SKI Technical Report 92:3

Project SEISMIC SAFETY

Characterization of seismic ground motions for probabilistic safety analyses of nuclear facilities in Sweden

SUMMARY REPORT

April 1992

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STATENS KÄRNKRAFTINSPEKTION
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The project SEISMIC SAFETY
is sponsored and directed by
the SWEDISH NUCLEAR POWER INSPECTORATE (SKI)
with the assistance of
VATTENFALL,
SYDKRAFT and OKG

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PREFACE

In Scandinavia seismic activity is generally low. Only a few incidents have been registered in historic time, which might have damaged an industrial plant of today. The risk of a nuclear accident in Sweden, caused by an earthquake, may thus be considered to be low.

The two latest reactors Forsmark 3 and Oskarshamn 3 have been analysed and designed to resist a specified earthquake. For the older reactors no corresponding analyses or designs have been made initially. Their general design is robust and was considered to provide enough safety with regard to earthquakes of the magnitude reasonably to be taken into account.

In the last ten years period the demands on safety with respect to nuclear power has increased. This fact has necessitated studies of possible incidents with a lower and lower probability. In order to obtain a complete picture of the risk, it is therefore also necessary to evaluate the seismic safety for the older reactors and to apply this knowledge during operation and in connection with alterations of existing plant design.

The basis and the methodology used in the design of Forsmark 3 and Oskarshamn 3 with respect to seismic safety is not in all parts suited to be employed for the older reactors. The methods imply a number of simplifications which may be a practical approach in connection with a new design but which might cause too conservative judgements of existing designs. The development of methods is therefore a vital part in the analysis.

The Swedish Nuclear Power Inspectorate, Vattenfall AB, Sydkraft AB and OKG AB have performed such a development of methods in a joint research programme: "Project Seismic Safety" ("Seismisk Säkerhet"). The aim of the project was to develop methods for calculating the ground response to be used in the safety analysis of nuclear power plants in Sweden, as well as to demonstrate its application to the power plants at Ringhals and Barsebäck. The project also includes a survey of geological and seismological conditions in the regions around the power plants studied.

The project "Seismic Safety" has now been finalized and the result is presented in this report. The project has in all essential parts reached the aims put up. The methods developed within this project are useful not only for nuclear power stations but also when considering seismic risks within other areas.

FÖRORD

Inom Skandinavien är den seismiska aktiviteten allmänt sett låg. Endast ett fåtal händelser finns registrerade i historisk tid, vilka skulle ha kunnat skada en modern industrianläggning. Risken för en kärnkraftolycka i Sverige orsakad av en jordbävning kan därför bedömas vara låg.

De två senaste reaktorerna Forsmark 3 och Oskarshamn 3 har beräknats och konstruerats för att klara en specificerad jordbävning. För de äldre reaktorerna har inte motsvarande beräkningar eller dimensionering gjorts. Den allmänt robusta konstruktionen har ansetts ge tillräcklig säkerhet med hänsyn till jordbävningar av den styrka det funnits sannolik anledning att räkna med.

Under den senaste 10-årsperioden har kraven på kärnkraftens säkerhet ökat, vilket medfört att händelser med allt lägre sannolikhet studeras. För att riskbilden skall bli komplett, måste således även den seismiska säkerheten för de äldre reaktorerna analyseras och eventuellt beaktas under drift och vid utformning av anläggningsändringar.

De underlag och metoder som använts vid konstruktionen av Forsmark 3 och Oskarshamn 3 beträffande seismisk säkerhet är inte i alla stycken lämpade att användas för de äldre reaktorerna. Metoderna innefattar ett antal förenklingar, vilka kan var praktiska i samband med nykonstruktion, men som skulle ge onödigt konservativa bedömningar av befintliga konstruktioner. Metodutveckling är därför en nödvändig del av ett analysarbete.

Kärnkraftinspektionen, Vattenfall AB, Sydkraft AB and OKG AB har genomfört en sådan metodutveckling i ett gemensamt forskningsprojekt, Seismisk Säkerhet. Projektets målsättning var att utveckla metoder för beräkning av markskakningsförlopp att användas vid säkerhetsanalys av kärnkraftverk i Sverige samt att demonstrera deras tillämpning på kraftverken i Ringhals och Barsebäck. Projektet skulle även innefatta översikter över geologiska och seismologiska förhållanden i regionerna kring de studerade kraftverken.

Projekt Seismisk Säkerhet är nu avslutat och resultatet redovisas i denna rapport. Projektet har i allt väsentligt nått de uppställda målsättningarna. De utvecklade metoderna är användbara inte endast för kärnkraftverk utan även för seismiska riskbedömningar i andra sammanhang.

Project SEISMIC SAFETY

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Project
SEISMIC SAFETY

May 1989

SUMMARY REPORT

CHARACTERIZATION OF SEISMIC GROUND MOTIONS FOR PROBABILISTIC SAFETY ANALYSES OF NUCLEAR FACILITIES IN SWEDEN

CONTENTS

1. INTRODUCTION

The study project SEISMIC SAFETY is sponsored and directed by the Swedish Nuclear Power Inspectorate (SKI) with the assistance of VATTENFALL, SYDKRAFT and OKG. The basic objective of the study is to evaluate the seismic risk relating to the Swedish nuclear facilities, including characterization of possible earthquake-induced ground motions at an extremely low probability level. Since the intention is to identify and account for the specific geological and seismological conditions in Sweden and adjacent areas and to utilize, judiciously, well-documented empirical relationships and data from other regions, it is anticipated that the study will generate an improved specification of the seismic load, compared with the design load specified during the end of the 70's, on a less selective basis, for the third reactor units of the Forsmark NPP and the Oskarshamn NPP and for the intermediate spent fuel storage CLAB.

