Snow avalanche at Bleie, Ullensvang, January 1994

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ABSTRACT. A major snow avalanche hit the farms at Bleie, municipality of Ullensvang, January 27 1994. Three dwelling houses were completely destroyed, and several other buildings were destroyed or damaged. The history of the Bleie farms dates back to 1293 a.d. In this period no avalanches are known to having been nearby the farms. Based on historic evidence and climatic records the return period for the avalanche is calculated to 1000 years. The horisonthal length of the avalanche was about 3600 m, α-angle 20°, comprising to -1 standard deviation of runout in the NGI runout model. Based on velocity and volume calculations different methods of protections were assessed by NGI. One of the proposed alternatives was a 10 m high and 110 m long concrete retaining wall 750 m upslope of the farms. The municipality of Ullensvang engaged INSTANES A/S, Consulting Civil Engineers, Bergen, for the design of the structure. The engineering was carried out by civil eng. Bjarne Instanes, and the chosen design is not known to have been used for similar purposes previously. The main feature of the structure is five-and-a-half half-cylindrical shells bound together in a monolithic structure and anchored to the bedrock by 22 rock anchors altogether. At the base the width of the structure is increased by ribs that increases the stability considerably. The global design takes care of the tilting moment as well as shear forces resulting from external loads. The thickness of the reinforced concrete wall is only 0.35 m. Compared with a conventional gravity concrete retaining wall, the saving in construction costs is approximately 40%.

INTRODUCTION

A catastrophic snow avalanche was released in the morning of January 27, 1300 m a.s.l. in the mountains of Sørfjorden, Hardanger, municipality of Ullensvang. The avalanche struck the Bleie farms and destroyed 3 dwelling houses, one barn and 3 other farm buildings. Several persons were in the buildings, but none was severely injured.

The written history of the Bleie farms dates back to 1293 a.d. Archeological investigations prove that the Bleie settlement existed during the times of the Iron Age, and probably also in the Stone Age.

Due to detailed descriptions of the outcome and production at the farms, it is obvious that no earlier major avalanches have hit the farm the last 1000 years.

NGI was engaged by the municipality of Ullensvang to assess the avalanche hazard and to propose avalanche protection for the farms. Based on the local topographic and climatic conditions, and the historic records from Bleie, the return period of the avalanche was estimated to 800-1000 years.

Different alternatives for protection measures were studied, three alternatives of catching dams, two alternatives of a concrete deflecting walls, and one of a concrete retaining wall.

LOCATION AND TOPOGRAPHY OF THE AVALANCHE PATH AT BLEIE.

The Bleie farms are located between sea level and 30 m a.s.l., on the west side of the fiord Sørfjorden, which is a

Fig. 1 The Bleie area

branch of the main fiord Hardangerfjorden, see map fig 1.. To the west the terrain arises to the Folgefonna glacier field 1300-1500 m a.sl. From the sea level, the terrain inclination gradually increases uphill to 300 m a.s.l., except for a more gentle area between 245-265 m a.s.l. The average inclination at this 800 m long stretch is 20°. From the 300 m level the inclination decreases to 11° along a stretch of 1300 m up to 550 m a.s.l. At this altitude the inclination changes to 20°, and farther uphill the terrain gets steeper, to about 30° at 1200-1300 m a.s.l., which is the upper limit of the starting zone. At this height the terrain abruptly flattens off to a gently undulating plateau that forms the topographic base of the glacier Folgefonna, Norways second biggest glacier field.

