

# **NEW INNOVATIVE TECHNIQUE FOR STRENGTHENING OLD BUTTRESS DAMS AND MULTIPLE ARCH DAMS**

Thomas Konow<sup>1</sup>

## **ABSTRACT**

This article presents a new method for reconstruction and strengthening of old buttress dams, where the old dam is used as a shell or formwork for construction of a new dam. The technique has been patented in Norway and has proven to be cost efficient in cases where construction of a new dam is the only solution. The solution can also be applied at a full reservoir level, which can be a major advantage in many cases.

The new technique is presently applied on a flat slab buttress dam in Norway. At this project, the solution has proven to give 40 % cost savings compared to demolition of the existing dam and reconstruction of a new dam. In addition the solution results in a very stable and safe structure, as shown by examples in this paper.

It is assumed that the solution can be particularly relevant for slender buttress dams such as flat slab buttress dams and multiple arch dams. Examples of how the technique can be applied on these dams are also presented in this paper.

It is considered that the technique described in this paper can be the preferred solution even though the construction costs of a new dam is comparable, because the safety gained is very favourable compared other traditional dam types.

## **INTRODUCTION**

According to International Commission On Large Dams (ICOLD), Technical dictionary of dams, there are three types of buttress dams:

- Flat slab buttress dams (or deck dam)
- Multiple-arch dams
- Solid head buttress dams

Buttress dams are characterized by a water-tight upstream side that is supported by a series of buttresses on the downstream side. The buttresses transfer the force from the water pressure to the foundation. The buttresses normally have a constant spacing along the dam. Typically, the buttresses are placed at intervals of 5 to 20 meters, depending on the size and design of the dam. Buttress dams are also sometimes referred to as hollow dams because of the open sections between the buttresses on the downstream side of the dam.

In the US, flat slab buttress dams are sometimes called Ambursen dams, since this dam type was patented in the US by the Norwegian engineer Ambjørnsen who immigrated to

---

<sup>1</sup> Thomas Konow, Consultant Engineer – Dam Safety, Norconsult, Brusetveien 73, N-1395 Hvalstad, Norway. E-mail: [thomas.konow@gmail.com](mailto:thomas.konow@gmail.com)

the US. In Norway, the flat slab buttress dam is also called “Grøner-dam”. This is a further development of the Ambursen-dam made by the engineer C.F. Grøner (former ICOLD President). Here the vertical slab joints are placed at the point of zero moment in the slab and thereby reducing the required reinforcement in the slab. Due to these two engineers, Norway and the US are considered to be the countries with the most slab buttress dams worldwide. In Norway there are a total of 240 slab buttress dams whereof 44 are defined as “large dams”.

As the age of the buttress dams’ increase, the need for repair and rehabilitation also increases due to general deterioration and age. In addition, many dams do not meet today's requirements for strength or over-all stability, as the required level of safety for dams in general has been increasing over the years. As a result, several of today’s buttress dams are in need of rehabilitation and in some cases construction of a new dam may be the only solution.

### CHALLENGES WITH NORWEGIAN BUTTRESS DAMS

With a few exceptions, all of the Norwegian buttress dams are of the type “flat slab” buttress dams.

Most of these dams were constructed during the 1950s and 1960s. The general condition of these dams depends on the age combined with the general quality of the construction works and the environment the structure has been exposed to. Mechanisms that affect the general condition of the structure can be frost and thaw effects, reinforcement corrosion and alkali aggregate reaction (AAR). Often, a combination of these different deterioration mechanisms is present at the same time.

In addition the structure need to have sufficient stability according to today’s safety requirements. In Norway, the requirements for stability changed with the new regulations that came into force in 2001. The present requirements for stability of buttress dams are shown in the below table.

Table 1. Norwegian requirements for stability of slab buttress dams

Load situation	Factor of safety for	
	Overturning	Sliding
1. Ice pressure (100 kN pr. m)	1,4	1,4
2. Design flood ( $Q_{1000}$ )	1,4	1,4
3. Design flood excluding rock anchor/bolts ( $Q_{1000}$ )	1,1	1,1
4. Probable maximum flood (PMF)	1,3	1,1

The new regulations are also applied on existing dams. As a result, many of the existing slab buttress dams do no longer meet the stability requirements against sliding and/or overturning.

