JNC TY5410 2005-001

COMPUTATION OF AMPLIFICATION FUNCTIONS IN THE WAKKANAI FORMATION, HORONOBE AREA

(Document on Collaborative Study)

April,2005

National Cooperative for the Disposal of Radioactive Waste
Japan Nuclear Cycle Development Institute

〒319-1184 茨城県那珂郡東海村村松４番地49
核燃料サイクル開発機構
技術展開部 技術協力課
電話：029-282-1122 （代表）
ファックス：029-282-7980
電子メール：jserv@jnc.go.jp

Technical Cooperation Section,
Technology Management Division,
Japan Nuclear Cycle Development Institute
4-49 Muramatsu, Tokai-mura, Naka-gun, Ibaraki 319-1184, Japan

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Philip Birkhäuser[1], Corinne Lacave[2], Hidefumi OHARA[3], Tadafumi NIIZATO[3]

Abstract

The JNC borehole B-2 in the region of Horonobe in northern Japan is equipped with two accelerometers, one at the surface and one at the bottom of the borehole, at a depth of some 138 metres. The borehole is located in a rock formation, which shows alternation of beds of sandstone and siltstone over a thick formation of hard shale.

The goal of this study was to determine the frequency dependent amplification function by calculation of the ratio between the surface response spectrum and the response spectrum at depth. A 1D model (CyberQuake) was used for the computations, because it could be concluded from the local geology that there are no significant 2D effects to be expected. A check has been performed with the program SHAKE2000 showing nearly perfect resemblance.

Acceleration time histories from a weak motion local earthquake at a depth of 13 and 16 km recorded on July 20th (M 0.7) and August 18th (M 0.8) 2003 and from the Tokachi off-shore earthquake to the south of Hokkaido located some 430 to 450 km away from the borehole, recorded on September 26th (M 8.0) plus an aftershock recorded on September 27th 2003 were available as input data. All events are characterised by rather small acceleration values.

The amplifications seem to be magnitude dependent. With the data at hand, the observed amplification functions are however rather unstable, showing different shapes for the different earthquakes and for two components of a single event. The observed ground motion amplification was much higher than the one calculated. Possible explanations for the observed discrepancy are

1) an incorrectness in the derivation of the input S-wave velocity profile used for the calculations of this study, or

2) problems with the recording instruments (e.g. differences in coupling of the tools to the ground)

It is therefore recommended to check the basis of the derivation of the S-wave velocity input data and, if possible, perform direct S-wave downhole logging or S-wave crosshole measurements. It is further recommended to plan for an installation of high quality accelerometers in the future JNC Horonobe URL shaft.

Additional measurements of field data would allow to record a more reliable dataset for proving and characterising significant attenuation of earthquake accelerations with depth, which also will be an important argument for feasibility studies related to the site investigations for geological disposal elsewhere in Japan or worldwide.

This work was performed by NAGRA under contract with Japan Nuclear Cycle Development Institute.

1 National Cooperative for the Disposal of Radioactive Waste (Nagra)
2 Résonance Ingénieurs-Conseils SA
3 Japan NuclearCycle Development Institute, Horonobe Underground Research Center

JNC TY5410 2005-001
April, 2005

幌延地域に分布する稚内層における地震動の増幅関数の解析

（共同研究報告）

Philip Birkhäuser[1]，Corinne Lacave[2]，大原英史[3]，新里忠史[3]

要　旨

本研究の目的は，サイクル機構が幌延町内で掘削した試錐孔 B-2 に設置してある 2 つの地震計(地表と試錐孔底：深さ 138m)の地震観測記録について，地表と孔底とで観測された地震波形の応答スペクトルの比を解析することにより，地震波形の周期に依存する増幅特性を求めることである。二次元効果の影響がないと推定されたので，一次元モデル(Cyber Quake)を用いて解析を行った。本モデルによる計算結果の妥当性の評価は，類似のプログラムである SHAKE2000 にて行い，両者の結果がほぼ一致することを確認した。

解析に使用した入力加速度波形は，2 つの近地地震(2003/7/20,(M:0.7),8/18,(M:0.8))，および地震計から 430～450km 離れた遠地地震の十勝沖地震(9/26, (M:8.0))とその余震(9/27, (M:6.2))である。これらのイベント波形は，小さな加速度によって特徴づけられる。

これら増幅特性はマグニチュードに依存していた。観測された増幅特性関数は非常に変わりやすく，異なる地震を比較した場合，また単発地震の異なる 2 成分を比較した場合には，異なる関数形を示す。観測された地震動は，解析により求めた地震動に比べて，はるかに大きくなる傾向がある。解析結果と観測記録とが異なる原因として，1)解析に用いた S 波速度構造が誤っている，2)地震計自体の不良，が考えられる。

上記問題点を解決するために以下を提案する。

- 入力した S 波速度構造データを確認すること。また，可能ならば，B-2 試錐孔にて直接 S 波速度の測定を実施し，速度構造を求めること。
- サイクル機構が幌延町内に建設する地下研究施設の立坑において，高品質の地震計設置を計画すること。原位置での観測により、地震加速度の減衰特性を把握するために必要な，より信頼できるデータセットが得られると考えられる。

また，それらデータセットは，日本もしくは世界におけるサイト特性調査に関連したフィージビリティ・スタディにおいて，重要な論拠になると考えられる。

本報告書は、NAGRA が核燃料サイクル開発機構との契約により実施した共同研究業務成果に関するものである。

1　National Cooperative for the Disposal of Radioactive Waste (Nagra)
2　Résonance Ingénieurs-Conseils SA
3　核燃料サイクル開発機構　幌延深地層研究センター　深地層研究グループ

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1. INTRODUCTION AND OBJECTIVE

The JNC borehole B-2 can be found in the region of Horonobe in northern Japan and it is equipped with two accelerometers, one at the surface (50m away from the HDB-2 borehole, Kamihoronobe) and one at the bottom of the borehole, at a depth of 137.88 m (Figure 1).

A previous study (Nagra & Résonance, 2003) was conducted in order to determine the amplification functions between the surface and at depth in the borehole (ratio between surface response spectrum and at depth response spectrum) and to make a comparison between :

- the observed amplification function (amplification function obtained by making the ratio between observed response spectrum at the surface and observed response spectrum at the bottom of the borehole),
- and the calculated amplification function, using a 1-D program. The motion recorded at the surface was used as input motion for a de-convolution module available in the program. In this way, considering the motion recorded at the surface, and the given soil layer structure, the program calculates the motion that should have been recorded at a given depth.

In this early study, the Nakatombetsu M 2.8 earthquake was used, recorded by both accelerometers. The results based on this single earthquake showed that the observed ground motion amplification was much higher than the one calculated.

As it was difficult to explain these results, more detailed information about the geological structure of the site, as well as other earthquake recordings from the same accelerometers were thought to allow a better understanding of the observed depth to surface amplification. The present report shows complementary results obtained from these additional data.

2. INPUT DATA

2.1 VELOCITY PROFILE

In the previous study of 2003, the question was raised whether the site might be characterised by a strong 2-D effect. This would be the case if the site were located in a deep narrow valley, filled with quaternary deposits. A study of the available geological cross sections in this area (Figure 2) led to the conclusion that this site was not significantly affected by 2D effects. The borehole is located in a rock formation, which shows alternation of beds of sandstone and siltstone over a thick formation of hard shale. Thus, in the present study, a 1D model was used for the computations.

A compilation was made from all available geological and geotechnical information, particularly the data collected for the HDB-2 borehole (Figure 3). Based on this input-data, a velocity profile for the 1D calculations has been defined up to a depth of 800 m. The velocity profile used is given in Table 1 and Figure 4. The densities used are those given in the data from the HDB-2 borehole.

A constant G/Gmax = 1 and a constant damping value of 1 % were assumed for all layers. The recorded accelerations are very low, which makes a linear approximation well adapted for these computations.