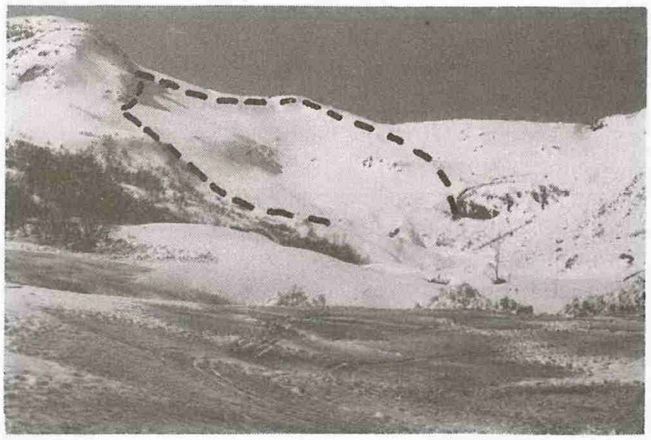

Fig 2 The starting zone of the Bleie avalanche

The starting zone is formed like an open bowl, 800 m wide, where most of the terrain is between 25° and 30° steep, see fig 2. The steepest part of the starting zone has an inclination of 35°, with an area of 50.000 m^2. The total area of terrain steeper than 30° is about 360.000 m^2.

When the avalanche was released on 27th January, almost all of the bowl area was included. The maximum width of the rupture was 800 m, and a volume of about $0.7 \cdot 10^6$ m^3 to $1 \cdot 10^6$ m^3 took part in the rupture. Entrainment of snow from the terrain above 500 m a.sl. probably increased the total volume of avalanche snow to $1.5 \cdot 10^6$ m^3.

The total horizontal length of the avalanche path is 3600 m, and the vertical drop 1300 m, corresponding to an average inclination, $\alpha = 19.9^\circ$.

Between 800 m a.s.l and 550 m a.s.l, there is a gradual confinement of the track, as the width of the avalanche decreased from 800 m to 200 m. 700 m farther downhill the width increased to 300 m, and thereafter gradually decreased to 100 - 120 m towards 75 m a.sl.

At the location of the farms the avalanche had a width of 110 m, and at the last 75 m towards the sea, the width was 50 m, see fig 3.

From the starting position and down to 375 m a.s.l., the avalanche width are more or less guided by the lateral topography, as the terrain formations on both sides of the track consist of higher, steep mountain sides. From 375 m a.s.l. and downwards to the sea, there are no such limiting terrain formations, and the avalanche followed a shallow

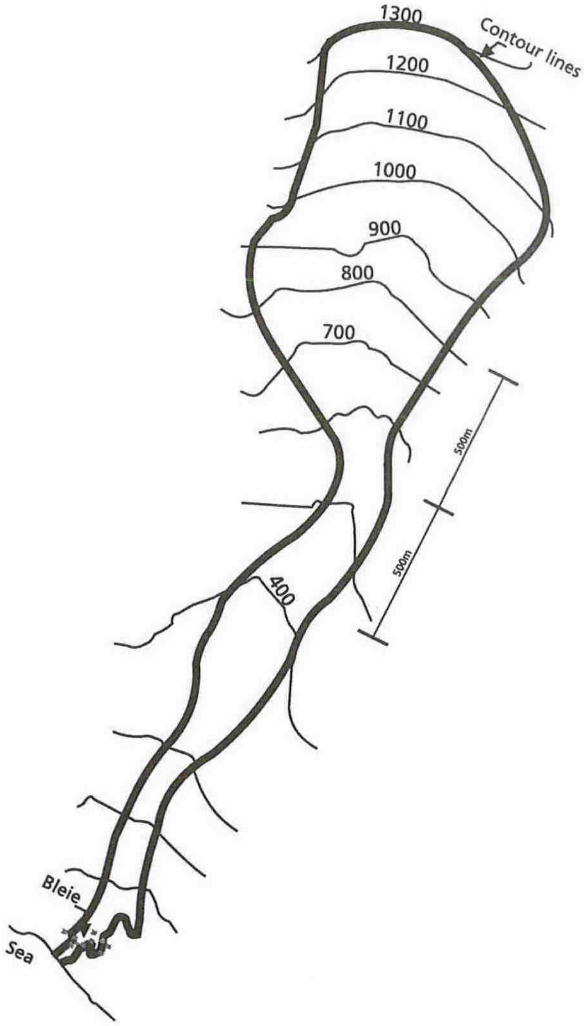

Fig. 3 Map of the Bleie avalanche path

depression of a small brook. However, there was no tendency for the avalanche to widen its track, as it descended more or less perpendicular to the contour lines all the way towards the sea.