In addition, the Norwegian dam safety authorities have an intention to not allow slab buttress dams in the highest hazard class, and this also applies for existing dams.

In Norway, the above mentioned factors have resulted in an increased number of cases where slab buttress dams needs strengthening or rehabilitation. In some cases decommissioning and reconstruction of a new dam is the only option.

### **RECONSTRUCTION OF DAM KROKAVATN**

Dam Krokavatn is 19 m high and has a total length of 100 m, where the main dam is a flat slab buttress dam about 50 m long.

The dam design is typical for Norwegian flat slab buttress dams. It is constructed with an upstream slab inclined at about  $50^\circ$  to the horizontal and supported by 8 concrete buttresses at 5 m spacing. Originally, the upstream deck had a thickness of 0.30 m at the top and increasing to a thickness of 0.80 m at the foundation.

At the right abutment there is a 50 m long concrete gravity spillway. Between the spillway and the buttress dam there is a corner along the dam axis. Through several years a crack had developed in the concrete wall located at the corner between the buttress dam and the spillway (see figure 2), and resulted in a large leakage through the crack at full reservoir level.



Figure 1. Dam Krokavatn. 50 m long slab buttress dam (near side) and the spillway on the far side. Notice that the dam axis has a corner on the far side between the buttress dam and the spillway.



Figure 2. Cracking of concrete at the buttress wall at the corner between the spillway and the slab buttress dam, due to 15 mm expansion of the upstream slab.

### **Dam Safety Evaluation**

In 2012, the dam owner conducted a safety evaluation of the dam, where the overall safety was assessed.

The safety evaluation identified that the dam did not meet today's requirements for stability against sliding and overturning. As the dam is a high hazard dam, the Norwegian dam safety authorities required a reconstruction of the dam.

### **Alkali Aggregate Reaction (AAR)**

The dam safety evaluation also concluded that AAR was present in the concrete. This was not a surprise, as observations from the dam showed a relative movement of 15 mm at the buttress wall next to the spillway (see figure 2), over a length of 8.45 m.

This corresponded to an elongation of 0.18 % and indicated a tensile stress of  $360 \text{ N/mm}^2$  in the reinforcement. As the characteristic strength of the reinforcement was  $400 \text{ N/mm}^2$ , the tension in the reinforcement was close to yielding, and it was therefore concluded that the reservoir should be restricted to maximum 2.5 m below maximum operating level. This section of the dam was only 4 m high and a collapse of the concrete slab would therefore not have any serious consequences.

## **Rehabilitation Works**

To upgrade the dam it was decided to use the old buttress walls as formwork to cast new buttresses in every second hollow area, as shown in the figure below. The additional weight from the buttresses would then secure the required stability of the dam.

In addition, a new concrete slab on the upstream side of the old slab was necessary since the load capacity of the slab was not sufficient due to AAR.

