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Survey about Damage, Repair and Safety of Norwegian Concrete Dams

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ABSTRACT: The paper present results and assessments from a survey carried out by SINTEF in 1998. A questionnaire was mailed to all VTA persons in Norway and answers from 287 concrete dams (432 including combination dams), equal to 27% of all main types of concrete dams under public supervision in Norway, were received. 89 dams are so called "large dams" higher than 15 meter. The survey shows that the majority of dam owners follow requirements and recommendation by NVE. Most concrete dams contain few damages of various types without any consequent for the function and safety. However, damages categorized as many occur in up to 5% of the dams, which might influence safety and reliability in a short or long time span. Surprisingly many concrete dams were repaired (44%) or will be repaired in the near future (40%) and 10% of existing repair has been repaired more than one time. Large dams are generally more damaged than smaller dams and it looks like dams constructed around 1950 to 1960 are more damaged than other periods.

1 FIELD INVESTIGATIONS OF NORWEGIAN CONCRETE DAMS

Already in the 1920s considerable damage was recorded on some of the dams which were in operating at that time. In 1925 the Norwegian Engineers Association appointed a committee in order to have the condition of the dams investigated. The results of these investigations were published in a 251-page report - Halvorsen et al. (1930). The conclusion of the report was that the water's corrosive character and the comparatively severe climate were assumed to be the main factors causing the damage. In some dams leaching of calcium had totally disintegrated the concrete into gravel. In a few cases a high content of humus in the sand and organic matter in percolating water had disintegrated the concrete. Generally the use of a lean concrete and inhomogeneous poor concrete quality had increased the deterioration of the concrete. To reduce the damage in construction of new dams it was recommended to use impervious concrete, free of cracks. In later dam constructions impervious concrete was obtained by substantially increasing the cement content in the concrete.

A later dam investigation appointed by ICOLD (International Committee On Large Dams) 132 dams were investigated during the period 1962 to 1968, but a final report was never published. According to Heggstad & Myhren (1967) some damage due to freezing and percolation of water was recorded, but the slender reinforced ambursen - arch dams were generally in better condition than gravity dams built at the same time. Severe damage was mostly found on older dams, normally caused by local errors or weak spots during the construction the work. In ambursen dams comprehensive cracks and fissures were observed in dam plates even dilatation joints had been used. In concrete where crushed rock had been used with crushed rock aggregates a distinctly lower cracking tendency occurred compared to concrete where natural sands had been used. The lower cracking tendency in concrete where crushed rocks had been used was attributed to increased bond between the aggregates and the cement paste. Of all the Ambursen dams and the reinforced arch dams built during the last 10 years, there are only two which are completely free of fissures, and for these dams both the fine and the coarse aggregate were made exclusively of crushed granite. Dams built around 1955 contain generally more initial cracks and fissures than dams built earlier.

A third national dam investigation appointed by the Norwegian Water Resources and Energy

Administration (NVE) was carried out in the period 1988-1990. Here 55 dams were inspected. A final report was published by Gautefall (1990), which concluded that frost -thaw deterioration was the most frequent cause of damage. Generally, concrete damages in Norwegian dams were insignificant according to the dams bearing and function capacities. However about 50% of the dams were map cracked and recommended for a further phase 2 investigation for Alkali Aggregate Reaction. Increased cracking in slender reinforced dams built around 1960 compared to older dams, was observed here, too, and it was recommended that these dams were supervised in the future.

Field investigations in Southern Norway, generally for Alkali Aggregate Reaction, carried out in the period 1989 to 1992 by Jensen (1993) also reveals an increased cracking tendency of concrete road bridges and concrete dams built in the mid 1950s.

