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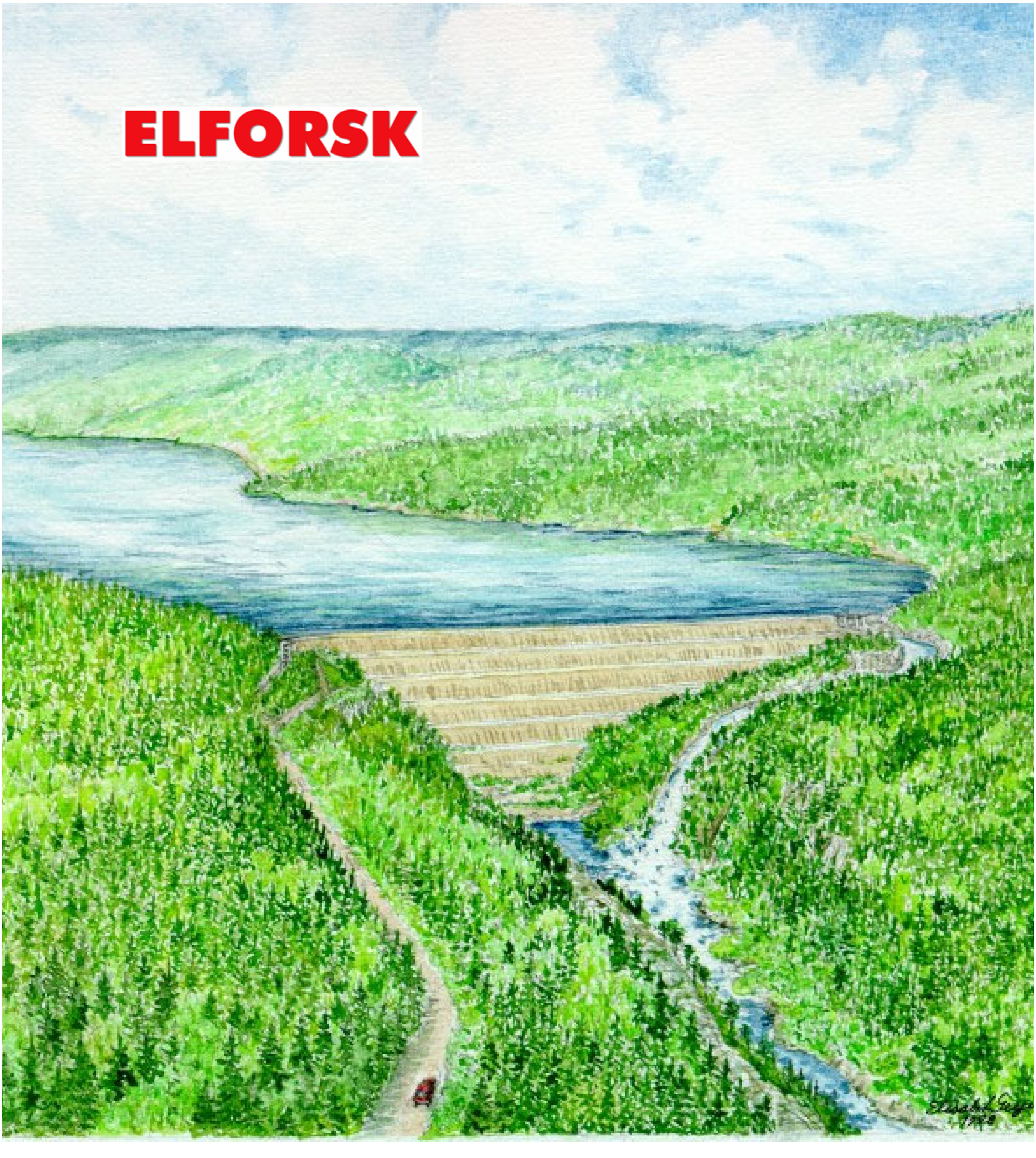

DAM SAFETY

EARTHQUAKE HAZARD FOR DAMS IN SWEDEN

Rapport 06:72

Earthquake Hazard for Dams in Sweden

Elforsk rapport 06:72

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Förord

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Denna rapport är ett delresultat inom Elforsk ramprogram Dammsäkerhet.

Kraftindustrin har traditionellt satsat avsevärda resurser på forsknings och utvecklingsfrågor inom dammsäkerhetsområdet, vilket har varit en förutsättning för den framgångsrika utvecklingen av vattenkraften som energikälla i Sverige.

Målen för programmet är att långsiktigt stödja branschens policy, dvs att:

- Sannolikheten för dammbrott där människoliv kan vara hotade skall hållas på en så låg nivå att detta hot såvitt möjligt elimineras.
- Konsekvenserna i händelse av dammbrott skall genom god planering såvitt möjligt reduceras.
- Dammsäkerheten skall hållas på en god internationell nivå.

Prioriterade områden är Teknisk säkerhet, Operativ säkerhet och beredskap samt Riskanalys.

Ramprogrammet har en styrgrupp bestående av: Jonas Birkedahl – FORTUM, Malte Cederström - Vattenfall Vattenkraft, Anders Isander – E.ON, Lennart Markland – Vattenregleringsföretagen, Urban Norstedt - Vattenfall Vattenkraft, Gunnar Sjödin – Vattenregleringsföretagen, Olle Mill Svenska Kraftnät samt Lars Hammar - Elforsk

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Sammanfattning

En studie av hotet från jordskalv mot svenska dammar presenteras i denna rapport. Studien består av två delar. Den första delen behandlar den seismska situationen i Sverige. Den baseras på makroseismisk och instrumentell information. En relation som visar sambandet mellan ett jordskalvs magnitud, dess avstånd och den maximala accelerationen för berg-i-dagen används för att uppskatta förväntade intensiteter och markaccelerationer för framtida jordskalv. En kort framställning av magasinframkallade jordskalv och deras betydelse presenteras.

Den andra delan av rapporten behandlar hur dammar uppför sig vid eventuella markskaningar från jordskalv. Markaccelerationen för berg-i-dagen och dess förstärkning upp genom dammen behandlas och beräkningar av krönets maximala acceleration visas. Från dessa resultat är det möjligt att bestämma ett approximativt värde på dammens permanenta deformation efter den har utsatts för en skakning. Detta görs för tolv höga dammar och i princip alla dammar i syd-västra Sverige, där drn svenska seismiciteten är som störst.

Resultatet är att det seismiska hotet mot dessa dammar är litet. Möjligen kan någon av de allra högsta dammarna, Trängslet, Seitevare, Messaure eller Surovas östra damm, ta någon lätt skada. Sannolikheten att detta inträffar är mycket låg.

Summary

A study of the seismic hazard is presented in this report. It consists of two parts. The first part, chapters 2-5, is about the seismic situation in Sweden and is based on macroseismic and information from instruments. A relation, attenuation relation, shows the connection between the magnitude of an earthquake, its distance and the maximum out-cropping-rock acceleration is used to determine expected maximum accelerations and intensities for future events. A short presentation of reservoir induced earthquakes and their importance for Swedish dams is also presented.

The second part, chapters 6-12, is about the behavior of dams when excited by ground motion from earthquakes. The out-cropping-rock acceleration and its amplification through the dam is discussed and the results of calculations of the maximum crest acceleration are shown. From these results it is possible to determine an approximate value of the permanent deformation of the dam after the excitation. This is performed for twelve high dams and in practice for all dams in south-western Sweden, where the Swedish seismicity is greatest.

The result is that the hazard is small. It might be possible for some of the highest dams, Trängslet, Seitevare, Messaure eller Surova east dam to experience slight damage. The probability for this to happen is very low.