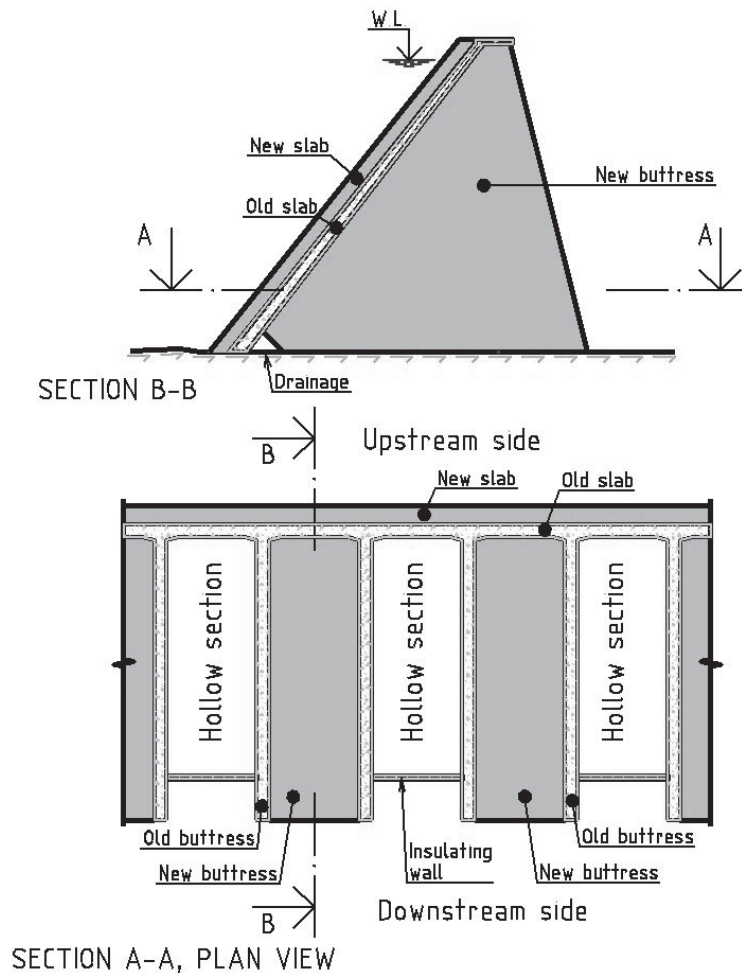


Figure 3. General arrangements for reconstruction of dam Krokavatn.

After reconstruction, the original dam is only a shell, and has no function in regard to stability or strength of the new structure.

This solution was by far considered to be the cheapest solution compared to the alternative, which would be construction of a new dam.

Cost estimates of different solutions are shown below.

Table 2. Cost estimate of different alternatives (1 NOK = 6.43 US\$)

Alternative	Cost (NOK)	Cost (US\$)	Difference (%)
1. Buttress dam – Reconstruction	22 000 000,-	3 420 000,-	-
2. New gravity dam in concrete	31 000 000,-	4 820 000,-	+41%
3. New rockfill dam	41 000 000,-	6 370 000,-	+86%

### Evaluation of Stability

Calculations of the dam stability proved that the solution (alternative 1, table 2) was very favourable in terms of stability. This is mainly due to the additional weight from the new buttresses. In addition, the weight of the new upstream slab and a less inclined upstream face also contribute to the improved stability of the dam.

A comparison of the stability before and after reconstruction are shown in the figures below.

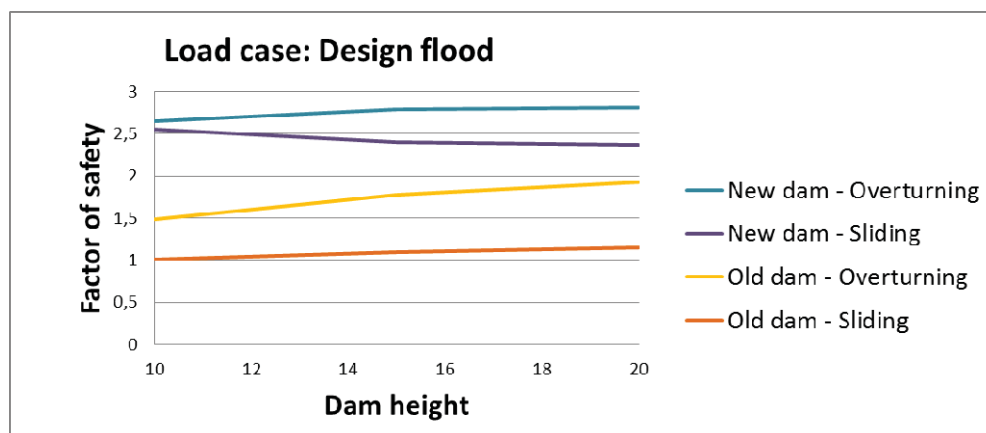


Figure 4. Computed stability of the existing dam (old dam) compared to that of the reconstructed buttress dam (new dam) for a design flood 0.5 m above normal water level.

