Report

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CCSP – Carbon Capture and Storage Program
Task 4.2.1 Terminals and intermediate storage

Seismic monitoring applications and possible regulations for seismic hazard

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1 Introduction

Seismic monitoring of induced earthquakes is a common method applied in mines (for example Mendecki, 1997) and in rock repositories (for example Saari & Malm, 2014 and 2015). First part of this report (Chapter 2) describes briefly what kind of seismic monitoring systems are used at some of the CO_2 storage sites around the world. All of these examples are storage sites for more permanent storing of CO_2, which is a different task than the intermediate storage planned in Finland. Nevertheless, the sites referred in this study give good examples of possible seismic monitoring systems that could also be applied for an intermediate storage site. The injection of CO_2 will alter the pore pressure and increase stress levels in the bedrock, and possibly even reactivate pre-existing faults or fractures or even create new ones (Verdon et al., 2010; Zoback and Gorelick, 2012). Proper geological investigations at the planned intermediate storage site are important to detect possible faults or fractures, which could act as pathways for CO_2 leakage.

The second part (Chapter 3) describes possible regulations for seismic hazard at CO_2 storage site. The Eurocode 8 regulations (EN 1998-1: 2004) on Design of Structures for earthquake resistance Part 1 could be used as a basis for evaluating response spectrum for the intermediate storage. A site specific hazard evaluation is still needed, because Finland has no National Annex for seismic zoning (Eurokoodi Help Desk, 2015).

2 Seismic monitoring applications in some CO_2 storage sites

2.1 Weyburn, Canada

This chapter is based on the study of Verdon and other (2010) at the Weyburn storage site in the Weyburn-Midale Field in the Williston Basin of southern Saskatchewan, Canada. The reservoir is at depth ~1430 meters. Both controlled-source 4D seismic monitoring and passive seismic monitoring has been used at this site. The passive seismic monitoring system used at the Weyburn CO_2 storage site in Canada is a cost effective method compared to many other geophysical monitoring methods like reflection seismology, electromagnetinc sounding, and others. The seismic monitoring system in Weyburn consists of eight triaxial 20 Hz geophones which are located in an inactive vertical well within 50 meters of a planned new vertical CO_2 injection well. Geophones were spaced at 25 meter interval between 1181 - 1356 meters.

The monitoring system was using so called triggered mode, where event data was stored when the processed signal levels exceeded the trashold limit on five of the eight geophones. The monitoring has been going on semi-continuously since August 2003. Exception was 11 months downtime from December 2004 to October 2005. Approximately 100 microseismic events have been located in within the monitoring period (August 2003 – January 2008). The moment magnitude of the events range mostly between M = -3.0 … -1.0. Seismic array on the ground surface would have limited use because of the magnitude-distance distribution of the events (Figure 2-1). The surface array would need to be very dense to trigger such small events at such depth.

The detected microseismic event rates correlate with periods of elevated CO_2 injection rates. Also the changes n production in the nearby wells seem to affect the seismic activity. Overall the rates of seismicity are low in the Weyburn area.

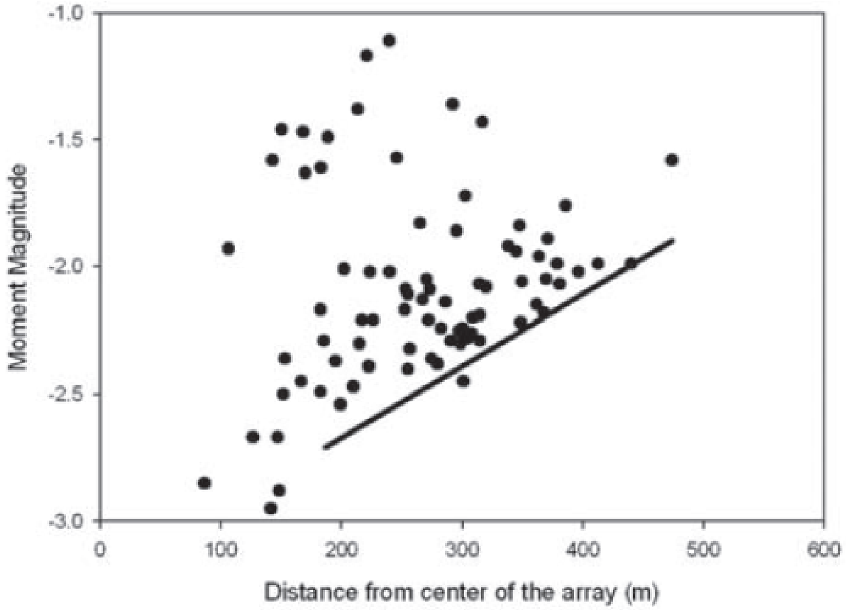

Figure 2-1 Magnitude versus distance plot for events up to July 2004 at Weyburn site (Verdon et al., 2010).