2 BACKGROUND

The Norwegian Water Resources and Energy Administration (NVE) requires inspection programs and routines for all Norwegian dam structures NVE (1990). In 1993 NVE introduced requirement for competent and qualified personnel responsible for the safety of each dam structure, in Norwegian called "vassdragsteknisk ansvarlig" (VTA). The VTA-person has to be civil engineer, must have minimum 3 years experience, follow technical courses and have good knowledge about the safety and condition of the dams he is responsible for, NVE 1993a. Because of the technical knowledge of VTA-persons it was reasonable to prepare a questionnaire with questions about safety, damages and the general condition of the dams. Questions were mostly categorized as yes/no, none, few, many or don't know. The competence of the VTA person was a precondition for the survey of Norwegian dams presented in this paper. The aims with the survey are to obtain information about safety, damages, inspection routines and repair. The enquiry deals with concrete dams, embankment dams (fill dams) and hydro power plants, but only results from concrete dams are presented here. However, results from embankment dams are presented by another paper in this conference by Skoglund (2001).

3 THE QUESTIONS

The questionnaire was mailed to all registered VTA persons in Norway in 1998 according to a list from NVE, all together 222 persons. Questions related to concrete dams were of the following types:

- Owner, name, age, dimensions, use and location
- Inspection routines according to NVE's requirements
- Damages and deterioration processes
- Repair, existing and planned to be carried out
- Safety and rebuilding, now and in the future

The last filled in questionnaire from dams was received in May 1998. A professional company, NORFAKTA, was hired to punch data into a database. This work was concluded in June 1998. Jensen & Skoglund (2000) report results and assessments from the enquiry as anonymous tables and figures, which can not be recorded to any specific dam structure.

4 RESULTS

The survey received answers from 461 dams classified as main types, whereas 287 were concrete dams, see Table 1

Table 1. Main type of dams

Type of dam:	Number	Percent
Concrete dam	287	54
*Fill dam**	*95*	*18*
Fill dam with concrete dam	79	15
Total	461	100

**Not presented in the paper*

Embankment dams, e.g. rock fill dams and earth fill dams are not presented in the paper as mentioned earlier. The total number of concrete dams in the enquiry is higher than 287, namely 432 because combination dams e g. fill dam with smaller concrete dam is included too, see figure 1.

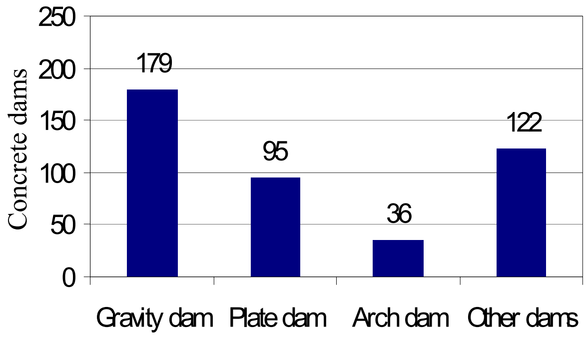

Figure 1. Type of concrete dams in the enquiry

Figure 2 shows the age distribution of concrete dams, which varies from 1880 to 1996. Note that the majority of dams are built in the period 1950 to 1990.

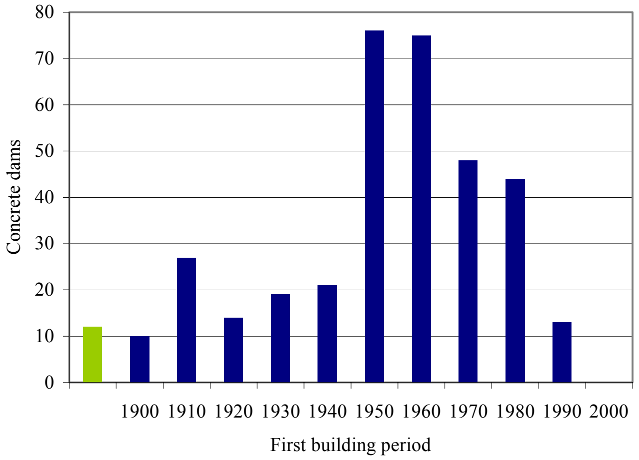

Figure 2. Concrete dams related to first building period

Figure 3 deals with inspection routines. Note that only 6 dams do not have an inspection programme.