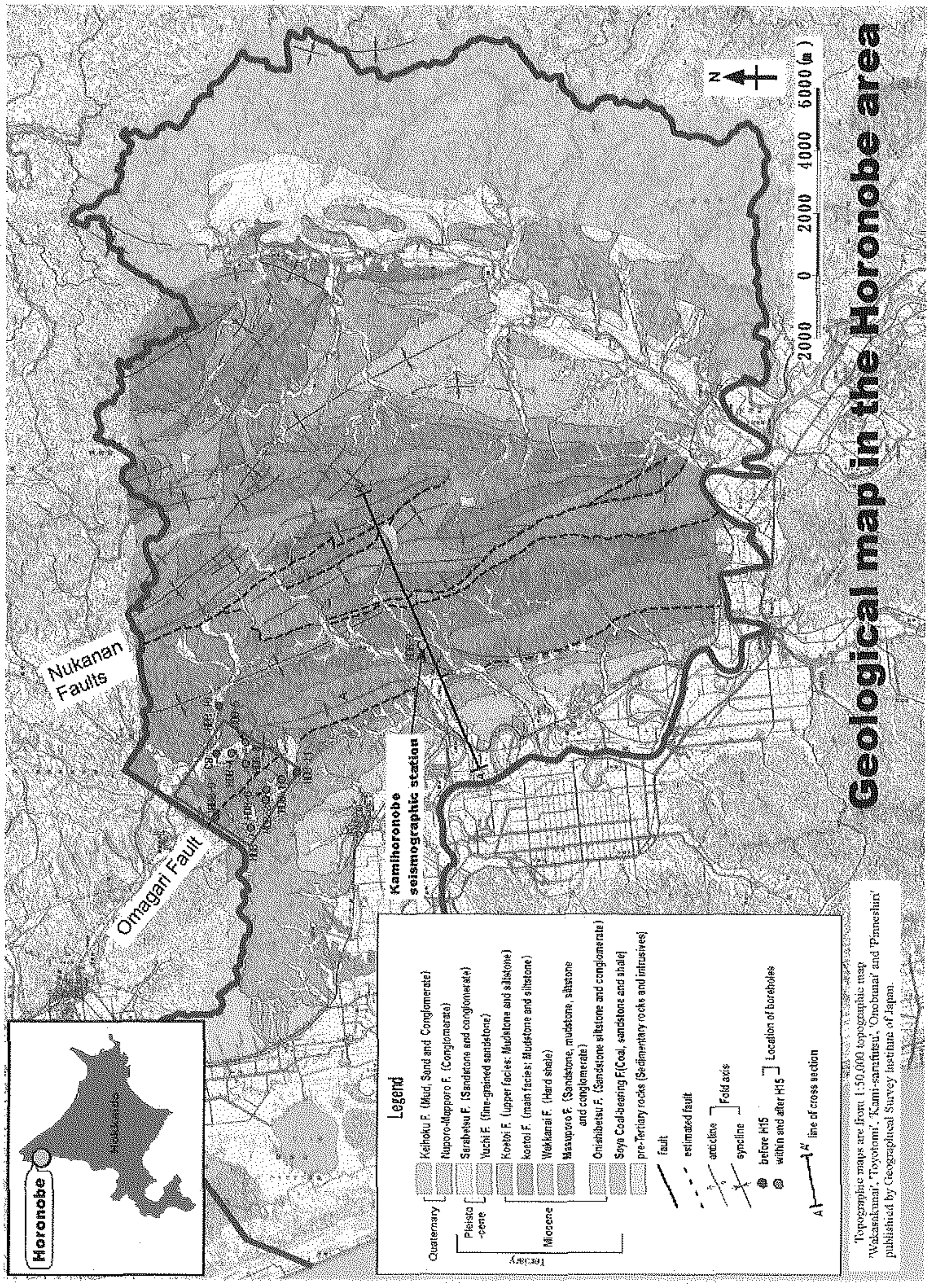

Figure 1: Geological map of the Horonobe area.

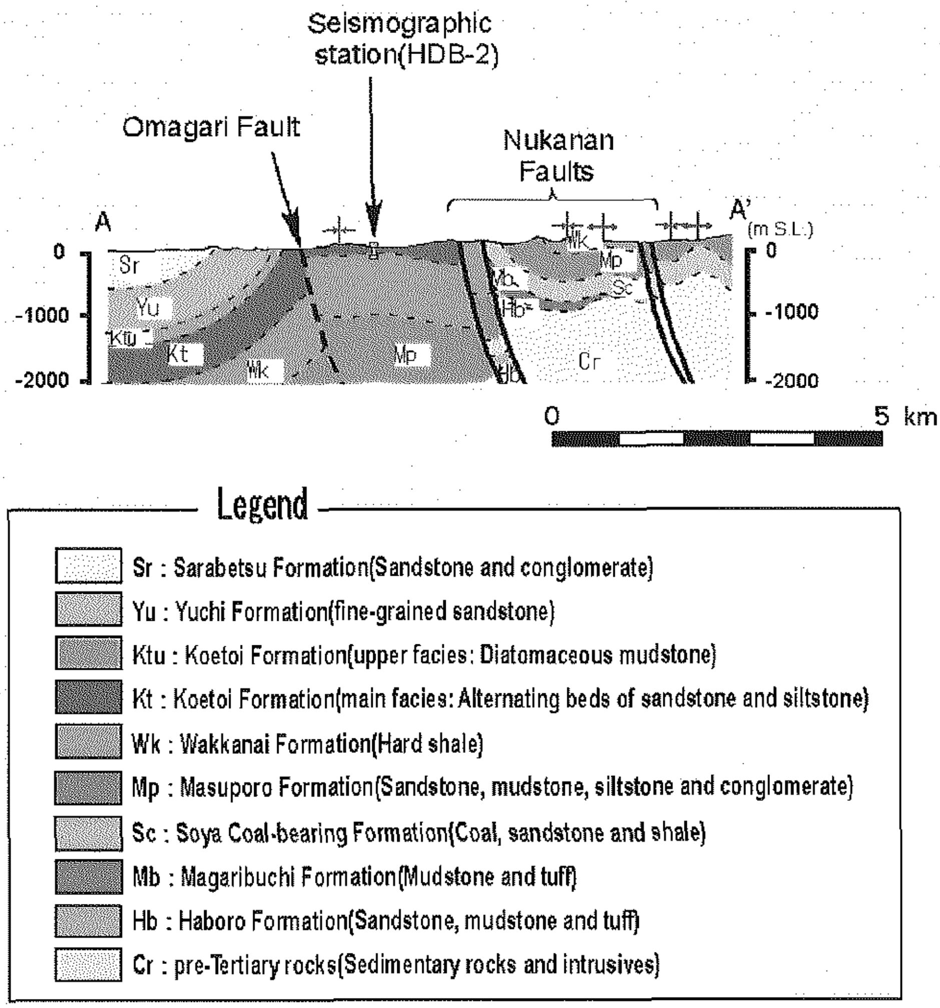

Figure 2: Geological cross-section A-A' (see Figure 1).

