UNLINED WATER CONDUITS IN NORWAY

A documentation on
unlined pressure shafts
and - tunnels with static
head in excess of 150 m

Sandvika, 22.4.83
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UNLINED WATER CONDUITS IN NORWAY

Unlined water tunnels and shafts with pressure of any significance came into use in Norway at the end of World War I in 1919. After the first four shafts were built, no unlined high pressure conduits were constructed before the mid fifties. From then on a number of shafts and tunnels with steadily increasing pressure on unlined rock have been constructed. Starting in the seventies a number of hydropower plants have been constructed with unlined air cushion surge chambers in rock. Two common lay-outs of tunnels and shafts are shown on fig. 1. The choice of actual lay-out is dependent upon topography, access and the need for secondary intakes.

An unlined pressure conduit is a tunnel or shaft which is not lined to withstand internal water pressure. As the rock is a material with a certain permeability albeit low, water will migrate into or out of a tunnel depending on the relation between natural ground water pressure and the pressure in the tunnel. This is shown in principle on fig. 2.Lining for rock support purpose is applied as necessary as is grouting and sealing of pervious zones. Average length of lining very seldom exceeds 5 % of total tunnel length.

In exhibit 1 a listing of hydropower plants which have tunnels and shafts with static head higher than approximately 150 m are given. Some plants with lower pressure which are of special interest due to failures or heavy leakage have been included. The list in exhibit 1 gives only the maximum static head on unlined rock. One reference may therefore include several kilometers of tunnels with lower, but still comparatively high head. The total length of unlined pressure conduits in operation in Norway today is not known exactly, but is estimated to exceed 2000 km. There is of course also a number of hydropower stations which have a maximum static head on unlined rock lower than 150 m. Except for a few interesting cases these power stations, approximately 150 in number, are not included in the list. The information given in exhibit 1 is based partly on an unpublished report, NGI-54402 from the Norwegian Geotechnical institute, partly on the Norwegian publications listed in the bibliography in exhibit 2, and partly on information from the various owners.

The design principles used for the first shafts are not known, but from reports written on the failures of two of the four shafts built around 1920 an understanding of the need for an overburden pressure to counteract the waterpressure can be discerned.

For the plants built in the fifties and sixties the need for a certain excess overburden pressure or rather positive effective rock stresses were recognized and used as a design principle. There excisted, however, only a number of rather crude empiric methods for estimating rock stresses.

The need for a better understanding of the problems and a more reliable design method was realized in the early seventies when three pressure shafts and tunnels suffered hydraulic splitting. The Norwegian Geotechnical Institute undertook a systematic analysis of excisting pressure shafts and tunnels and the Department of Geology at the Norwegian Technical University developed a finite element programme for stability analysis.

A summary of the data compiled by NGI is given on fig. 3 and an example of a finite element model with dotted equilibrium lines representing various heads is given on fig. 4.

After the newer and more precise design methods came into use, problems with failures seem largely to have been overcome. The increasingly common practice of checking the design values by in situ stress measurements and pore pressure measurements has contributed to the successful construction and operation of a number of high head conduits and air cushion surge chambers in the late seventies. Currently there are 17 separate conduits with static head on unlined rock in excess of 400 m in operation, the highest beeing 780 m.

A number of high head plants are under construction today (1983).
The shaft with highest pressure under construction is Tjodan with 890 m static head on unlined rock and shafts with head in excess of 1000 m are planned.

