Working Report 2007-03

Raise Boring of the Ventilation Shaft in Olkiluoto, 17.–23.5.2006

– Preliminary Analysis of Seismic Signal

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January 2007

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ABSTRACT

In Olkiluoto, Posiva Oy has operated a local seismic network since February 2002. The purpose of the microearthquake measurements at Olkiluoto is to improve understanding of the structure, behaviour and long term stability of the bedrock. The studies include both tectonic and excavation-induced microearthquakes. An additional task of monitoring is related to safeguarding of the ONKALO.

The possibility to excavate an illegal access to the ONKALO, have been concerned when the safeguards are discussed. Therefore all recorded explosions in the Olkiluoto area and in the ONKALO are located. If a concentration of explosions is observed, the origin of that is found out. Also a concept of hidden illegal explosions, detonated at the same time as the real excavation blasts, has been examined. According to the experience gained in Olkiluoto, it can be concluded that, as long the seismic network is in operation and the results are analysed by a skilled person, it is practically impossible to do illegal excavation by blasts.

In this report a possibility of seismic monitoring of illegal excavation done by tunnel boring machine has been investigated. Characteristics of the seismic signal generated by the raise boring machine are analysed. According to this study, it can be concluded that the generated seismic signal can be detected and the source of the signal can be located. However, this task calls for different kind of monitoring system than that, which is currently used for monitoring microearthquakes and explosions.

Keywords: Seismic monitoring, raise boring, safeguards

Olkiluodon ilmastointikuilun nousuporaus 17. – 23.5.2006
– Seismisen signaalin alustava analyysi

TIIVISTELMÄ

Posiva Oy:n paikallinen seisminen asemaverkko aloitti toimintansa vuoden 2004 helmikuussa. Mikromaanjäristysmittausten avulla pyritään lisäämään tietoa Olkiluodon kallioperän rakenteesta, liikkeistä ja stabiilisuudesta. Tutkimuksen kohteena ovat tektoniset ja louhinnan indusoimat mikromaanjäristykset. Mittaukset ovat myös osa ONKALOn ydinsulkuvalvontaa.

Ydinsulkuvalvontaan liittyen Olkiluodon alueella ja ONKALOssa tehdyt räjäytykset on paikallistettu. Mikäli samaan paikalta on havaittu useampia räjäytyksiä, on niiden alkuperä selvitetty. Myös ajatus, että laiton räjäytys voitaisiin piilottaa laukaisemalla se samanaikaisesti ONKALOn louhintaräjäytyksen kanssa, on tutkittu. Olkiluodon mittauksista saadun kokemuksen perusteella voidaan todeta, että jos seisminen asemaverkko on toiminnassa ja sen havainnot analysoi ammattitaitoinen henkilö, laiton louhinta räjäyttämällä ei ole käytännössä mahdollista.

Tässä raportissa tutkitaan mahdollisuuksia monitoroida seismisesti laitonta louhintaa, joka tehdään tunnelikairauslaitteen avulla. Raportissa analysoidaan nousuporauksen synnyttämän seismisen signaalin ominaisuuksia. Tutkimuksen perusteella voidaan todeta, että seisminen signaali voidaan havaita ja signaalin lähde voidaan paikallistaa. Tämä kuitenkin edellyttää, että käytössä on toisenlainen monitorointijärjestelmä kuin mitä nyt käytetään mikromaanjäristysten ja räjäytysten monitoroinnissa.

Avainsanat: Seisminen monitorointi, nousuporaus, ydinsulkuvalvonta

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ABSTRACT

TIIVISTELMÄ

1. INTRODUCTION

The possibility to excavate a hidden space close to the ONKALO or an illegal access to it, have been concerned when the safeguards are discussed. Normal explosions and excavation blasts in the Olkiluoto area are well detected and located by the Posiva's seismic network. The expected sensitivity of the network is ML = -2.5…-2.0 (ML = magnitude in local Richter scale) near the ONKALO. Also a concept of hidden illegal explosions, detonated at the same time as the real excavation blasts, has been presented. According to the experience gained in Olkiluoto, it can be concluded that, as long the results are analysed by a skilled person, it is practically impossible to do so. In 2005 there are several examples of legal explosions performed close in time and space (Saari 2006a). The origins of such kind of the events are always checked from the daily blast record delivered by the contractor of the ONKALO project.

Lately, a possibility to use tunnel boring machines (TBM) in purpose to build illegal constructions has been presented. On 17.-23.5.2006, a ventilation shaft of the ONKALO was constructed (See Appendix 1) The construction method was raise boring, where the boring was done upwards, from the level -91 m to the earth surface. The diameter of the drilled hole was 3.5 m. That was not recorded by the Posiva's seismic network.

The network is designed for monitoring excavation induced microearthquakes and explosions occurring inside the rock volume surrounding the ONKALO (Saari 2003 and 2005). Later, in February 2006, the network was expanded suitable for monitoring explosions and tectonic microearthquakes in the Olkiluoto region as well (Saari 2006b).