List of symbols used

A	ground acceleration, cm/s^2
AF	amplification function
a_{crest}	acceleration at the crest, cm/s^2
a_{max}	maximum peak ground acceleration, cm/s^2
A_0	ground acceleration at epicenter, cm/s^2
a_0	non-dimensional frequency (in general complex valued)
$a0$	non-dimensional frequency (real part of a_0)
c_b	shear wave velocity at the base, m/s
c_{bar}	average shear wave velocity in the dam, m/s
c_{barb}	average shear wave velocity along the base, m/s
c_r	shear wave velocity in the rock, m/s, p. 18
c_{Ss}	shear wave velocity of a soil layer below dam, m/s
D	damping ratio
e	pore number
f	frequency, Hz
f_1	lowest resonance frequency of dam, Hz
G	shear modulus, N/m^2
G_b	average shear modulus along the base, N/m^2
G_{max}	maximum shear modulus, kN/m^2
H	height of dam, m
I	intensity, MSK-scale
M	magnitude
M_L	local magnitude
M_{Lmax}	largest observed magnitude
M_{100}	maximum expected magnitude in 100 years
$P(50)$	probability of non-exceedance in 50 years
$P(100)$	probability of non-exceedance in 100 years
R	epicentral distance, km
U	permanent deformation, cm
z	distance from the crest, m

Δ	epicentral distance, km, p. 4
γ	impedance ratio
ρ	density of soil in dam, kg/m^3
ρ_r	density of rock, kg/m^3
ρ_s	density of soil in a layer below dam, kg/m^3
σ_0'	mean effective stress, kPa
ζ	non-dimensional distance from the crest

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Appendices

1 Introduction

This report summarizes the work conducted upon the request of the "Svenska Elföretagens Forsknings och Utvecklings – ELFORSK – AB", Elforsk project nr 1762, dated November 11, 2005.

The main objective of the present report is an assessment of seismic hazard for selected high dams in Sweden. The term *high dam* is here used rather ambiguously. We focus our investigation on dams of height of 50 m and higher, nevertheless two dams, 20-50 m high, are also included. Generally speaking, there are two types of earthquakes which expose dams to danger. Firstly, tectonic (natural) quakes of significant magnitudes which occur at short distances from the dam and secondly, induced shocks which have been triggered by impounding of large water reservoirs. The latter take place beneath the reservoir or in its nearest vicinity. The two types of hazard will be treated separately below.

In this report, *seismic hazard* is used as a term to indicate the probable level of ground shaking (usually its acceleration) occurring at a given point within a certain period of time. We treat here in more detail 11 Swedish dams (Table 1.1) of different types (rockfill, earth) with heights between 20 m (Fageråssjön) and 122 m (Trängslet), located between 60.86^{o}N (Fageråssjön) and 67.51^{o}N (Suorva). Otherwise, the selection was random and hence the work presented here should be considered as a pilot study which may not be fully representative for all dams in Sweden (probably several hundred sites).

TABLE 1.1. 11 dams in northern Sweden

Dam	**Site coordinates**		**Height**
	^{o}N	^{o}E	[m]
Fageråssjön	60.86	12.88	20
Flåsjön	62.76	13.71	55
Gallejaur	65.13	19.48	56
Harsprånget	66.90	19.82	51
Håckren	63.19	13.62	67
Höljes	60.96	12.54	80
Letsi	66.51	20.37	85
Messaure	66.69	20.34	101
Seitevare	66.98	18.57	106
Suorva	67.51	18.28	30-67
Trängslet	61.38	13.73	122

2 Seismotectonics

Geologically speaking, Fennoscandia (Norway, Sweden, Finland and NW Russia) belongs to a plate interior devoid of major seismic activity. It consists mainly of the Precambrian Baltic shield (SE Norway, Sweden, Finland and NW Russia) and of the much younger Caledonian mountain belt (rest of Norway). Swedish earthquakes take place at large distances from the nearest tectonic plate boundaries, namely from the Mid-Atlantic ridge and/or from the Mediterranean region (collision between the African and Euroasian plates). They are classified as typical intraplate events with a rather diffuse geographical pattern of epicentres, low rate of occurrence and shallow focal depth, usually around 15 km. Epicenter locations do not reveal any clear correlation with known major geologic boundaries or geologic regions which complicates understanding of the origin of Fennoscandian, Swedish in particular, quakes. At least two hypotheses were launched so far. Firstly, plate driving forces originating along the northern Mid-Atlantic ridge and secondly, the postglacial uplift which is still continuing, reaching the maximum rate of 8-9 mm/yr in northern Gulf of Bothnia and which totally amounts to nearly 900 m.

The observed spatial distribution of epicentres in Sweden, however scattered, reveals local concentrations in three broad geographical zones. The most active is the Telemark-Vännern zone which also includes the 1904 Oslo event (M=5.5-6.0), the largest Fennoscandian shock during the last more than 100 years. The remaining and less active zones are the Bothnia zone which runs along the Swedish east coast and the somewhat diffuse Lappland zone in northern Sweden [14]. Only recently, spectacular neotectonic faults have been discovered in northern Sweden [23] and earlier also in northern Finland [18]. Among these the most striking is the Pärve fault which stretches almost unbroken for 165 km, west of Kiruna, approximately parallel with the Norwegian border. The vertical offset is about 10 m. Most of these faults trend close to SSW-NNE and involve the uplift of the eastern block relative to the west. Geologists believe that the fault developed in direct connection with the last de-glaciation about 9000 years ago. A question of primary interest is of course how fast the fault developed. If the total displacement released momentarily it must have generated a shock with magnitude of the order of 8. Field investigations do not indicate any present movements [23]. Current seismic measurements however reveal a low-magnitude ($M_L \leq 3$) activity along the Pärve and other faults (e.g. Lansjärv) in northern Sweden.

3 The method

3.1 Tectonic earthquakes

Most of the current methodologies employed for the assessment of seismic hazard rely on the basic principle of geology that *the past is the key to the present.* The sesmicity of the studied region is evaluated from past macroseismic and instrumental data. The maximum expected magnitude and the rate of occurrence of the associated earthquakes are assessed. By processing these parameters it is possible to derive hazard estimates for selected sites or regions.

To quantify seismic hazard for low-seismicity regions, like e.g. Sweden, certain specific problems arise. Reports on historical events are generally incomplete. The interpretation of earthquake observations in terms of active faults and/or geologic structures is difficult. There is often shortage of data in each potential sub-region which may increase the level of personal judgements in the evaluation.

In engineering applications, seismic hazard is usually expressed as probability of occurrence of a certain ground acceleration at a studied site. Unfortunately, in Sweden, systematic measurements of strong motions (accelerations) have not, as yet, been carried out. Consequently, we are forced to choose an alternative approach. We can make use of collected macroseismic intensities which have a close relation to peak ground accelerations. For example, as a global average for hard rock, intensity of VI corresponds to ground acceleration of 25-50 cm/s^2 [29]. Båth [7] presents a formula relating ground acceleration, A, and seismic intensity, I, for Swedish shocks and frequency range 2-10Hz. The formula reads

$$\log A = 0.47I - 1.43 \qquad (3.1)$$

where A is in cm/s^2 and I is intensity on the MSK scale, often used for events in Europe. Note that accelerations deduced from eq. (3.1) are somewhat lower when compared with those listed by Willmore [29]. An analogous relation can be written [8] also for M_L (focal depth ≈15 km)

$$\log A_0 = 0.69M_L - 1.40 \qquad (3.2)$$

where A_0 in cm/s^2 is the acceleration at the epicentre. Due to these and similar relations, macroseismic intensity is very serviceable in engineering applications for seismic disaster managements. For Sweden, an excellent record of macroseismic observations is provided practically for all Swedish quakes felt during the time interval 1891-1995 by Båth [4], [5], and by Kulhanek and Wahlström [19, 20, 21, 22]. These works are gold mines of information.

Still another possibility is to employ the diagram in Båth [7] which relates (for quick approximate estimations) magnitudes with intensity or acceleration for different epicentral distances (Fig. 3.1).

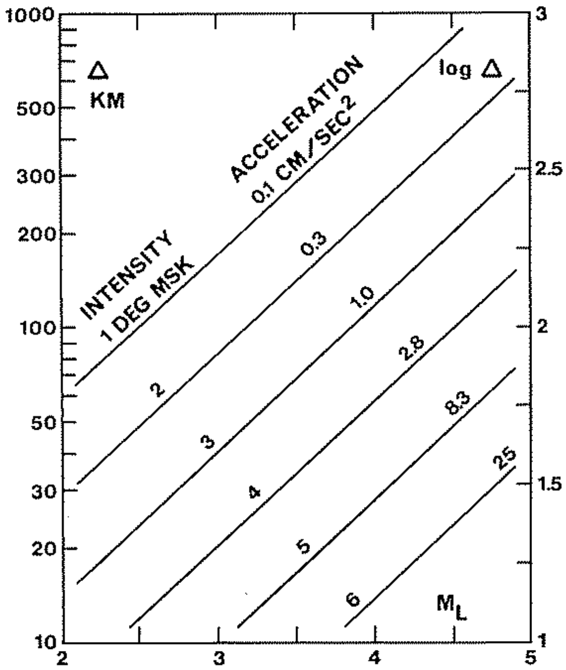

Figure 3.1 Approximate seismic intensities (ground accelerations) for given magnitude and epicentral distance (from [7])

Next step in hazard evaluations is the estimate of the maximum expected magnitude and of recurrence rates, i.e. of numbers of events for different magnitudes during a certain time interval. Båth [6] divided Fennoscandia into 92 sub-regions (2^o in latitude by 2^o in longitude) and calculated for each region the probability of occurrence of a certain magnitude (M_L = 2.0-5.0) for time windows of 1 and 10 years. With respect to the usual life-time of high dams (50-100 years), periods of 1 or 10 years are obviously too short and hence the results of Båth [6] are here not applicable. Extrapolations to considerably longer periods should be very cautious since they may have no connection to reality.