Sandvika, 11.4.83

B. Buen

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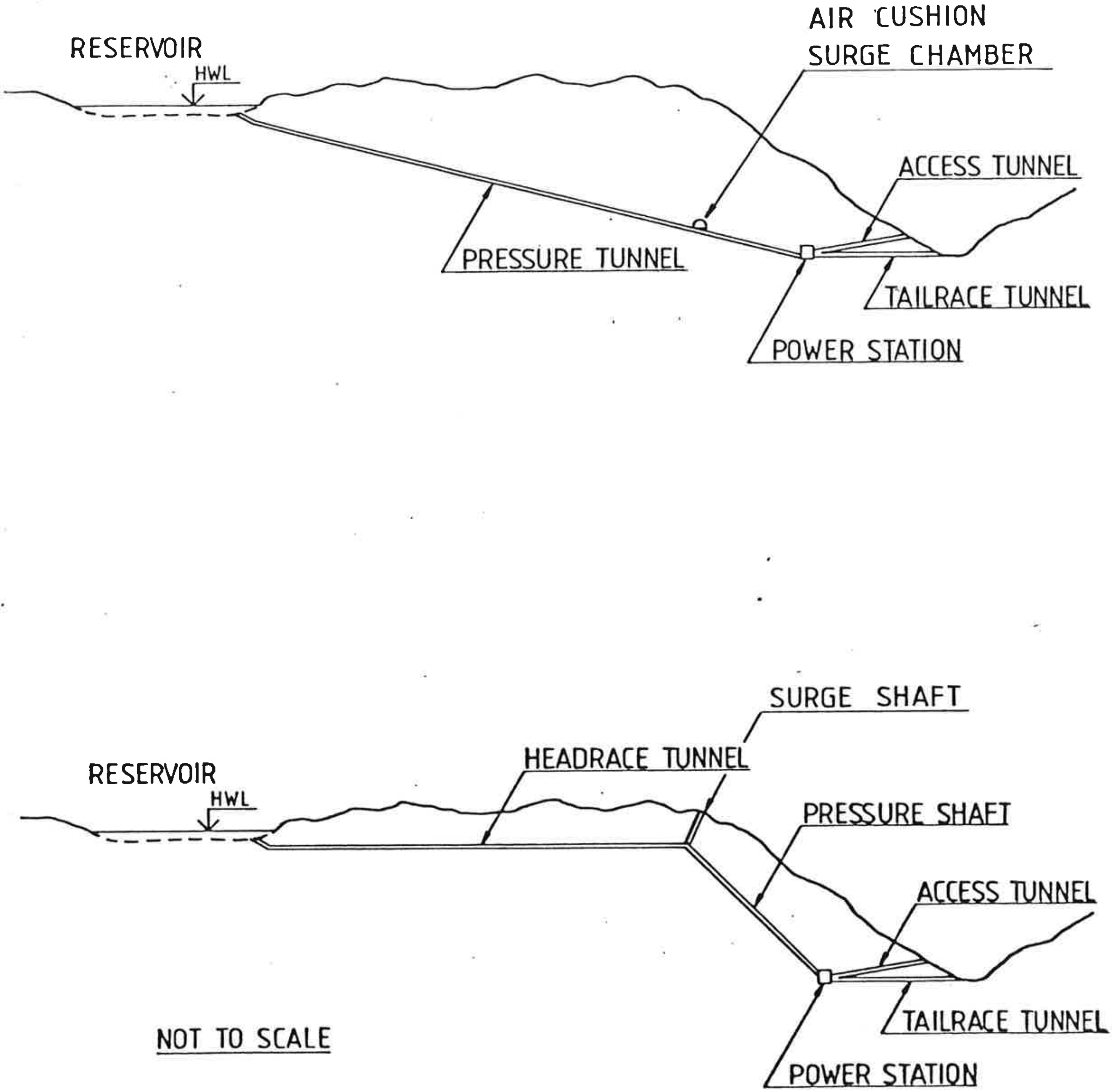

AIR CUSHION
SURGE CHAMBER
RESERVOIR
HWL
ACCESS TUNNEL
PRESSURE TUNNEL
TAILRACE TUNNEL
POWER STATION
SURGE SHAFT
HEADRACE TUNNEL
RESERVOIR
HWL
PRESSURE SHAFT
ACCESS TUNNEL
TAILRACE TUNNEL
NOT TO SCALE
POWER STATION