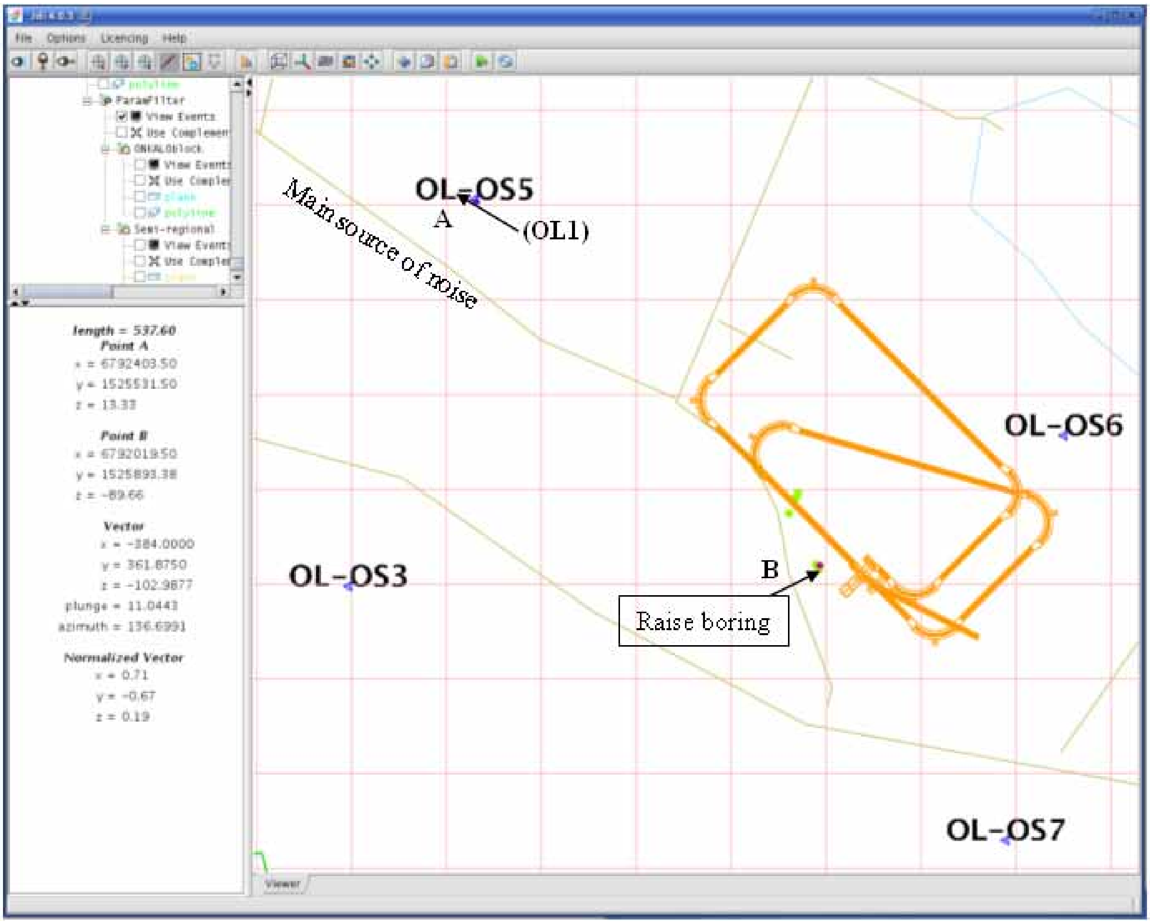
Due to the high sampling rate (6000 Hz) used in microearthquake monitoring automatic detection of the brief seismic signals from the continuous data flow of noise is desirable. The SAQS unit controls the continuous data flow and when a pre-set trigger value is exceeded a potential seismic signal is recorded to its hard disk drive.

The event detector of the SAQS unit compares the short term average (STA) of the amplitudes to the long term average (LTA) of the amplitudes. The event detector starts recording data when the STA/LTA ratio exceeds the pre-set trigger value. The field stations monitor continuously, but only signals, which can be related to a seismic event, are sent to the central site computer. The recordings which are related to the same seismic event are associated automatically. An event is sent, when a predetermined number of seismic stations detect earth vibrations that exceed the trigger value within a certain time window. After the expansion of the seismic network, the number of sensors applied in event association has been four. In addition to that, another number of associations for the group of the 1 Hz seismic stations was set. If three of those five stations can be associated, the recordings are interpreted to be from the same source.

The seismic signal generated by the raise boring machine has quite different to the signals generated by seismic events. The signal can be described as a continuous vibration that seems to start slowly. In traditional seismic monitoring that kind of seismic signal is called as seismic noise. The current seismic network is designed to reject any kind of seismic noise. It can be temporary (generated by traffic, wind, human beings or animals close to sensor, etc) or more or less continuous (generated by turbines, generators, large pumps, electric power lines, TBM, drilling, etc.). Monitoring of continuous seismic noise calls for different kind of monitoring system.

The Institute of Seismology, Helsinki University had three triaxial 1 Hz seismometers in the Olkiluoto area in May 2006. The data of these stations is stored to removable hard disk drives with a sampling rate of 200 Hz. One of stations (OL1) was in Olkiluoto in the same place as OL-OS5 and two of them were outside Olkiluoto, about 5 km from the ONKALO (Figure 1-1). At these two stations there were no signs of raise boring. However, raise boring was clearly observed in station OL1. The following results are based on recordings of that station.

Figure 1-1 was used in order to determine the location of the raise boring relative to the geophone (OL1). They are presented by violet dots (Point A = OL1 and Point B = starting point of the raise boring). Distance between those points is about 540 m. The azimuth of the seismic signal coming from point B should be about 135° (estimated clockwise from the north). The angle of incidence of the signal coming from the starting point of the raise boring should be about 10°. The location and excavation of the crosscut to the ventilation drift is reported in the monthly report (Saari 2006c).



```
length = 537.60
Point A
x = 6792403.50
y = 1525531.50
z = 13.33

Point B
x = 6792019.50
y = 1525893.38
z = -89.66

Vector
x = -384.0000
y = 361.8750
z = -102.9877
plunge = 11.0443
azimuth = 136.6991

Normalized Vector
x = 0.71
y = -0.67
z = 0.19
```

Figure 1-1. *The triaxial geophone (OL1) of the Seismological Institute is located in the Posiva's seismic station OL-OS5. There are also the locations of two simultaneously blasted rounds (10.5.2006 at 06:38 UTC). The southern blasts are at the location where the raise boring started. The crosscut to the other ventilation drift is not presented in the ONKALO model available. The distance between the grid lines is 100 m.*

2. RESULTS

2.1 Data and methods

The time schedule, length of boring and other describtive information was taken from the contractors site records (see Appendix). The seismic measurement are conducted in UTC time and that time is also used in Appendix (UTC time = Finnish time – 3 h, in May). The software package called *geotool* (Coyne and Henson 2006) was used in the analysis of the recordings. The software was available in the Institute of Seismology where they also had tools to convert the recorded data to the format suitable for *geotool*.