2.2 Ketzin, Germany

This chapter is based on the study by Santonico and other (2012) at the salin aquifer near Ketzin, Germany. The reservoir used for CO_2 injection in the Ketzin site is at 650 meters depth. The permanent seismic monitoring system consists of eight three-component geophones and 17 hydrophones along a line of 130 m length and at depths up to 50 m (Figure 2-2). The system has been recording passive seismic data continuously since September 2009. Automatic location and detection is used. Over 20 000 seismic events has been detected within two months (November and December 2009), of which the 200 strongest ones has been analysed more carefully. More than 99% of the events originate from industrial activity. Only low seismicity has been detected in the Ketzin area.

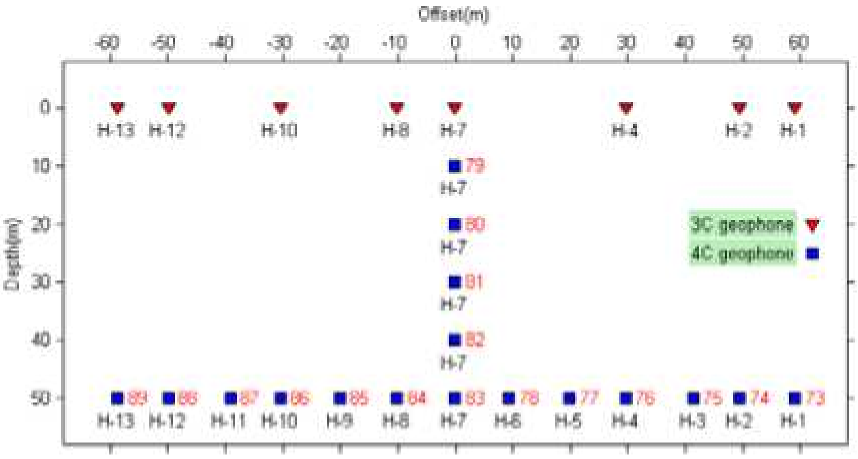

Figure 2-2 Layout of the 2D seismic array at Ketzin site in Germany (Santonico et al., 2012). 3C geophones at the surface, 4C receivers at 50 meters depth and a central vertical array of 4C receivers. The hydrophone trace numbers are indicated in red.

2.3 Longyearbyen, Norway

This chapter is based on the study by Ote and others (2013a) at the proposed CO_2 storage site in Longyearbyen, Norway. In 2011 the seismic network consisted of a 5-level three-component geophone string in vertical observation well Dh3 (nearly 300 meters depth and 50 meters level spacing) and five shallow wells, Sh 1-5, with one three-component geophone each (at nearly 12 meters depth). In 2013 additional 8-level three component geophone string was deployed in one of the deeper observation wells, Dh4 (Figure 2-3). The combined surface and downhole geophone network enables the detection of very weak microearthquakes associated with the injection tests.

Automatic processing was used on the recorded seismic events, but manual quality control was needed to separate the fluid injection induced events from local mining operations, glacial movements, and regional earthquakes. A microseismic event with M ~ 1 was detected near the injection well after a larger water injection test in August 2010. The event was followed by seven small aftershocks. Later injection test did not induce any recordable microearthquakes.