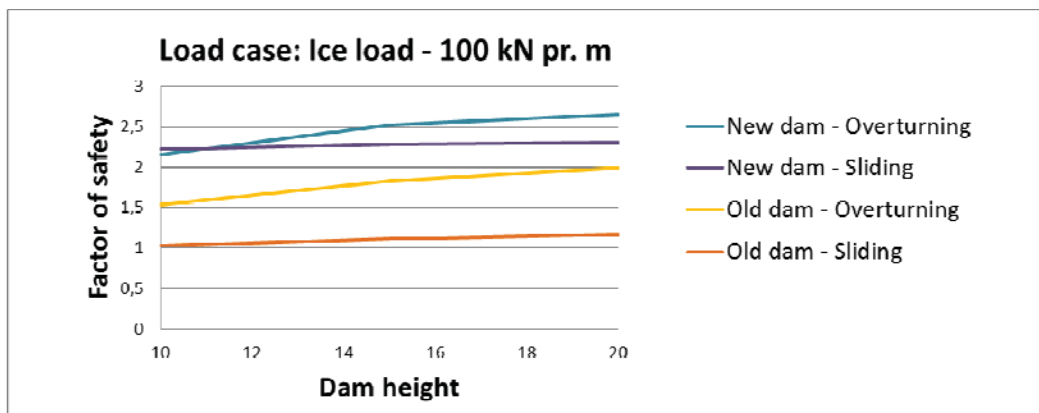


Figure 5. Computed stability of the existing dam (old dam) compared to that of the reconstructed buttress dam (new dam) for a design ice load of 100 kN pr. m length.



The calculations of stability show that the new dam has a very high level of safety. The factor of safety is higher than 2 and is much higher than the required level of safety in Norway. In general the factor of safety against sliding is increased with more than 1, compared to the existing dam.

As a simplification, it can be said that the new dam can be looked up on as a combination of a flat slab buttress dam and a solid head buttress dam, where the massive buttresses and the stabilizing weight of the water above the inclined slab together with a reduced pore pressure results in a very safe dam structure.

### **Pictures of the Construction Works in 2014**

As mentioned, the safety evaluation in 2012 concluded that a reservoir restriction of 2,5 m below normal operating level was necessary due to the damages due to AAR. The dam owner therefore wanted the reconstruction carried out as soon as possible.

The construction works started in 2014. During the summer a new road of 7 km was constructed and the new upstream slab was cast. The new buttresses will be constructed during the summer in 2015. As the dam is located in a mountain area, it is not accessible during the winter and the work has to be carried out in the period June to October.

Some pictures from the dam reconstruction are shown below.



Figure 6. Reinforcement of two of the upstream slabs.



Figure 7. New slab on the upstream side with insulation of the concrete during hydration due to the cold climate in the late autumn 2014.

### **OTHER METHODS FOR STRENGTHENING FLAT SLAB BUTTRESS DAMS**

The solution used at dam Krokavatn can be modified in order to suit other types of flat slab buttress dam, and some of these solutions are described with text and illustrated with figures.

#### **New Slab on the Downstream Side (Alternative A)**

This alternative solution is illustrated in the figure below.

The figure shows a cross section D-D of a new buttress where a new concrete slab is constructed on the downstream side of the existing upstream slab. Section C-C shows one possible solution for placing the construction joints and thereby connecting the new buttresses and the new concrete deck. This can be done by casting the new buttresses before cutting through the buttresses of the existing dam.

This solution does not require a full drawdown of the reservoir which can be a great advantage in some cases. The solution may be used on buttress dams where both stability and strength of the structure may be a problem.



