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JUSTIFICATION FOR SELECTING A FACTOR OF SAFETY FOR DAMS

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NORWAY

1. INTRODUCTION

Requirements for stability of concrete dams in the current Norwegian dam safety regulations are based on simplifications, which in many cases are conservative. As a result, rehabilitation works may be carried out on dams that are safe, but does not meet the safety requirements.

Norwegian dams have to meet a minimum safety standard, defined by a Factor of Safety (FoS). It is often assumed that the FoS includes all of the uncertainties in the calculations. However, how these variables affect the FoS are generally not known or not accessible. It is therefore a need to acquire more knowledge on how different assumptions affect the calculations of stability of FoS.

How different parameters affect the dam stability is essential in order to identify which parameters that are most important for stability and sensitivity of the overall dam safety. This knowledge is of particular interest in assessing existing dams. By gaining more knowledge about different parameters, it is possible to reduce the uncertainty connected to these parameters, and thereby reducing the overall uncertainty. This knowledge can thereby be used to reduce the calculated FoS without affecting the safety level of the dam.

In general, a probabilistic analysis would be suitable to identify these type of uncertainties. Due to a very limited budget, we had to use a different approach to the issue. Our selected method and the results from the calculations are described in this paper.

The calculations have been carried out on both concrete gravity dams and masonry dams. For simplicity, this paper only presents the results related to concrete gravity dams with a height > 8 m.

2. REQUIREMENTS FOR DAM SAFETY IN NORWAY

In Norway, dam stability is checked for both overturning and sliding.

Calculation of the sliding resistance require a safety factor of minimum 1.5 against normal design loads. For accident loads a minimum FoS of 1.1 is applied. If cohesion is included, a higher FoS is necessary. However, as this require documentation by testing, the cohesion is generally never included.

Safety against sliding is estimated with the shear friction factor method, where the FoS is generally defined as the following:

$$SF_{sliding} = \frac{\sum F_{horisontal\ capacity}}{\sum H_{horisontal\ load}} = \frac{\sum V \tan(\phi + \alpha)}{\sum H}$$

where ϕ is the fiction angle and α is the inclination of the foundation.

Stability against overturning for concrete gravity dams, is acceptable when calculations show that the resultant force is within the central dam foundation, so that it can be assumed pressure throughout the dam foundation.

To simplify the output of safety against overturning, the FoS is calculated instead of the eccentricity of the resultant force. Safety against overturning thereby defined as:

$$SF_{overturning} = \frac{\sum M_{stab.}}{\sum M_{destab.}}$$

3. METHOD AND ASSUMPTIONS

The calculations has been based on a computing tool for stability control, developed by Dr. Techn. Olav Olsen. To make the calculations more efficient, a script was developed with the programming language, Python. The script defines changes of different variables, and then generates calculations with these assumptions.

The result of the stability calculation of each parameter is presented graphically, where the resulting FoS is plotted against the varying parameters for each dam height. Variation in the FoS are shown for both sliding and overturning. This paper only presents a sample of the results that have been produced.

The method used, has proven to give a very powerful and flexible tool for estimating stability of all types of concrete dams with different variables. In total, the report has been based on approximately 7000 separate calculations with different variables.

3.1. VARIABLES

Assumptions of for the calculations are shown in the table below. “Initial values” are used to generate dam section as described in the next chapter.

Table 1.
Assumptions used for the computations

Variable	**Initial value**	**Min. value**	**Max. value**	**Step for calculations**	**Comment**
Friction angle	40°	35°	60°	1°	
Water level (H_w)	h	h – 1 m	h	0.01 m	h = Dam height
Self-weight (kN/m^3):	22	21	24	0.1	
Drainage constant (k)*	1.00	0.50	1.0	0.05	Changes in pore pressure defined by k and dx*.
Drainage position (dx)*	0	$0.1H_w$	$0.5H_w$	$0.1H_w$	
* Both the drainage constant (k) and the drainage position (dx) was changed, - see figure below (i.e. 6 * 11 = 66 different calculations for each dam height)					

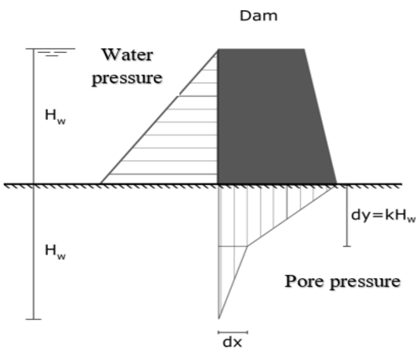


Fig. 1.
Illustration of assumptions to generate pore pressure.