The starting zone consists partly of a small glacier, or snow patch, surviving during the summer. Farther down in the starting zone there is exposed rock and loose deposits, heavily influenced by numerous smaller avalanches. From 400 m a.s.l.farming land dominates the path, partly leveled out artificially. Below 300 m a.s.l., where the terrain gets steeper, the hillside was covered by mature woodland of birch, older, and spruce, which was all cleared away by the avalanche

CLIMATIC CONDITIONS PRIOR TO THE AVALANCHE

January 1994 was characterized by high winds and abundant snow fall. From the 21st to the 27th, 4 major depressions passed Western Norway with heavy snow fall and wind velocities of 15-25 m/s. According to the Norwegian Meteorological Institute (DNMI), the main wind direction was westerly, see table 1. The air temperature at sea level fluctuated around zero degrees during the week before the avalanche, except for a warm spell at the 21st, when the maximum air temperature reached 7.2°C.

Table 1 Weather conditions during the last week from January 21st to 27th 1994.

Date	Temp. max (°C)	Temp min. (°C)	Wind speed (m/s)	Wind dir.	Prec. (mm)
21	7.2	3.4	10.5	212	100.4
22	4.2	1.6	14.3	263	94.2
23	3.8	0.1	16.9	260	43.7
24	1.8	-0.1	15.1	302	38.4
25	0.8	-1.2	7.1	215	26.7
26	1.3	-0.7	8.7	258	25.8
27	0.2	-1.2	12.1	225	15.2

The total precipitation during this week was 344.4 mm, measured at the Kvåle precipitation station west of the Folgefonna glacier at 348 m.a.sl, corresponding to about 3.5 m of new snow. Due to the orographic effect, the precipitation in the starting zone was considerably higher, probably about 500 mm. During the last three and five days, precipitation was 67.7 mm and 149.5 mm respectively. The seven day- and five day precipitation was especially high for Norwegian conditions. According to Bakkehøi (1987), at a five-day precipitation of this magnitude the probability of an avalanche release is almost 100%. The three day precipitation is more moderate, with a 80% possibility of release. The figures cited here is based on other avalanche paths, and must therefore be regarded as average numbers to indicate only the degree of hazard.

What seems to be surprising is the fact that the avalanche was not released after the first three or five days period, when the precipitation was 238.3 mm and 303.0 mm respectively, but after a period of decreasing precipitation intensities. This fact may be explained by the maximum temperature of 7.2°C the 21st, which probably caused rain all the way to the top of the starting zone. By the normal wet adiabatic temperature reduction of 0.6°C pr 100 m elevation, the maximum temperature should be 0.6°C at the top of the starting zone, and most of the staring zone must have been subjected to heavy rain or sleet which settled and stabilized the snow pack.

One other reason for the high precipitation amounts necessary to release the avalanche is the inclination of the starting zone which is fairly gentle: 30° on the average, and about 35° at the steepest, as described earlier.

Return period of the avalanche

Based on the historic evidence from the Bleie farms, with its known existence for more than 1000 years without any observations of a similar avalanche, it is clear that the return period of the disastrous avalanche must be very long. The local climatic records confirm this view, as the combination of heavy snowfalls and temperatures below zero at sea level is very infrequent in the area. A similar 7 days precipitation magnitude has a return period of 40-50 years, and similar low temperatures will occur every 20th year (DNMI, 1994). Provided that the two weather parameters are independent variables, the probability for a similar weather situation is 1/800-1/1000 per year.