The present project is thus a fundamental part of a comprehensive seismic risk evaluation concerning the Swedish nuclear facilities. This evaluation comprises the following main tasks:

- Pre-evaluation of the seismic risk associated with selected structures and components. (Conservative estimates, based on the above-mentioned design loads, performed mainly in connection with the installation of the filtered containment pressure-relief systems FILTRA in the reactor systems, completed before 1989).

- The present project, comprising two phases:

    * The main task, aiming at the presentation of a complete set of seimic load data, reviewed against the state-of-the art, in mid 1989.

    * A subsequent phase of supplementary review and refinement, based on a selective processing of data from recent events in Scandinavia and an additional input from international sources.

- Assessment of seismic responses and capacities of safety related structures and components within the Swedish nuclear plants. Quantification of the seismic contribution to the risk associated with each plant. The assessments are based on the seismic load input presented as a result of the main task mentioned above, to be adjusted, if necessary, on the basis of revisions carried out during the refinement period.

The present study has been documented in the following series of reports:

- Report No. 1: Probabilistic assessment of seismic ground motion characteristics for Swedish hard rock sites.

- Report No. 2: Seismic response spectra for characterization of ground motions in Swedish hard rock.

- Report No. 3: Synthetic time-histories for characterization of ground motions in Swedish hard rock.
- Report No. 4: Characterization of seismic ground motions for Barsebäck NPP.
- Report No. 5: Geological aspects on seismic hazard assessments for the Ringhals and Barsebäck NPP sites.

In these reports the models and procedures employed for the ground motion characterization and the probabilistic assessments are described and results are presented.

The present Summary Report starts with the presentation of a fundamental outcome of the work reported in the above documents: the characterization of ground motions for a "typical hard rock site". The objectives of the study are judged to be most easily explained and illustrated by these results which can then serve as a background for the description of the applied basic methodology and of further processing to account for specific site conditions etc.

The results presented in Report Nos 1-3 are relating to "a typical Swedish hard rock site" with the following basic seismological and geological characteristics:

- The "seismicity" is defined by "the average Fennoscandian seismicity function". (The word seismicity is used in a broad sense in this report, implying the rate of occurrence of earthquakes, past and expected, over the entire scale of magnitudes and other characteristics). The derivation of the seismicity function is described in Report No. 1.
- The transmission of the seismic waves from the source to the surface of the ground is through hard rock with the average properties of Swedish basement rock in respect of its effects on the wave propagation.

Since the large scale geological and seismological conditions around the individual nuclear plant sites are not very different as regards their expected effects on the seismic ground motion, the results obtained for the "typical hard rock site" can be taken as a basis for the characterization of the ground motions at the individual sites, after appropriate transformations to account for specific local conditions, seismological as well as geological.

Within the scope of the present project such considerations have been made for Ringhals NPP and Barsebäck NPP. On the basis of seismicity considerations accounted for in Report No. 1 and geological studies accounted for in Report No. 5 the following conclusions have been drawn:

- The characterization of ground motions for the "typical hard rock site" is directly applicable to the Ringhals site without any modifications.

- The same characterization of ground motions can be taken as representative for an imaginary outcrop of the basement rock at the Barsebäck site. The characteristics of the ground motion at the building foundation levels can then be determined by assessment of the transformation of the seismic waves from the real basement rock through the existing layers of sedimentary rock and surface deposits as described in Report No. 4.

Site specific ground motion characterizations for the Forsmark and Oskarshamn nuclear plant sites are not within the scope of the present project. The ground motion characteristics for the "typical hard rock site" are, however, applicable also to these two sites as a basis for assessing the corresponding site specific characteristics by appropriate modifications, to account for possibly deviating local seismicity and other conditions.

In Report No. 1 the probabilistic parts of the assessment of ground motion characteristics for the "typical hard rock site" are accounted for. In Report No. 2 it is described how the spectral characteristics are related to the fundamental source and wave path parameters, viz. the seismic moment and the focal distance. In Report No. 3 the generation of synthetic ground motion time-histories is described.

Report No. 5 contains descriptions of the near-field geological conditions at Ringhals and Barsebäck and analyses of the near-field from a seismotectonic point of view.

2. BASIC OBJECTIVES AND RESULTS

The overall purpose of the Swedish study is to provide a reliable basis for the prediction of the responses of nuclear structures and equipment at various defined levels of extremely low probability. For this purpose the ground motions (GM) at the sites of the facilities had to be predicted at various specified probability levels, closely to the extreme levels associated with the ultimate capacities of structures and equipment. For the nuclear plants the qualification levels are set at 10^{-7} and 10^{-5} annual events for the exceedance of the containment integrity limit and the safe shutdown and core cooling limit, respectively.

For engineering purposes the ground motions have been characterized by means of ground response spectra and corresponding synthetic GM time-histories (accelerograms etc.). Response spectra were provided for various ratios of structural damping. The spectra were outlined for a horizontal (principal) and for the vertical GM direction. The time-histories were produced for the vertical and two statistically independent orthogonal horizontal directions. Basically, the ground motions were characterized for a generalized "typical" hard rock site with an outcropping basement rock, and site specific conditions were then accounted for, where necessary, by modelling strata of sedimentary rocks and soil overlying the basement rock, for example.

For the sake of brevity the following description of the Swedish study starts with a demonstration of results in the form of a set of ground response spectra which will then be referred to as a basis for further explanations of objectives and applied methodology.