3.2. GENERATION OF DAM SECTION

The dam-sections were generated, satisfying the following requirements:

- Compression throughout the entire foundation (i.e. the resultant force is within the central dam foundation)
- FoS against sliding equal to 1.0.

By changing crest width and downstream slope (see Figure 2) an optimal cross section was found using the “initial values” given in Table 1.

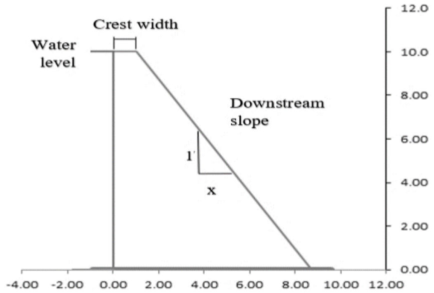


Fig. 2.
Dam section was selected by varying crest width and downstream slope.

It was not possible to generate a cross section that satisfied the assumptions mentioned above. Therefore, the required FoS against sliding was increased from 1.0 to 1.1 as shown in the table below.

Table 2.
Geometry and FoS for dam-sections generated.

Dam height [m]	**Crest width [m]**	**Downstream slope [1:x]**	**FoS**	
			Sliding	**Overturning**
8	0.81	0.77	1.1	1.5
10	1.01	0.77	1.1	1.5
12	1.21	0.77	1.1	1.5
14	1.41	0.77	1.1	1.5
16	1.61	0.77	1.1	1.5
18	1.82	0.77	1.1	1.5
20	2.02	0.77	1.1	1.5
25	2.52	0.77	1.1	1.5
30	3.03	0.77	1.1	1.5

The above table shows that optimization of the cross sections provided a minimum FoS of 1.1 against sliding and 1.5 against overturning, with the assumptions used. In presentation of the results, the FoS for the initial dam section was normalized. This implies that the computed FoS against sliding was divided by 1.1, while the results against overturning was divided by 1.5.

It can also be noted that when the friction angle was increased to 50º, the FoS against sliding increases to ~1.5, which is the same FoS as for overturning.

4. RESULTS

In this chapter, the results of the calculations with different variables are presented and discussed.

4.1. FRICTION ANGLE (AND ANGLE OF FOUNDATION)

Variation in friction angle is also valid for inclination of the foundation, since horizontal capacity is defined as $\sum V \tan(\phi + \alpha)$ (see chapter 2). The friction angle has no effect on the FoS against overturning.

The computations show that the FoS against sliding is the same for all different dam heights. This imply that friction angles is directly related to FoS, and that the dam height do not influence the results. This means that a change in the friction angle will give the same change of the FoS regardless of the dam height. This can, of course, also bee seen directly from the definition of FoS against sliding.

The friction angle will normally be conservative where the friction angle also "includes" possible cohesion and shear capacity due to rock surface roughness. This implies that the corresponding safety factor from friction, should be 1,0. The calculations carried out, also show that a conservative friction angle will result in a high level of safety that is not necessarily reflected in the computed FoS for the dam.

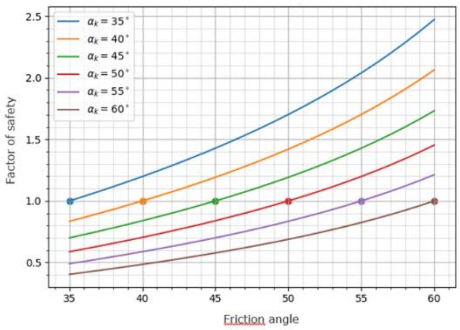
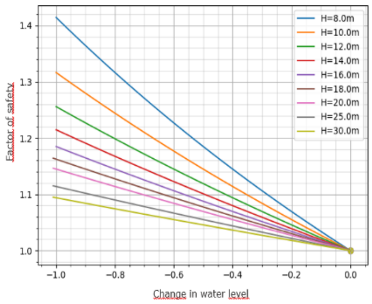


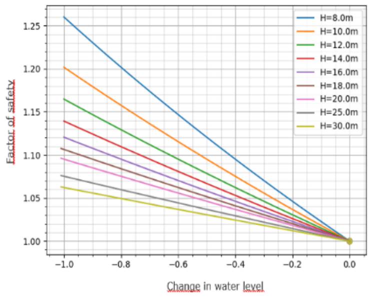
Fig. 3.
Correlation between FoS and friction angle. α_k is the initial friction angle where the different dam sections have a FoS = 1.0.

4.2. WATER LEVEL

How variations in the water level influence the FoS, will identify how sensitive the dam is to changes in flood water level. Changes in design water level can for instance be caused by changes in future flood calculations etc. How much this affects the safety in relation to different dam heights is calculated and presented graphically in the following figures.