Significant contributions in evaluations of maximum magnitudes and corresponding return periods for Fennoscandia and for Sweden were made by Mäntyniemi et al. [25] and by Kijko et al. [16], respectively. The former presents maximum magnitudes for eight seismic regions in Fennoscandia and probabilities of occurrence in 50-year intervals for a suite of magnitudes. For example, for the Telemark-Vännern zone, the largest observed magnitude M_{Lmax}=5.51. The probability of non-exceedance of M_L=5.5 in 50 years is 0.998, i.e. very high. For an interval of 100 years, the maximum expected magnitude M_{100}=4.7. Corresponding values are given for inland northern Sweden, the Bothnia zone and for the Lappland zone extended by NW Russia. We summarize the relevant results of [25]in Table 3.1.

TABLE 3.1 Characteristic magnitudes from [25]

Region	M_{Lmax}	M_{100}	$P_{(50)}$
Telemark-Vännern zone	5.51	4.7	4.5 (0.527) 5.0 (0.850) 5.5 (0.998)
Inland northern Sweden	4.28	3.8	4.0 (0.790)
Bothnian zone	4.34	4.0	4.0 (0.606)
Lappland zone & NW Russia	5.87	4.7	4.5 (0.462) 5.0 (0.795) 5.5 (0.951)

M_{Lmax} is the maximum observed magnitude, M_{100} is the magnitude to be exceeded once in 100 years and *P(50)* is the magnitude and corresponding probability (in parenthesis) of non-exceedance in 50 years.

Kijko et al. [16] carried out a similar investigation for four regions in Sweden, including northern Sweden (north of 60^{o}N) and a sub-region covering the coast of Gulf of Bothnia, with the maximum expected magnitude of 4.3±0.5 during a time span of 331 years. Even though the zonation is not the same as in [25], results compare nicely, at least for the coast of Gulf of Bothnia. Table 3.2 is a summary of relevant results from [16]. Symbols used are the same as in Table 3.1 with the exception that probabilities of non-exceedance here correspond to 100-year intervals.

TABLE 3.2 Characteristic magnitudes from , [16]

Region	M_{Lmax}	$P_{(100)}$
Northern Sweden (north of 60^{o}N)	4.3	4.0 (0.26) 4.2 (0.76)
Coast of Gulf of Bothnia	4.3	4.0 (0.29) 4.2 (0.76)

3.2 Reservoir induced seismicity, RIS

Over the last 50 years, or so, it has become apparent that increases in seismic activity have resulted from the impounding of reservoirs behind high dams. Below, we shall use the adjectives *triggered* or *induced* for this type of events. We on purpose omit here the term *man-made* because it may give the erroneous impression that the construction of the dam (human activity) is the primary cause of the earthquake, rather than just the trigger that acts to release pre-existing stress of tectonic origin. Note that a water column of 100 m produces a load of 10 bar which is too low to break a compact rock. The specific danger of RIS lies in the fact that large water reservoirs are capable of significantly changing the seismic regime around the dams and thus violate the basic principle of standard hazard evaluation.

Induced earthquakes cover a wide range of magnitudes from micro-earthquakes ($M \approx 3$) to large events with magnitudes 6 and above. They are shallow events, with focal depth usually less than 15 km. Their origin is still poorly understood. The theory offers several explanations: the rapid increase of elastic stress that follows the loading of the reservoir and/or the increase and diffusion of pore pressure in the rock surrounding the reservoir. For some of the well studied reservoirs (Nurek, Kremasta, Monticello), the seismicity initiated immediately after the first rapid increase of the water level. For others (Kariba, Koyna, Oroville), large earthquakes occurred many years (e.g. Aswan 17 years) after the impoundment.

Since the nature of induced events implies that they will occur near the dam responsible for triggering them, even small earthquakes ($M \approx 5$) are generally cause of concern [28]. Induced earthquakes were first associated with the initial filling of Lake Mead in the late 1930´s. In recent years, numerous other examples of RIS have been identified and described in the literature. So far, the largest triggered quake was the M=6.5 event at Koyna reservoir in India in 1967. It killed 200 people and caused a serious damage to a nearby town.

Many of the Swedish dams have been built and/or reconstructed around the middle of the last century, some even earlier. To the best of our knowledge, seismic criteria have not been incorporated into their design. Parts of engineering community often show general reluctance to consider the significance of RIS. The common argument is the relatively small percentage (2% [2]; 15% [13]) of large reservoirs which generated significant RIS.

4 Earthquake data

To achieve success in any seismic hazard investigation an access to high quality observational data (earthquake catalogues) is crucial. We request lists of events which are complete (above a certain threshold earthquake size), homogeneous, accurate and which cover long time intervals (with respect to the life-time of exposed structures).

The oldest known report of a seismic event in Sweden dates back to an earthquake with intensity of VI on Gotland in 1375. In those days and during the following five centuries, collection of information on quakes in Sweden was rather irregular and highly inaccurate. Systematic acquisition and analysis of macroseismic observations started first at the end of the 19^{th} century. Probably the first homogeneous macroseismic data base is that by Båth [4] which comprises the whole Fennoscandia and covers the time period 1891-1950. Instrumental observations in Scandinavia started in 1904 and 1905 by installations of seismographs, respectively in Uppsala and in Bergen. In the 1950´s, started an expansion of seismographic stations equipped with modern instruments and with good coverage of the whole Fennoscandia. A new phase began towards the end of the last millennium when the Swedish analog stations have been equipped with digital broad-band instruments and many new stations have been installed. Uppsala University operates the Swedish National Seismic Network, SNSN, which at this writing (January 2006) consists of 49 modern seismographic stations covering a large part of the territory of Sweden [3].

As mentioned above, results of systematic analysis of macroseismic data in Sweden are available for approximately the last 100 years (1891-1995). In 1981, the Institute of Seismology at Helsinki University undertook to perform a routine analysis of instrumental seismic data for the whole Fennoscandia, Denmark and NW Russia. Results (location, time of occurrence, size) are presented in a catalogue, known by its acronym FENCAT. We believe that currently this is the best source of information concerning quakes in Sweden. The FENCAT catalogue contains data for the period 1375-2005. Obviously, the quality of data (accuracy, homogeneity, completeness) is not the same for the whole catalogue. A closer look at the cumulative number of reported events [1] reveals three distinct time intervals. Approximately from 1750 to 1880 (macroseismic data only), 550 events were detected, i.e. 4.2 events/yr. Around 1890 started a systematic collection of macroseismic data and the first seismographs were installed in 1904 and in 1905. During the period 1880-1940 (macroseismic and instrumental data), 1250 events are listed in the FENCAT catalogue, i.e. 20.8 events/yr. Finally, in the mid 1950´s a vast expansion of new seismographic stations took place which is also reflected in the number of detected events. Between 1960 and 1980 (instrumental data only), 950 events were detected, i.e. 47.5 events/yr. The increase of detected events per year does not mean that the seismicity has increased. It merely shows that more and better seismographic stations press down the threshold magnitude i.e. increase the detectability. Employing the results of [1] we conclude that the FENCAT catalogue is well suited for the present study, this because it may be considered as a homogeneous source for $M_L \geq 2.0$ from 1956 to date.

Figure 4.1 exhibits the seismicity of Fennoscandia during the period 1956-2004 reproduced from the FENCAT catalogue. Only instrumental data have been used. For this time period the catalogue can be considered as homogeneous, complete for $M_L \geq 2$ and sufficiently accurate with epicentral location accuracies ≈10 km or better. There are 5307 epicenters ($M_L \geq 2$) plotted in Fig. 4.1. The three zones of concentrated seismicity in Sweden, mentioned above, are discernible in the figure. Note that inland Sweden, approximately north of 60°N, shows low seismicity, with exceptions around 66°N and 68°N. The latter can be, at least partially, associated with the Pärve fault.