The co-called "Envelope Ground Response Spectra", displayed in Figure 1, may also be referred to as "Uniform Hazard Spectra". The spectral values represent limits of single-degree-of-freedom responses that are expected to be exceeded at the frequencies of 10^{-7}, 10^{-6} and 10^{-5} annual events per site, respectively. Since the exceedance of a certain spectral value may derive not only from one but from several types of earthquakes, from strong distant to moderate near-field events, the combination of modal responses obtained from one single envelope spectrum implies a certain approximation. However, in the actual case of a fairly uniform regional seismicity distribution, the envelope spectra become rather narrow and can be used with a good approximation for multi-degree-of-freedom structures, particularly for the large buildings of the nuclear plants, for which the fundamental (rocking) modes of vibration are quite predominat. Due to this realistic feature of the envelope spectra, the corresponding synthetic GM time-histories can be generated and generalized for each probability level, and it is not necessary to use several event specific spectra.

An example of such a synthetic time-history is displayed in Figure 2. For the sake of realism the strong motion duration has been chosen so as to represent the typical duration of the shear-wave phase of near-field earthquakes with magnitudes of 5 - 6 which category contributes predominantly to the seismic risk associated with the Swedish nuclear plants.

A complete set of Envelope Ground Response Spectra for the "Typical Hard Site" is enclosed as APPENDIX 1. The corresponding spectra for Barsebäck are presented in APPENDIX 3.

The synthetic seismograms displayed in APPENDIX 2 and 4 constitute two complete sets of GM time functions to be used as input loads for computing structural responses at the various defined spectral exceedance levels. The seismograms of APPENDIX 2 are relating to the "typical hard rock site" and those of APPENDIX 4 to the Barsebäck site.

The numerical values are stored on discettes compatible for IBM PCs.

The seismograms have been given a sufficient degree of realism to be used not only for linear elastic response calculations but also for calculation of nonlinear response and effects of repeated cyclic loading. As regards the realism of the seismograms it has to be accepted that the lowermost frequency waves cannot always be simulated in a completely realistic manner only by random phasing. However, it appears that the seismograms for Horizontal Direction No. 1 and those for Vertical Direction are fairly realistic also in respect of the lowermost frequency waves. This is most clearly manifested in the velocity and displacement time-histories. The seismogram for Direction No. 1 shall therefore be used with priority to represent the horizontal ground motion along a principal axis of the ground motion. In case the structural response has to be determined for ground motions along two principal horizontal axes the seismograms for Direction No. 2 shall represent the motions along the second principal axis, orthogonal to Direction No. 1.

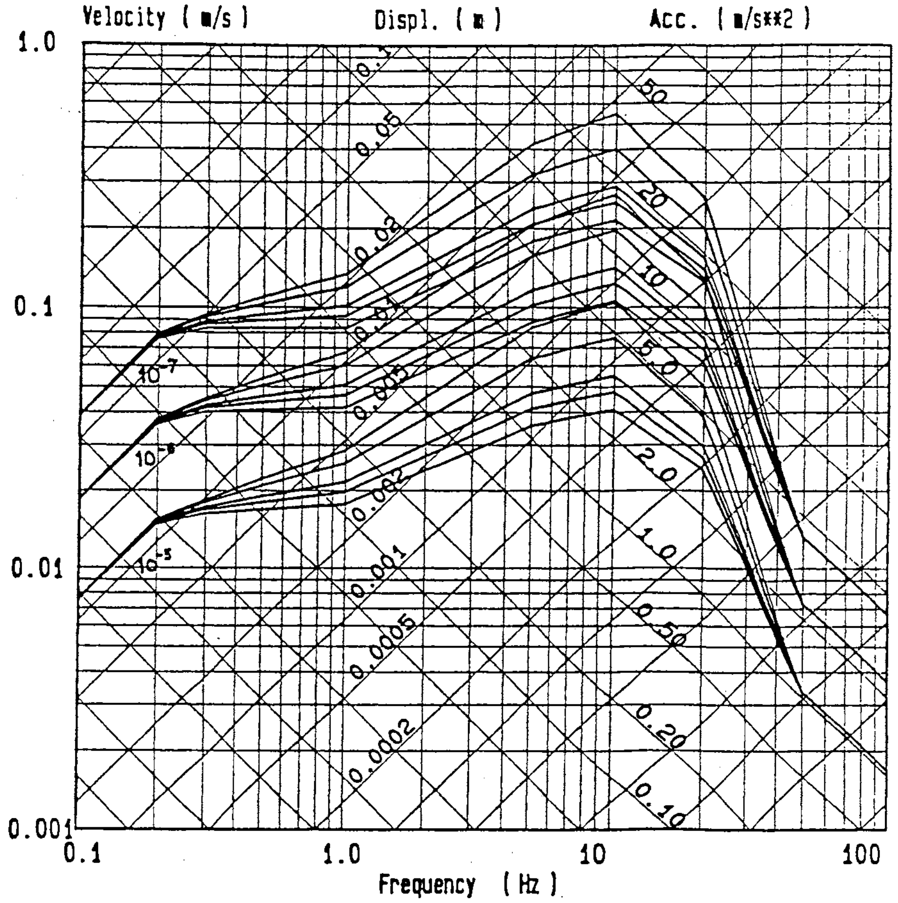


FIGURE 1: Envelope Ground Response Spectra for a (principal) horizontal GM direction, relating to exceedance frequencies 10^{-5}, 10^{-6} and 10^{-7} annual events per site and damping ratios 0.005, 0.02, 0.05, 0.07 and 0.10.