Fig. 1

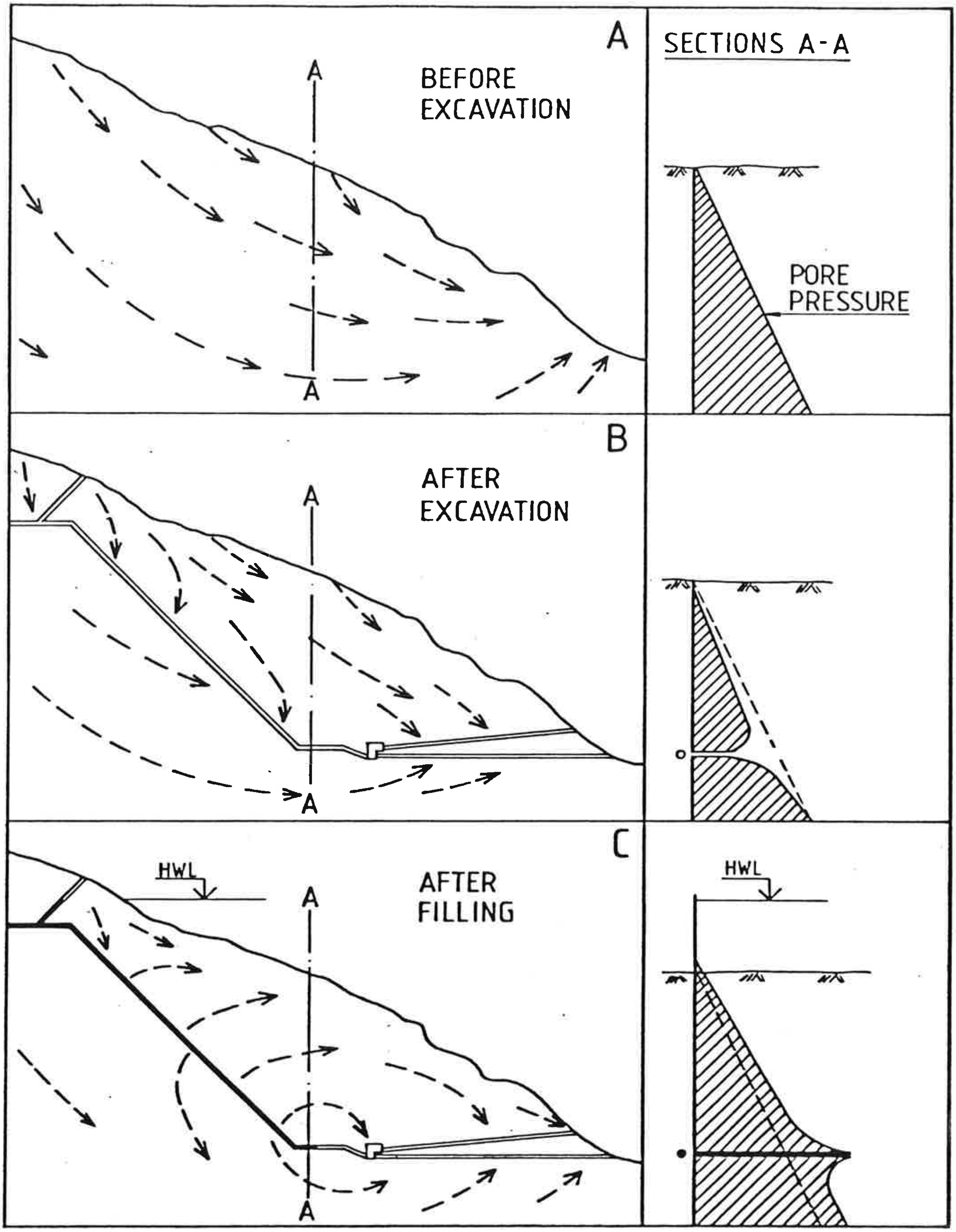
