de la courbure des barrages-poids a été étudié. Les calcules imposent que la courbure horizontale d´un barrage-poids influence comparablement peu sa stabilité. Seulement dans le cas des vallées très étroites les contraintes de compression sont réduites à la fondation du barrage. En conclusion, on peut dire que des analyses de stabilité par modélisation 3D auraient été raisonnables pour environs 20 % des barrages-poids Allemands.