It is a well known fact among the local population that avalanches are released every winter from the bowl shaped starting zone. Normally the avalanches come to rest below the steepest part of the hillside at 500 m a.s.l., or at the 1 km long, gentle slope beneath this point. Only once, in 1776, a wet snow avalanche travelled as far as to 300 m a.s.l., 700 m uphill from the farms, where the debris could be seen from the farms at Bleie.

Based on these calculations and facts, it was found that the location of the farms fulfilled the safety demands in the Norwegian Planning and Building Act, where the maximum avalanche frequency is $3 \cdot 10^{-3}$ per year for a rebuild after a damage. On the other hand, a rebuild without physical measures that could increase the safety for the living houses was difficult to accept in the local society, and it was decided to plan for protection works.

RUNOUT AND VELOCITY CALCULATIONS

By applying the topographic runout model developed by Lied and Bakkehøi (1980) and Bakkehøi, Domaas and Lied, (1983), the predicted runout expressed in terms of α is 20.9°, in contrast to the observed α = 19.9°, see terrain profile fig 4. The difference comprises to a standard deviation of 0.5 (1,2°). This figure may seem small expressed in degrees, but because of the low angles, and the relatively steep part of the path towards the farms, the difference between the calculated "normal" runout, and the observed is 1060 m. On the other hand, according to the α-value, the observed runout is very long, as only 6 avalanches of the total number of 206 extreme avalanches in the topographic model are observed with $\alpha < 21°$.

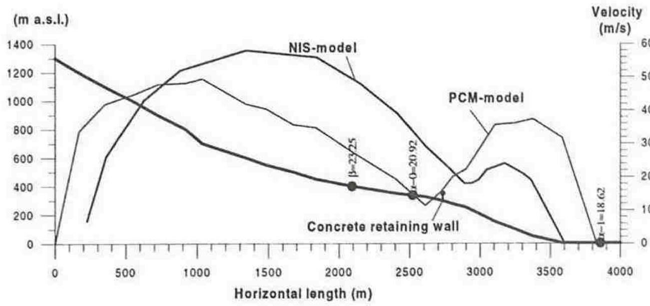

Fig 4. Terrain profile, runout- and velocity calculations

Velocity calculations are performed according to the PCM-model (Perla *et al.* 1980), and the NIS-model (Norem *et al.*

1987). In fig 4 the velocity distribution for one set of friction parameters are shown. The parameters are adjusted to match the observed runout.. The applied friction parameters in the PCM - model: μ = 0.15, M/D = 750 represent friction figures normally used for Norwegian avalanches when the runout of a 1000 year avalanche is computed, and matches the observed runout. According to Bakkehøi *et al.* (1983), it is considerably lower than the mean value for slopes with $\beta < 31^\circ$, which was found to be μ = 0.20, M/D = Y·0.5, where Y = total vertical drop of the avalanche.

Maximum velocity of the avalanche is computed to 44 m/s at 700 m a.sl. From this point the velocity slowly decreases along the gentle inlined slope of 11°, to its minimum of 16 m/s at 300 m a.s.l., before the velocity increases at the last stretch downhill towards the Bleie farms.

PROTECTIVE MEASURES

Six different alternatives of protective measures for the Bleie farms were outlined by NGI. Three of these were cathing dams located between 245 and 300 m a.s.l.. Two of the cathing dams were planned to be built by earth materials, and one by blasted rock.

Design height was 15 m, overall length 110-130 m, with total volume ranging from 66.000 m^3 for the blasted rock dam, to 124.000 m^3 for the earth material dams, see fig.5.

Because of the big area occupied by the retaining dams, which mainly consisted of farming land owned by the neighbouring farm Reiseter, which is not subjected to avalanche danger, these solutions were not popular.

Three alternative solutions based on concrete walls were outlined. Two of these were located close to the farms as deflecting walls, 5 - 8 m high, with lengths of 225 m and 110 m respectively, se fig 5. The shortest of these alternatives gave protection to one farm only, and implied a rebuild of one of the destroyed farms at a new location. The longest alternative was meant to protect all the exposed buildings. Due to the shortage of areable land, and the close location to the living houses, these deflection walls were not accepted by the Bleie farmers.