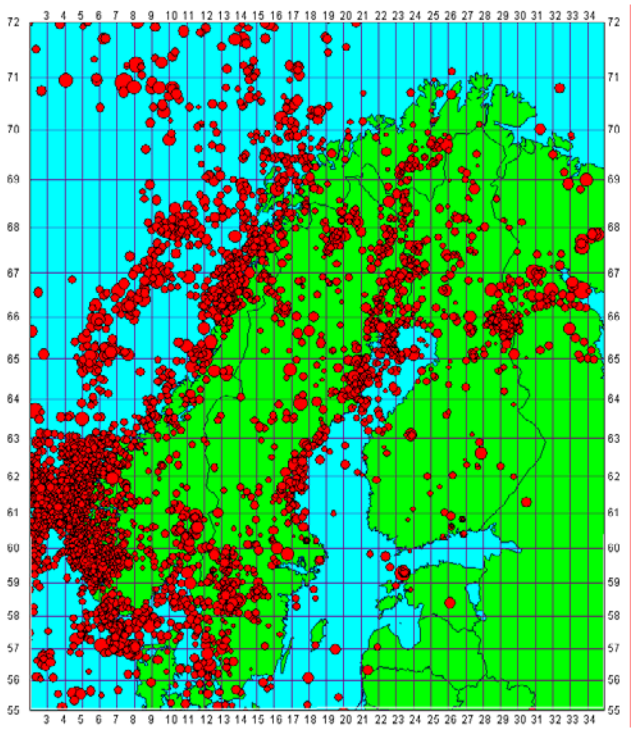

Figure 4.1 Earthquakes in Fennoscandia, 1956-2004, M_L>1.9, according to FENCAT catalogue. The size of circles corresponds to magnitude.

5 Results and discussion on seismicity

In Fig. 5.1 there are displayed locations of the 12 dams considered in the present study (Table 1.1) together with the seismicity between 1956 and 2004 within the area limited by 60°-68°N and 11°-21°E. The largest event in Fig. 5.1 is the so called Solberg earthquake of September 29, 1983, in the province of Ångermanland (63.9°N, 17.5°E), with magnitude M_L=4.1 and the maximum felt intensity of V. The second largest shock (M_L=4.0, I_o=V-VI) is the Vilhelmina event of January 5, 1993 in Lappland (64.7°N, 16.9°E). Note that none of the studied dams is located close to these two shocks. From Fig. 5.1 it seems that between 1956 and 2004, Fageråssjön and Höljes dams were

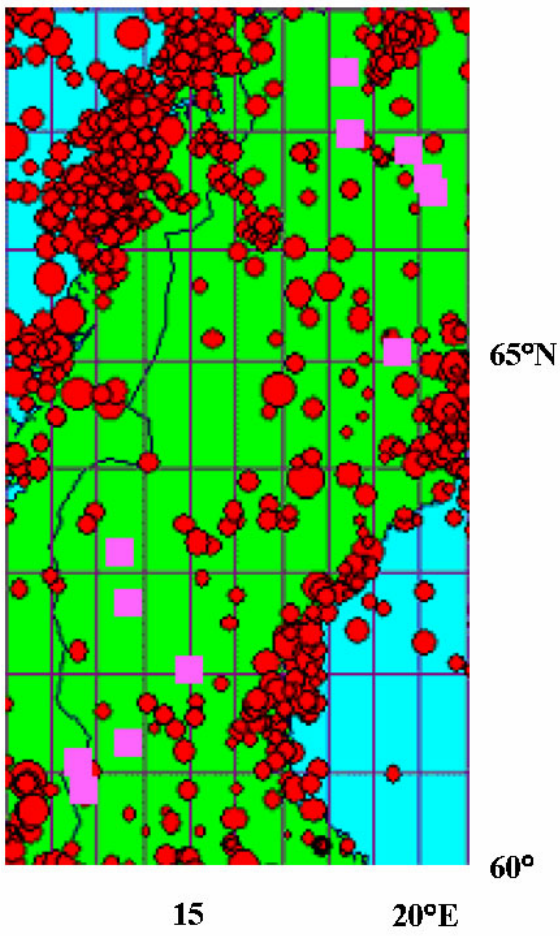

Figure 5.1 Part of northern Sweden with the studied dams (squares). Circles show epicenters of earthquakes during the period 1956-2004. Only events with M_L>1.9 are displayed.

exposed to the highest seismic hazard due to the event of May 12, 1970, M_L=3.2 (61.0^{o}N, 12.8^{o}E) which occurred respectively, 28 km and 14 km from the mentioned dam. Due to the paucity of observations, we shall below evaluate the hazard for the whole region, roughly demarked by the dam locations, rather than to consider each dam site (Table 1.1) separately.

5.1 Macroseismic information

Generally speaking reported felt intensities in Sweden seldom reach degree of VI. From the diagram in Fig. 3.1, we obtain that an intensity of VI (ground acceleration of 25 cm/s^2) will be generated by an event of magnitude 4 at en epicentral distance of 15 km. Ahjos and Korhonen [1] report on two Swedish events in 1497 and 1759 with maximum felt intensity of VII. These two events took place in southern Sweden (south of 60^{o}N) i.e. outside the area of consideration. Information concerning their source parameters (place, time, size) are obviously rather dubious. The Oslo fjord event in 1904 generated intensity of VII in a limited area on the Swedish side of the macroseismic field.

For the shock of May 12, 1970, mentioned above, macroseismic observations are not available. However, by making use of the diagram in Fig. 3.1, we estimate that intensities were III and V at Fageråssjön and Höljes, respectively. Corresponding ground accelerations (Fig. 3.1, eq. 3.1) are 1 cm/s^2 and 8.3 cm/s^2. Båth [7] summarized the maximum observed seismic intensities in Sweden from 1951 to 1976. His work reveals that intensities larger than IV were not reported from inland Sweden north of 60^{o}N. By consulting the other sources of macroseismic data, i.e. [5, 19, 20, 21, 22] we conclude that during the last 100 years none of the dam sites listed in Table 1.1 were exposed to ground shaking exceeding intensity IV which roughly corresponds to an acceleration of 3 cm/s^2.

5.2 Instrumental data 1956-2004

Kijko et al. [16] estimated the maximum-expected-magnitude earthquake to occur in northern Sweden (approximately the area displayed in Fig. 5.1) to be 4.3±0.5, for a period of 331 years. For an event of magnitude 4.2 they derived a probability of non-exceedance of 0.76 for a 100-year period (Table 3.2). Comparable results for northern Sweden are given in [25]. They estimate return periods for earthquakes exceeding magnitude 3.8 and 4.0 to be 100 years and 200 years, respectively. Probability that magnitude 4 will not be exceeded in 50 years is 0.79 (Table 3.1).

Following the values presented by Kijko and colleagues and making use of eq. (3.2), we obtain that an event of magnitude 4.2 will generate an epicentral ground acceleration of 31.5 cm/s^2. Thus, we have a 76% probability that a ground acceleration of 31.5 cm/s^2 will not be exceeded during a period of 100 years anywhere in northern Sweden. For an event with magnitude 4, it follows from eq. (3.2) that the epicentral ground acceleration will amount to 23 cm/s^2. Making use of the results in [25,]we deduce that there is a

79% probability that this acceleration will not be exceeded during an interval of 50 years anywhere in northern Sweden. Results based on estimates from [16]and from [25] are in good agreement with each other. It should be emphasizes that the calculations performed here relate to the “worst possible case”, i.e. we assume that the event took place beneath the dam. As soon as the hypocenter moves from the dam site, the above estimated accelerations will rapidly diminish (cf. Fig 3.1).

A valuable contribution to the problem studied in the present work can be found in Mäntyniemi et al. [26] who performed a probabilistic seismic hazard assessment of the northern European intraplate. For the region displayed in Fig. 5.1, their map provides peak ground accelerations between 0.005% and 0.015% of *g*, with 90% probability of no-exceedance for an exposure time of 50 years. These estimates, namely 5 cm/s^2 to 15 cm/s^2, even though somewhat lower, are in good agreement (of the same order) with those given by [16] and [25].

In the “Global Seismic Hazard Map” prepared by the GSHAP project [12], raw values of expected ground accelerations in the study region of northern Sweden are between 20 cm/s^2 and 40 cm/s^2 with a 90% probability of non-exceedance in 50 years.

Summarizing, we can postulate that several independent sources employed above provide comparable results. For northern Sweden and time intervals 50-100 years it is rather unlikely that the ground accelerations caused by regional earthquakes will exceed levels of, say, 40 cm/s^2.