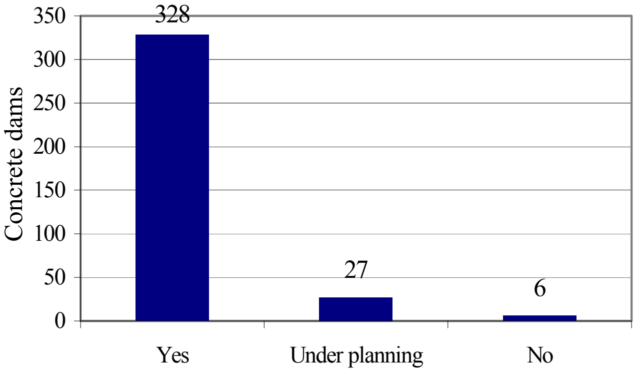

Figure 3. Inspection program is established

Figure 4 shows the frequency of periodically inspections (left) and main inspections (right).

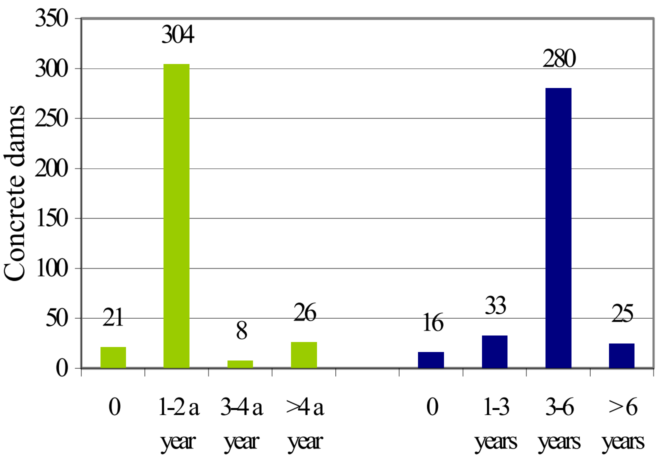

Figure 4. Periodically - (left) and main inspections (right)

According to NVE (1993b) periodically inspection should be carried out minimum twice a year and main inspection each 3 – 6 years.

Table 2 gives answers (percent) of damages in the whole dam structure. Note that up to 4% to 5% of the dams have many crack and map cracking.

Table 2. Damages in the whole dam

Type of damage	Dams	Few (%)	Many (%)	Don't know (%)
Horizontal crack	346	48	5	2
Vertical crack	343	52	4	2
Water leakage	348	31	1	2
Map cracking	337	32	4	4
Delaminating	346	45	2	2
Free reinforcement	341	23	1	1
Erosion	342	30	1	2
Deformation	340	12	2	2
Leaching/efflorescence	343	46	3	4
Corrosion (rust)	335	22	0	4
Casting defect	338	42	3	2
Other damage	79	8	1	4

Table 3 shows damages in joints. Note that 4% of the dams have sealing material squeezed out from the joints and 2% have reduced joints width.

Table 3. Damage in joints .

Type of damage	Dams	Few (%)	Many (%)	Don't know (%)
Squeezed joint material	311	20	4	3
Reduced joint width	312	13	2	6
Water leakage	317	24	1	3
Movement/crushing	314	12	0	5
Reduced ground contact	308	3	0	10

Table 4 deals with problems under water level and problems related to gates in the spillway. Note that 16% answer "yes" for occurrence of damages below water level and 4% to 8% for problems with the gate.

Table 4. Damage under water level and on gates

Type of damage	Dams	Yes (%)	No (%)	Don't know (%)
Damage below water level	307	16	52	31*
Locking of gate	267	4	92	4
Reduced free way of gate	257	8	91	6
Other problems with gate	114	6	87	7

**Not investigated*

Table 5 deals with damages on dam plates/arches and if damages have increased during the last years. Note that 36% of the dams have damages related to dam plates and arch and 6% to 7% have observed increasing delaminating and cracking during the last years.

Table 5. Damages on dam plates/arches

Damage has increased the last years?	Dams	Yes (%)	No (%)	Don't know (%)
occur on dam plates/arch	297	36	60	4
increase as: delaminating	305	7	87	7
cracking	306	6	89	5

Table 6 deals with which type of investigation there has been carried out on the dam.

Table 6. Type of investigation

	Dams	Yes (%)	No (%)	Don't know (%)
Field investigation	358	48	52	0
Instrumentation	351	6	94	0
Laboratory analyses	347	9	89	1

Table 7 deals with type of deterioration process and reasons for the damages in the dam. Note that 5% categorize freeze – thaw, 4% Alkali Aggregate Reaction and 5% insufficient or bad concrete work as many.