One alternative was found to be acceptable; a 10 m high and 110 m long concrete retaining wall. The wall was located at 300 m a.s.l., at the lower end of the 1300 m long, gentle inclined part of the avalanche track. At this point the avalanche velocity is at its minimum, before the avalanche starts the last decend towards sea level.

Due to the strong wish from the local farmers to preserve farmland, it was necessary to find a protection construction which occupied as little arable land as possible. The use of a concrete gravity wall suggested by NGI was therefore preferred by the community.

To outline and plan the details of the retaining wall, the municipality of Ullensvang engaged INSTANES A/S Consulting Civil Engineers, Bergen, to carry out a preliminary project and a cost estimate, as recommended by NGI. The concept was a traditional gravity retaining wall of reinforced concrete supported by triangular ribs on

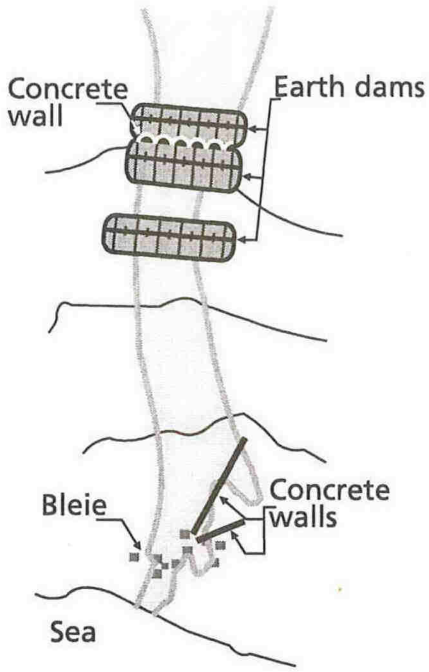

Fig 5 Location of protective measures

the lower side. The wall had a length of 113.4 m and a minimum height above the terrain of 10 m.

The total cost of the project was calculated to approximately 10 mill. NOK. The municipality decided that the project was too costly, protecting only the two farms exposed to the avalanche. The project was, therefore, postponed.

In 1995 B. Instanes presented a new concept which drastically reduced the construction costs. This led to a revitalising of the project, and the municipality ordered the detailed engineering to be carried out for the new concept. Tender documents were worked out, and contract with value NOK 4,5 mill. was signed on 25th June 1996, with the contractor NCC Eeg-Henriksen Anlegg AS.

DIMENSIONING CRITERIA

The dimensioning criteria for the wall was as follows:

Avalanche velocity,	v_1 = 20 m/s
Velocity of snow cloud,	v_2 = 30 m/s
Density, avalanche flowing snow,	ρ_1 = 200 kg/m^3
Density, resting avalanche snow,	ρ_2 = 500 kg/m^3
Density, snow cloud,	ρ_3 = 10 kg/m^3
Avalanche flowing height,	h_1 = 3.0 m

Height of the retaining wall

The descission to build a retaining wall started with a long discussion of alternatives at different locations and ended with the 10 m high concrete wall at 300 m a.sl. Up to present NGI has mostly designed retaining dams made of earth materials with gentle slopes (1:1.5), which for the Bleie avalanche indicated a dam height of slightly above 15 m. The vertical concrete structure will however induce a larger energy loss to the avalanche front than a gentler inclined earth dam. Based on a calculated velocity of 20 m/s at the dam the resulting ascending height is 8.4 m, when 50% of the energy is lost at the impact. According to this figure, the dam is capable of stopping the avalanche front. The long tail of the avalanche will create gentler shear planes against the wall, and partly flow over the top edge, and partly around both ends of the wall. The wall is located at the end of a 1,3 km long gentle inclined slope, giving a large storing capacity.