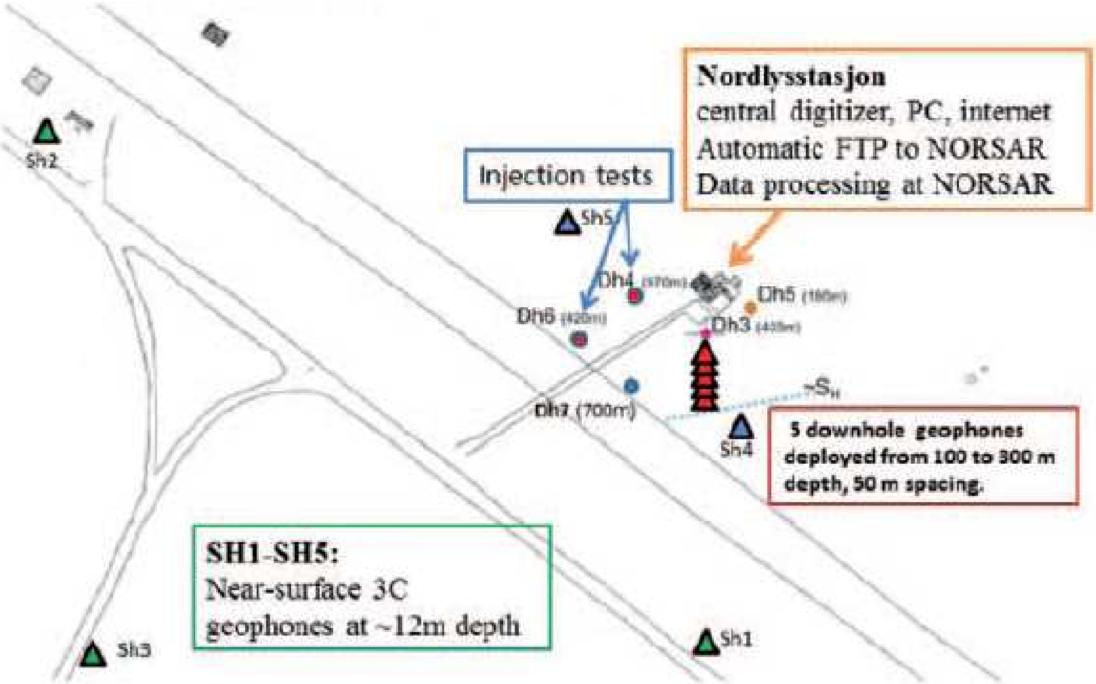

Figure 2-3 The CO2 Lab site in Longyearbyen, Norway (Oye et al., 2013a). The injection tests were conducted at wells Dh4 and Dh6. Geophones are installed at five depth levels within Dh3 (red triangles) and in shallow wells at about 12 m depth (green and blue triangles). All geophones are connected by cable to the central digitizer hub, placed in a building (Nordlysstasjon). Maximum cable length is approx. 600 m.

2.4 In Salah, Algeria

This chapter is based on the study by Oye and others (2013b) at the In Salah site in Krechba, Algeria. The In Salah CO_2 storage site has three wells for injection. The monitoring system consist of one-dimensional array with 48 three-component downhole geophones in single vertical well (30 - 500 meters with 10 meter spacing). Continuous waveform data with 500 Hz sampling rate is collected. More than 1500 injection induced microseismic events have been detected during the monitoring period (August 2009 - May 2012). The event occurrency correlates with increased injection rates and well-head pressures (Figure 2-4). The location accuracy of the events is very low (error up to 1 kilometer). In June and July 2010 the fracture pressure was exceeded and observed seismic activity increased immediately. Events were detected with automated P- and S-wave phase onset picking and polarization analysis. The extension of the monitoring system would improve event locations and classification.