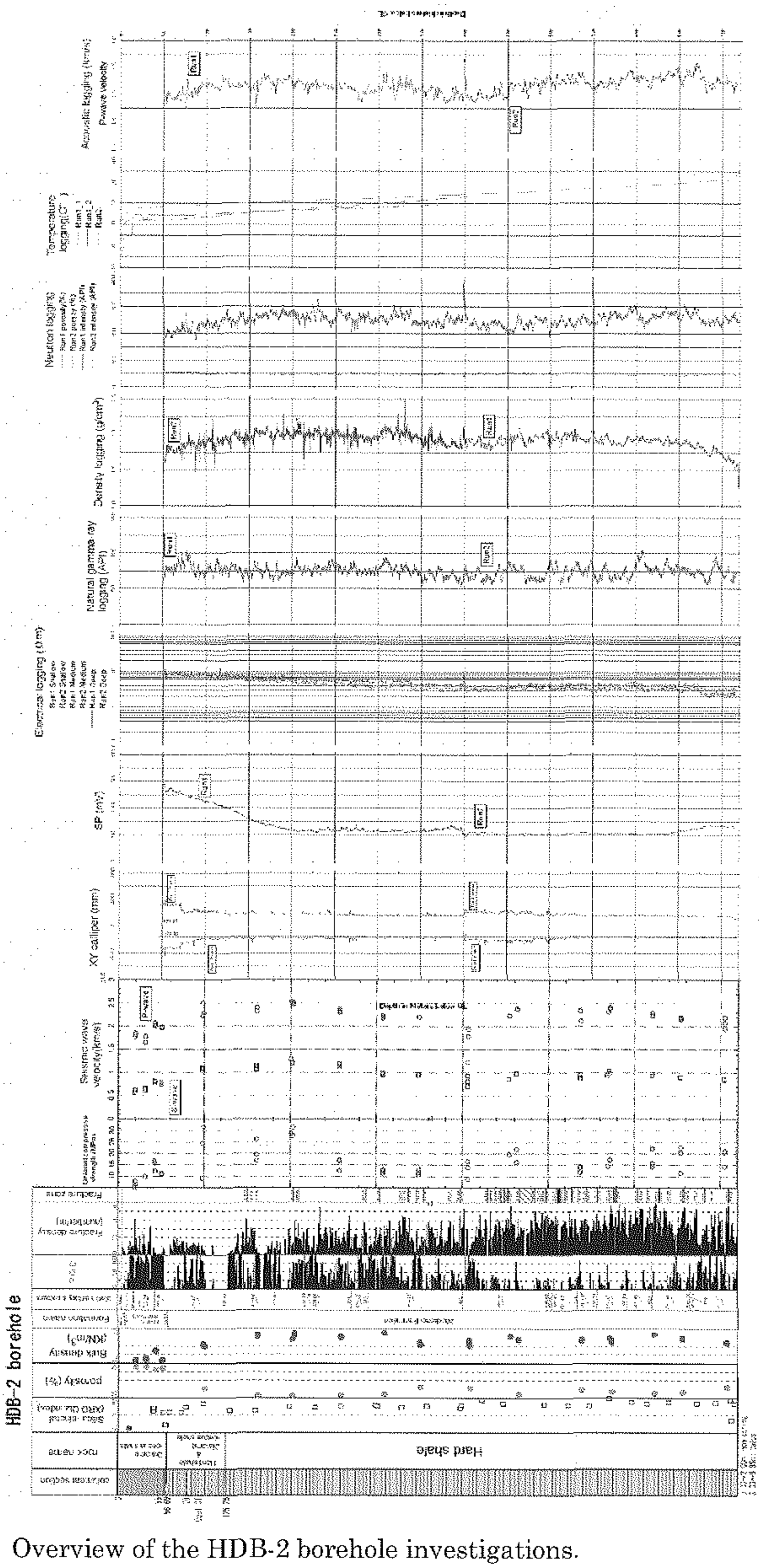

Figure 3: Overview of the HDB-2 borehole investigations.

Table 1: Profile used for the 1-D simulations.

Layer	Depth of top of layer (m)	Thickness (m)	S-wave velocity (m/s)	Density (kg/m3)	Material
Layer 1	0	11	320	1700	Inelastic
Layer 2	11	24	590	1700	Inelastic
Layer 3	35	18	770	1700	Inelastic
Layer 4	53	48	850	1700	Inelastic
Layer 5	101	29	960	1750	Inelastic
Layer 6	130	14	960	1750	Inelastic
Layer 7	144	16	1100	1875	Inelastic
Layer 8	160	40	1200	1900	Inelastic
Layer 9	200	140	1100	1875	Inelastic
Layer 10	340	220	1000	1900	Inelastic
Layer 11	560	120	1100	1900	Inelastic
Layer 12	680	120	1050	1900	Inelastic
"Bedrock"	800	infinite	1050	1900	Elastic

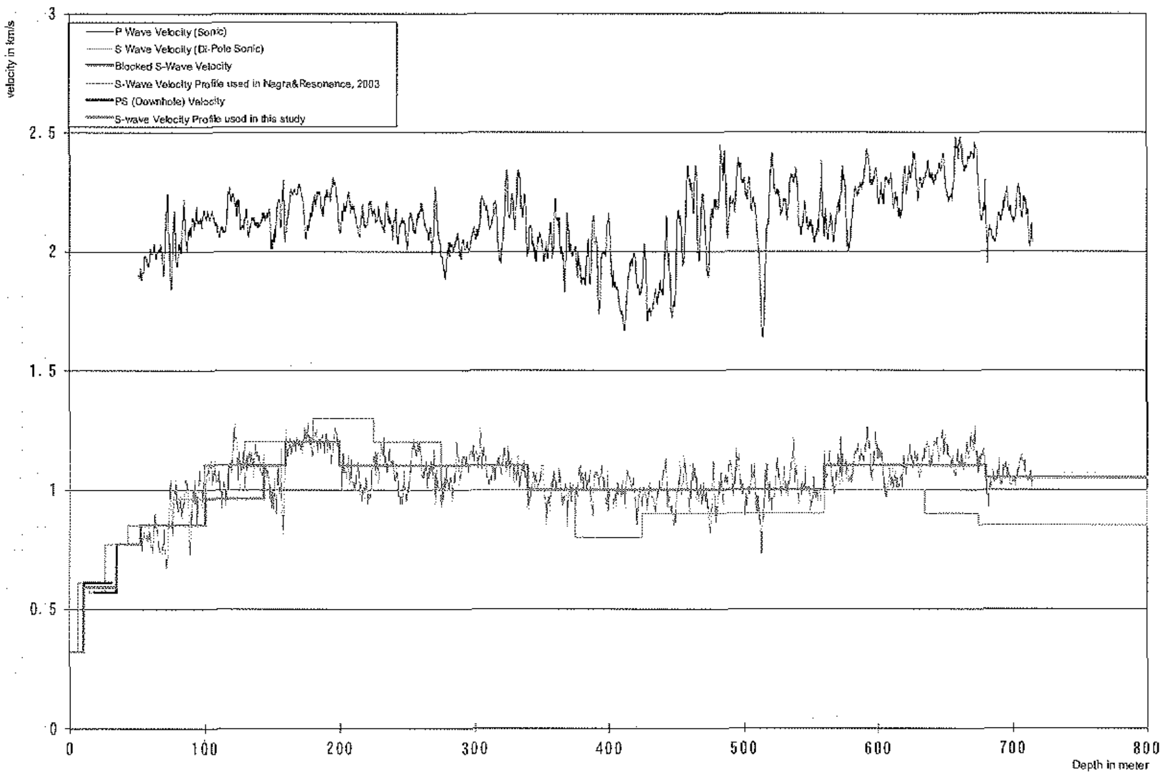

Figure 4: New S-wave velocity profile (orange line) used for the 1-D simulations. The velocity profile (pink-coloured line) was obtained by the B-2 borehole logging.

2.2 EARTHQUAKE RECORDINGS

For the computations presented in this report, acceleration time histories of 4 earthquakes were available (see Figure 5 for the location of the earthquakes). Two from these earthquakes (acc1 and acc2) were very small local events, located just under the borehole, at a depth of 13 and 16 km. The two other earthquakes (acc3 and acc4) were distant strong events off-shore to the south of Hokkaido, located some 430 to 450 km from the borehole. Table 2 gives the characteristics of the 4 events used for the computations and the corresponding temporal records are shown in appendix A. All events are characterised by rather small acceleration values. In particular, events named acc1, acc2 and acc4 have maximum acceleration values lower that 5 mm/s². The event named acc3 has maximum acceleration values lower than 100 mm/s². Only the two horizontal components were used for the simulations.

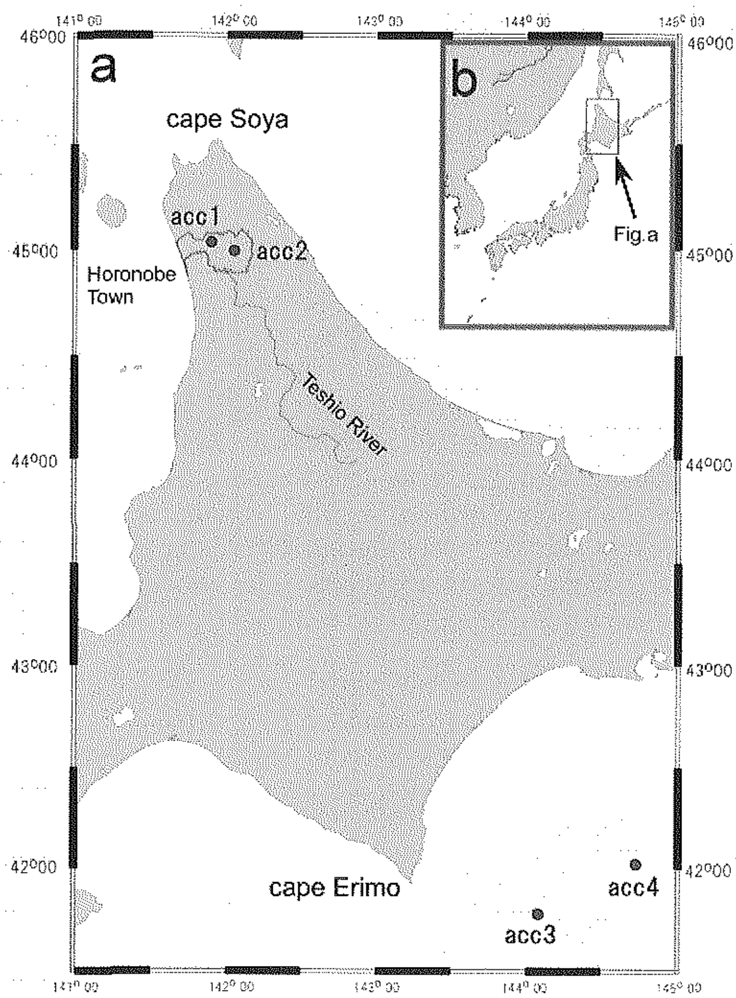

Figure 5: Location of earthquakes used for the 1D-simulations, which are plotted by using of GMT (Wessel & Smith, 1991).