5.3 Reservoir induced seismicity, RIS

As mentioned above, to derive seismic hazard estimates for RIS in Sweden is difficult if not impossible. We can only note that during the last 50 years, or so, no seismic pattern has been observed that could be related to dam sites listed in Table 1.1. One possible exception is the Höljes dam and the magnitude 3.2 event of May 12, 1970 which took place about 14 km east of the dam. There has been no seismicity recorded around the dam either prior to or after 1970, and so, it is difficult to decide whether or not the event has been triggered. On the other hand, the isolation of the 1970 shock together with its relatively large distance from the reservoir indicates that a tectonic origin is more likely. A temporary seismic network deployed around the Höljes dam can shed some light into the uncertainty.

6 Behavior of dams

6.1 Introduction

In the preceding chapters of this report the seismic hazard for earthquakes in Sweden is presented. In the following chapters of the report an assessment of the ground motions and the motions of the dams together with a discussion of permanent displacements of selected dams in Sweden are addressed. Dams selected are the high dams presented in Table 1.1 and dams in south-western Sweden; Telemark-Vänern zone in chapter 3. The latter are regarded as the most excited dams, as the strongest earthquakes occur in that region. Tiling dams from mining are not dealt with as they require a different analysis and constitute another kind of hazard. They are though much more vulnerable to earthquake motion than ordinary dams.

Most dams have performed excellently during earthquakes [15]. Embankment dams seem to be more vulnerable to ground motion than concrete dams. The following points are of importance: An earthquake should not cause an embankment dam

-to fail due to liquefaction of the material in the dam or its foundations;

-to collapse due to movement at a slip surface in the slope or through its foundation;

-to loose its freeboard

-to develop uncontrolled leakage through cracks or at interfaces with structures or abutments;

-spillways and hydraulic controls to be damaged to the extent that dangerous conditions develop.

The analysis in Part II concerns soil embankment dams and rock fill dams which have withstood very strong ground motions without failing.

6.2 Chain of assessments

A ground motion can be regarded as consisting of many sinusoidal motions with different frequencies and different amplitudes. (The sinusoidal motions can also be out of phase in relation to each other). The frequency bandwidth of Swedish earthquakes according to [7] is in the range 2-10 Hz. The higher the magnitude of an earthquake, the lower the fundamental frequency.

A space limited body, as a dam, shows resonance frequencies i.e. amplitudes of these frequencies are amplified from the base of the dam to its crest. If the lower resonance frequencies coincide with the frequencies of the ground motions, amplitudes are amplified. It is therefore important to calculate the amplification from the bottom of the dam to its crest for different magnitudes.

In order to assess the dynamic and permanent movements of a dam excited by earthquake ground motions, the following scheme has been employed. First, some relevant magnitudes are chosen then characteristic distances for the chosen earthquakes are assumed. The measure of the motion is, in earthquake engineering, normally described by the maximum value of the horizontal particle acceleration, A_{max}. From a relation describing how the maximum acceleration is attenuated with distance to the hypo- or epicenter (attenuation relation) the maximum acceleration of the ground can be calculated at the site of the dam as the distances are known.

The amplification of motions through the dam can be calculated, [11]. The amplification refers to an increase in motion from an out-cropping rock at the site of the dam to the crest of the dam. The amplification depends much on the height of the dam as different heights yields different resonance frequencies. The higher the dam, the lower the resonance frequency. From the knowledge of the maximum acceleration of the crest it is possible to give an upper bound of the permanent displacement of the dam from a simplified method proposed in [24]. This upper bound will be a measure of the five points presented above. The chain of assessments will be the disposition of the following chapters of the present report.

A special problem arises when dams are founded on soil. The soil profile has its own resonance frequencies. If the lowest of these coincides with the lowest of the resonance frequencies of the dam a kind of double resonance can occur. In principle there will be an amplification of motions from the rock below the soil profile to the base of the dam and then the motions are amplified once more from the bottom of the dam to the crest.

The interaction of the dam with its reservoir has not been taken in consideration in this report.

7 Magnitudes, distances and attenuation relation

7.1 Magnitudes and distances

It is important to consider different magnitudes as they have different fundamental frequencies and will affect dams of different heights in different ways. From Table 3.1, M_{100} is the magnitude to be exceeded once in 100 years. Both for the Telemark-Vänern and the Lappland zone the highest local magnitude is 4.7. Therefore, local magnitudes for which the following analysis is performed will be M_L= 3.0, M_L= 4.0 and M_L= 5.0.

In Part I, the acceleration at the epicenter was presented as a relation from Båth [8], as equation (3.2) for focal depth of 15 km. For the chosen magnitudes the following table can be constructed.

TABLE 7.1. Epicentral acceleration, A_{max}, for different local magnitudes.

Magnitude, M_L	3.0	4.0	5.0
Epicentral acceleration, cm/s^2	4.7	23	112

1 cm/s^2 is equal to g/1000.

There is a dramatic increase of the acceleration values with an increasing local magnitude. The probability that the dam will be situated exactly at the epicenter is very small. Therefore a characteristic value of the epicentral distance is here set to 20 km. The maximum accelerations at this distance can be calculated as soon as the attenuation relation is presented.

7.2 Attenuation relation

The most important relation and, at the same time, the one which is often difficult to obtain is the relation between the maximum horizontal particle acceleration and the distance from the earthquake source. This relation is different for different parts of the world. Fortunately, ground motions from Swedish earthquakes have been studied thoroughly. Here, the relation presented in [7] will be used. The relation is presented graphically in Figure 3.1. The relation can approximately be written mathematically as:

$$A_{\max} = 2.24 \cdot 10^{0.73M} \cdot \frac{1}{R^{1.61}} \qquad (7.1)$$

where A_{max} is the acceleration in cm/s^2 and R is the epicentral distance in km. If the characteristic distance of 20 km is inserted in the relation the following table is obtained.

TABLE 7.2. Acceleration, A_{max}, for different magnitudes, at a distance of 20 km.

Magnitude, M_L	3.0	4.0	5.0
Acceleration at 20 km, cm/s^2	2.8	15	80

As expected, the acceleration values at 20 km are lower than the epicentral values. They are regarded as more reasonable as the probability of an earthquake to occur within a radius of 20 km is much higher than an earthquake to occur just below the dam.

8 Amplification of motion

8.1 Fundamental frequency

The fundamental frequencies of Swedish earthquakes have not been studied extensively. Above, it was mentioned that the band width for these earthquakes is 2-10 Hz. One of the author´s experience (O.K.) is that the three magnitudes here studied will yield fundamental frequencies as: 7 Hz (M_L= 3.0), 5 Hz (M_L= 4.0) and 3 Hz (M_L= 5.0).

8.2 Amplification of motion and maximum crest acceleration

The theory of calculating the amplification of the motion through the dam is taken from [11]. It is important to realize that Gazetas modeled embankment dams as perfect triangles with the crest as a sharp point. So the crest acceleration calculated below is a fictive entity.

In order to apply the amplification formula several parameters must be determined. The shear modulus, G, varies within the dam according to mean effective stresses within the dam. Gazetas makes it credible that the variation can approximately be written as

$$G = G_b \cdot \varsigma^{2/3} \tag{8.1}$$

where G_b is the average shear modulus along the base and $\zeta= z/H$ where H is the height of the dam and z is the distance from the crest to the point of observation.

The average shear modulus at the base can be calculated by applying formulas from the literature relating the maximum shear modulus, G_{max}, with the mean effective stress, σ_o', and pore number, e. Here, a relation proposed for non-cohesive material has been used, [17]:

$$G_{\max} = \frac{13000 \cdot (2.17 - e)^2}{1 + e} \cdot (\sigma_0')^{0.55} \tag{8.2}$$

The maximum shear modulus and the mean effective stress must be expressed in kPa in eq. (8.2). G_{max} is the shear modulus for small strains (motions). If the strains (motions) increase the shear modulus decreases. The maximum value of G_{max} at the base can be calculated as the height of the dam and lateral stress ratio of the material are known. The average shear modulus, G_b, is obtained by dividing by 1.55.

In order to obtain realistic values, the internal damping of the material has to be included in the calculations. Here it is modeled by regarding the average shear modulus as a complex quantity whose imaginary part is $2G_bD$, where D is the damping ratio; here set to 0.10 (10 percent) even if it also varies with strain.