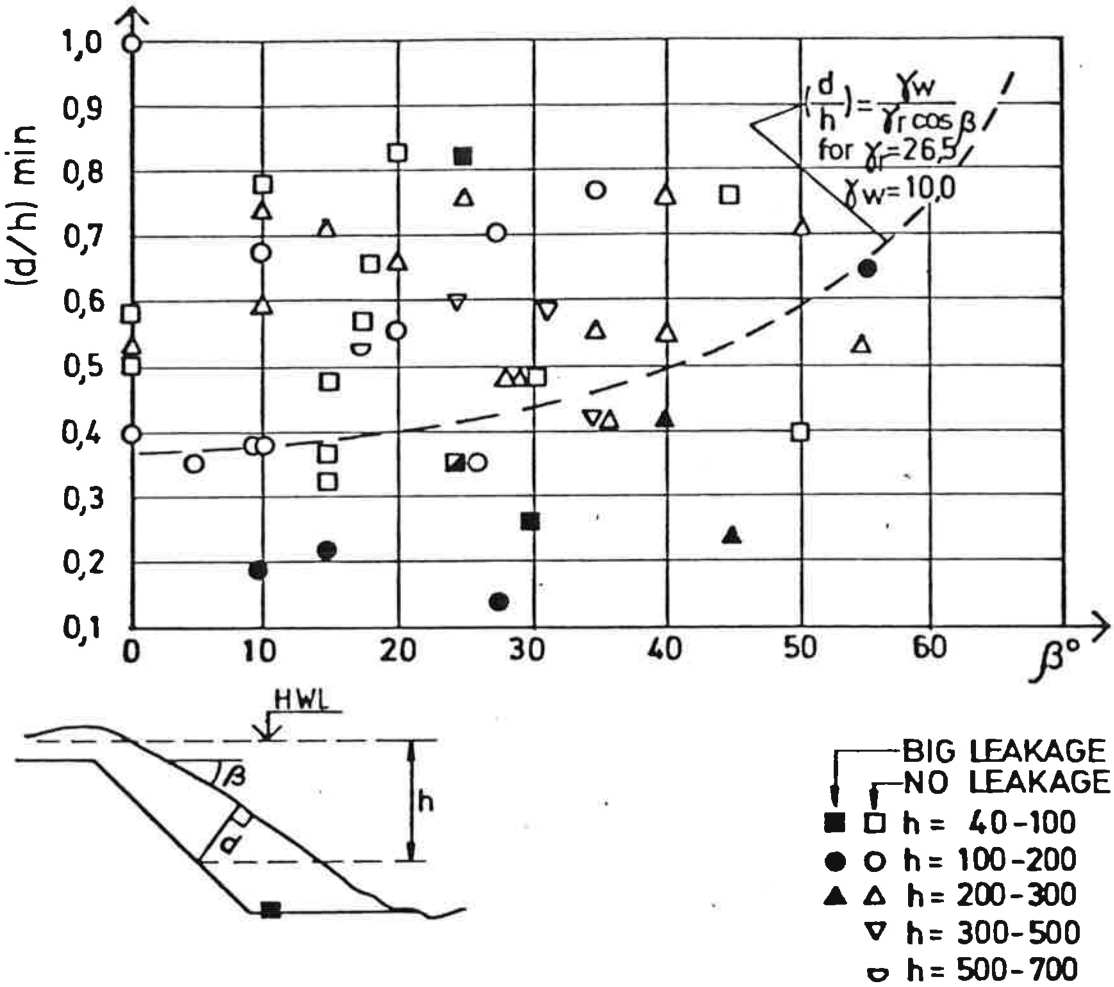