Table 2: Characteristics of the earthquakes used for the 1-D simulations, after web page of High Sensitivity Seismograph Network Japan, National Research Institute for Earth Science and Disaster Prevention.

Earthquake ID	Type	Origin time	Latitude	Longitude	Depth (km)	Magnitude
acc1	Local earthquake	July 20th,2003, 05:59:45	45.0360N	141.8970E	13.1	0.7
acc2		Aug. 18t, 2003, 06:03:37	44.9950N	142.0510E	16.2	0.8
acc3 Main shock 2003 Tokachi off-shore earthquake	Distant earthquake	Sep. 26th, 2003, 04:50:07	41.7760N	144.0820E	45	8.0
acc4 After shock 2003 Tokachi off-shore earthquake		Sep. 27th, 2003, 05:38:22	42.0230N	144.7320E	34.4	6.2

3. COMPUTATIONS OF AMPLIFICATION FUNCTIONS

Computations were performed using a 1D program identical to SHAKE, named CyberQuake (BRGM, 1998). The 1D calculations were carried out for each of the two horizontal components of the 4 recorded earthquakes. The motion recorded at the surface was used as input motion for a de-convolution module available in the program. In this way, considering the motion recorded at the surface, and the given soil layer structure, the program calculates the motion that should have been recorded at a given depth.

Then, the amplification function (ratio between surface response spectrum and at depth response spectrum) was computed (note that this is different from the ratio between the surface response spectrum and a surface reference rock response spectrum).

Figures 6 and 7 present a comparison between the observed and calculated amplification functions for each of the two local events (acc1 and acc2 respectively). Figure 8 shows the same comparison for the earthquake used in the previous study (Nagra & Résonance, 2003). Finally, Figures 9 and 10 show the comparison between the observed and calculated amplification functions for each of the two distant events (acc3 and acc4 respectively).

Figure 11 shows the average observed and calculated amplification functions for local and distant events. This comparison, as well as the individual curves plotted in Figures 6 to 10, lead to the following observations:

- there is an extreme variability between amplification functions obtained for the different events, and also between the two components of a single event, particularly for local events ;
- the three local events lead to a higher amplification than the two distant events,
- one of the two distant events is characterised by nearly no amplification (acc3),
- calculations strongly underestimate the real amplification in the case of local events,
- calculations are in better agreement with observations in the case of the two distant events.

These observations, drawn on only two distant events and three local ones, are neither sufficient to derive any statistics, nor to draw solid conclusions. General remarks based on experience from other sites or other site effect studies are:

- There is no reason why local events should lead to a higher amplification. A higher amplification could be observed for lower acceleration levels, compared to strong motions for which some non-linear effects could lead to lower amplification. But in the present case, all events are weak motion data.
- In the case of a 1D structure, the amplification observed on N-S and E-W components should be similar.
- In the case of two earthquakes with very close epicentres, and similar azimuth (the two local events, or the two distant events), amplification functions should look very similar, and the amplified frequency range should also be very similar, which is not the case with the present dataset.

A check has been performed with another 1D program, in order to be sure that the results obtained were not due to any error in the program, or misuse of the program. This check has been performed on the NS component of the recording of event acc1. The motion at the bottom of the borehole has been calculated using the recorded motion at the surface, with the program SHAKE2000. The resemblance of the response spectra obtained with CyberQuake and SHAKE2000 programs is nearly perfect. This shows that the computations were performed correctly, although the results are very difficult to understand and interpret.

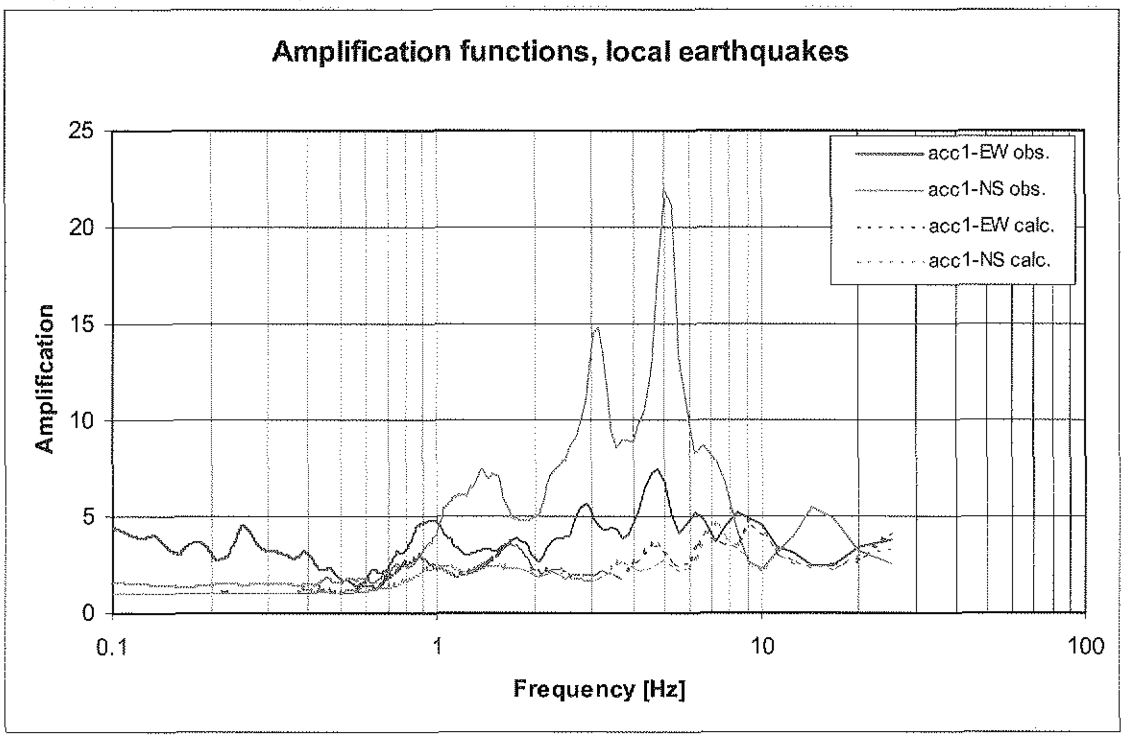

Figure 6: Comparison between the observed (obs.) and calculated (calc.) amplification functions for local event acc1.