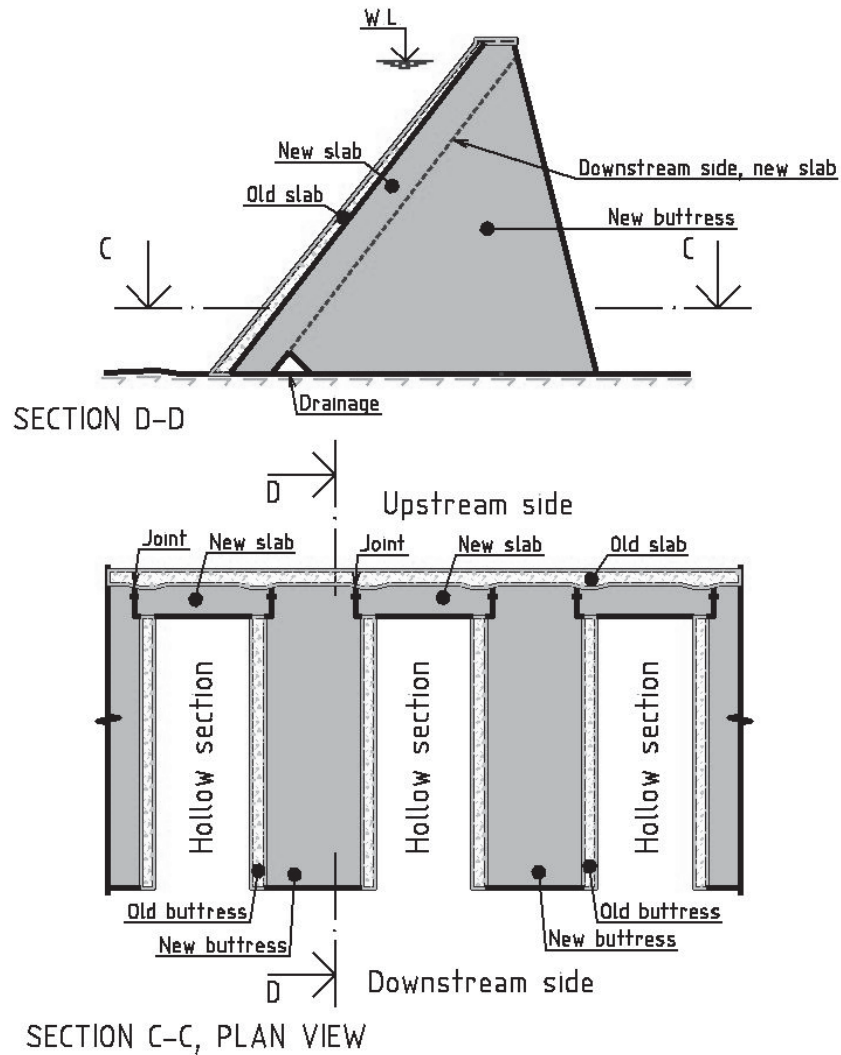


Figure 8. Reconstruction with a new slab on the downstream side.

### **New Buttresses Only (Alternative B)**

The solution is illustrated in the figure below.

The figure shows a cross section H-H of a new buttress where a new concrete deck is not required. Section G-G shows a plan view with a possible solution for strengthening the slab in cases where this may be necessary. This can for instance be done by installing a row of beams to support the existing slab. The solution requires that the existing upstream slab do not have any major damages or leakages and can still work as an upstream watertight seal for the dam.

This solution does not require a drawdown of the reservoir and can be used where both stability and strength of the structure may be a problem. The new buttress can influence the static load distribution of the existing slab and may result in the need for strengthening the existing upstream slab.