The avalanche from 1994 had a estimated volume of 70.000 - 80.000 m^3 beyond the location of the dam. The calculations indicate that the wall is able to stop most of the avalanche volume, but a portion will travel further, both over- and to the side of the dam.

The reason for accepting retaining wall which is not able to stop the whole avalanche, is the fact that the avalanche extent has been observed only once in 700 years. Moreover, the weather analysis indicates a 800 - 1000 year average return period of similar weather situations, as earlier described. According to the Norwegian Building code it is legal to rebuild damaged houses in areas with a maximum avalanche probability of $3 \cdot 10^{-3}$. The structure was accepted to be built after a long discussion on accepting the avalanche risk for the housing area as it was estimated.

Dynamic and static avalanche load

The snow masses are first supposed to hit the wall between 1 m and 4 m above the ground. Thereafter the avalanche mass will gradually pile up towards the wall, shifting the point of attack of the load to higher positions. The most unfavorable load situation occurs when the avalanche has moved to the top of the wall. When this point is reached, the avalanche consists of a 3m flowing layer (h_1), above h_2 = 7 m of avalanche snow at rest.

According to Norem (1990) the total dynamic load consists of:

-velocity independent pressure: $p_{vi} = k_p \cdot \sigma_v$
-velocity dependent pressure: $p_{vd} = \rho_1 \cdot v_1^2$

where:

k_p = Passive snow load coefficient = 2
σ_v = Vertical snow load

At the base of the flowing avalanche, $\sigma_v = \rho_1 \cdot g \cdot h_1$, and the velocity independent pressure at the base of the flowing avalanche is:

$$p_{vi} = 2 \cdot 200 \cdot 9.81 \cdot 3 \text{ Pa} = 12 \text{ kPa}$$

The velocity dependent pressure is:

$$p_{vd} = 200 \cdot 20^2 \text{ Pa} = 80 \text{ kPa}$$

The total dynamic load by the flowing part is:

$$p_{vi} + p_{vd} = 92 \text{ kPa}$$

The load by the snow cloud is, $p_2 = \rho_3 \cdot v_2^2 = 9$ kPa. This load is supposed to be evenly distributed along the wall.

According to Larsen *et al.* (1985), the average static snow pressure against a construction may simplified be expressed as:

$$p_{stat} = k_a \cdot \sigma_v,$$

where

k_a = Active snow load coefficient = 0.65

When the avalanche hits the top of the wall, the vertical load at the ground is:

$$\sigma_v = \rho_1 \cdot g \cdot h_1 + \rho_2 \cdot g \cdot h_2$$

The load consists of two parts; the weight of avalanche snow in motion, ($\rho_1 = 200$ kg/m^3), and the weight of stagnant avalanche snow ($\rho_2 = 500$ kg/m^3). The corresponding static load at the base of the wall is:

$$p_{stat} = 0.65(200 \cdot 9.81 \cdot 3 + 500 \cdot 9.81 \cdot 7) \text{ Pa} = 26.1 \text{ kPa}$$

The load is assumed to be evenly distributed.

Vertical lifting load

A vertical load, F_0, acts upwards along the wall as the avalanche snow hits the structure and is forced upwards. Based on measurements on avalanche galleries, the dry friction coefficient $\mu = 0.3$. The vertical lifting force per unit length along the wall is:

$$F_0 = (p_{vi} + p_{vd}) \cdot \mu \cdot h = 0.5(80 + 92) \cdot 0.3 \cdot 3 \text{ N} = 77.4 \text{ kN/m}$$

Forces acting on the end shells

According to Harbitz (1996), the dynamic loads have to be calculated specifically at the outer ends of the wall where the avalanche is allowed to flow around the wall instead of being totally deflected or stopped. By comparison with empirical values of drag coefficients for various geometries, the velocity dependent part of the dynamic pressure at the midpoint of the outer curved shell is $p_{vd} = 0.9\ \rho_1 \cdot v_1^2$, i.e. 10% less than the velocity dependent part of the dynamic pressure along the middle part of the wall.