All the recordings and spectrograms presented in this chapter are from the time when the boring machine was at the depth of 90 m (18.5.2006). Corresponding figures from lower depths are quite similar. However, when the particle motions from various depths were examined the results are different (see end of this chapter).

Figure 2-1 shows typical recordings of OL1 during one day. Periods of higher constant amplitudes represent raise boring and breaks are seen as intervals of lower amplitude. During raise boring the amplitudes seem to be 2-4 times larger than during breaks.

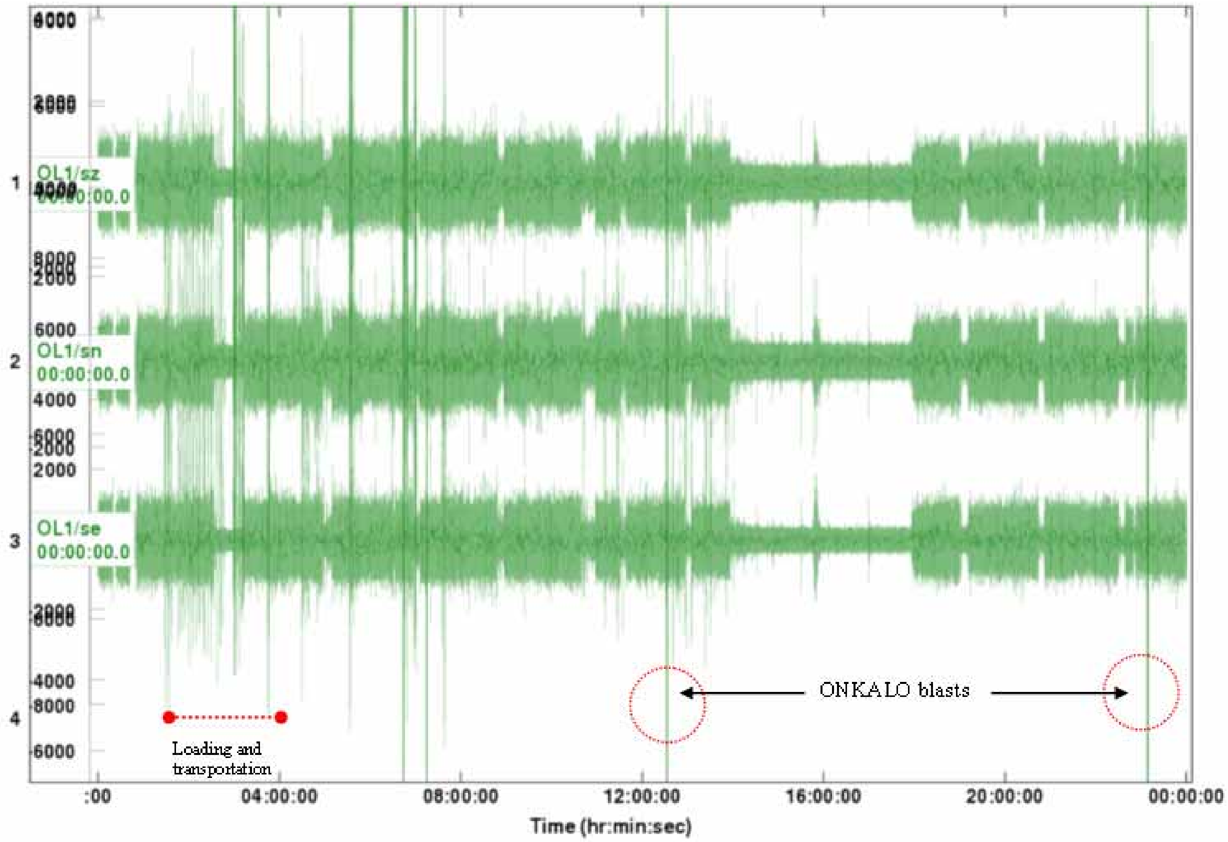


Figure 2-1*. 24 hours of OL1 recordings on 18.5.2006. Vibration caused by raise boring is clearly seen in all three components. Breaks are seen as periods of lower amplitude. High amplitudes mainly caused by traffic. Values on Y-axis are in counts. Station is not calibrated.*

The true amplitude cannot be estimated, because the sensor was not calibrated. However, Posiva's station OL-OS8 has a comparable 1 Hz sensor and it is about as far from raise boring as OL1. A short sample of raise boring was recorded before an ONKALO blast in OL-OS8. The amplitude of raise boring was about $1*10^{-6}$ m/s. Usually, the amplitude level of background noise in OS-OL8 is about $1\text{-}5*10^{-7}$ m/s.

The first hour and last 11 hours in Figure 2-1 represent mainly raise boring with some short breaks. According to the daily reports of the contractor (SK-Kaivin Oy), about 1 o'clock starts about three hours long interval of loading and transportation in the ONKALO. That can be seen clearly as higher amplitudes in Figure 2-1. However, those higher amplitudes are seen until 13 o'clock UTC (16 o'clock local time). Those amplitudes from 1 o'clock to 13 o'clock are mainly caused by heavy trucks driving along the road few tens of meters from OL1 (see Figure 1-1). Only two of the spikes are caused by ONKALO blasts.