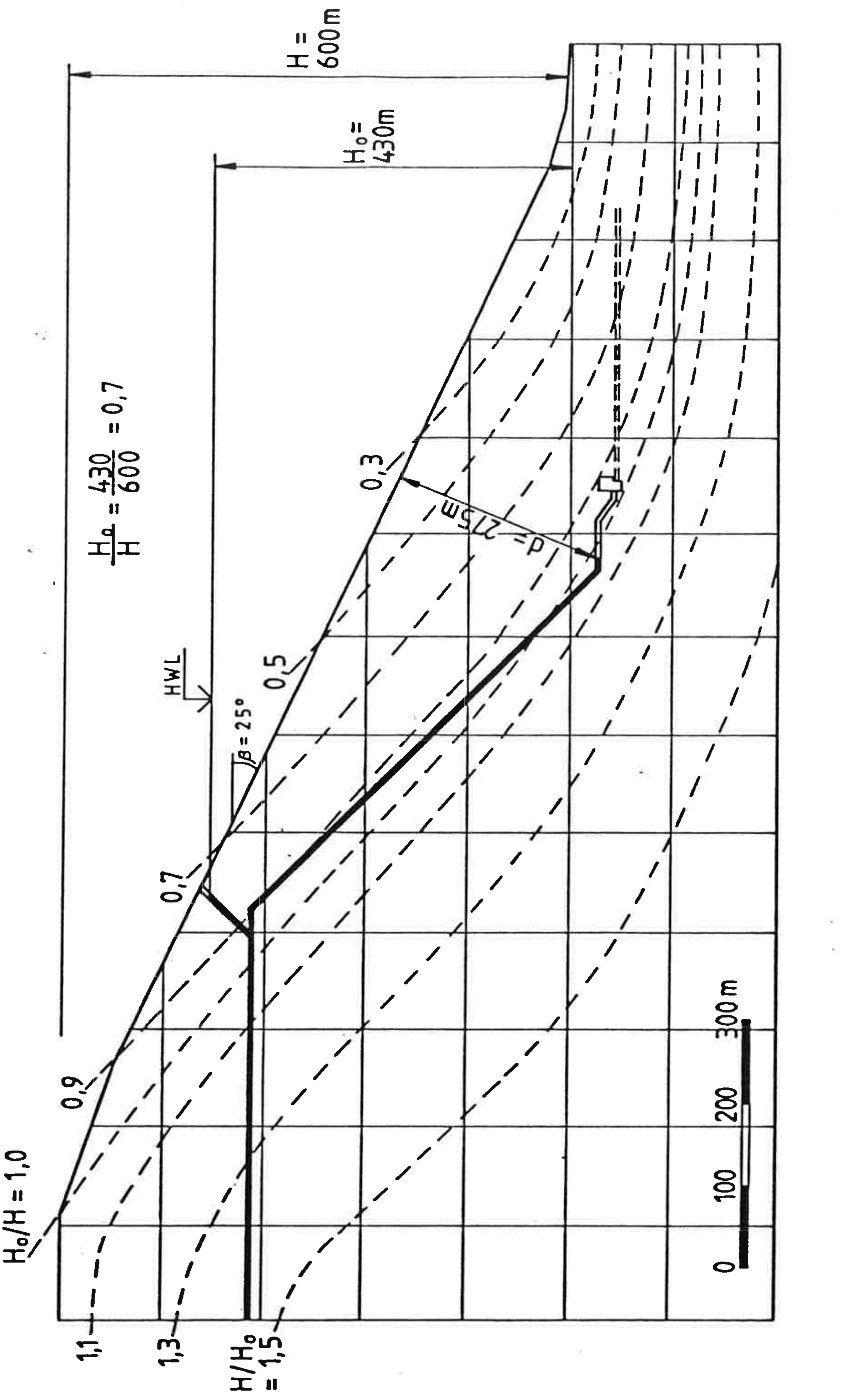