At the outer edge where the avalanche flows along the wall, the hydrostatic snow pressure at the base of the flowing avalanche is $p = \rho_1 \cdot g \cdot h_1$. The value ρ_1 is used without regard to the effects of compression. Hence the snow pressure is here slightly underestimated.

The shear stress on the outer curved segment is found by multiplying the dynamic pressure by the dry friction coefficient, μ. A parabolic distribution of pressure and shear stress is assumed between the midpoint and the edge of the outer curved segment.

ENGINEERING DESIGN OF THE WALL

The concept of the new design was to construct a retaining wall, able to withstand the design loads, and using a minimum of building materials. The design loads acting on the wall and its height and length were provided by NGI, see fig 6. In addition to the loads parallel to the surface shown on the figure, an upward vertical friction load increases the tilting moment.

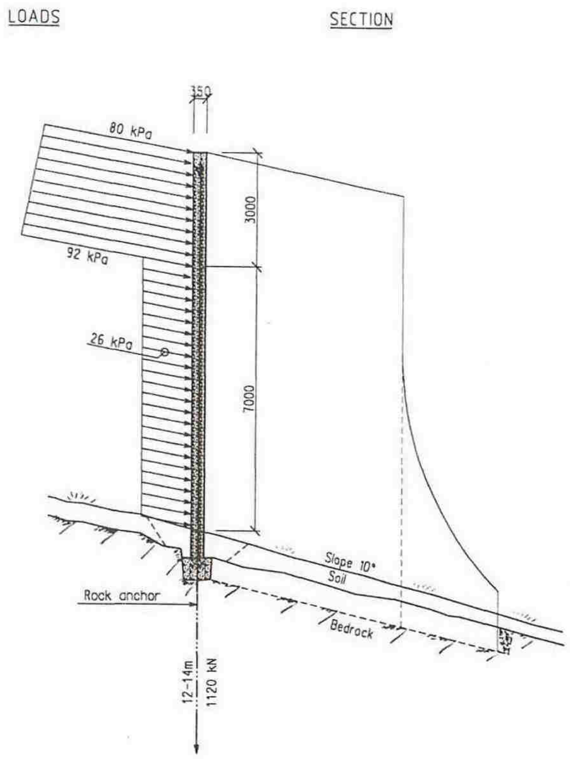

Fig.6 Wall section and loads

The aesthetic considerations were also a strong issue, as there was some opposition to a «monster» like this in the picturesque landscape of the Hardanger fjord. The wall consists of five-and-a-half half-cylindrical shells monolithically connected to form the 113.4 m long wall, see fig.7.

After excavation of the soil, a trench of 1m x 1m was blasted under the footings of the wall. The reinforced concrete foundations were poured directly into the rock trench and thus conveying the shear loads from the wall to the bedrock. At the connecting point of the cells, the wall width was extended by a 1 m thick concrete rib as shown on figs. 7 and 8. This increases the tilting stability considerably. However, the most important feature of the design is that each shell is anchored to the bedrock by four tension rock anchors, each with a capacity of 2800 kN. The tilting moment for each shell is 59.000 kNm and the shear force is 8.500 kN. The global design has a safety factor of 1.8 against tilting. The structure is also analysed for a number of asymmetrical loads.

The structure is a double reinforced concrete wall of only 0.35 m thickness, which has the necessary capacity for all load cases. The free end of the wall against the Bleie river is supported by two Y-shaped ribs. An opening for a tractor road was arranged in shell no. 3. Also a sufficient number of 1m x 1m drainage openings were provided. Special emphasis was laid on the aesthetic design of the structure. The rounded forms of the half-cylindrical shells are repeated in the ribs and other details, thus achieving a uniform, sculptural appearance, see fig. 7.