2.2 Spectral characteristic of raise boring

Comparison of the spectrograms of prevailing seismic background noise to the seismic signal generated by raise boring brings out the characteristic frequencies of raise boring (Figure 2-2). Raise boring shows up as even red band at frequencies 15 – 25 Hz. At this frequency range the amplitudes of raise boring are much higher than during breaks.

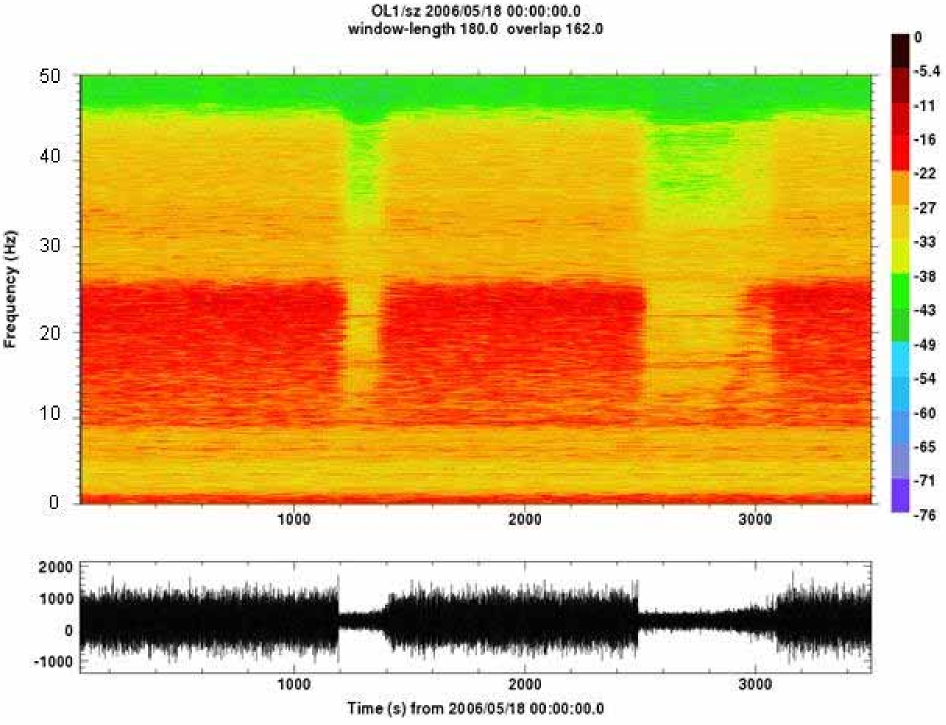


Figure 2-2. *Spectrogram of vertical component. 18.5.2005, 00:00 - 01:00. Seismogram below. Characteristic frequencies of raise boring: 15-25 Hz. First break is not reported by the contractor.*

Spectrogram and seismogram in Figure 2-3 represent an interval of increased noise. Loading and transportation has started about one o'clock. About half on hour after that, higher amplitudes (red colour) can be seen on higher frequencies. These high amplitudes are mainly generated by heavy trucks passing by the seismic station.

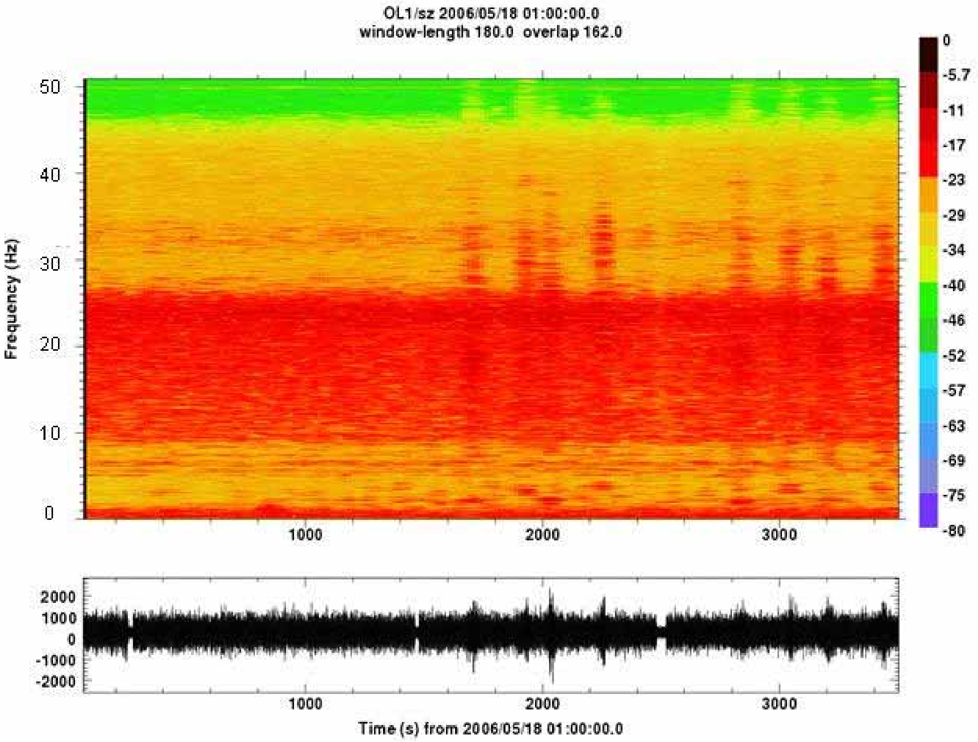


Figure 2-3. *Spectrogram of vertical component. 18.5.2005, 01:00 - 02:00. Seismogram below. Characteristic frequencies of raise boring: 15-25 Hz. Higher frequencies are mainly caused by heavy trucks passing by.*

The next spectrogram and seismogram (Figure 2-4) show the phase when the raise boring is interrupted. That occurs about 2:30, i.e. 2000 seconds after the beginning of the sample. After that some indications of traffic can be seen.