Results for sliding



Results for overturning

Fig. 1.

Reduced water level (x-axis) vs. FoS for different dam heights (y-axis).

As shown in the above graphs, higher dams are, of course, less sensitive to changes in water levels than lower dams. This is summarized in the following table.

Table 3.

Effects of changes in water level on the FoS for different dam heights.

Change in water level	FoS - Sliding		FoS - Overturning	
	Dam height 8 m	**Dam height 30 m**	**Dam height 8 m**	**Dam height 30 m**
0,2 m	1,07	1,02	1,05	1,01
1,0 m	1,41	1,09	1,26	1,06

The table shows that changes in water levels have more influence on the FoS against sliding than FoS against overturning.

Dam height (i.e. static water pressure) is crucial for how uncertainties in flood calculation and flooding affect stability. When the dam height increases, changes in flood water have little significance for the dam stability.

As uncertainties in floods and operating levels will have different impact on the FoS dependent on the dam height, it is reasonable that these uncertainties are handled in the flood calculations and are not included in the FoS. For instance, a dam dependent on floodgates will have other uncertainties related to flood handling and flood levels than a dam with a free overflow spillway. This implies that the corresponding safety factor from static water pressure, should be 1,0.

4.3. SELF-WEIGHT

The self-weight is essential for the stability of a concrete gravity dam. The calculations carried out show that variations in the self-weight is directly related to the FoS and the dam height does not influence the results.

JCSS, "Probabilistic Model Code", 2015, Table 2.1.1, recommends a coefficient of variation of 0.04 on self-weight. This corresponds to a load factor of

0.96, which imply a reduced self-weight from 24 to 23 kN/m^3. The correlation between a load factor of 0,96 and the FoS are shown in the table below.

Table 4.
Correlation between load factor and FoS.

	Load factor	**FoS**
Sliding	0,96	1,08 (=1/0.93)
Overturning	0,96	1,04 (=1/0.96)

A graphic presentation of the correlation between self-weight and FoS is shown below (blue line = sliding; orange line = overturning).

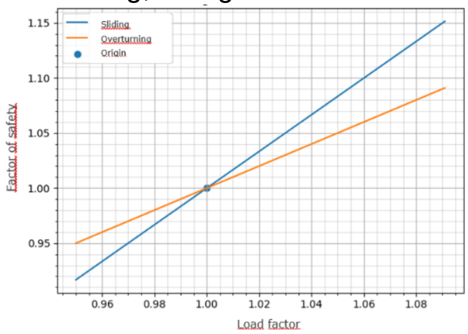


Fig. 5.
Load factor (x-axis) vs. FoS (y-axis) when the friction angle = 40º

The dam geometry also represents an uncertainty, which also can be illustrated by variating the self-weight. However, probabilistic analysis carried out on a gravity dam in Norway indicate that deviations in the geometry do not have a significant effect on the FoS.

4.4. PORE PRESSURE

The pore pressure represents an uncertainty that can be difficult to predict and therefore difficult to quantify in terms of a specific FoS. This would imply that the pore pressure should be subjected to a relatively high FoS to take account of the uncertainty it represents.

In Norway, requirements for stability against overturning assume that the resultant force is within the central dam foundation. Thereby, a linear decreasing pore pressure can be assumed as there is pressure throughout the entire dam foundation. In addition, a check of accident load is required, where the resultant force should be upstream 1/6 of the dam foundation. In this case, full pore pressure can be assumed on the upstream half of the foundation (where there is no pressure on the foundation) and then linearly decreasing to the downstream side. The assumptions for design loads and accident loads are shown in the following figure.

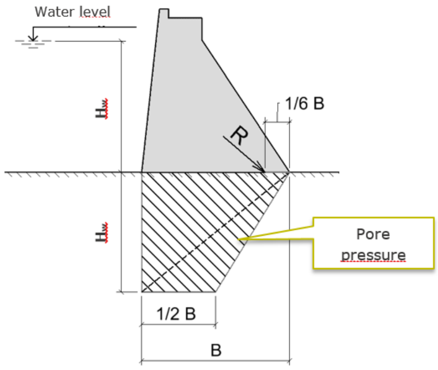


Fig. 6.
Maximum allowable pore pressure assumed for accident loads. Pore pressure distribution for normal design loads is shown as a dotted line.

The criteria for pore pressure distribution provides a logical correlation between the load effects from the dam and the resulting pore pressure for normal design loads. When there is pressure in the entire foundation, the bond between the concrete and the foundation can be assumed to be intact. Thereby, a linearly decreasing pore pressure under the dam will probably be a conservative assumption and generally contribute to a high safety level.