CONSTRUCTION

The construction was carried out within 5 months as scheduled. The contractor started the work on site 10th July 1996, and the wall was completed 1st December 1996. An access road and a railroad for a construction crane were built along the upslope side of the wall. The formwork was carried out using prefabricated elements for each shell.

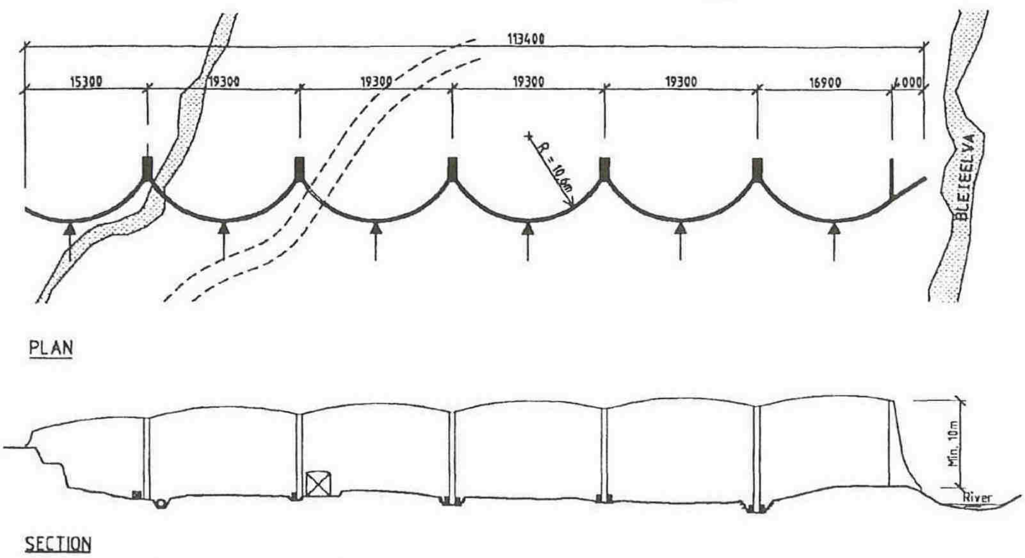

Fig 7 Plan and section of the retaining wall

After the concreting, the formwork was removed and the elements were erected for the next shell. Also the reinforcing mats were pre-shaped on the ground and lifted in place with the crane. The retaining dam is shown on fig.8.

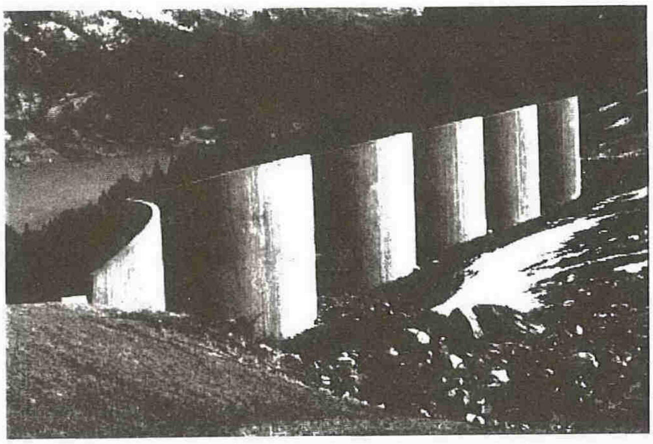

Fig 8 Photo of the wall

Key data of the construction works

Client:
Ullensvang Herad, Hardanger, Norway

Consulting Civil Engineer:
INSTANES A/S, Bergen, Norway

Contractor:
NCC Eeg-Henriksen Anlegg A/S, Bergen, Norway

Geometry:

Total length:	113.4 m
Height (min):	10 m
Wall thickness:	0.35 m

Construction materials:

Concrete:	C45 - 650m^3
Reinforced steel:	K 500 TE - 120 000 kg
Rock anchors:	22 x 2800 kN total capacity 61 600 kN

Construction period:
5 months

Construction costs:
NOK 5.6 million (incl. access road)

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