In the last spectrogram and seismogram (Figure 2-5) is a round blasted during raise boring (see also Figure 2-1). The amplitudes of the blasts are much higher than during raise boring. The true frequencies of the blasts are much higher than in Figure 2-5. Frequencies higher than 35 Hz are strongly filtered in OL1.

Figure 2-6 shows typical spectral characteristics of raise boring and natural seismic noise. The higher amplitudes of raise boring in frequency range from 15 Hz to 25 Hz are evident.

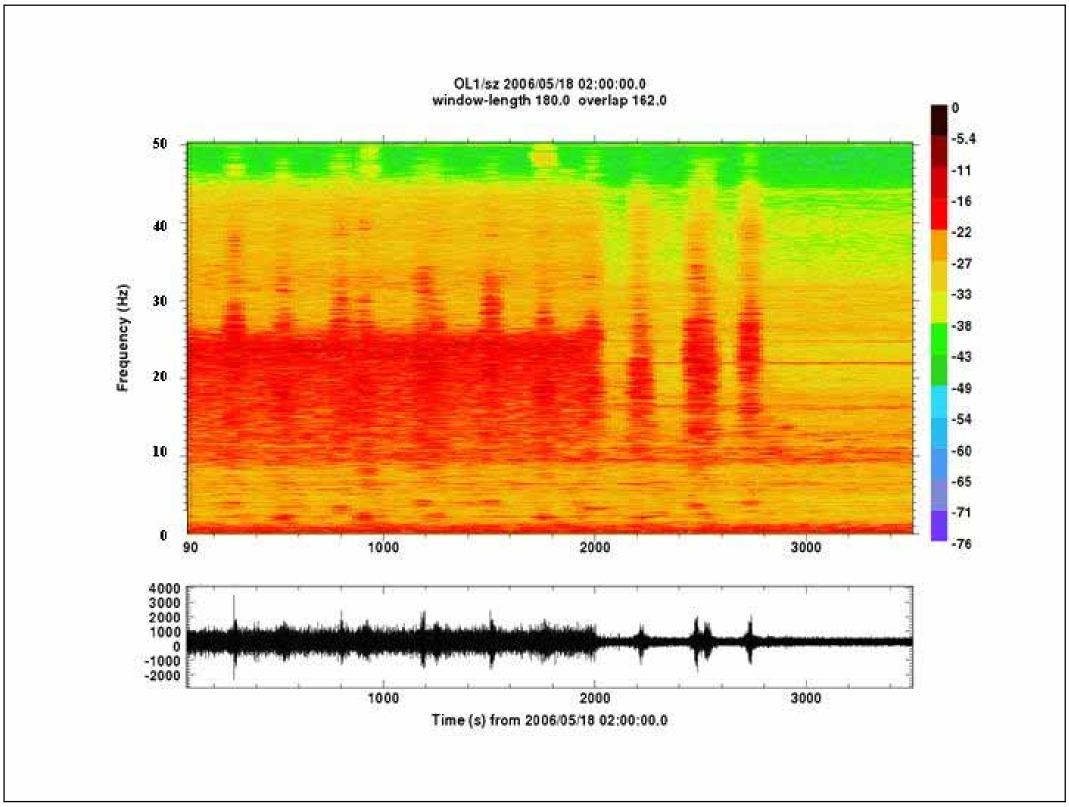


Figure 2-4. *Spectrogram of vertical component. 18.5.2005, 02:00 - 03:00. Seismogram below. Ending phase of raise boring. Higher frequencies are likely caused by traffic passing by.*