A
BEFORE
EXCAVATION
SECTIONS A-A
PORE
PRESSURE
A
A
B
AFTER
EXCAVATION
A
A
C
HWL
AFTER
FILLING
A
A
HWL

Fig. 2



1,0
0,9
0,8
0,7
0,6
0,5
0,4
0,3
0,2
0,1
(d/h) min
0
10
20
30
40
50
60
β°
(d/h) = γw / γr cos β
for γr = 26,5
γw = 10,0
HWL
β
h
d
BIG LEAKAGE
NO LEAKAGE
h = 40-100
h = 100-200
h = 200-300
h = 300-500
h = 500-700

Fig. 3



H = 600m
H_o = 430m
$\frac{H_o}{H} = \frac{430}{600} = 0,7$
0,3
d = 275m
0,5
HWL
β = 25°
0,7
0,9
H_o/H = 1,0
1,1
1,3
H/H_o = 1,5
0
100
200
300m

Fig. 4

EXHIBIT 1

LIST OF NORWEGIAN UNLINED PRESSURE SHAFTS AND TUNNELS

Reference number	Name of project	Year of commis-sioning	Type of conduit	Static head	Geologic conditions	Comments
1.	Herlandsfoss	1919	Pressure tunnel and shaft	136	Hornblende schist inter-bedded with mica schist	Hydraulic splitting of a low - level high - pressure tunnel occured immediately after first filling and again after repairs with reinforced concrete lining and grouting. The whole horizontal tunnel was even-tually steel lined to compensate for inadequate rock cover.
2.	Skar	1920	Pressure tunnel	142	Granitic gneiss with lenses of amphibolite, partly weathered	Hydraulic splitting occured during testing at a head of 81 m and again after repairs at a head of 116 m. Due to insufficient rock cover in general the lower tunnel was replaced by a penstock on the surface.
3.	Svelgen	1921	Pressure shaft and tunnel	152	Massive gray-green sandstone	Leaks of 3-4 l/sec occurred during testing, but were stopped by grouting.
4.	Tafjord K3	1958	Pressure shaft	286	Banded gneisses	Small leaks into the shaft have been observed when the shaft is emptied. Cracks in concrete lined section with faulted rock is probably due to expanding clay.
5.	Daja	1958	Pressure shaft	144	Mica schist, horizontal foliation	No leaks observed from the shaft.
6.	Porsa	1959	Pressure shaft and tunnel	222	Greenschist with a short section of quartz dolo-mite and shale	Problems with leakage in the dolomite during construction. The leaks were stopped with grouting and shotcrete. No leaks reported during operation.

7.	Svartelva	1959	Pressure shaft	100	Mica schist	No operational problems reported.
8.	Fortun	1963	Pressure tunnel	186	Arkose	Concrete lining of faulted and fractured zones. Sealing of leaks encountered during construction by grouting. No operational problems reported.
9.	Sokna	1964	Pressure shaft	174	Greenschist, phyllite and graywacke	No operational problems reported.
10.	Straumsmo	1966	Pressure shaft	232	Mica schist	Zones with faulted rock in the shaft supported by grouted dowels and reinforced shotcrete.
11.	Tafjord K 4	1966	Pressure shaft	450	Banded gneiss	No rock support or sealing required. No operational problems reported.
12.	Ørteren	1966	Pressure shaft	160	Gneiss partly schistose	Joint opening and leakage during first filling. Leak was sealed by grouting and no further problems are reported.
13.	Håen	1966	Pressure shaft and tunnel	200	Mica schist	No operational problems reported.
14.	Kalvedalen	1967	Pressure shaft	225	Gabbro and quartz diorite	No operational problems reported.
15.	Tysso II	1967	Pressure shaft	217	Granite	No operational problems reported.
16.	Uvdal II	1967	Pressure shaft and tunnel	170	Granitic gneiss	No operational problems reported.
17.	Søa	1967	Pressure shaft	267	Granitic gneiss	No operational problems reported.
18.	Rana	1968	Pressure shaft	220	Gneiss partly schistose	Some leaks encountered during construction. Moderate to high intensity rock burst.

19.	Trollheim	1968	Pressure shaft	297	Gneiss with high quartz content	Grouted, dowels, shotcrete and concrete lining used for rock support in faulted areas. Some leaks encountered during constructions. No operational problems reported.
20.	Byrte	1968	Pressure shaft	303	Gneiss and granitic gneiss	Small leaks encountered during construction. Hydraulic splitting occured due to insufficient rock cover, and the whole shaft had to be steel lined.
21.	Blåfalli III	1968	Pressure shaft	302	Granite	No operational problems reported.
22.	Hove	1969	Pressure shaft	320	The lower 100 m of the shaft lies in gneiss and separated from the upper 300 m in phyllite and mica schist by a thrust fault	Faulted and fractured zones supported by grouted dowels, shotcrete and cast in place concrete. No operational problems reported.
23.	Målset	1969	Pressure tunnel	190	Phyllite and mica schist	No operational problems reported.
24.	Småvatna	1969	Pressure shaft	220	Phyllite and quartzbearing schist	No operational problems reported.
25.	Guolasjokka	1970	Pressure shaft	180	Quartzose mica schist and thin layers of graphite schist	No operational problems reported.
26.	Fjone	1970	Pressure shaft	250	Granitic gneiss	Faulted zone supported by cast in place concrete and sealed by grouting. No operational problems reported.