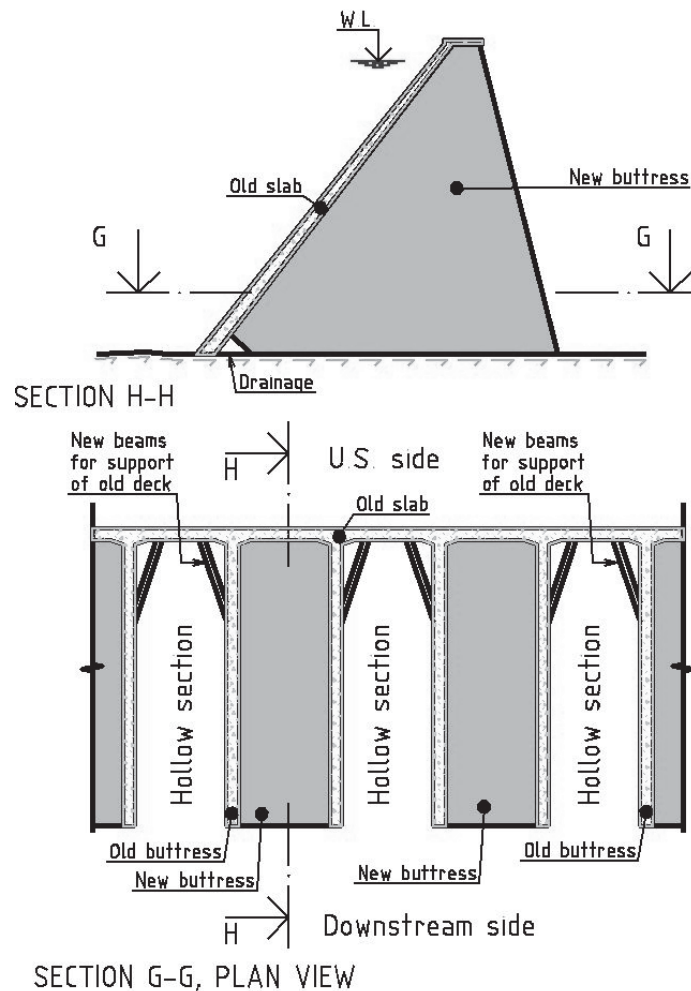


Figure 9. Reconstruction without a new upstream slab.

## STRENGTHENING OF MULTIPLE ARCH DAMS

A multiple arch dam is designed with same principles as the flat slab buttress dam, with an inclined upstream face. Normally, this is also a slender dam structure where the vertical weight of the water above the slab gives a major contribution to the stability of the dam.

Multiple arch dams are generally higher than the flat slab buttress dam and have a greater spacing between the buttresses, as the arches can have a larger span than the flat slab. The stresses in the structure and on the interface to the foundation are therefore much higher compared to a flat slab buttress dams. On some older buttress dams, FEM analysis has identified unacceptable stresses in these types of dams.

In the following examples it is illustrated how multiple arch dams can be strengthened with the same method used for dam Krokavatn.

### **Reconstruction to a Solid Head Buttress Dam (Alternative C)**

The solution is illustrated in the figure below.

The figure shows a cross section L-L of a new buttress in a reconstructed multiple-arch dam with a new concrete slab on the upstream side of the existing upstream concrete arch slab. Section K-K shows a plan view where the new buttresses are cast in every second hollow section. The new upstream concrete slab is designed as an upstream buttress head so that the structure can be defined as a solid head buttress structure. The figure shows a constant thickness of the upstream concrete slab, however the thickness may vary with the dam height and water pressure.