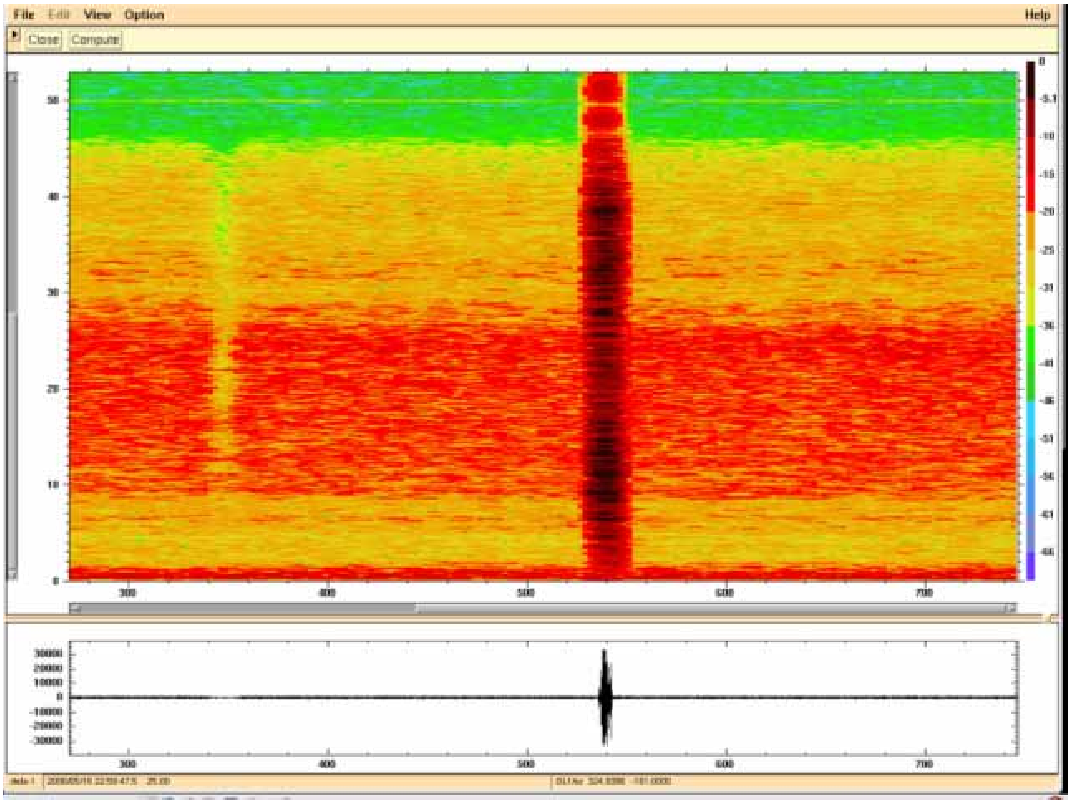


Figure 2-5. *Excavation blast during raise boring (18.5.2006 at 22:59).*

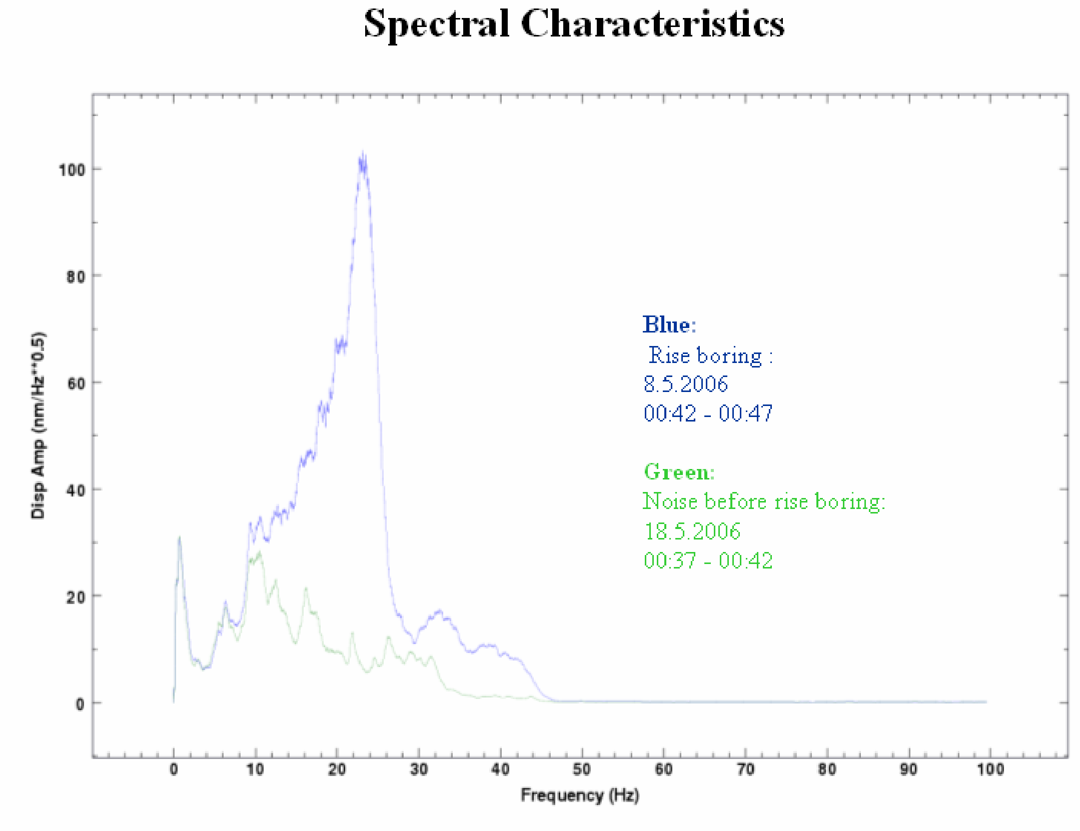


Figure 2-6. *Spectral characteristics of raise boring and noise before that.*

2.3 Particle motion generated by raise boring

The wave motion for actual seismic motions can be presented as particle motion recorded on 3-component seismograms. Particle motion diagrams were examined in order to see the azimuth and the angle of incidence of the seismic motion generated by raise boring machines. The angle of incidence could not be estimated in the diagrams. The true angle (10 degrees or less relative to horizontal) was maybe too small or the particle motion was too complicated. However, the azimuth of the seismic wave was rather clear when the raise boring machine was in greater depths (See Figure 2-7).

Figure 2-7 shows particle motion diagrams generated by the raise boring machine at the depth of 90 m, 45 m and 10 m. The true azimuth is about 135^{o}. At depth of 90 m the NW-SE orientation in the particle motion diagram is clear. Also at depth of 45 m the true orientation can be seen, but close to the surface the bedrock is so fractured and the seismic signal so complex that the azimuth cannot be estimated.