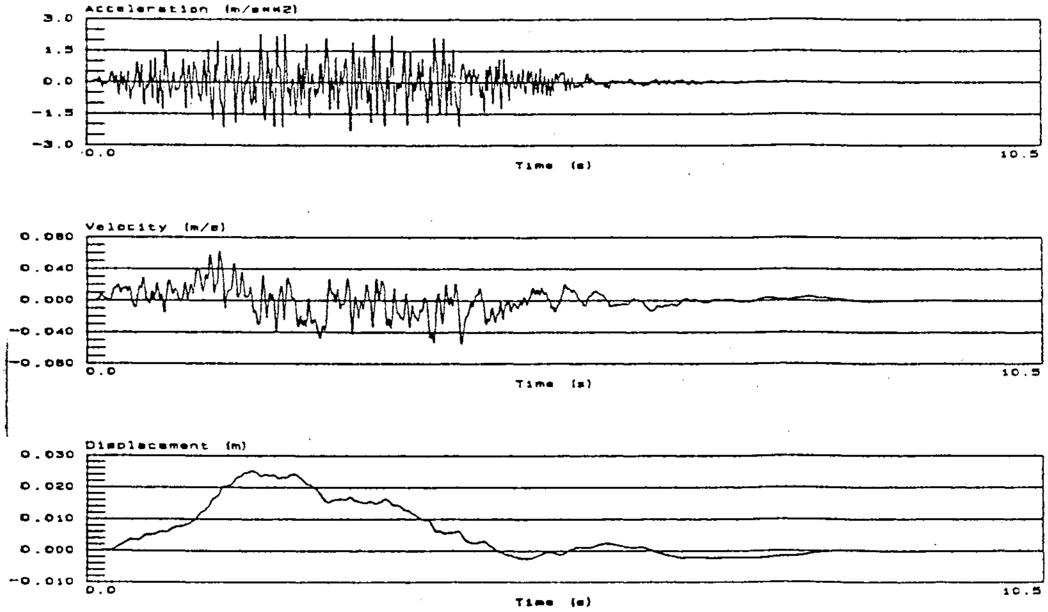


FIGURE 2: Synthetic GM time-histories corresponding to the response spectra for the exceedance frequency 10^{-6}.

3. METHODOLOGY

3.1 General approach

The basic structure of the applied methodology is schematically indicated in Figure 3. Some of the processes involved are conventional and will not be dwelled upon much in this presentation which will focus on the systematization of the process and on some novel features.

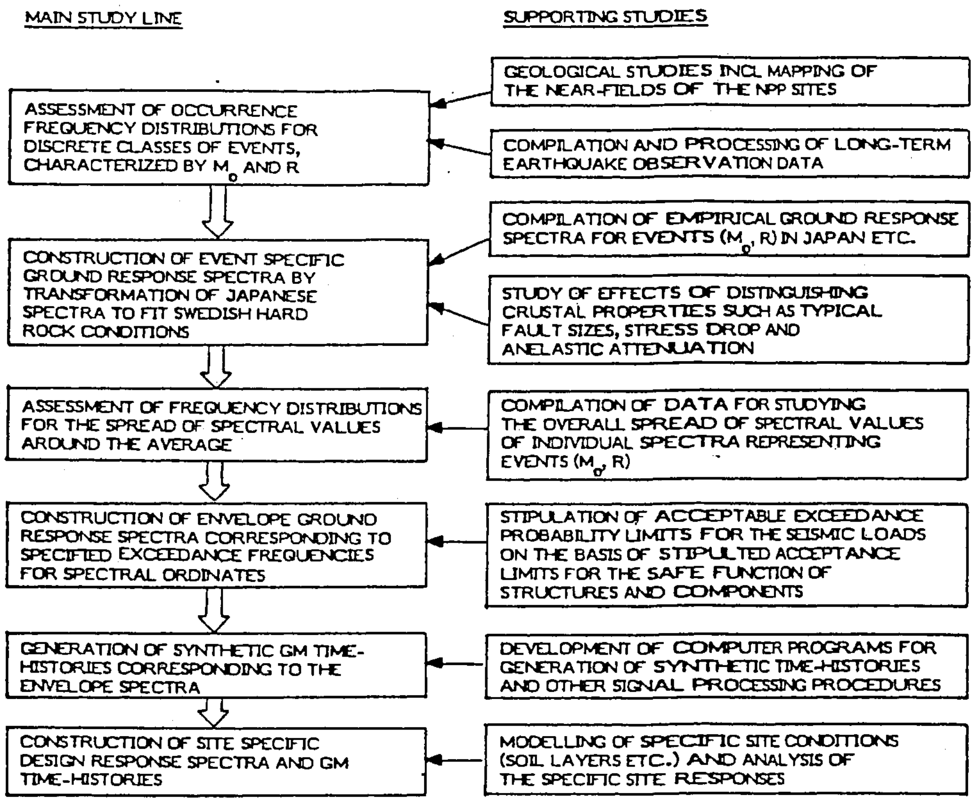


FIGURE 3: Project strategy

3.2 Assessment of occurrence frequency distributions of seismic events

The geometrical characteristics of the seismic hazard model are illustrated in Figure 4. The probabilistic calculations can be summarized as follows:

- Over the entire significant range of earthquake sizes and locations the events were categorized in respect of the seismic moment M_o and the focal distance R. The width of the classes were determined so as to be approximately equal in respect of the ratios between GM values at the upper and lower boundaries of each class of M_o and R.
- Large scale seismicity zoning and seismotectonic considerations resulted in the choice of an average Fennoscandian function of epicentral density, directly applicable to at least two nuclear plant sites (Ringhals and Barsebäck) with respect to the seismicity.
- For each volume element of the crustal model (Figure 4) the occurrence rates of the various classes of events were determined on the basis of an epicentral density function, indicated in Figure 5, and the probability density distribution of focal depths (Figure 4). The epicentral density function was derived from available catalogues, covering earthquake events in Fennoscandia for a period of almost 500 years.