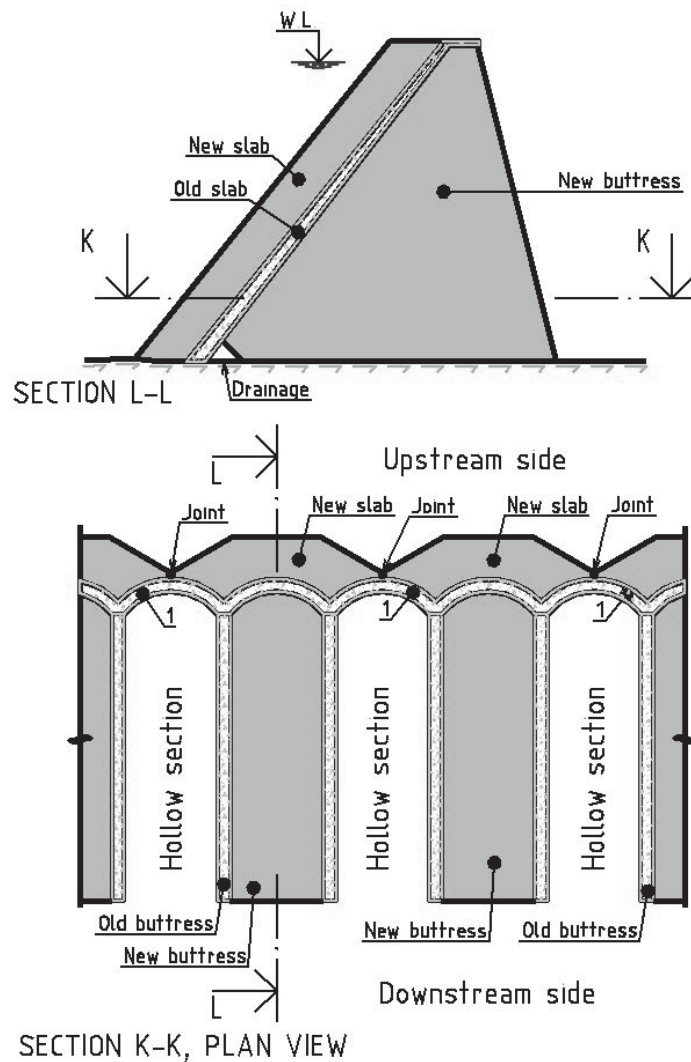


Figure 10. Reconstruction to a solid head buttress dam.

### New Buttresses Only (Alternative D)

The solution is illustrated in the figure below.

The figure shows a cross section N-N of a new buttress in a reconstructed multiple-arch dam where a new upstream concrete deck is not required, as also illustrated in the plan view (Section M-M). The solution can be used to improve the overall stability of the dam, or where the existing buttresses do not have sufficient safety and require strengthening. The solution implies that the existing arches have sufficient safety.

To obtain a satisfactory waterproofing it is possible to e.g. install a watertight geomembrane on the upstream side of the dam. It is also possible to construct a new upstream deck at a later stage, if this is considered necessary.

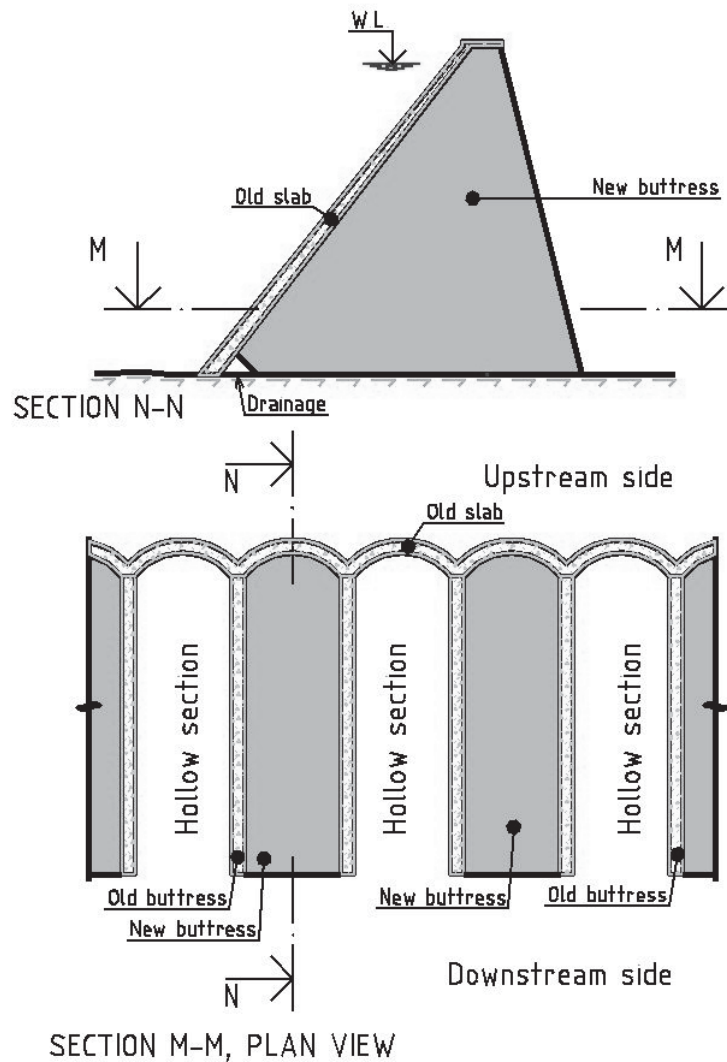


Figure 11. Reconstruction with new buttresses only.

### New Slab on the Downstream Side (Alternative E)

The solution is illustrated in the figure below.

The figure shows a cross section P-P of a new buttress where a new concrete arch is constructed on the downstream side of the existing arch. Section O-O shows one possible solution for placing the construction joints and thereby connecting the new buttresses and the new concrete arch. This can be done by casting the new buttresses before cutting through the buttresses of the existing dam.