It is also necessary to know the average shear wave velocity in the dam, c_{bar}. It can be calculated first by obtaining the average shear wave velocity at the base from the well-known formula $c_b=(G_b/\rho)^{0.5}$ where ρ is the total density of the material. Then this quantity is multiplied by 0.75 in order to obtain c_{bar}.

The lowest resonance frequency f_1 can now be calculated as

$$f_1 = \frac{c_{bar}}{2.57 \cdot H} \tag{8.3}$$

The amplification will depend on the frequencies of the ground motions. Therefore a frequency parameter is introduced as $a_0= 2\pi fH/c_{bar}$. Now, the amplification function of the motions from the outcropping rock to the crest, AF, of the dam can be given.

$$AF = \frac{a_0}{\sin(a_0) + i\gamma\left(\frac{\sin(a_0)}{a_0} - \cos(a_0)\right)} \tag{8.4}$$

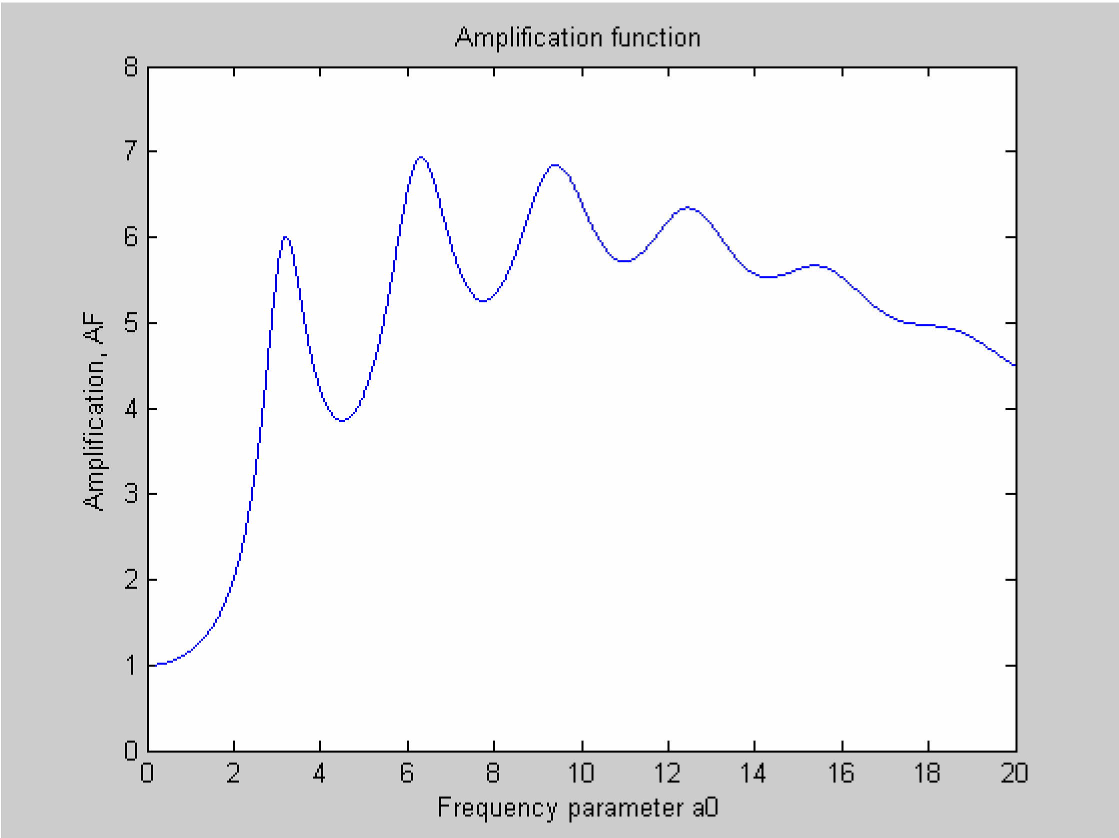

Figure 8.1. Amplification function for a triangle with γ= 0.20 and D= 0.10.

where γ is the impedance ratio $\gamma = \rho\sigma_s c_{barb}/(\rho_r c_r)$, *r* refers to rock. c_{barb} is the mean shear velocity in the basement. The amplification as a function of frequency parameter *a0* is shown in Figure 8.1.

The acceleration at the crest can now be calculated as $a_{crest} = a_{max}\,AF$. The maximum acceleration is obtained either from Table 7.1 or Table 7.2. As the different magnitudes are characterized by single different frequencies, the calculated crest acceleration will be too high. The value should be divided by a factor of 2 – 4. In the following calculations the acceleration is divided by two. Remember that this acceleration is a somewhat fictive entity as the cross section of real dams is cut triangles and not perfect triangles.

9 Permanent deformation

In order to get a measure on the deformations and damages on a dam from ground vibrations the deformation concept used in [24] was applied. The paper comprises earthquakes of magnitude 6 and greater but by extrapolating to magnitude 5 a conservative estimation of permanent deformations can be obtained.

The average acceleration level for the whole dam is approximated to $0.36a_{crest}$. Makdisi and Seed found that the parameter $U/(0.36a_{crest})*f_1$ is a measure on the permanent deformation, U. In order to perform an estimation this parameter was here set to 0.20 s , which according to Makdisi and Seed is a conservative estimation, (it is also too high for magnitudes 3 and 4). So

$$U = 0.20 \cdot 0.36 \cdot a_{crest} / f_1 \qquad (9.1)$$

The crest acceleration and the first fundamental frequency are already discussed in subchapter 8.2.

10 Dams founded on soil

As was mentioned above, dams founded on soil constitute a special problem as the soil layer itself has resonance frequencies. The interested reader is referred to [10]. The amplification function from an out-cropping rock site to the surface of one single horizontal soil layer with thickness H and shear wave velocity c_S is given in eq. (10.1) and displayed in Fig. 10.1. The impedance ratio is $\gamma = \rho_s c_{Ss}/(\rho_r\, c_r)$ where s refers to soil and r to rock.

$$AF = \frac{1}{\cos(a_0) - i\gamma \cdot \sin(a_0)} \qquad (10.1)$$

where a_0 has been defined earlier as $a_0 = 2\pi f H / c_{Ss}$.

The lowest resonance frequency is obtained for $a_0 = \pi/2$ or $f_1 = c_{Ss}/(4H)$. As this case needs data of the geotechnical properties and the depth of the soil they are not analyzed in this report.

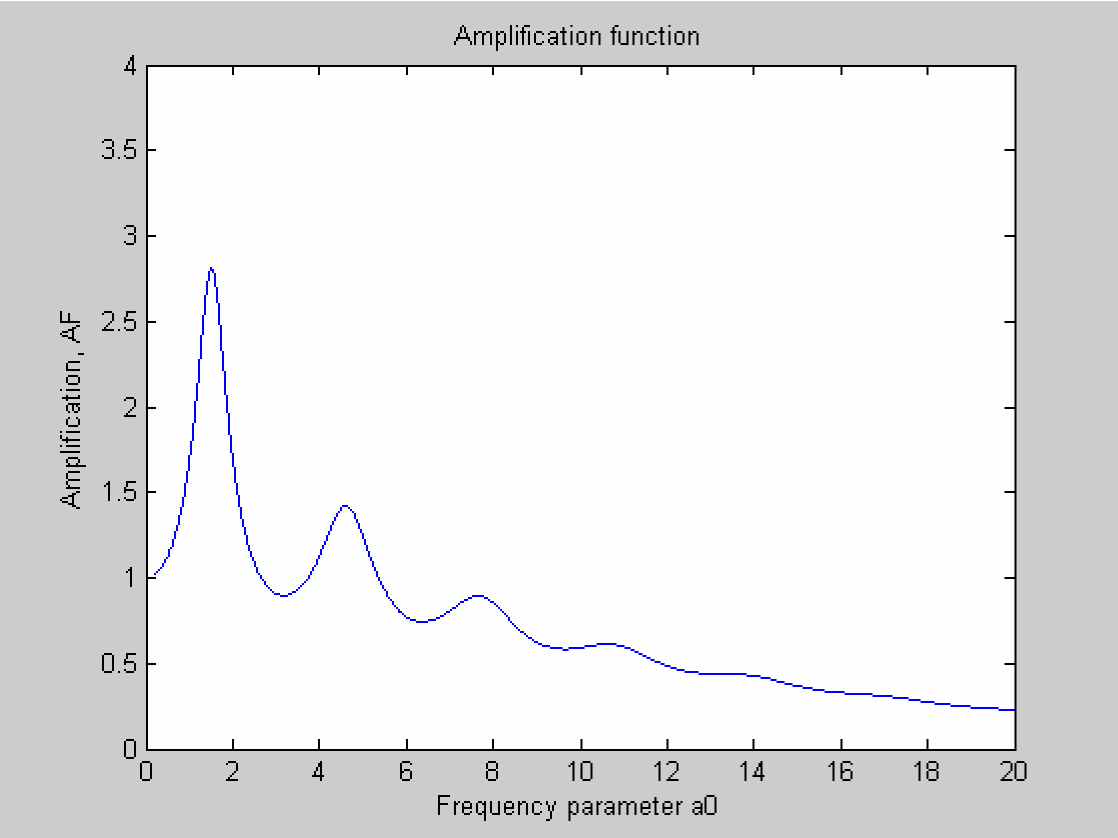

Figure 10.1. Amplification function for a soil layer with γ= 0.20 and D= 0.10.