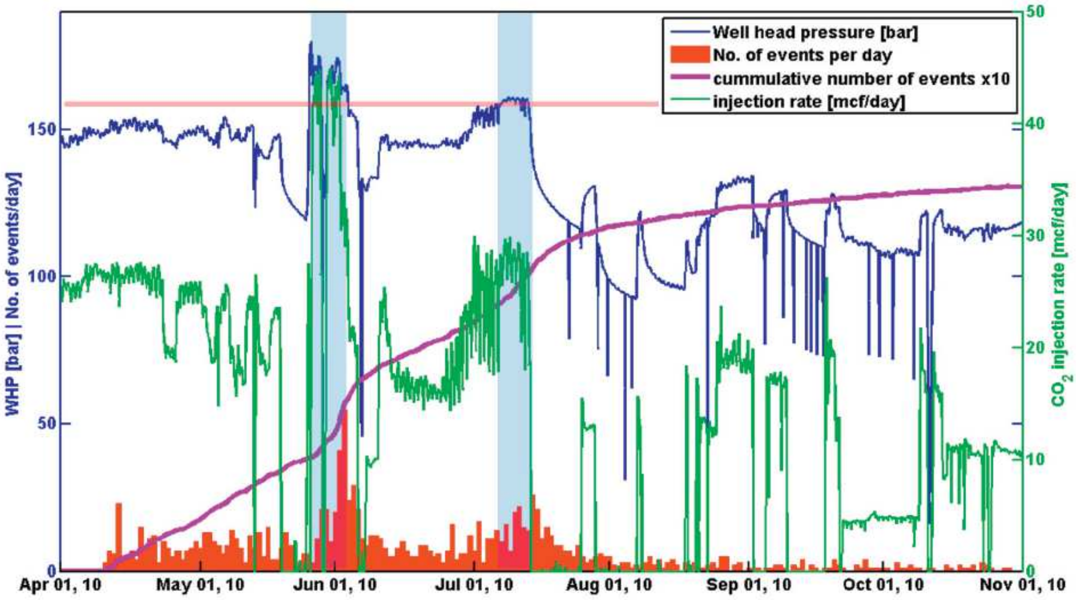

Figure 2-4 Temporal evolution of CO_2 injection rate, well-head pressure and microseismic events at In Salah site, Algeria (Oye et al., 2013b). A clear increase in microseismic activity of more than about 20 detected events per day coincides with high injection rates and high well-head pressures. The horizontal red line indicates fracture pressure.

2.5 Aquistore, Canada

This chapter is based on the study by White and others (2014 at the Aquistore site in Saskatchewan, Canada. The Aquistore site has a large permanent seismic array. In 2012 630 vertical-component geophones wereinstalled in shallow boreholes at 20 meters depth and 2,5 x 2,5 kilometers grid (Figure 2-5). In 2013 three broadband seismograph stations were installed on the surface around the Aquistore site. The large array enables cost-effective repeatable 3D seismic surveys and passive microseismic monitoring in the site area.

50 seismic stations have been operated continuously since 2012 to investigate the background seismicity prior to the CO_2 injection. Monitoring of actual CO_2 injection is not presented in this study. A baseline study of 3D vertical seismic profiling (VSP) was conducted in November 2013 with 60-level three component array of geophones in an observation well at depths 1470 – 2355 meters to acquire the natural variability of the site area. With VSP higher resolution seismic images of the reservoir are acquired within 500 meters of the observation well. Also cross-well tomography study has been conducted in the Aquistore site.