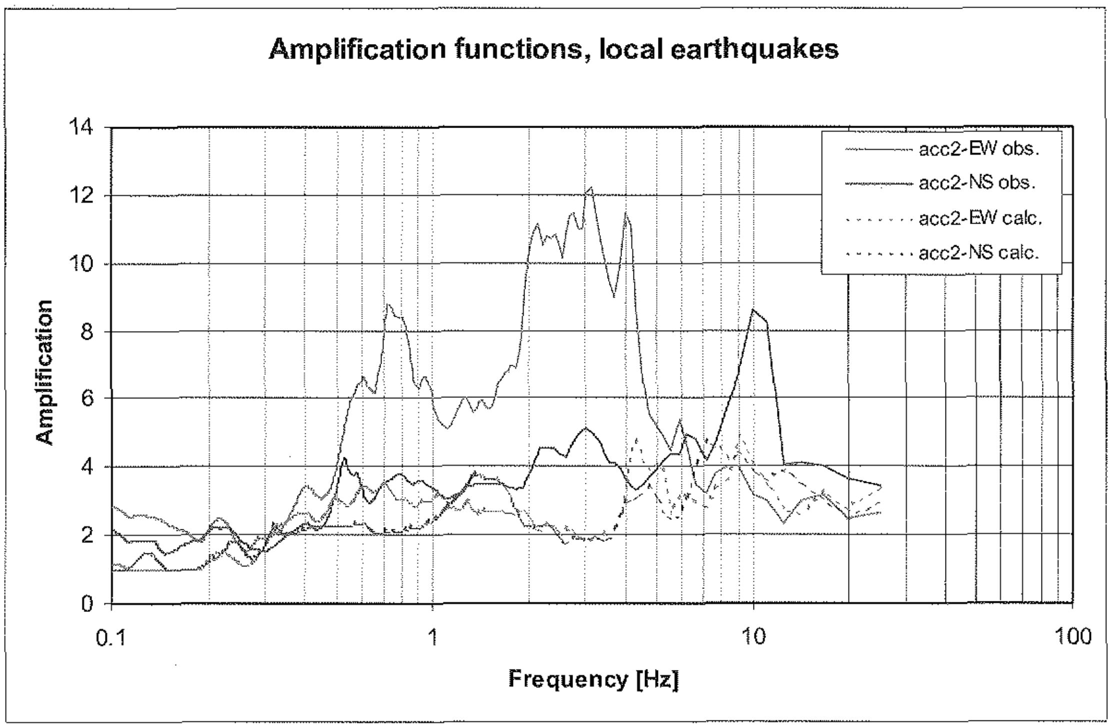

Figure 7: Comparison between the observed (obs.) and calculated (calc.) amplification functions for local event acc2.

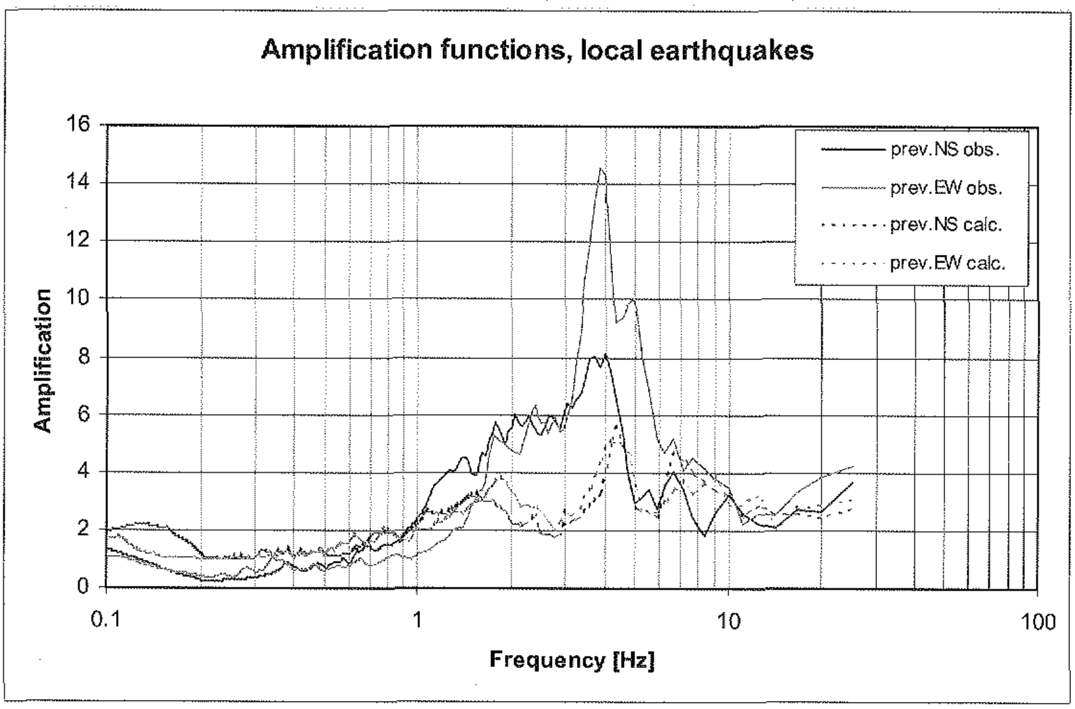

Figure 8: Comparison between the observed (obs.) and calculated (calc.) amplification functions for the earthquake used in Nagra & Résonance, 2003.

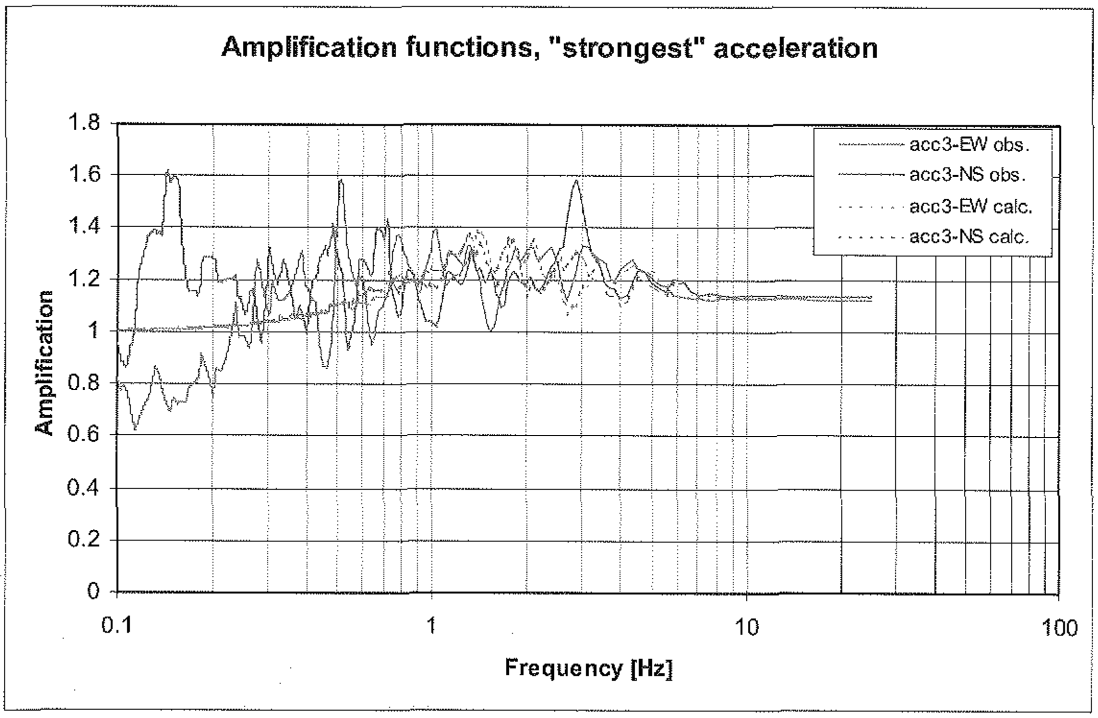

Figure 9: Comparison between the observed (obs.) and calculated (calc.) amplification functions for distant event acc3.