  Since, in the basic model, the occurrence of all sizes of earthquakes are assumed to be randomly distributed over the entire Fennoscandia, the calculations could be simplified by regarding hemisperical volume elements, each with the same proportion of the total frequency of earthquakes affecting the site at the centre of the model, either when regarding a certain size of earthquakes or when including the entire significant range of sizes.

The result of this first step of the probabilistic assessment was a matrix of occurrence frequency values for each selected class of events characterized by a certain combination of the seismic moment M_o and the hypocentral distance R (Table 1).

R	Seismic moments Mo (Nm)							
(km)	0.10E+16	0.40E+16	0.10E+17	0.40E+17	0.10E+18	0.40E+18	0.10E+19	SUM:
3.0	16	16	6	2	1	0	0	41
7.0	208	202	74	27	10	4	2	527
11.0	851	823	304	112	41	15	9	2159
16.0	3529	3433	1261	463	170	63	36	8955
22.0	5638	5487	2015	740	272	100	58	14310
30.0	14278	13895	5104	1875	689	253	147	36240
42.5	32158	31296	11495	4222	1551	570	330	81621
62.5	78803	76689	23167	10346	3600	1396	809	200011
100.0	258511	251578	92402	33940	12467	4581	2655	656135
SUM:	393991	383424	140828	51727	19001	6982	4047	1000000

SCALE FACTOR = 7.36246E-09
TOTAL SUM = 7.36246E-03

Table 1: Incremental recurrence rate values

The reasons for using the seismic moment M_o as the fundamental source parameter are mainly relating to its direct relationship with the mechanism of a fault slip: the released energy, the stress drop, the displaced area, the displacement. Since all these factors are interrelated through the seismic moment and determine the character of the emitted waves, it is appropriate to use the seismic moment as the basic earthquake size parameter.

As regards the probability assessments, the choice of M_o as the basic probabilistic parameter does not really improve the quality of the database, since the sizes of the historical events, both in Fennoscandia and in other regions, are usually expressed in terms of magnitudes that are in turn sometimes estimated rather roughly, from intensity observations etc. However, magnitude scales are different and since a homogenization must be carried out on this point under all circumstances, this homogenization can very well have the form of a transformation from magnitudes expressed in the various scales to the equivalent seismic moments.

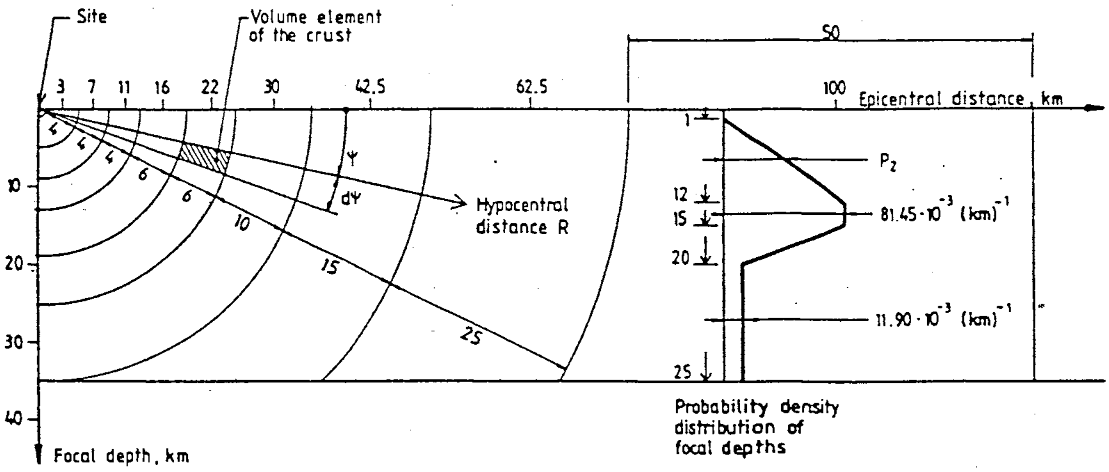


FIGURE 4: Geometrical division and distribution of focal depths adopted for the calculation of hypocentral densities of occurrence