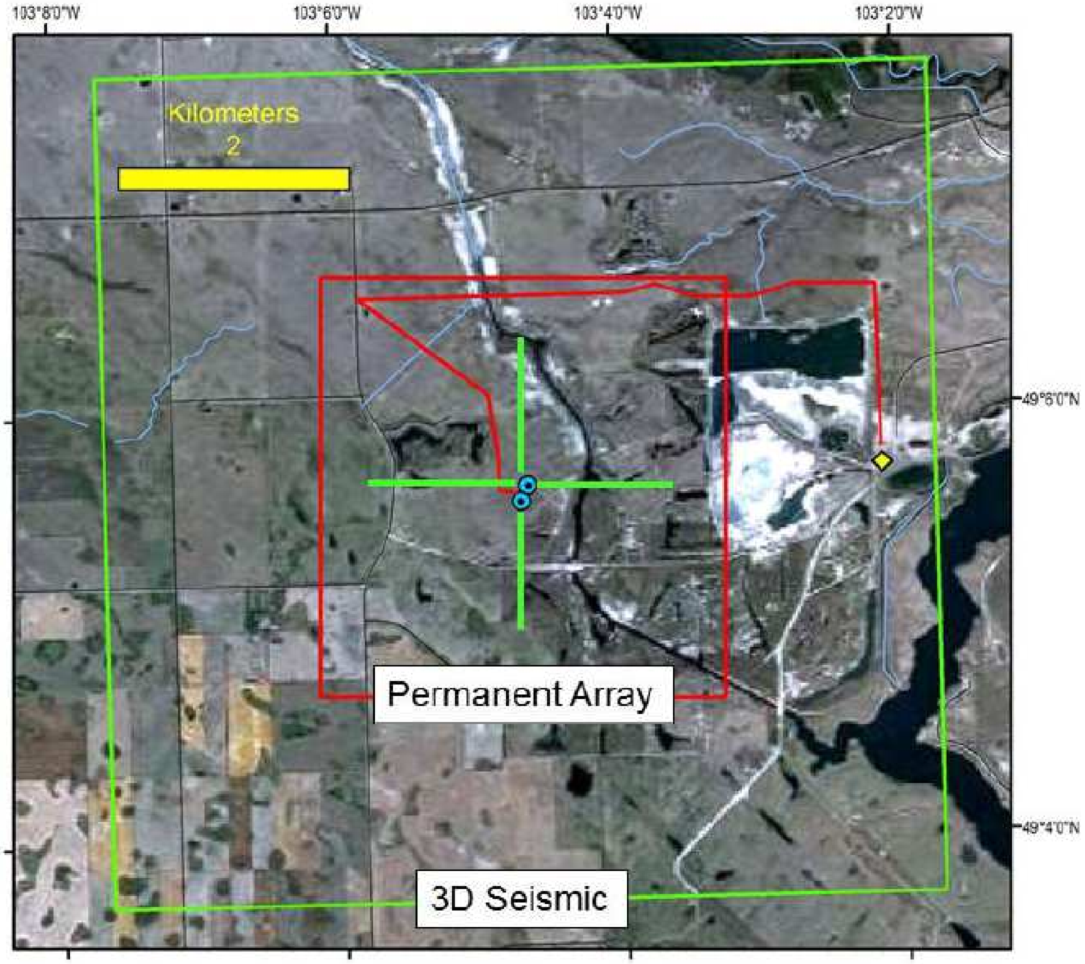

Figure 2-5 The 3D seismic survey and permanent geophone array at Aquistore site, Canada (White et al., 2014). Green lines: passive monitoring geophones. Red line: CO_2 *pipeline. Blue circles: injection and monitor wells.*

3 Possible regulations for seismic hazard at CO_2 storage site

This chapter concentrates on the Eurocode 8 regulations (EN 1998-1: 2004) on Design of Structures for earthquake resistance Part 1: General rules, seismic actions and rules for buildings. If a silo or a tank would be used for intermediate storage of CO_2, some other regulations need to be considered (EN 1998-4: 2006).

The soil conditions have an important part in seismic design. The ground type where the intermediate storage for CO_2 would be based on affects the shape of the response spectrum of Eurocode 8 (Table 3-1, Figures 3-2 and 3-3). In Finland the most probable base is ground type A (rock), which also has the lowest ground acceleration values compares to other ground types (Figures 3-2 and 3-3). There are two types of spectra depending on the evaluated maximum magnitude of the site area. The use of Type 1 spectrum is recommended when earthquakes that contribute most to the seismic hazard have a surface-wave magnitude M_s above 5.5 (EN1998-1:2004, Table 3-2, Figure 3-2). The Type 2 response spectrum should be used with surface wave magnitudes lower than $M_s = 5.5$ (Table 3-3, Figure 3-3).

Eurocode 8 uses Equations 3.1, 3.2, 3.3 and 3.4 to define horizontal components of the seismic action (see also Figures 3-2 and 3-3):

$$0 \leq T \leq T_B : S_e(T) = a_g \cdot S \cdot \left[1 + \frac{T}{T_B} \cdot (\eta \cdot 2{,}5 - 1)\right] \tag{3.1}$$

$$T_B \leq T \leq T_C : S_e(T) = a_g \cdot S \cdot \eta \cdot 2{,}5 \tag{3.2}$$

$$T_C \leq T \leq T_D : S_e(T) = a_g \cdot S \cdot \eta \cdot 2{,}5 \left[\frac{T_C}{T}\right] \tag{3.3}$$

$$T_D \leq T \leq 4s : S_e(T) = a_g \cdot S \cdot \eta \cdot 2{,}5 \left[\frac{T_C T_D}{T^2}\right] \tag{3.4}$$

where $S_e(T)$ = the elastic response spectrum, T = vibration period of a linear single degree of freedom system, a_g = design ground acceleration on type A ground, S = soil factor, T_B & T_C = lower (T_B) and upper (T_C) limit of the period of the constant spectral acceleration branch, T_D = value defining the beginning of the constant displacement response range of the spectrum and η = damping correction factor with a reference value of η = 1 for 5% viscous damping.

Eurocode 8 Part 1 has four importance classes (I – IV) for buildings depending on the consequences of collapse for human life, on their importance for public safety and civil protection in the immediate post-earthquake period, and on the social and economic consequences of collapse (EN 1998-1:2004). Intermediate storage for CO_2 would most probably belong to the highest importance class IV, because of possible threat for public in case of leakage of CO_2. The importance class IV requires the estimated peak ground acceleration for the target site to be multiplied with the importance factor γI = 1.4. In Eurocode 8 Part 4 (EN1998-4:2006) even higher importance factor could be required if the intermediate storage for CO_2 is classified for class IV (γI = 1.6). The classification for silos and tanks refers to situations with a high risk (class III) or exceptional risk (class IV) to life and large economic and social consequences of failure.