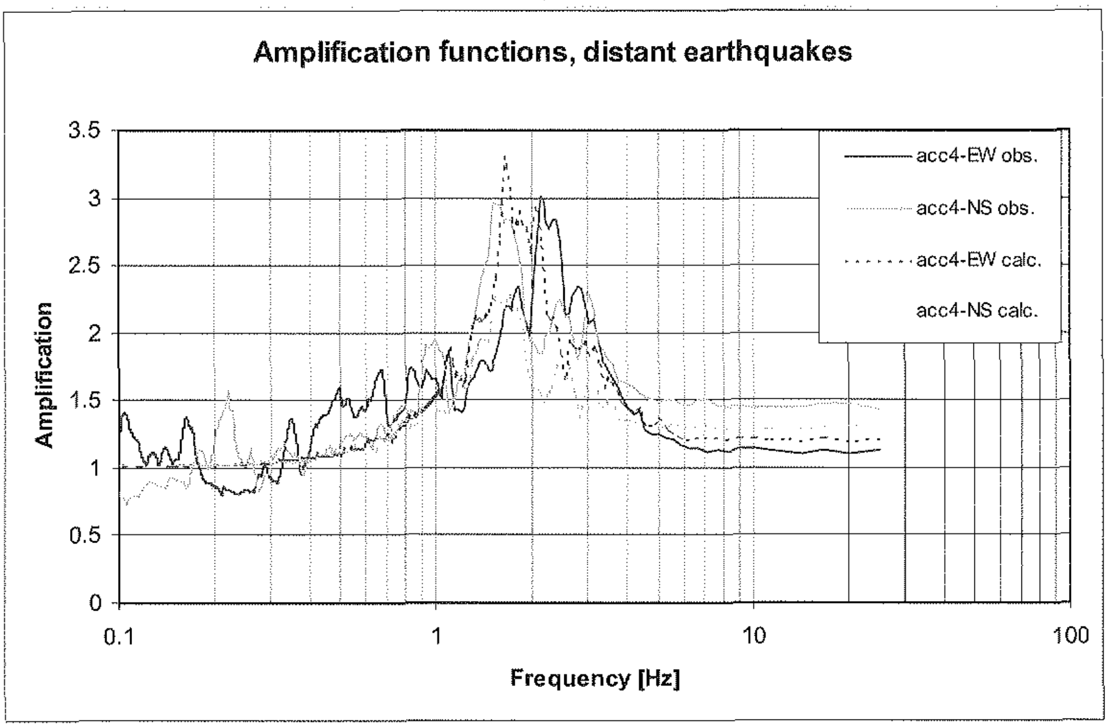

Figure 10: Comparison between the observed (obs.) and calculated (calc.) amplification functions for distant event acc4.

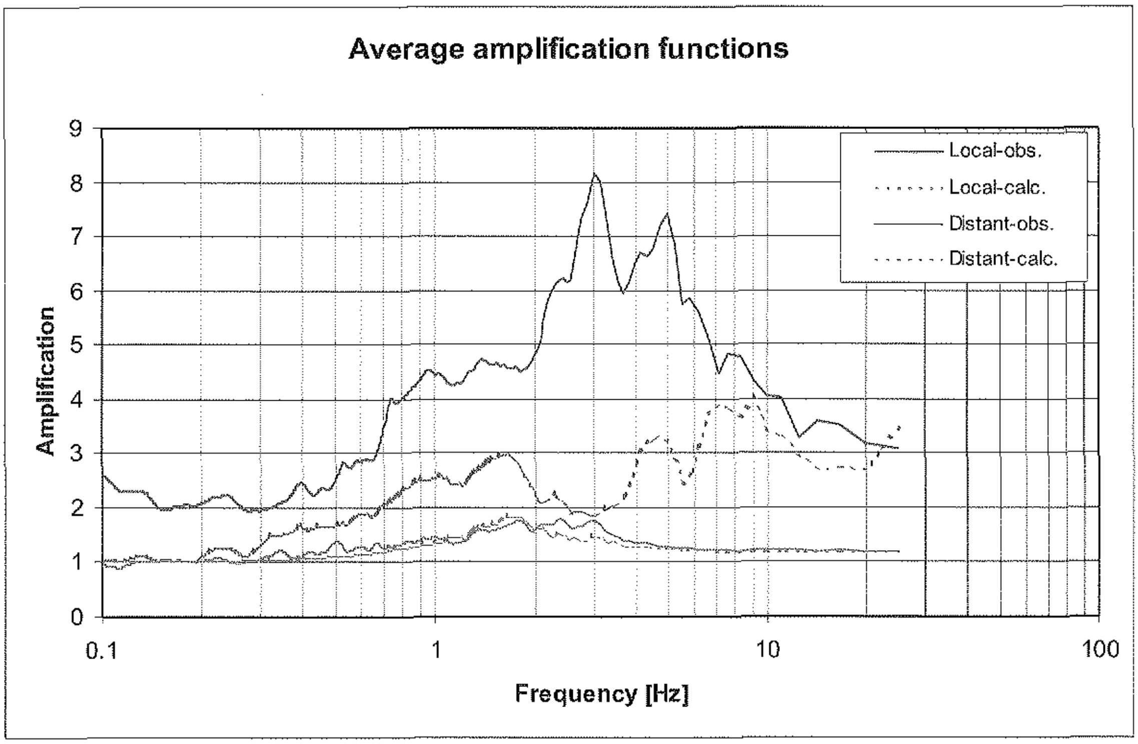

Figure 11: Comparison between the average observed (obs.) and calculated (calc.) amplification functions for distant and local events.

4. FOURIER SPECTRA

Response spectra are not very intuitive and often difficult to interpret physically. In order to try to better understand the results observed on the amplification functions, the Fourier spectra were also investigated. Figures 12 and 13 compare the observed and calculated average horizontal Fourier spectra for local and distant events, respectively, at the bottom of the borehole.

These comparisons show great differences between the observed and calculated horizontal Fourier spectra, for both local and distant events. This suggests that the differences observed could be linked to the velocity profile which might not be appropriate for the site.

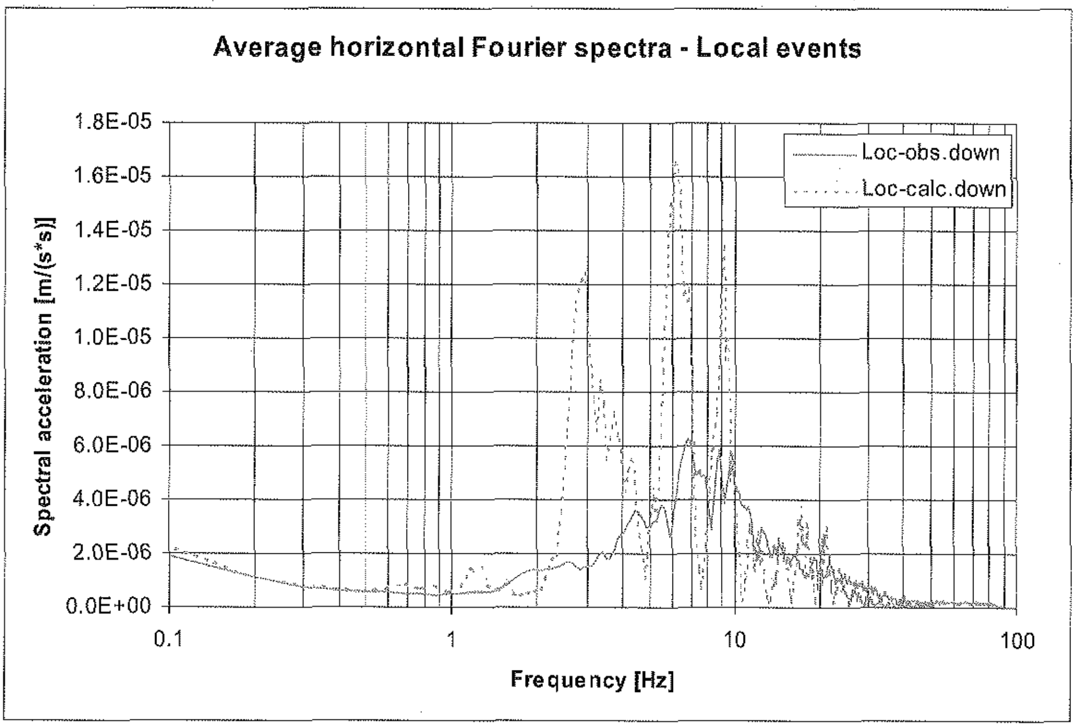

Figure 12: Comparison between the observed (obs.) and calculated (calc.) average horizontal Fourier spectra for the recorded local events.