11 Results and discussion on behavior of dams

The results of the assessments for 10 high dams are given in Appendix 1. In Appendix 2 results for dams with heights 7, 14, 21, and 28 m are shown. In south-western Sweden no dam is higher than 28 m, except the Höljes dam which belongs to the 12 high dams.

Six of the high dams will acquire a maximum crest acceleration more than 200 cm/s^2 or 0.2g for a magnitude 5.0 event. They are in order of decreasing acceleration: Trängslet, Seitevare, Messaure, Suorva-Vietas east dam and Harsprånget. This magnitude of crest acceleration may cause some slight damage in the crest area and equipment mounted on top of the dam.

A measure of damage of the dam itself the permanent deformation proposed in [24] is used. The six highest values of the permanent deformation, all more than 8 cm for a magnitude 5.0 event, were for the dams, in decreasing values: Trängslet, Seitevare, Messaure, Letsi, and Suorva-Vietas east dam. The highest value for Trängslet was 18 cm which must be regarded as a small value.

Four of the dams appear in both categories: They are in decreasing order of vulnerability: Trängslet, Seitevare, Messaure and Suorva-Vietas east dam. However the probability for a magnitude 5.0 earthquake to occur in the north of Sweden is very small.

The dams in south-western Sweden are all less than 28 m in height will not acquire maximum accelerations or permanent deformations which are damaging to dams in that region, even for magnitude 5.0 events. Such events are more probable in south Sweden than in the north.

In Norway a seismic zonation study was published in1998, [27]. Some of the high dams in Sweden are situated close to the border to Norway so it is possible to make an extrapolation for the out-cropping rock maximum acceleration. The dams in question are Fageråssjön, Höljes and Suorva-Vietas east dam. The first two are close to each other so they will be excited by more or less the same excitation. For these two dams the extrapolation will give that the 10,000 year event will yield 0.18 g or 180 cm/s^2 and the 1,000 year event will yield 0.06 or 60 cm/s^2. For the Suorva-Vietas east dam the numbers are: for the 10,000 year event the maximum acceleration is extrapolated to 0.10 g or 100 cm/s^2 and fro the 1,000 year event will give 0.04 g or 40 cm/s^2. Seismic excitation is apparently lower part of Sweden than in the northern parts. The magnitudes of the maximum accelerations from the Norwegian work are consistent with those used in this report.

12 Conclusions

The conclusion of the work presented in this report is that for the dams in south-western Sweden there is no hazard from earthquakes.

Provided the dams are well built, the seismic hazard against high dams in middle and northern Sweden is small. Slight damages on top of the dams may occur but the probability for this to happen is very small.

The case with dams founded on soil should be investigated in more detail.

13 Acknowledgements

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14 Referenses

[1] Ahjos, T. and Korhonen, H.; “On a catalogue of historical earthquakes in Fennoscandian area”, Inst. Seismol., Univ. Helsinki, Report S-10 , 24 pp., 1984

[2] Allen, C.R.; ”Reservoir-induced earthquakes and engineering policy”, Calif. Geol., **35**: 248-250, 1982

[3] Bödvarsson, R. and B. Lund; “The SIL seismological data acquisition system – as operated in Iceland and in Sweden”, In: Methods and Applications of Signal Processing in Seismic Network Operations, (Eds.) T. Takanami and G. Kitagawa, Lecture Notes in Earth Sciences, **98**, Springer Verlag, Berlin, 2003.

[4] Båth, M.; “An earthquake catalogue for Fennoscandia for the years 1891-1950”, Sv. Geol. Surv. Yearb, **50**, no.1, 52 pp., 1956

[5] Båth, M.; “Earthquakes in Sweden 1951-1976”, Sv. Geol. Surv., C 750, Yearb. **72**, 79 pp., 1979a

[6] Båth, M.; “Seismisk risk in Fennoscandia. Tectonophysics”, **57:** 285-295, 1979b

[7] Båth, M.; “A method for mapping seismic intensities applied to Sweden.”, Tectonophysics, **66**: T11-T18, 1980a

[8] Båth, M.; “Intensity relations for Swedish earthquakes”, Tectonophysics, **67**: 163-173, 1980b

[9] Båth, M., Kulhanek, O., van Eck, T. and Wahlström, R., ”Engineering analysis of ground motion in Sweden”, Seismol. Inst., Report 5-76, 48 pp., 1976

[10] Cramer, S.; “Geotechnical Earthquake Engineering”, Prentice Hall, 1996

[11] Gazetas, G., ”Seismic response of earth dams: some recent developments”, SoilDynamics and Earthquake Engineering, **Vol 6**, No. 1: 2-47, 1987

[12] Giardini, D. and Basham, P.; “The global seismic hazard assessment program (GSHAP)”, Ann. Geofis., **36**: 3-13, 1993

[13] Gough, D.I.; “Induced seismicity. In: The assessment and mitigation of earthquake risk”, Paris, UNESCO, pp 91-117, 1978

[14] Husebye, E., Bungum, H., Fyen, J. and Gjoystdal, H.; “Earthquake activity in Fennoscandia between 1497 and 1975 and intraplate tectonics”, Norsk Geol. Tidskrift 1: 51-68, 1978

[15] ICOLD; “Seismicity and dam design”, Bulletin 46, 1983

[16] Kijko, A., Skordas, E., Wahlström, R. and Mäntyniemi, P.; “Maximum likelihood estimation of seismic hazard in Sweden”, Natural Hazards, **7**: 41-57, 1993

[17] Kokusho, T., Esashi, Y.; “Cyclic triaxial tests on sand and coarse materials”, Proceedings of the 10th International Conference on Soil Mechanics and Foundation Engineering, Stockholm, **1**:673-676, 1981

[18] Kujansuu, R.; ”Nuorista siirroksista Lapissa. Summary: Recent faults in Lappland”, Geologi, **16**: 30-36, 1964

[19] Kulhanek, O. and Wahlström, R.; ”Macroseismic observations in Sweden 1977-1979”, Sv. Geol. Surv., C 776, Yearb. **74**, 13 pp., 1981

[20] Kulhanek, O. and Wahlström, R.; “Macroseismic observations in Sweden 1980-1983”, Sv. Geol. Surv., C 808, Yearb. **79**, 28 pp., 1985

[21] Kulhanek, O. and Wahlström, R.; “Macroseismic observations in Sweden 1984-1990”, Sv. Geol. Surv., C 825, 38 pp., 1992

[22] Kulhanek, O. and Wahlström, R.; “Macroseismic observations in Sweden 1991-1995”, Sv. Geol. Surv., Reserch papers, C 829, 24 pp., 1996

[23] Lagerbäck, R.; “Neotectonic structures in northern Sweden”, Geol. Fören. Stockh. Förh., **100**, 263-269, 1979

[24] Makdisi, F.I., Seed, H.B.; “Simplified procedure for estimating dam and embankment earthquake-induced deformations”, Journal of Geotechnical Engineering, ASCE, **104**, GT7, 849-867, 1978

[25] Mäntyniemi, P., Wahlström, R., Lindholm, C. and Kijko, A.; ”Seismic hazard in Fennoscandia: a regionalized study”, Tectonophysics, **227**: 205-213, 1993

[26] Mäntyniemi, P., Kijko, A. and Retief, P.; “Parametric-historic procedure for seismic hazard assessment and its application to northern Europe”, Boll. Geofisica, **42**: 41-56, 2001

[27] NORSAR and NGI; “Seismic Zonation for Norwegian Territories”, Prepared for Norwegian Council for Building Standardization, 1998

[28] Simpson, D.W.; "Triggered earthquakes", Ann.Rev. Earth Planet. Sci., **14**: 21-42, 1986