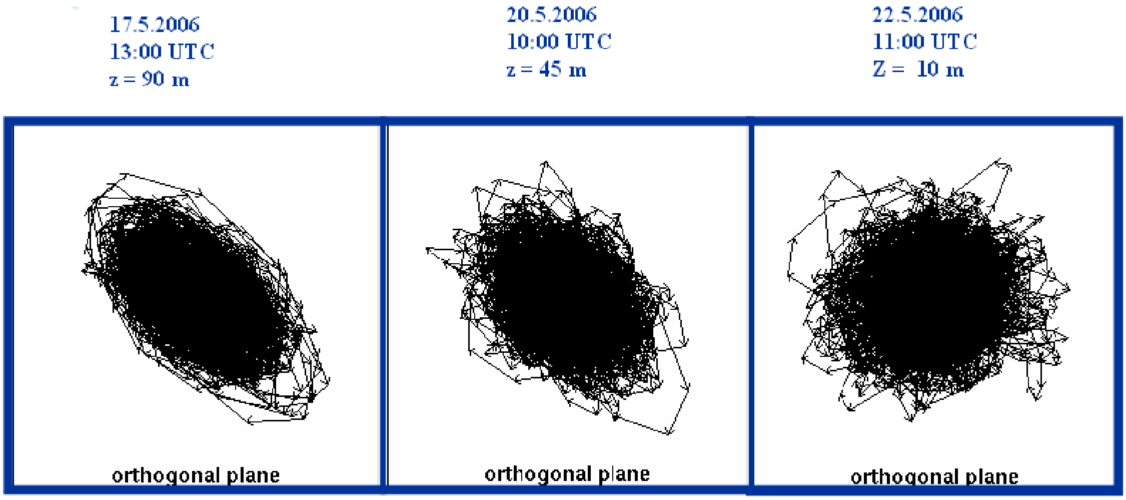


Figure 2-7. *Particle motion diagrams for selected depths of raise boring. True azimuth is 135°. Each sample is based on 30 seconds of triaxial recordings. North is upwards and East to the right.*

3. DISCUSSION OF THE RESULTS

3.1 Quality of the results

Three continuously recording triaxial seismic stations were operating in the Olkiluoto area. Seismograms of those stations were analysed in order to get preliminary information about the characteristics of generated signal. The measurements were not designed for monitoring seismic signal generated by raise boring machine. The location of the stations, as well as their frequency range was designed for monitoring local seismic events. In addition, the stations were not calibrated, i.e. the true amplitude of seismic signal is not accurately known. However, many important characteristics of the seismic signal generated by the raise boring machine were defined.

The results of this study are preliminary. However, on the basis of the data available it can be concluded that seismic signal generated by tunnel boring machines can be detected and located.

The seismic signal generated by raise boring machine was clearly distinguishable at the distance of about 500 m, but not at the distance of 5 km. The signal represents continuous seismic vibration where amplitudes between frequencies 15 - 25 Hz were most characteristic. It should be remembered that frequencies larger than 35 Hz were filtered away from the recordings of OL1. However, according to Posiva's network, raise boring is not clearly visible in those frequencies.

The frequencies below 1 Hz are not recorded in the Olkiluoto area. Seismometers measuring those frequencies are mainly used for monitoring teleseismic events (distance to sensor from few hundreds to few thousands of kilometres). The rotation speed of the bore was generally 6 round/minute (1 round/10 sec = 0.1 Hz). It is possible that seismic signal is generated also in frequencies around 0.1 Hz. If it is so and the signal is strong enough, there could be more option to design the monitoring. Lower frequencies of seismic signal tend to attenuate slower than higher frequencies, thus they might be recorded from larger distances than the generated 15 – 25 Hz signal.

Particle motion diagrams can be utilised when the location of the boring machine is approximated. The diagrams show the azimuth of the seismic signal and the opposite direction. The geographical coordinates of the boring machine can be defined when at least two seismic station record the same source. The source is at the intersection point of the lines drawn from seismic station when these lines are parallel to the orientation of particle motion. Of course, when two stations and the boring machine are on the same line or close, the intersection point cannot be defined. The geometry of a monitoring network consisting of at least three seismometers can be designed so the intersection point can always be determined.

The azimuth of the seismic signal is more accurate at greater depths than at the surface. Close to the surface the azimuth was not definable. Location of the boring does not include depth of seismic source, at least, when the depth is less than 90 m. Below that depth the signal might be less complex and the angle of incidence could be easier to estimate.

Comparison of day time and nigh time seismograms shows some discrepancies. Intervals of increased noise, typical in day time, are seen as increased amplitudes in higher frequencies (above 25 Hz). However, continuous noise generated by raise boring was clearly seen regardless the time of day. In seismograms the amplitudes were higher than in general and in spectrograms increased amplitude in frequency range remained clear.

3.2 Recommendations

When the seismic stations are favourable located relative to the boring machine, two triaxial seismometers are enough to locate the boring machine. However, in certain directions location is uncertain or impossible to determine by means of two seismic stations. A seismic network of three or more seismometers would offer more certain location accuracy in all directions and they would give a better coverage in the ONKALO area. In addition, an operation failure of one station would not interrupt the continuous monitoring. The network geometry should be designed so that all stations and the seismic source are never on the line.

When the next raise boring is conducted it might be reasonable to design a monitoring test. Three objectives could be set for the test:

(1) In what distances from the raise boring the generated seismic signal can be detected?

(2) In what distances the orientation of the particle motion is well determined?

(3) Is there is seismic tremor generated by raise boring machine in frequencies below 1 Hz and what are the spectral characteristics in that frequency range?

The characteristics of the raise boring signal should be known more in details, before the technical design of possible final monitoring system is reasonable. For example, should it be based on triaxial 1 Hz seismometers (suitable for boring frequencies found in this study), on triaxial broadband seismometers (frequency range 0.01 Hz – 30 Hz, for example) or on some kind of combination of those?

Another crucial question is how the analysis of the signal should be done? Analysis of one day done as described above took approximately one working day. That procedure was suitable for research purposes. The final data processing technique should be economically and technically more efficient. For example by lowering the sampling frequency of seismograms the amount of data could be smaller. That data could be possibly moved automatically (via telephone lines, radio links or internet) from seismic stations to PC where the analysis is done.

The processing steps from recordings to spectrograms should be more or less automatic. When the characteristic frequencies are discovered, particle motion of each recording should be analysed in order to find the source of those frequencies.

When the main seismological facts of the raise boring signal and the demands of the safeguards of nuclear materials are known, scientific institutes and commercial manufacturers can be contacted. One of them might offer a solution, which is cost-effective (including daily operation practice) and of good quality.