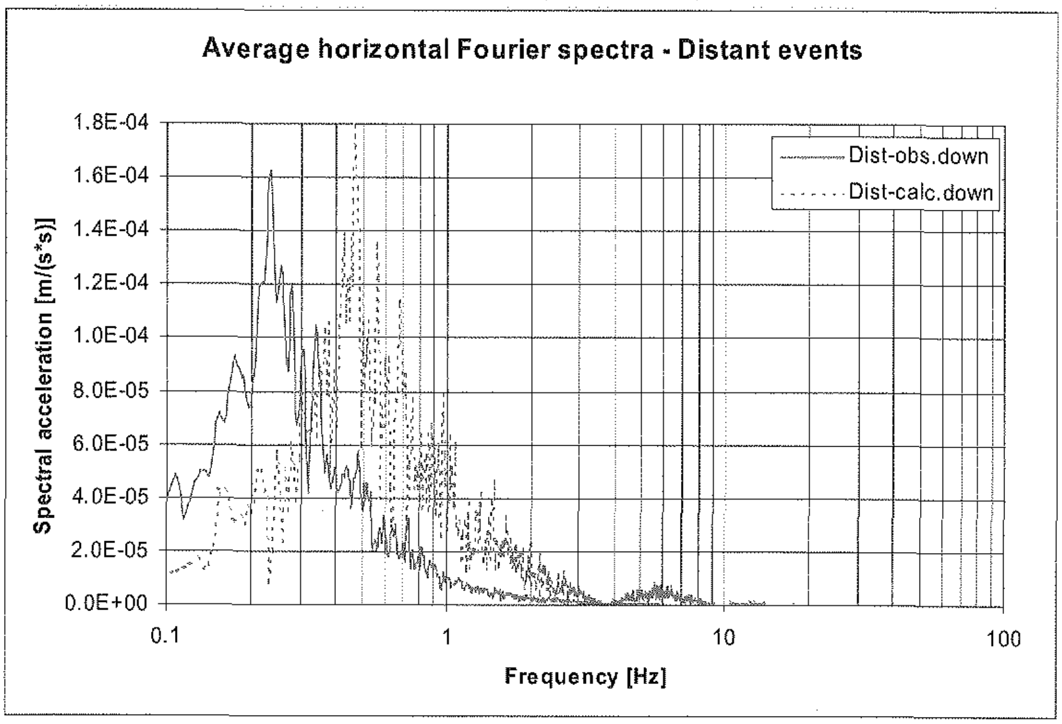

Figure 13: Comparison between the observed (obs.) and calculated (calc.) average horizontal Fourier spectra for the recorded distant events.

5. CONCLUSIONS AND RECOMMENDATIONS

5.1 CONCLUSIONS

With the data measured at the Horonobe URL site in Japan, we demonstrated that frequency dependent attenuation of earthquake accelerations with depth can be analysed and results displayed can be used for the purpose of scientific / public discussions.

Observed and calculated amplification[1] functions were plotted for three local and two distant events. The amplifications seem to be magnitude dependent. With the data at hand, the observed amplification functions are however rather unstable, showing different shapes for the different earthquakes and for two components of a single event. The comparison between observed and calculated amplification functions shows that the calculation strongly underestimates the amplifications apart for one event (acc4-EW), for which there is good agreement.

[1] *Amplification* of acceleration values measured between a recording station buried in the ground and one situated at the surface is inverse equivalent to the *attenuation* of the same accelarations if the measured values are compared in the other direction, form surface to depth.

For quality control purposes, the correctness of the input data has been thoroughly checked by JNC and calculations of the amplification functions were checked with a second numeric 1D program. Both calculations gave the same results. A data input or program error can thus be excluded.

The observed and calculated horizontal Fourier spectra also show strong discrepancies. This is difficult to understand since, in general, 1D calculations give rather satisfactory results as long as the velocity profile is correct and as long as significant 2D effects (basin edge effects, effects of deep valleys, etc.) can be excluded, as is the case here. The reasons for the observed data inconsistencies could possibly be:

- An incorrectness in the derivation of the input S-wave velocities used to generate the blocked S-wave velocity profile for the calculations of this study (Figure 4).
- Problems with the recording instruments (e.g. differences in coupling of the tools to the ground)

5.2 RECOMMENDATIONS

To eliminate the above mentioned first possible source of error, it is recommended to check the basis of the derivation of the S-wave velocity input data. Additional direct S-wave downhole logging or S-wave crosshole measurements are strongly recommended. The second source of error can probably neither be excluded nor eliminated in the case of the recording instruments used for this study, installed at the B-2 borehole. In order to improve on this subject, it is recommended to plan for an installation of high quality accelerometers in the future JNC Horonobe URL shaft. It is recommended to install three or more accelerometers, one at the surface, one or more at intermediate depth levels and one at total depth of the shaft. Measurements of field data would then allow to record a reliable dataset for proving and characterising significant attenuation of earthquake accelerations with depth, which in turn is an important argument for feasibility studies for radwaste disposal site investigations elsewhere in Japan or worldwide.

With the new recording instruments, as well as with the existing ones which gave input to this study, it is recommended to perform ambient vibration measurements in addition to new earthquake recordings.

In order to allow sufficient characterisation of the attenuations, earthquake recordings should possibly:

- come from different epicentral locations, with different azimuths and different epicentral distances;

- be linked to earthquakes with different source mechanism[2], different fault types and depth;
- have different acceleration levels: weak motion, intermediate and strong motion recordings.

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[2] Some simulation studies (see for instance Fäh et al. 1995 and Fäh and Suhadolc 1994) showed that site effects may vary with source characteristics, as the type of waves exciting the structure is different from one source mechanism and position to another one.

6. LITERATURE

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Appendix A

Recorded acceleration time histories

Appendix A

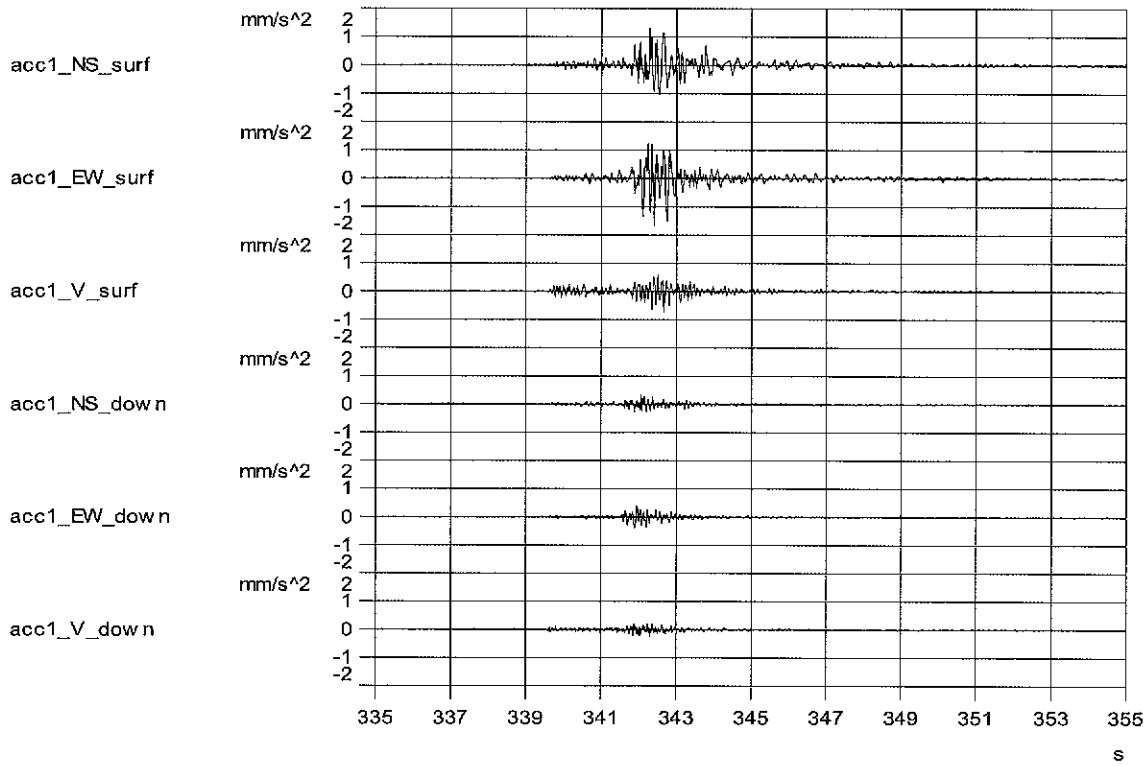

Figure A1: Recorded 3-component acceleration at the surface (surf) and in depth (down), for event "acc1".