The additional check for accident loads provides an extra safety in case the pore pressure should be greater than assumed for normal design loads.

If the maximum permissible pore pressure for accident loads represents the uncertainty in the pore pressure distribution, the difference of pore pressure between design load situation and accident load situation may be defined as the corresponding load factor. This difference represents an increase in pore pressures of 43%, or a load factor of 1.43. The correlation between the FoS for design loads and accident loads can thus be expressed as shown in the following figure, where FoS = 1 represent a linearly decreasing pore pressure distribution under the dam.

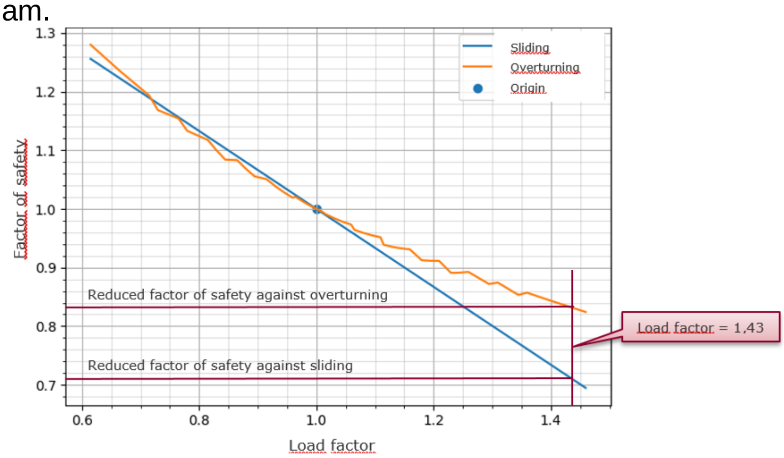


Fig. 7.
Computed correlation between load factor and FoS with changing pore pressure (blue line = sliding; orange line = overturning).

5. SUMMARY AND CONCLUSION

The following table summarizes the suggested FoS for each variable as discussed in this paper. Multiplying the different factors is assumed to represent the overall FoS.

Table 5.
Total FoS as a product of the individual safety factors.

Variable	FoS - Sliding		FoS - Overturning		Reference
	Design	**Accident**	**Design**	**Accident**	
Friction	1,0	1,0	Not relevant		Chapter 4.1
Water level	1,0	1,0	1,0	1,0	Chapter 4.2
Self-weight	1,08	1,08	1,04	1,04	Chapter 4.3
Pore pressure	1,40	1,00	1,20	1,00	Chapter 4.4
SUM	1,51	1,08	1,25	1,04	Overall FoS
Current FoS	1,5	1,1	N.A.*	N.A.*	
* Safety against overturning is defined by position of the resultant					

Elements constituting the total FoS given in the Norwegian dam safety regulations is not publicly available. The factors of safety suggested in the above table can, however, be used to justify the current requirements, but this has not been confirmed by the Norwegian dam safety authority.

How different parameters affect the dam stability is essential when assessing the degree of uncertainty of the calculations. This will make it easier to identify which parameters that are most important for the stability and that influences the ucertainties of the overall dam safety.

By improving the knowledge related to the individual variables, the uncertainties can be reduced and thereby reducing the overall required FoS for the dam in question. This is of particular interest in cases where existing dams do not meet the safety requirements.

It must be underlined that results in this report is valid with the given methodology and assumptions described in chapter **Error! Reference source not found.** and **Error! Reference source not found.**, and a validation of the results is recommended.

6. ACKNOWLEDGEMENTS

We would like to thank EnergiNorge that has supported this project, and thereby made this contribution possible.

7. REFERENCES

This article is based on a study documented in a report by EnergiNorge in Norwegian. When this article was written, the report was not published. The report will in time available on: https://www.energinorge.no/publikasjoner/

SUMMARY

The study presented in this paper is part of a lager Norwegian Research and Development project, named “Dam safety in an overall perspective” that is administrated by EnergiNorge. This is a joint project with participants from the Norwegian dam safety sector. One of the objects of this project is to look at alternative approaches to evaluate safety of existing concrete- and masonry dams.

This paper presents a study carried out to identify how different variables affect the estimated safety for dams. To do so, a series of calculations has been carried out to understand how the FoS is affected for a wide range of variables and assumptions.

The calculations have been carried out by combining a computing tool for stability calculations with a script that runs the calculations. This method has proved to produce a very powerful and flexible tool for computing stability with varying assumptions. In total, the report is based on approximately 7000 separate calculations with different variables

The study gives suggestions on how uncertainties related to loads and other assumptions can be represented in the overall FoS. The results can also be used to justify the current practice and safety level applied by the Norwegian dam safety regulations.