Table 7. Damages caused by processes/reasons

	Dams	Few (%)	Many (%)	Don't know (%)
Reinforcement corrosion	251	19	0	9
Alkali Aggregate Reaction	243	14	4	16
Freeze – thaw	248	45	5	4
Erosion	251	45	2	2
Leaching	243	19	2	7
Deformation/expansion	246	18	2	4
Bad concrete work	245	38	5	4

Table 8 and 9 deals with repair and repair cost. Note that 40% respectively 44% of the dams answer "yes" to planned and existing repair and estimate the planned repair cost to be 2.5 billion NOK and existing repair cost to be 20 billion NOK.

Table 8. Repair

	Dams	Yes (%)	No (%)	Don't know (%)
Planned repair	331	40	58	2
Existing repair	336	44	52	3

Table 9. Repair cost

Known cost	Dams	Yes (%)	No (%)	Amount million (NOK)
Planned	109	12	88	2539
Existing	110	36	64	20115

The questionnaire also includes questions dealing with type and amount of repair and where in the dam repair is planned or has been performed. Durability of existing repair is questioned, too. Interesting is that 10% of existing repairs have been repaired more than one time (140 answers). Type and amount of repair are not commented in this paper.

Table 10 deals with questions related to safety and rebuilding/demolishing, in the short run and long run; because of the present condition of the dam. Note that 8% answer "yes" to major rebuilding and 5% answer "yes" that the dam should be demolished or rebuild in the near future. In case damages goes on will there be risk for safety or close down? For this question 6% answer "yes" for the present situation, 5% answer "yes" for less than 10 years and 12% answer "yes" for more than 10 years.

Table 10. Safety, close down and major initiative

	Dams	Yes (%)	No (%)	Don't know (%)
Major rebuilding	317	8	92	1
Demolishing/new dam	315	5	95	0
Risk for safety/close down	324	6	94	1
in less than 10 years	299	5	83	
in more than 10 years	299	12	83	

5 DISCUSSION

5.1 *Representativity*

The survey includes a high number of Norwegian concrete dams suggesting the investigation is representative of Norwegian dams. As main types, the survey includes 27 % of the total registered concrete dams (1056) under public supervision according to NVEs database "VAREG", Lindland (2001). The total number of dams in the survey is 432 because the questionnaire includes combination dams, too. 89 dams are higher than 15 meter. This is 61% of the total number of large dam's (145) registered in Norway; in case the dams are main types. The age distribution of concrete dams, which have been constructed in the period from 1880 to 1996 and the location all over Norway also suggest a representative investigation of concrete dams in Norway.

Table 11 gives the number of concrete dams sorted in failure classes and compared to NVE's database "VAREG", NVE (1993c). According to NVE (1993d) failure class 1 is the worst case and might cause damage to more than 20 houses/persons. From the 1st January 2001 failure classes are classified in reverse order according to NVE (2000a,b).

Table 11. Failure classes related to "VAREG"

Failure class*	Survey, dams	VAREG, dams	%
Class 1 (3)	67	117	57
Class 2 (2)	117	279	43
Class 3 (1)	133	660	20

*parenthesis: new failure classes valid from 1st January 2001

Note that for dams related to the database VAREG, failure classes 1 have the highest percent dams represented, relative to class 2 and 3. This when all dams are classified as main types.

5.2 *Inspection routines*

With aims to assess ownership's eventually influence on inspection routines and obligations on requirements by NVE, data has been sorted in two groups, namely energy producers and municipal/other industry (mainly drinking water), see Table 12 and 13.

Table 12 deals with the question about inspection of the dam.

Table 12. Do you have an inspection program

Exist?	Municipal		Energy	
	dams	%	dams	%
Yes	79	77	249	97
Planned	18	18	9	3
No	5	5	1	0
Total	102	100	259	100

According to requirement from NVE (1993b), normally each third main inspection has to be more comprehensive and the dam safety has to be reassessed ("revurdering"), see table 13.