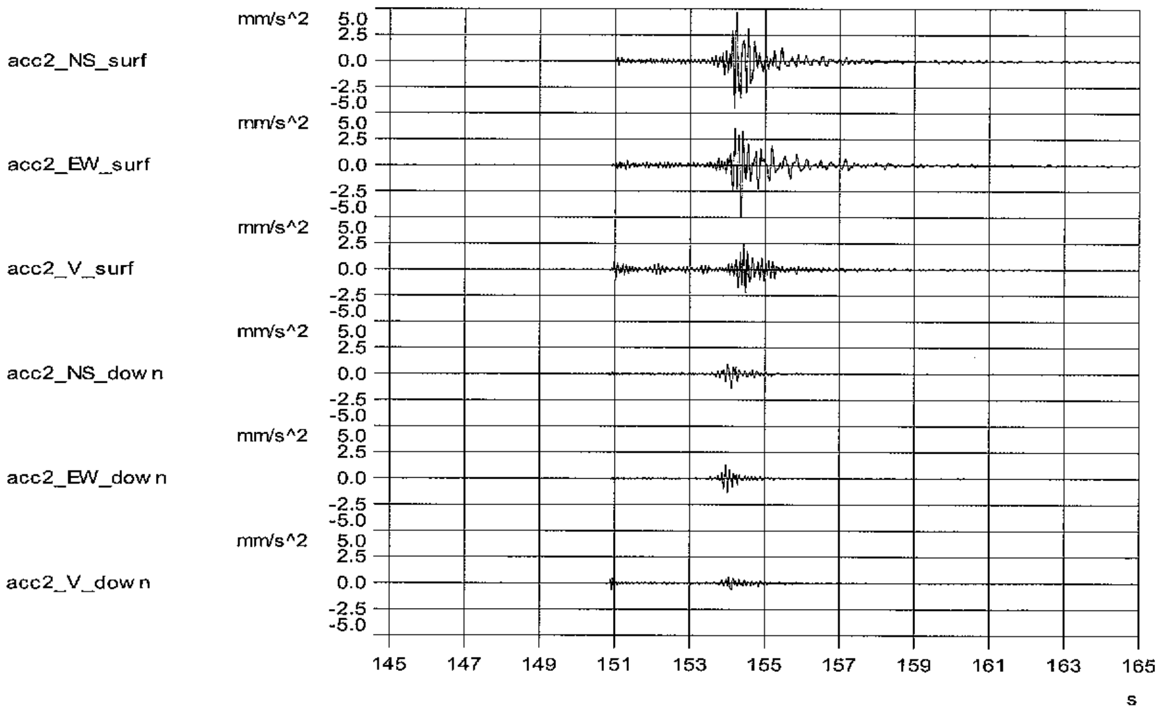

Figure A2: Recorded 3-component acceleration at the surface (surf) and in depth (down), for event "acc2".

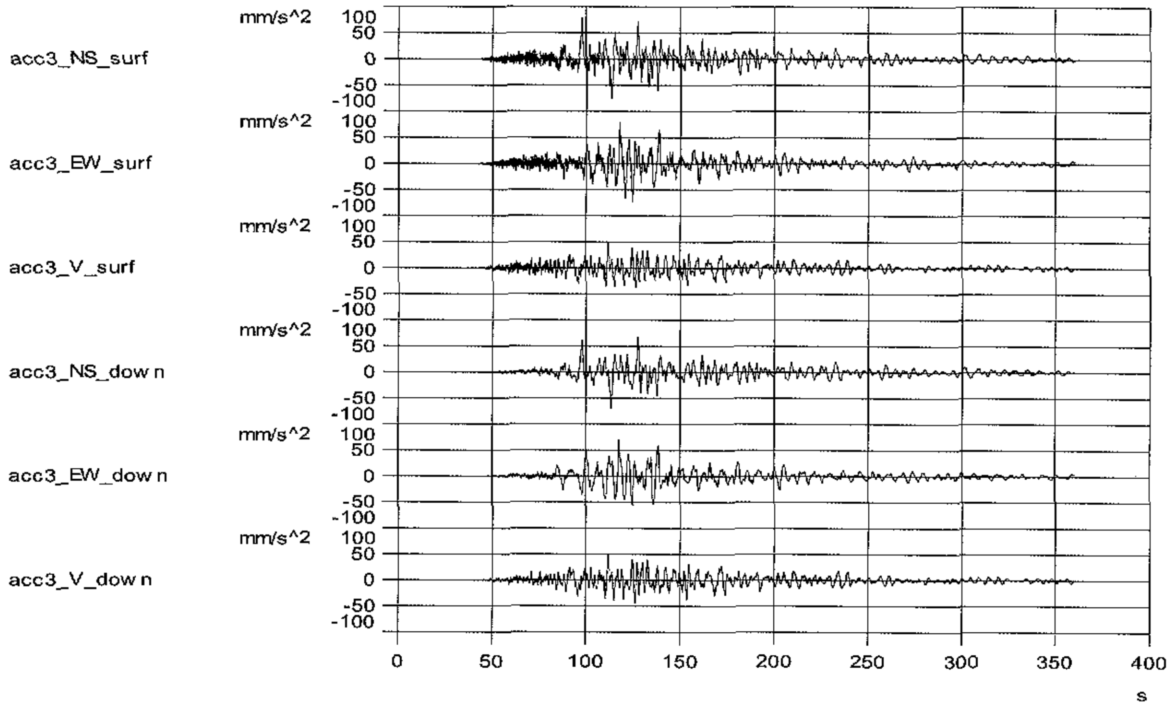

Figure A3: Recorded 3-component acceleration at the surface (surf) and in depth (down), for event "acc3".

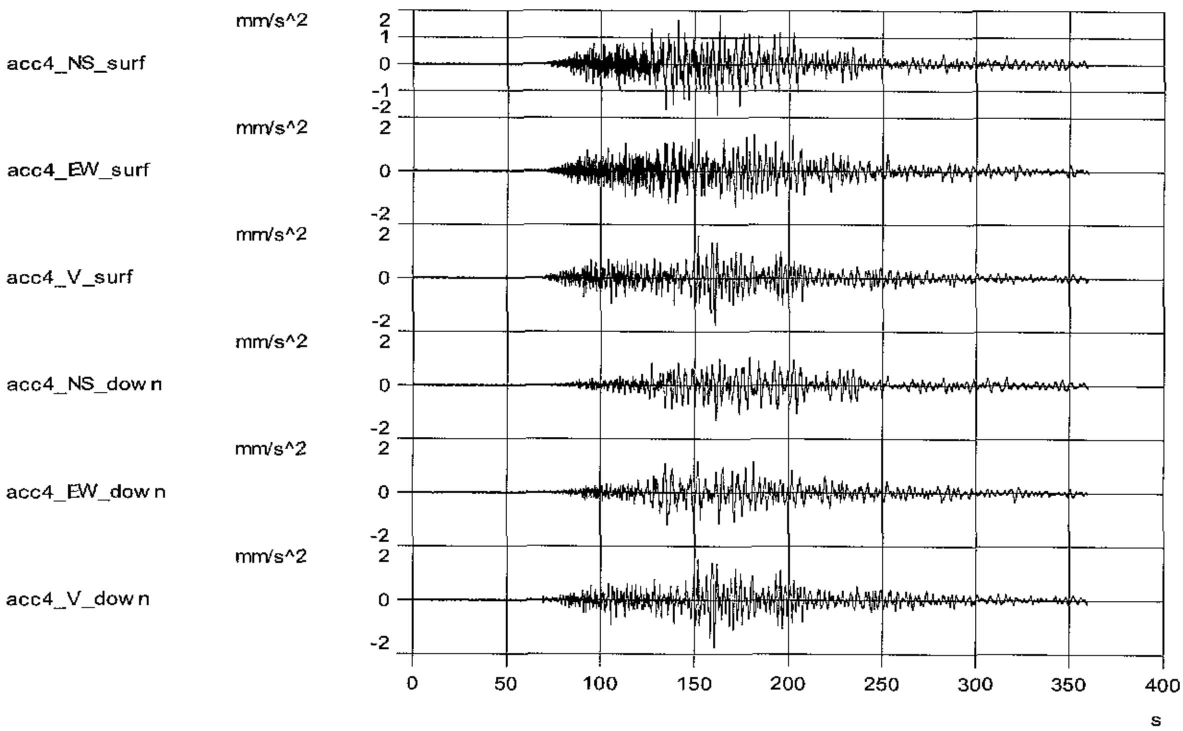

Figure A4: Recorded 3-component acceleration at the surface (surf) and in depth (down), for event "acc4".