[29] Willmore, P.L.; "Manual of seismological practice", World Data Center for Solid EarthGeophysics, 1979

Appendices

A Results for selected dams in Sweden

For each of the dams presented in Table 1.1 some of the results are presented below

Harsprånget

H, m	51
f_1, Hz	2.1
c_{barb}, m/s	273

	AF	a_{crest}, cm/s^2	U, cm
M_L= 3.0	5.6	7.9	0.3
M_L= 4.0	6.5	49	1.7
M_L= 5.0	5.7	231	7.9

Håckren

H, m	67
f_1, Hz	1.7
c_{barb}, m/s	295

	AF	a_{crest},, cm/s^2	U, cm
M_L= 3.0	6.8	9.5	0.4
M_L= 4.0	5.9	45	1.9
M_L= 5.0	4.0	160	6.7

Höljes

H, m	80
f_1, Hz	1.5
c_{barb}, m/s	309

	AF	a_{crest},, cm/s^2	U, cm
M_L= 3.0	5.9	8.3	0.4
M_L= 4.0	5.5	41	2.0
M_L= 5.0	4.1	164	7.8

Letsi

H, m	85
f_1, Hz	1.4
c_{barb}, m/s	314

	AF	a_{crest},, cm/s^2	U, cm
M_L= 3.0	6.3	8.8	0.4
M_L= 4.0	5.9	44	2.2
M_L= 5.0	4.3	175	8.7

Messausre

H, m	101
f_1, Hz	1.3
c_{barb}, m/s	330

	AF	a_{crest},, cm/s^2	U, cm
M_L= 3.0	6.0	8.4	0.5
M_L= 4.0	7.0	53	3.0
M_L= 5.0	6.0	241	14

Seitevare

H, m	106
f_1, Hz	1.2
c_{barb}, m/s	334

	AF	a_{crest},, cm/s^2	U, cm
M_L= 3.0	5.8	8.0	0.5
M_L= 4.0	6.7	50	2.9
M_L= 5.0	6.6	266	15

Suorva - Vietas Krv, Östra dammen (East dam)

H, m	50
f_1, Hz	2.1
c_{barb}, m/s	272

	AF	a_{crest},, cm/s^2	U, cm
M_L= 3.0	5.5	7.7	0.3
M_L= 4.0	6.2	46	1.6
M_L= 5.0	5.9	239	8.1

Suorva - Vietas Krv, Sågviksdammen

H, m	30
f_1, Hz	3.1
c_{barb}, m/s	236

	AF	a_{crest},, cm/s^2	U, cm
M_L= 3.0	5.6	7.9	0.2
M_L= 4.0	4.4	33	0.8
M_L= 5.0	3.1	124	2.9

Suorva - Vietas Krv, Västra dammen (West dam)

H, m	67
f_1, Hz	1.7
c_{barb}, m/s	295

	AF	a_{crest},, cm/s^2	U, cm
M_L= 3.0	6.8	9.5	0.4
M_L= 4.0	6.0	45	1.9
M_L= 5.0	4.0	160	6.7

Trängslet dam

H, m	122
f_1, Hz	1.1
c_{barb}, m/s	348

	AF	a_{crest},, cm/s^2	U, cm
M_L= 3.0	5.8	8.1	0.5
M_L= 4.0	5.8	43	2.8
M_L= 5.0	6.8	274	18

B Results for dams in south-western Sweden

Except for the Höljes dam the dams in south-western Sweden are lower than 28 m.. Therefore the results will be presented for dams with heights, 7, 14, 21 and 28 m.

Dams with height 7 m

H, m	7
f_1, Hz	8.8
c_{barb}, m/s	158

	AF	a_{crest},, cm/s^2	U, cm
M_L= 3.0	2.0	2.8	0.02
M_L= 4.0	1.4	10	0.08
M_L= 5.0	1.1	45	0.4

Dams with height 14 m

H, m	14
f_1, Hz	5.3
c_{barb}, m/s	191

	AF	a_{crest},, cm/s^2	U, cm
M_L= 3.0	7.4	10	0.1
M_L= 4.0	2.8	21	0.3
M_L= 5.0	1.4	56	0.7

Dams with height 21 m

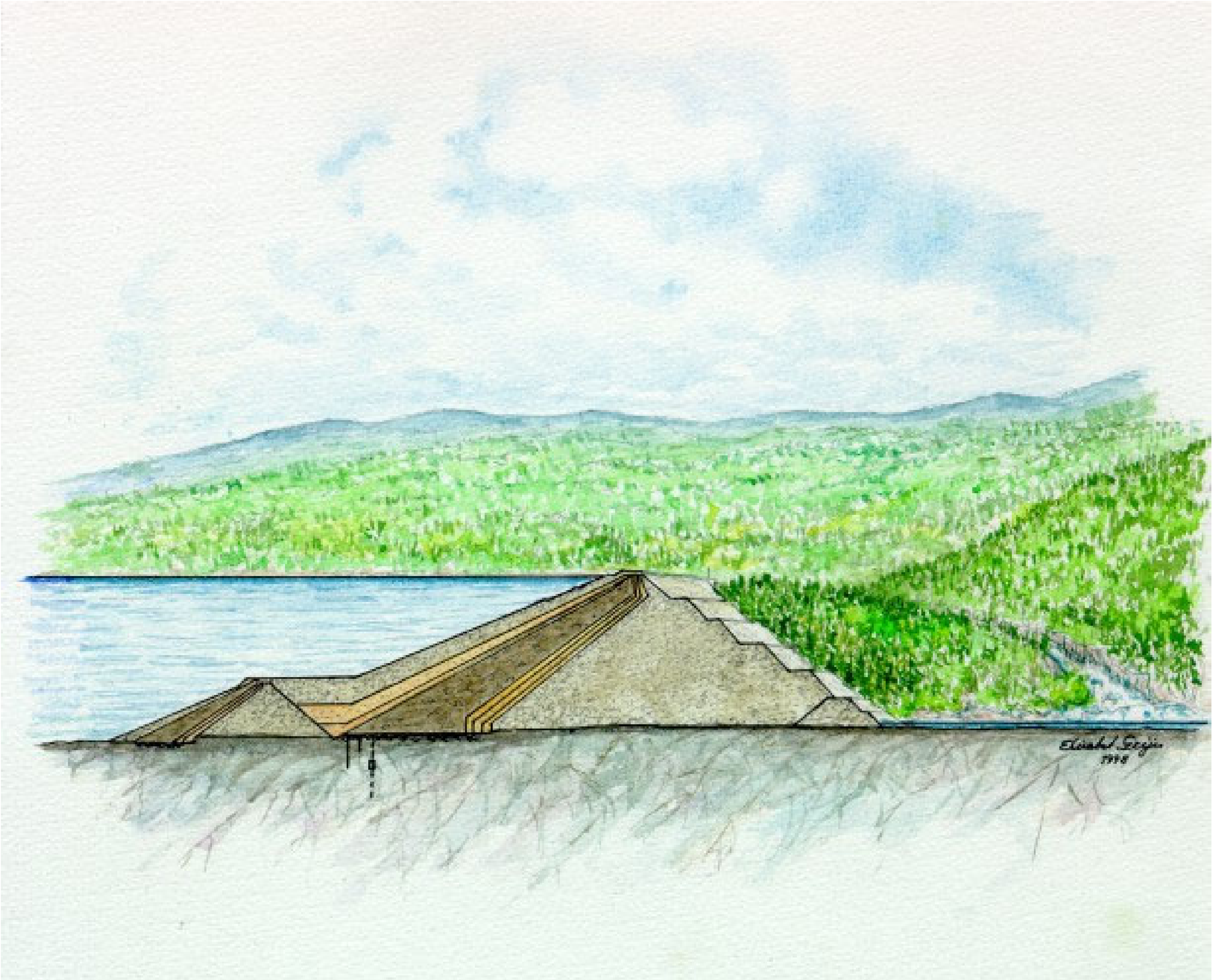
H, m	21
f_1, Hz	4.0
c_{barb}, m/s	214

	AF	a_{crest},, cm/s^2	U, cm
M_L= 3.0	4.1	5.6	0.1
M_L= 4.0	7.0	52	0.9
M_L= 5.0	1.8	74	1.3

Dams with height 28 m

H, m	28
f_1, Hz	3.2
c_{barb}, m/s	232

	AF	a_{crest},, cm/s^2	U, cm
M_L= 3.0	4.9	6.8	0.1
M_L= 4.0	4.9	36	0.8
M_L= 5.0	2.7	109	2.4



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