Table 13. Reassessment ("revurdering")

Performed?	Municipal		Energy	
	dams	%	dams	%
Yes	24	24	47	18
Planned	5	5	17	7
No	70	71	191	75
Total	99	100	255	100

About 5% of the municipal owned dams do not have (or planned to have) an inspection program. However, reassessment is carried out on more percentages municipal owned dams than Energy Company owned dams.

Table 14 gives data on reassessment, which has been completed, compared to failure classes. Note that most class 1 dams have completed reassessment, or planned to do so (23%+10%), relative to dams with lower consequences for damages.

Table 14. Dams sorted in failure classes compared to completed reassessment

Failure class *	Dams	Yes (%)	Planned (%)	No (%)
Class 1 (3)	67	23	10	67
Class 2 (2)	117	19	9	72
Class 3 (1)	133	18	3	79

*Parenthesis: new failure classes valid from 1st January 2001

5.3 *Damages*

Answers in the questionary should be given as "yes", "no", "do not know" or quantified as "none", "few" and "many". The VTA person's ability to give a correct estimate is very important here, but large individual judgements should be expected. However, it is supposed that the categories "few" and "many" are significant different and not mixed up by the VTA person. Few damages of different sorts (e.g. table 2) are probably "normal" and suppose not to reduce the dams function or safety at present time. In the other way, many damages are not normal and might influence the function and lifetime of the dam and probably causes increased maintenance costs. However, it has to be pointed out that many damages can not be used for assessment of the dam safety without a comprehensive investigation of the dam. Because of the high number of answers (250-400) within each damage type the percentage of damages are most likely statistically correct.

In 4% to 5% of the dams it has been observed "many" cracks and map cracking. For 2% to 3% of the dams "many" damages as casting defects, delamination, deformation/expansion and leaching have been registered. Water leakage through the dam has been registered as "many" in 1% of the dams. 2% to 4% of the dams have had "many" problems with joints and assemblages and 1% to 8% have had problems with gates in the spillway. 36% answers yes for occurrence of damages in the dam plates/arches and 6% to 7% that delamination, disintegration and cracking have increased during the last years.

Explanation and quantification of damages categorises, as "many" are freeze-thaw (5%), improper and bad concrete work (5%), Alkali Aggregate Reaction (4%), erosion, leaching and deformation/expansion (each 2%). Corrosion on reinforcement has not been observed as "many".

With aims to compare damages between small dams (<15m) and large dams (>15m) and assess if damages have been worse or more frequent in some time periods than others, a damage factor has been calculated. Damage factor is calculated as the sum of different damages where "few" is given the value 1, "many" the values 2 and "non" and "don't know" the value zero. For damages in the whole dams, the damage factor is calculated as the sum of all the 11-damage types (ex. other) given in Table 2 and the 5-damages types for joints in table 3.

Table 15 shows the average and maximum damage factor (whole dam) and percent of at least one answer as non, few or many between small and large dams.

Table 15. Damage factor (the whole dam) on small - and large dams

Size of dam	dams	Damage factor avg.	max.	At least one answer as: (%) non	few	many
Small	264	5	18	86	72	11
Large	89	6	14	91	83	12

Table 16 shows the same as table 15 but on joints.

Table 16. Damage factor (joints) on small - and large dams

Size of dam	dams	Damage factor avg.	max.	At least one answer as: (%) non	few	many
Small	264	4	5	79	27	1
Large	89	4	6	79	55	11

Note in Table 15 and 16 that only small differences in average damage factor occur between small – and large dams. For at least one answer in the categories "few" and "many" large dams have higher percentages compared to small dams; especially for damages in joints.

Figure 5 show the distribution of the damage factors calculated from the whole dam and Figure 6 from joints, both related to first building period of the dam. The larger numerical values obtained in Figure 5 compared to Figure 6 is because 11 damage types goes into the calculation for the whole dam compared to only 5 damage types for joints. Note that in figure 5 a peak height occurs around 1950 and in figure 6 around 1960. It looks like dams build in the period around 1950 and 1960 are more damaged than build in other periods. However, most dams were also constructed during the same period as shown in figure 2. Therefore, the average damage factor have been calculated from each decade and presented in figure 7. Note in Figure 7 that peak heights occur both for the damage factors "whole dam" and "joints", but not as significant as shown in figures 5 and 6. However, peak heights seem to occur around 1950 for damage factor "whole dam" and around 1960 for damage factor joints" when expresses by a regression line.