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APPENDIX 1

Raise boring history of the ventilation shaft of the ONKALO. Modified after raise boring record of Skanska Oy.

No	Date Start	UTC Start	UTC Stop	Minutes	R.O.P	Rpm	Rock Quality	Bored (m)
1	17.5.2006	4:20	9:30	410	0,1	1-2		0,72
2	17.5.2006	9:40	13:05	205	0,44	2-6	B1	2,24
3	17.5.2006	13:10	22:55	130	0,7	6	B2-B1	3,76
4	17.5.2006	23:00	0:40	100	0,91	6	B2-B1	5,28
5	18.5.2006	0:45	2:35	110	0,83	6	B2-B1	6,8
6	18.5.2006	3:15	5:00	105	0,86	6	B1 B2	8,32
7	18.5.2006	5:05	7:00	115	0,79	6	B1-B2	9,84
8	18.5.2006	7:05	8:50	105	0,86	6	B1 B2	11,36
9	18.5.2006	8:55	10:40	105	0,86	6	B1 B2	12,88
10	18.5.2006	11:00	13:00	110	0,82	6	B2 B3	14,4
11	18.5.2006	13:05	19:00	115	0,79	6	B1 B2	15,92
12	18.5.2006	19:05	20:40	95	0,96	6	B1-B2	17,44
13	18.5.2006	20:45	22:30	105	0,87	6	B1-B2	18,96
14	18.5.2006	22:35	0:15	100	0,91	6	B1-B2	20,48
15	19.5.2006	0:20	2:20	120	0,76	6	B1-B2	22
16	19.5.2006	2:25	4:35	115	0,79	6	B1-B2	23,52
17	19.5.2006	4:40	6:40	120	0,75	6	B1 B2	25,04
18	19.5.2006	6:45	8:45	120	0,75	6	B1 B2	26,56
19	19.5.2006	8:50	10:45	115	0,79	6	B1 B2	28,08
20	19.5.2006	10:50	12:55	125	0,73	6	B1 B2	29,6
21	19.5.2006	13:00	14:55	115	0,79	6	B1 B2	31,12
22	19.5.2006	15:15	17:05	110	0,83	6	B1 B2	32,64
23	19.5.2006	17:10	19:15	110	0,83	6	B1	34,16
24	19.5.2006	19:20	21:00	100	0,91	6	B1-B2	35,68
25	19.5.2006	21:05	22:30	85	1,07	6	B1-B2	37,2
26	19.5.2006	22:35	0:20	105	0,87	6	B1-B2	38,72
27	20.5.2006	0:25	2:10	105	0,87	6	B1-B2	40,24
28	20.5.2006	2:15	4:20	115	0,79	6	B1 B2	41,76
29	20.5.2006	4:25	6:10	110	0,83	6	B1 B2	43,28
30	20.5.2006	10:10	11:55	105	0,86	6	B1 B2	44,8
31	20.5.2006	12:00	13:40	100	0,91	6	B1 B2	46,32
32	20.5.2006	13:45	15:45	100	0,91	6	B1-B2	47,84
33	20.5.2006	15:50	17:25	95	0,83	6	B1-B2	49,16
34	20.5.2006	17:30	19:15	105	0,87	6	B1-B2	50,68
35	20.5.2006	19:20	21:05	105	0,87	6	B1-B2	52,2
36	20.5.2006	21:10	23:10	120	0,76	6	B2	53,72
37	20.5.2006	23:15	1:15	120	0,76	6	B2	55,24
38	21.5.2006	1:20	3:15	105	0,86	6	B2	56,76
39	21.5.2006	3:20	5:25	125	0,73	6	B2	58,28

40	21.5.2006	5:30	8:00	150	0,6	3-5	B2	59,8
41	21.5.2006	8:05	10:35	150	0,6	5-6	B2	61,32
42	21.5.2006	10:40	12:40	120	0,76	6	B2	62,84
43	21.5.2006	12:45	14:15	90	1,01	6	B2-B1	64,36
44	21.5.2006	14:20	15:55	80	1,14	6	B1-B2	65,88
45	21.5.2006	16:00	17:20	80	1,14	5-6	B2-B1	67,4
46	21.5.2006	17:35	19:55	140	0,65	4-5	B2, B3	68,92
47	21.5.2006	20:00	22:05	125	0,73	6	B1-B2	70,44
48	21.5.2006	22:10	23:45	95	0,96	6	B1-B2	71,96
49	21.5.2006	23:55	1:25	90	1,01	6	B2-B3	73,48
50	22.5.2006	1:30	2:45	75	1,22	6	C1-C2	75
51	22.5.2006	3:15	4:45	90	1,01	6	B1 B2	76,52
52	22.5.2006	4:55	6:25	90	1,01	6	B1 B2	78,04
53	22.5.2006	6:30	9:55	90	1,01	6	B1 B2	79,56
54	22.5.2006	10:00	11:30	90	1,01	5-6	B2 B3	81,08
55	22.5.2006	11:35	13:10	95	0,96	6	B1 B2	82,6
56	22.5.2006	13:15	14:45	90	1,01	6	B1 B2	84,12
57	22.5.2006	15:10	16:30	80	1,14	6	B1-B2	85,64
58	22.5.2006	16:35	18:10	95	0,96	6	B1-B2	87,16
59	22.5.2006	18:15	19:20	65	1,4	6	C1 C2	88,68
60	22.5.2006	19:25	20:40	75	1,22	6	C1 C2	90,2
61	23.5.2006	3:05	4:15	70	1,3	6-2	C1	91,72

*R.O.P = (Rod length (m)*60)/Drilling time (min)*
Rpm = Revolutions per minute
Rock Quality: A = Hard, B = medium and C = soft