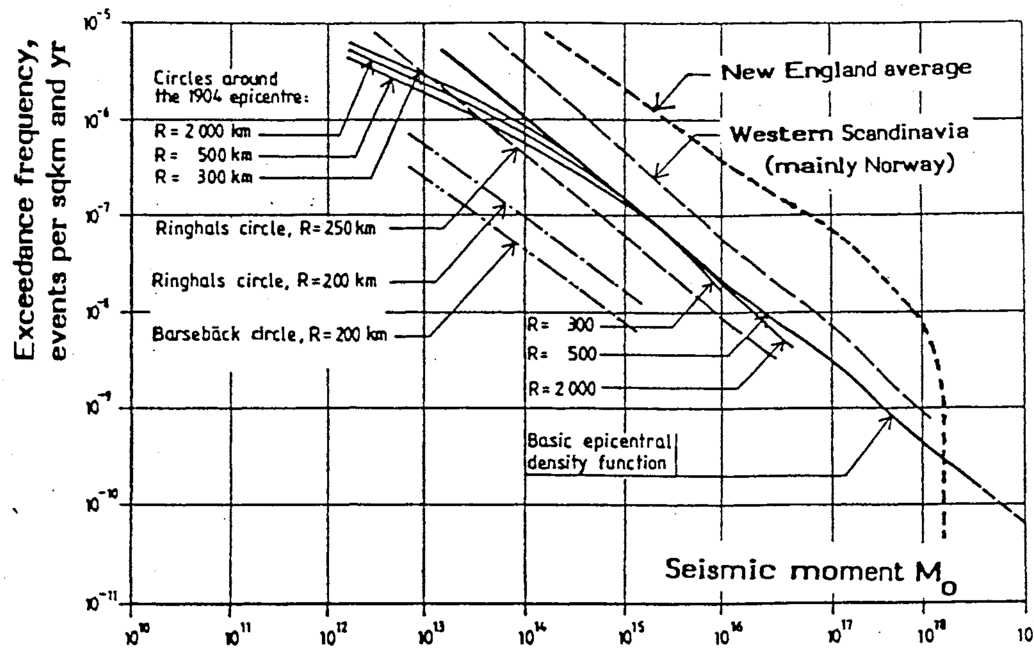


FIGURE 5: The adopted average Fennoscandian epicentral density function compared with curves connecting data points relating to various geographical zones.

3.3 Development of characteristic ground response spectra for various classes of events

The model used for the development of "event-specific" ground response spectra is based on the processing of empirical data from more seismic regions to suit the typical conditions in Sweden. The main rationales for the choice of this approach are the obvious lack of local data concerning ground motions generated by strong earthquakes, of the sizes judged to be decisive in the risk analysis of nuclear facilities, and the fact that generalized empirical expressions for effects of differential geological and seismological conditions indicate a moderate influence on the shapes of the ground response spectra.

A fairly comprehensive and well-defined database in the form of empirical ground response spectra, mainly from Japan, is now generally available (References 8-11). Since earthquakes with sizes that are extreme for Swedish conditions occur with a relatively high frequency in the more seismic zones in Japan, the empirical support for outlining response spectra concerning an intraplate region such as Fennoscandia is likely to be as strong as the corresponding support for extreme earthquake predictions in the more seismic regions, provided that the above-mentioned transformation is accurate.

The characteristic response spectra for Swedish conditions are therefore obtained by modifications of the corresponding Japanese spectra with respect to the influence factors that are expected to affect the spectra differently. These factors are associated with differences of source parameters such as stress drop and fault area, and of wave propagation effects like anelastic attenuation. Since the resulting differences are moderate, the transformation of the Japanese spectra has been based on generalized, best-estimate values of the influence factors.

For the transformation of ground response spectra from one geological region to another the differential source and wave path characteristics must be identified and quantified, at least relatively. This can be achieved on the basis of empirical relationships and simple energy consideration, coupling the seismic wave amplitudes to the most important source and wave path parameters. We will start from a Fourier amplitude spectrum formula of the type suggested by Aki(Ref. 25):

$$F_D = \mathrm{Const} \cdot F_{DO} \cdot (1 + (f/f_c)^{2n})^{-1/2} \cdot A(f,R) \qquad (1)$$

where the displacement wave amplitude F_D is a function of the "zero frequency amplitude" F_{DO}, the "corner frequency" f_c and the "anelastic attenuation function" $A(f,R)$. These parameters are related to the stress drop SD, the fault slip area S, the seismic moment M_o, the focal distance R and the shear modulus G through the following relationships, deriving from various empirically supported models of faulting and wave transmission.

$$M_o = \mathrm{Const} \cdot SD \cdot S^{3/2} \qquad (2)$$

$$M_o = \mathrm{Const} \cdot G \cdot F_{DO} \cdot S \qquad (3)$$

$$f_c = \mathrm{Const} \cdot S^{-1/2} = \mathrm{Const} \cdot (SD/M_o)^{1/3} \qquad (4)$$

$$A(f,R) = \exp - \frac{\pi \cdot R \cdot f^{0.5}}{Q_{OS} \cdot v_S} \qquad (5)$$

where Q_{OS} is the rock quality factor and v_S is the shear wave velocity.

We may select SD and G to constitute our differential source parameters. Within the frequecy range of major interest f is large compared with f_c and Eq. 1 can be written:

$$F_D = \mathrm{Const} \cdot F_{DO} \cdot (f/f_c)^{-n} \cdot A(f,R) =$$

$$= \mathrm{Const} \cdot f^{-n} \cdot \frac{1}{G} \cdot SD^{\frac{n+2}{3}} \cdot M_o^{\frac{1-n}{3}} A(f,R) \qquad (6)$$

A Japanese amplitude spectrum obtained for a certain class of M_o and R can thus be transformed to fit other geological conditions by scaling the spectral ordinates with respect to the ratios between the respective values of SD, G and Q_{OS} v_S, the latter product to account for differential wave path conditions. For the transformation from of Japanese to Swedish conditions the ratios were set at $SD_S/SD_J = 3$, $G_S/G_J = 2$ and $(Q_{OS}\ v_S)_S/(Q_{OS}\ v_S)_J=4$, based on typical generalized geological conditions. The spectral decay value n = 2 was taken as the most probable average.