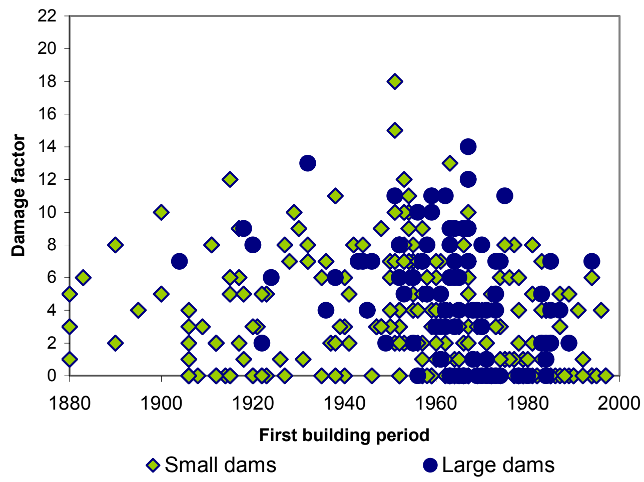

Figure 5. Damage factor for the whole dam related to first building period

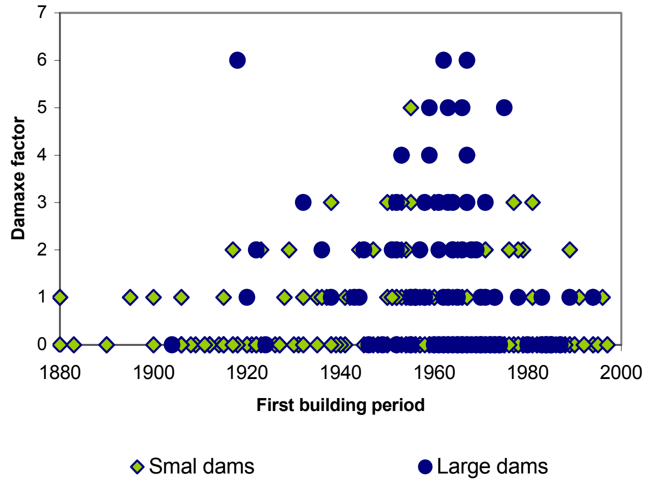

Figure 6. Damage factor for joints related to first building period

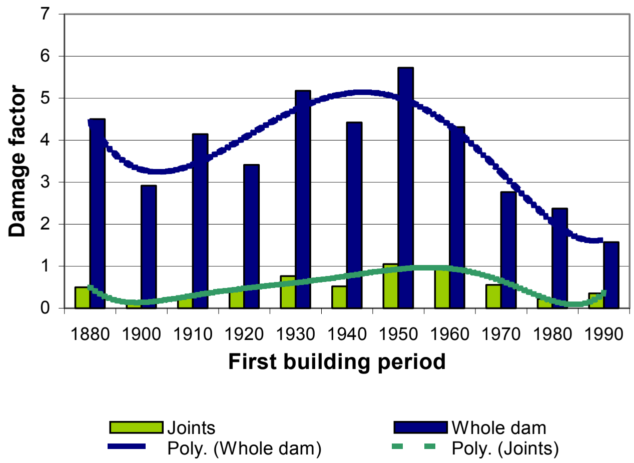

Figure 7. Average damage factor for the whole dam and joints related to first building period

Increased damage on concrete structures build around 1950 to 1960 observed by earlier investigations, e. g. Heggstad & Myhren (1967), Gautefall (1990) and Jensen (1993) seem to be confirmed by the present investigation.

5.4 *Repair*

Surprisingly many of the dams will be repaired in the near future (40%), or already have been repaired (44%). The planned repair cost given by 12% of answers is 2.5 billion NOK and 20 billion NOK for existing repaired dams (36% answers). Interesting is that 10% of existing repairs have been repaired more than one time (140 answers).

5.5 *Safety*

With goal to assess eventual difference on safety, risk for close down and need for major rebuilding on small and large dams the answers presented in table 10 have been sorted on small and large dams.