This solution does not require a full drawdown of the reservoir which can be a great advantage in some cases. The solution may be used on buttress dams where both stability and strength of the structure may be a problem.

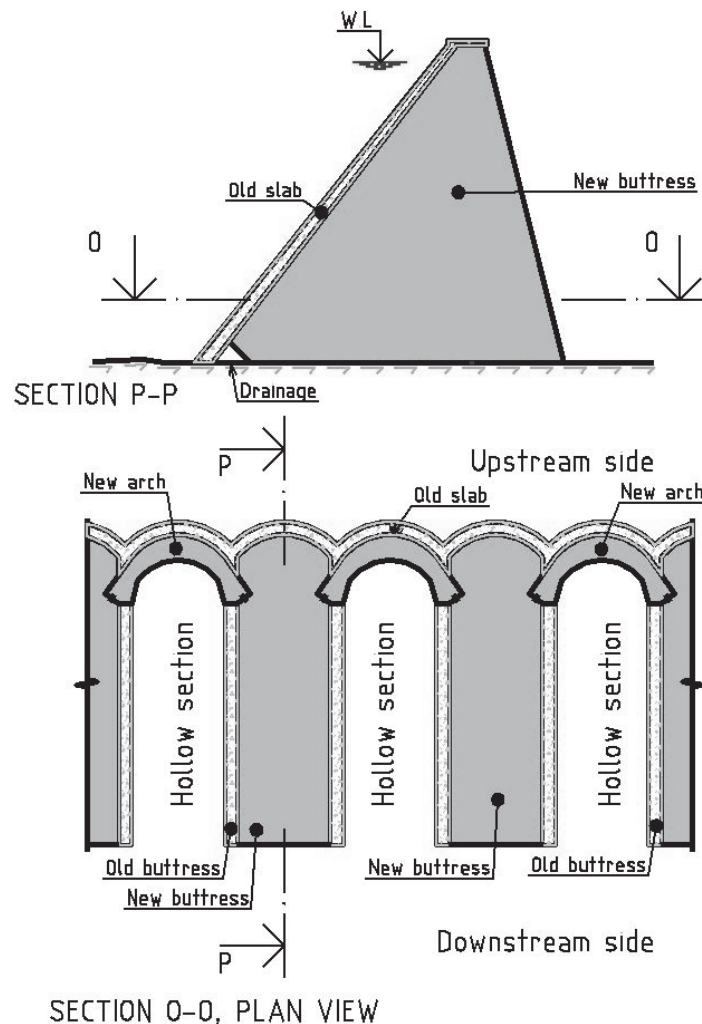


Figure 12. Reconstruction with a new arch on the downstream side.



## CONCLUSION

As the ages of the buttress dams increase, the need for repair and rehabilitation also increases due to general deterioration and age. In addition, many dams do not meet today's requirements for strength or over-all stability, as the required level of safety for dams in general has been increasing over the years. As a result, many of the existing buttress dams are in need of rehabilitation and in some cases construction of a new dam may be the only solution.

This paper presents a new technique for reconstruction of buttress dams where new buttresses are cast in between the buttresses of the existing dam. The technique has been patented in Norway, and an international PCT application has been filed.

As a simplification, the solution can be illustrated as a combination of a flat slab buttress dam and a solid head buttress dam, where the massive buttresses and the stabilizing weight of the water above the inclined slab together with a reduced pore pressure results in a very safe dam structure.

The technique is presently being used on a flat slab buttress dam in Norway and the paper gives a brief description of the safety evaluation and rehabilitation works of this dam.

Design of this dam has proved that the solution is very favourable in terms of stability. This is mainly due to the additional weight from the new buttresses. In addition, the weight of the new upstream slab and a less inclined upstream face also contribute to the improved stability of the dam.

At the above mentioned project, the solution has proven to be cost efficient compared to construction of a new dam, which was considered to be the only alternative solution.

The technique described in this paper may be the preferred solution even though the construction costs of a new dam is comparable, since the safety gained by this technique is very favourable.

The paper also presents several possible different applications for the technique and illustrates different methods of how it can be applied for slender buttress dams and multiple arch dams.