For the transformation of a response spectrum it is not sufficient to consider the wave amplitudes, however, since the amplification of the response also depends on the duration of the strong motion. Since the duration is determined by the extension of the fault slip, the scaling factor can be obtained from Eq. 7:

$$t_{DS}/t_{DJ} = (S_S/S_J)^{1/2} = (SD_J/SD_S)^{1/3} = 0.7 \qquad (7)$$

A shorter strong motion duration tends to reduce the amplification of lower-frequency responses. The order of that reduction was estimated by studying time-histories and corresponding response spectra typical of near-field earthquakes with magnitudes of the order of 5-6, which is the category giving the predominant statistical contribution. It was concluded that the reduction of the Japanese spectral values, due to the reduced strong motion duration, essentially neutralizes the effects of the differential stress drop and attenuation for frequencies below 10 Hz. The moderate influence of the differential attenuation is, of course, only applicable to the near-field.

For the spectral range of higher frequencies the higher stress drop and lower attenuation significantly increases the spectral ordinates of near-field earthquakes in Sweden compared with Japanese earthquakes of corresponding magnitudes and focal distances. This is, of course, as an average. It appears that the effects of differential geological conditions are, however, small compared with the variation of spectral values between different classes of M_0 and R. Therefore the prediction of GM characteristics for low-seismicity areas, such as Scandinavia, on the basis of data from higher-seismicity regions is judged to be much more reliable than predictions based on up-scaling of observational GM data from small earthquakes, however from similar geological zones.

An example of the adaptation of a Japanese standard response spectrum to Swedish conditions is shown in Figure 6. Correspondingly, so-called Event-specific Response Spectra were produced for the selected classes of events, each charactrized by M_0 and R (see examples, Figure 7).

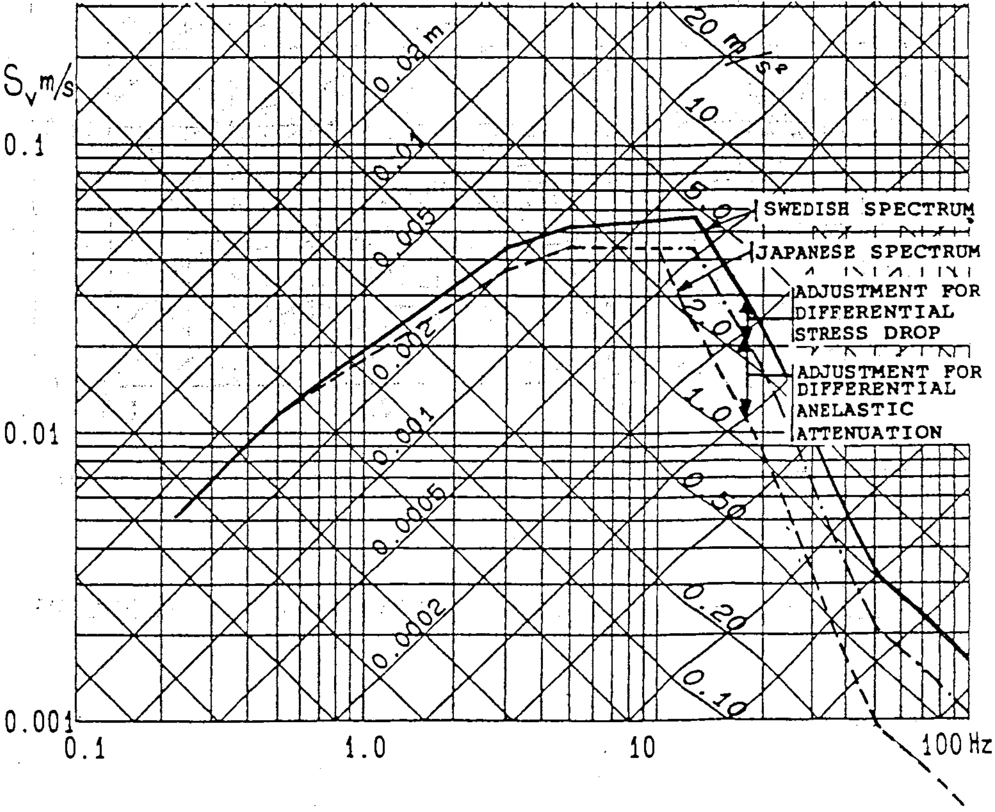


FIGURE 6: Example of the adaptation of a Japanese response spectrum to fit Swedish geological conditions.