Sufficient geological investigations should be done to make sure there are no recognized seismically active tectonic faults in the immediate vicinity of the possible intermediate storage site (EN 1998-5:2004). In EN 1998-1:2004 it is stated that national territories shall be subdivided by the national authorities into seismic zones, depending on the local hazard and by definition the hazard within each zone is assumed to be constant. Finland has no National Annex for seismic zoning (Eurokoodi Help Desk, 2015). Therefore the seismic zoning and local hazard evaluation need to be done site specifically.

Table 3-1. Ground types (EN 1998-1:2004). V_{s30} *= average value of propagation velocity of S waves in the upper 30 m of the soil profile at shear strain of* 10^{-5} *or less,* N_{SPT} *= Standard Penetration Test blow-count,* c_u *= undrained shear strength of soil*

Ground type	**Description of stratigraphic profile**	**Parameters**		
		V_{s30} (m/s)	N_{SPT} (blows/30cm)	c_u (kPa)
A	Rock or other rock-like geological formation, including at most 5 m of weaker material at the surface.	> 800	-	-
B	Deposits of very dense sand, gravel, or very stiff clay, at least several tens of metres in thickness, characterised by a gradual increase of mechanical properties with depth.	360 – 800	> 50	> 250
C	Deep deposits of dense or medium-dense sand, gravel or stiff clay with thickness from several tens to many hundreds of metres.	180 - 360	15 - 50	70 - 250
D	Deposits of loose-to-medium cohesionless soil (with or without some soft cohesive layers), or of predominantly soft-to-firm cohesive soil.	< 180	< 15	< 70
E	A soil profile consisting of a surface alluvium layer with *v*s values of type C or D and thickness varying between about 5 m and 20 m, underlain by stiffer material with *v*s > 800 m/s.			
S_1	Deposits consisting, or containing a layer at least 10 m thick, of soft clays/silts with a high plasticity index (PI > 40) and high water content	< 100 (indicative)	-	10 - 20
S_2	Deposits of liquefiable soils, of sensitive clays, or any other soil profile not included in types A – E or *S*1			