Table 17 shows the answers to the question; "is there risk for the dam safety or close down do to the present condition and distribution of damages"?

Table 17. Safety and close down for small and large dams

Size of dam	Dams	Yes (%)	No (%)	Don't know (%)
Small dam (< 15 m)	224	5	94	1
Large dam (> 15 m)	75	8	92	0

Table 18 shows the answers to the question; "do to the present condition and distribution of damages on the dam should larger rebuilding be carried out in the near future"?

Table 18. Larger rebuilding in near future for small and large dams

Size of dam	Dams	Yes (%)	No (%)	Don't know (%)
Small dam (< 15 m)	218	7	92	1
Large dam (> 15 m)	74	9	91	0

Table 19 shows the answers to the question; "do to the present condition and distribution of damages on the dam should the dam be demolished or rebuild in the near future"?

Table 19. Demolishing or building of a new small or large dam

Size of dam	Dams	Yes (%)	No (%)	Don't know (%)
Small dam (< 15 m)	216	5	95	0
Large dam (> 15 m)	74	7	92	1

Table 20 shows the answers to the question; "in case damages continue over time will there be risk for the safety or close down of the dam"? - in less than 10 years or more than 10 years?

Table 20. Risk for close down and dam safety in case damages continues.

Size of dam	Dams	Yes; <10 years (%)	Yes; >10 years (%)	No (%)
Small dam)	205	5	13	82
Large dam	71	6	8	86

Note that for all the questions given in table 17 to table 19 large dams have 2% to 3% higher "yes" answers than small dams. Risk for close down and the dam safety in less than 10 years, large dams have 1-% higher "yes" answer than small dams. However, for the same question, but "more than 10 years" small dams have 13% "yes" answer compared to 8% "yes" answer for large dams. The answers indicates that larger dams in the short time run, e.g. less than 10 years, are more effected to the questions given in table 17 to table 20, relatively to small dams. In more than 10 years small dams have a higher risk for the safety and close down than larger dams.

Anyway, the "yes" in table 17 to table 20, which varies from 5% to 13%, are surprisingly high. Suppose the percentages are representative for all 1056 Norwegian concrete dams registered as main types the affected number of dams are 42 to 137.

6 CONCLUSION

The high number of dams, the age distribution from 1880 to 1996 and geographical locations suggest the survey to be representative for concrete dams in Norway. The VTA persons have done a great work filling in the questionnaires.

All dam owners generally fulfill requirement about inspection programs and routines given by the government, NVE.

Ownership, sorted on energy producer and water supplier, does not have significant influence on inspection routines or government requirement, but small differences occur.

Generally, the failure class with worst damaging effects (old class 1) has the highest completion rate for reassessment (revurdering) than the lower classes.

For damages related to dams the following figures can be given:

- 8% to 52 % of the dams have "few" damages
- 1% to 5% have "many" damages in the dam
- 1% to 4% have "many" damages in joints
- 16% have damages below water level
- 1% to 8% have problems with gates
- 36% have damages in dam plates and arches
- 6% to 7% have observed increased delaminating and cracking during the last years
- 5% have "many" freeze-thaw damages or damages caused insufficient concrete work
- 4% have "many" Alkali Aggregate Reaction
- 2% have "many" damages as erosion, disintegrating, leaching, deformation and expansion
- Larger dams seems to be more damaged than smaller dams
- Dams build around 1950 to 1960 seems to be most damaged, which confirm observations done by 3 other field investigations in Norway
- 40% of the dams are planned to be repaired and 44% are already been repaired
- Repair cost are planned to be 2.5 billion NOK and for existing dams 20 billion NOK (only 12% and 36% answers)
- 10% of existing repairs have been repaired more than one time

Damages and the condition of the dam might have the following consequences:

- 5% small and 7% large dams might be demolished or rebuild in the near future
- 5% small and 9% large dams might have major maintenance
- 5% small and 8% large dams might have risk for close down or problems with the dam safety in near future

In case damages continues there will be risk for close down and dam safety:

- for 5% small and 6 % large dams in less than 10 years
- for 13% small and 8 % large dams in more than 10 years

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