27.	Åskåra I	1970	Pressure tunnel	210	Sandstone	Deformation and flushing out of clay-filled seams due to insufficient rock cover. Steel lining was extended and additional grouting performed, and no further operational problems are reported.
28.	Hovatn	1970	Pressure shaft and tunnel	475	Granitic gneiss	Faulted zones supported by cast in place concrete. Sealing of seams in tunnel and shaft by grouting. No operational problems reported.
29.	Jørundland	1971	Pressure tunnel	280	Amphibolitic foliated gneiss with some peg-matitic lenses	Seam in front of plug shotcreted and grouted. No operational problems reported.
30.	Bjerka	1971	Pressure tunnel	72	Foliated gneiss interbedded with mica schist	Deformation and flushing out of clay-filled seams due to insufficient rock cover. Steel lining was extended. No further problems are reported.
31.	Bogna	1971	Pressure shaft	280	Granitic gneiss	Rock support by shotcrete and cast in place concrete in faultzones partly with calcareous filling.
32.	Savalen	1971	Pressure shaft	250	Quartzitic mica schist	No operational problems reported.
33.	Finndøla	1972	Pressure shaft and tunnel	295	Granitic gneiss	No operational problems reported.
34.	Svelgen IV	1972	Pressure shaft and tunnel	160	Massive gray-green sandstone	No operational problems reported.

35.	Ylja	1973	Pressure shaft	210	Meta-arkose	Leakage occured during first filling probably due to an open joint. Sealing by shotcrete and grouting has reduced leakage to appr. 10 l/sec., an acceptable level.
36.	Sjona	1973	Pressure shaft	250	Calcareous sediments and mica schists	No operational problems reported.
37.	Skjomen	1973	Pressure tunnel	350	Granite	No operational problems reported. Average mass permeability calculated to be 3×10^{-9} m/sec. based on measurements during first filling.
38.	Driva	1973	Pressure tunnel	450	Gneiss	Air cushion surge chamber in unlined rock, volume appr. 3000 m3. Static pressure 42 bar. Air leakage too small to be measurable. No operational problems reported.
39.	Dividalen	1973	Pressure shaft and tunnel	278	Mica schist	No operational problems reported.
40.	Solhom	1973	Pressure shaft	200	Gneiss	Rock supported by unreinforced cast in place concrete. No operational problems reported.
41.	Mauranger	1974	Pressure shaft and tunnel	440	Gneiss	No operational problems reported.
42.	Ulvik	1974	Pressure shaft and tunnel	330	Partly phyllites partly gneiss	No operational problems reported.

43.	Øljusjøen	1974	Pressure tunnel	250	Gneiss	No operational problems reported. Average mass permeability calculated to be 1 x 10^{-8} m/sec. based on measurements during first filling.
44.	Jukla	1974	Pressure tunnel	250	Gneiss	Air cushion surge chamber in unlined rock. Volume appr. 4000 m3, static pressure 24 bar. Air leakage very low as predicted in final design. No operational problems reported.
45.	Grytten	1975	Pressure tunnel	310	Gneiss	No operational problems reported.
46.	Fagerli	1975	Pressure shaft and tunnel	215	Mica schist	No operational problems reported.
47.	Vemundsbotn	1976	Pressure shaft	250	Gneiss	No operational problems reported.
48.	Lassajavri	1977	Pressure shaft and tunnel	148	Quartzite and phyllite	No operational problems reported.
49.	Svandalsflona	1977	Pressure tunnel	203	Greenschist, phyllite and gneiss	No operational problems reported.
50.	Åmæla I	1977	Pressure shaft	500	Banded gneiss	No operational problems reported.
51.	Åmæla II	1977	Pressure shaft	514	Banded gneiss	No operational problems reported.
52.	Båtsvatn	1977	Pressure tunnel	210	Massive fine grained, granite	No operational problems reported.
53.	Brattsberg	1977	Pressure tunnel and shaft	150	Greenschist	No operational problems reported.