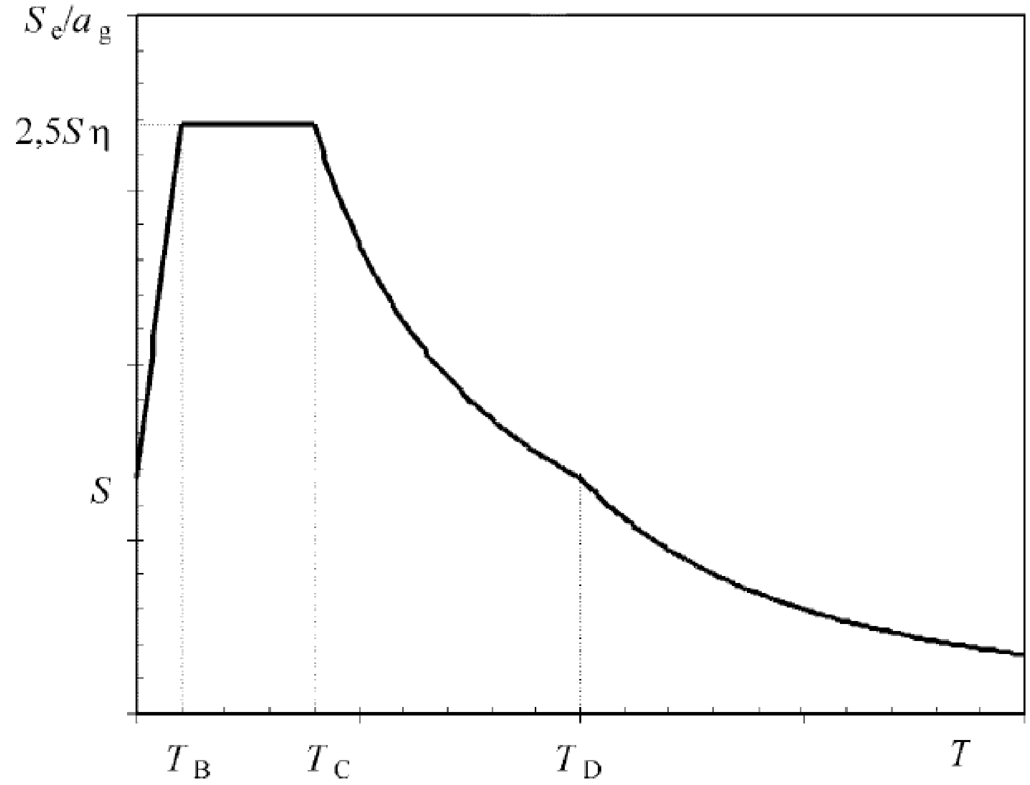

Figure 3-1. Shape of the elastic response spectrum from EN 1998-1:2004. S = soil factor, T_B *&* T_C *= lower (*T_B*) and upper (*T_C*) limit of the period of the constant spectral acceleration branch,* T_D *= value defining the beginning of the constant displacement response range of the spectrum (EN 1998-1:2004).*

Table 3-2. Values of the parameters describing the recommended Type 1 elastic response spectra (EN 1998-1:2004). S = soil factor, T_B = lower limit of the period of the constant spectral acceleration branch, T_C = upper limit of the period of the constant spectral acceleration branch, T_D = value defining the beginning of the constant displacement response range of the spectrum. Ground types are presented in Table 3-1.

Ground type	S	T_B (s)	T_C (s)	T_D (s)
A	1.0	0.15	0.4	2.0
B	1.2	0.15	0.5	2.0
C	1.15	0.20	0.6	2.0
D	1.35	0.20	0.8	2.0
E	1.4	0.15	0.5	2.0

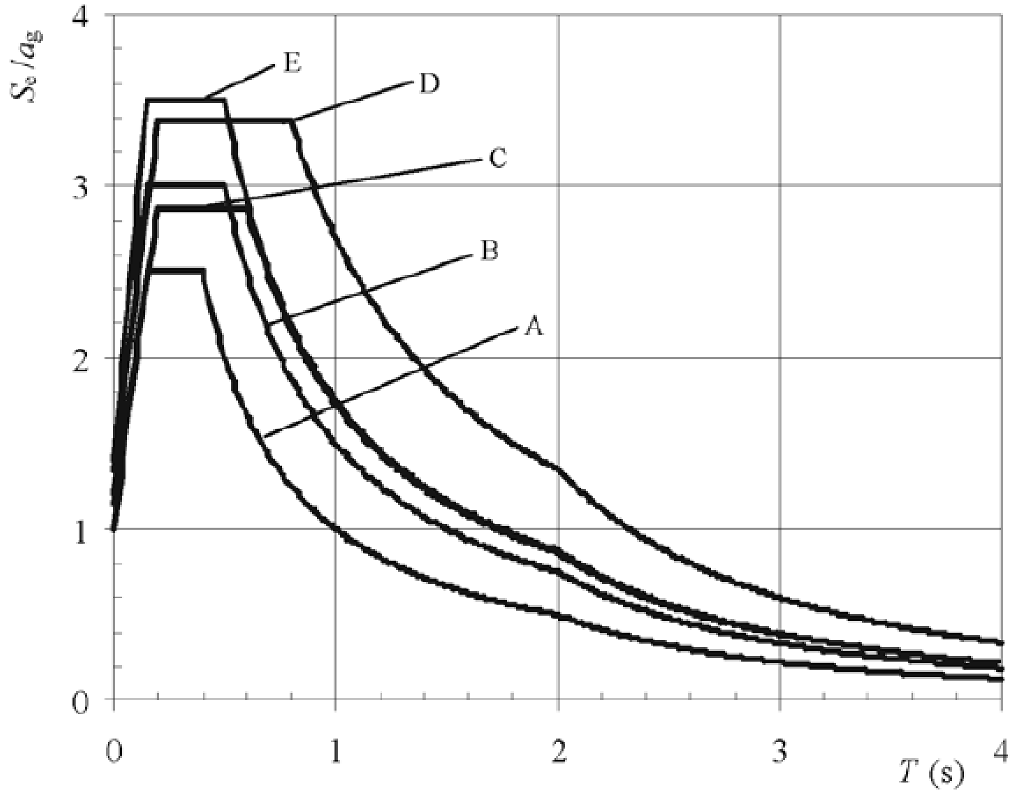

Figure 3-2. Recommended Type 1 elastic response spectra for ground types A to E with 5% damping (EN 1998-1:2004).

Table 3-3. Values of the parameters describing the recommended Type 2 elastic response spectra (EN 1998-1:2004). S = soil factor, T_B = lower limit of the period of the constant spectral acceleration branch, T_C = upper limit of the period of the constant spectral acceleration branch, T_D = value defining the beginning of the constant displacement response range of the spectrum. Ground types are presented in Table 3-1.