54.	Leirdøla	1978	Pressure shaft	450	Gneiss	No operational problems reported. Average mass permeability calculated to be 1 x 10^{-8} m/sec., based on measurements during first filling.
55.	Duge	1978	Pressure shaft	140	Gneiss	Partly lined with unreinforced concrete as rock support. No operational problems reported.
56.	Ål	1951 1978	Pressure tunnel	30	Gneiss	Hydraulic splitting gave considerable but still acceptable leakage. Plug was moved further into the tunnel in order to get sufficient overburden when the power station was renovated in 1978.
57.	Lomi	1979	Pressure shaft	570	Mica schist and phyllite	No operational problems reported. Average mass permeability calculated to be 5 x 10^{-8} m/sec., based on measurements during first filling.
58.	Skibotn	1979	Pressure tunnel	440	Mica schist	Grouted dowels, shotcrete and concrete lining for rock support in faulted zones. Average mass permeability calculated to be 3 x 10^{-8} m/sec., based on measurements during first filling. No operational problems reported.
59.	Kjela	1979	Pressure tunnel	180	Granitic gneiss	Deeply weathered rock. Open joints required extensive grouting. No operational problems reported.
60.	Kolsvik	1979	Pressure tunnel	430	Gneiss	No operational problems reported.

61.	Lang-Sima	1980	Pressure tunnel	520	Gneiss	Air cushion surge chamber in unlined rock, static pressure 49 bar, volume 6200 m^3. Recorded air leakage less than 0,1 NM^3/min.
62.	Oksla	1980	Pressure tunnel	450	Gneiss	Air cushion surge chamber in unlined rock, static pressure 44 bar, volume 17.000 m3. Air leakage too small to be measurable.
63.	Steinsland	1980	Pressure shaft	470	Gneiss	No operational problems reported.
64.	Nye Osa	1981	Pressure tunnel	200	Granite and arkose	Numerous water leaks encountered during excavation of tunnels, and extensive grouting necessary. Rock support in faulted areas by grouted dowels, shotcrete and concrete lining. Air cushion surge chamber in unlined rock, pressure 18 bar, volume 12.000 m3. Extensive grouting of surge chamber has reduced the air leakage to approx. 1 NM^3/min., which is well within acceptable operational limits.
65.	Sy Sima	1981	Pressure tunnel	290	Gneiss	No operational problems reported.
66.	Tafjord K 5	1981	Pressure shaft and tunnel	780	Gneiss	Air cushion surge chamber in unlined rock pressure 75 bar restrictions on operation due to air leaks. Grouting planned in 1983. Tunnel and shaft function properly.
67.	Holen	1981	Pressure shaft	320	Gneiss	No operational problems reported.

68.	Kvilldal	1981	Pressure tunnel	465	Gneiss	Air cushion surge chamber in unlined rock, pressure 41 bar, volume 110.000 m3. Recorded air leakage 1-4 NM^3/min., well within acceptable limits.
69.	Lavkajokka	1982	Pressure shaft and tunnel	122	Mica schist	No operational problems reported.
70.	Sildvik	1982	Pressure shaft	640	Mica schist	Moderate to high intensity rock burst in the lower part of the shaft. No operational problems reported.
71.	Grana	1982	Pressure shaft	430	Granodiorite and mica schist interbedded and folded	No operational problems reported. Locally moderate rock burst.
72.	Litjfossen	1982	Pressure tunnel	200	Mica schist	No operational problems reported.
73.	Brattset	1982	Pressure shaft and tunnel	230	Mica schist	No operational problems reported. Air cushion surge chamber, unlined rock, pressure 20 bar, volume 10.000 m3. Air leakage too small to be measurable.
74.	Sørfjord	1982	Pressure shaft and tunnel	450	Mica schist	No operational problems reported.
75.	Årøy	1983	Pressure tunnel	140	Granite	No operational problems reported.
76.	Slunkajavre	1983	Pressure tunnel and shaft	240	Phyllite and marble	No operational problems reported.

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EXHIBIT 2

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UNLINED PRESSURE

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