Ground type	S	T_B (s)	T_C (s)	T_D (s)
A	1.0	0.05	0.25	1.2
B	1.35	0.05	0.25	1.2
C	1.5	0.10	0.25	1.2
D	1.8	0.10	0.30	1.2
E	1.6	0.05	0.25	1.2

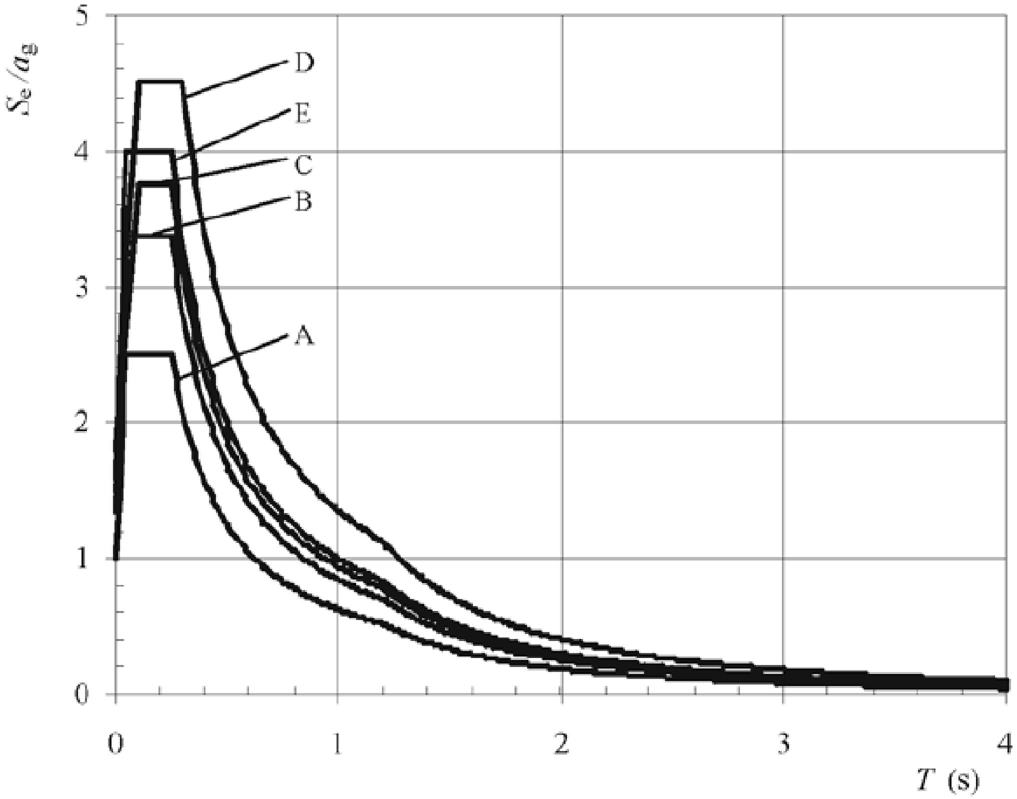

Figure 3-3. Recommended Type 2 elastic response spectra for ground types A to E with 5% damping (EN 1998-1:2004).

4 Conclusions

Different kinds of seismic monitoring systems for CO_2 storages have been applied around the world. Five storage sites were used as examples in this report: Weyburn and Aquistore sites in Canada, Ketzin in Germany, Longyearbyen in Norway and In Salah in Algeria. All of these storage sites have downhole seismometers and some use also surface arrays. Studies show some correlation between CO_2 injection and seismic activity.

Passive seismic monitoring can be used as a cost-effective way to to detect microearthquakes caused by fracturing and movements in the bedrock. The possible permanent seismic monitoring system should be designed specifically for the selected site of the intermediate CO_2 storage in Finland. In general it is suggested that seismic sensors are placed both on the ground surface and underground for better location accuracy. The seismic network should consist of sensitive geophones and/or accelerometers, because the possible expected ground movements are very small.

There are no clear regulations regarding seismic hazard for CO_2 storage site in Finland. The Eurocode 8 regulations are recommending two kinds of elastic response spectra depending on the surface wave magnitudes. The type 2 with surface wave magnitudes lower than $M_s = 5.5$ would mostly be more suitable in Finland. If an intermediate storage for CO_2 is planned to be established in Finland a site specific seismic hazard evaluation is suggested to be done.

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