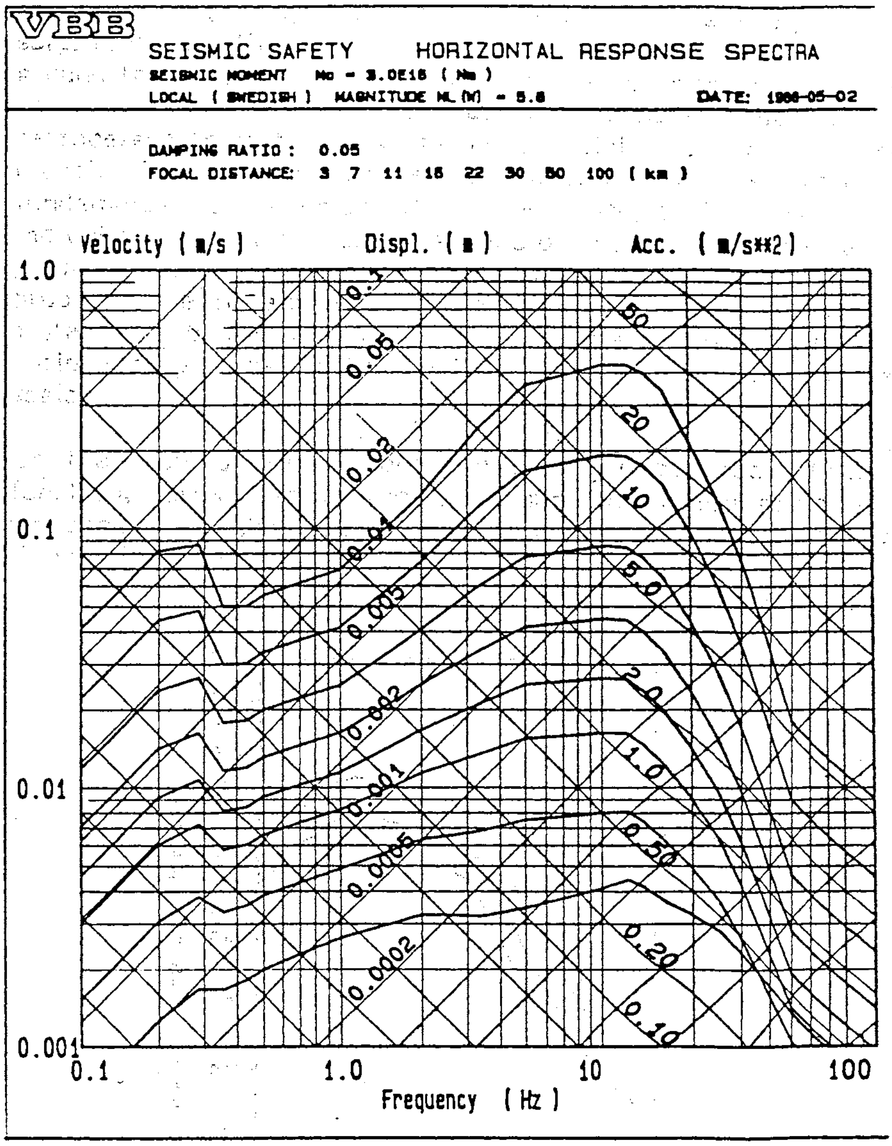


FIGURE 7: Examples of Event-specific Ground Response Spectra

3.4 Assessment of the spread of spectral values

Since the various selected events and their corresponding characteristic response spectra have been classified only with respect to the "fundamental parameters" M_0 and R, it is not surprising that there is a considerable spread of spectral values around the average. This spread has been assessed in a generalized way, once more on the basis of Japanese data (Ref. 2), reprocessed to suit the conditions pertaining to in the Swedish model. Thus the combined effects of other parameters than the fundamental are considered, though without identifying their individual contributions, that would not be possible at the present state-of-the-art. A considerable part of the spread is probably due to errors in the data acquisition and processing system, including the uncertainty associated with the use of various magnitude scales and transformations between such scales.

On the basis of the Japanese data a generalized distribution function, normalized to the mean spectral value as unity and independent of the frequency of vibration, was thus developed (Figure 8a and 8b).

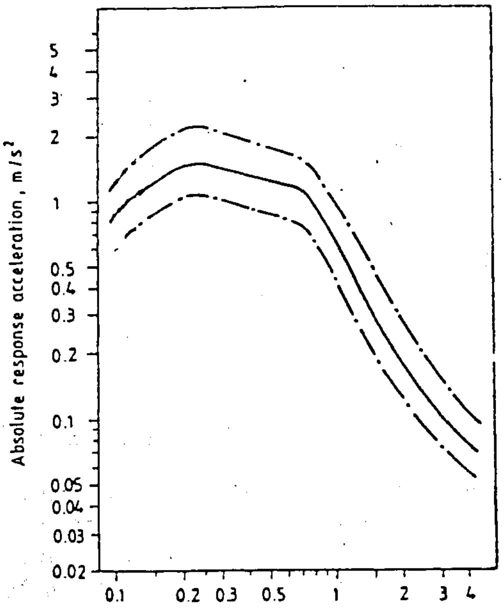


FIGURE 8a: A characteristic ground response spectrum for a certain class of M_0 and R and its 5-percentile general spread.

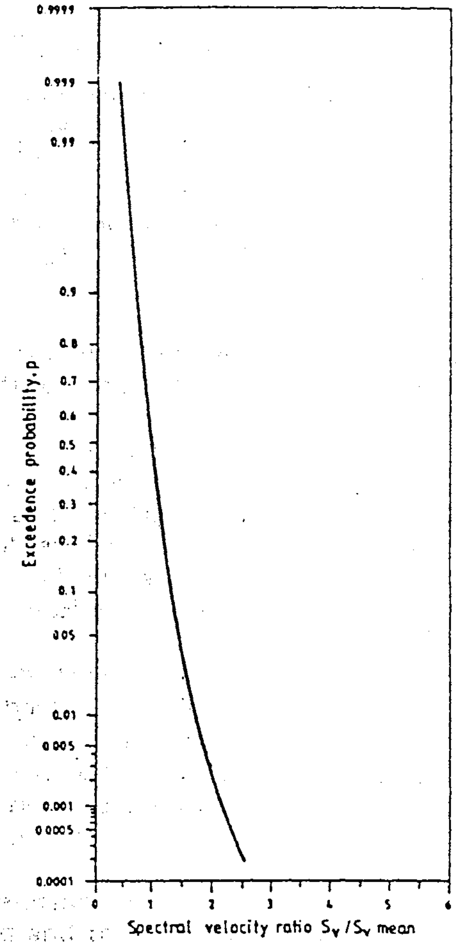


FIGURE 8b: Cumulative probability distribution of spectral ordinates.

3.5 Construction of Envelope Ground Respons Spectra

On the basis of the derived occurrence frequency distributions for discrete classes of events, the Event-specific Spectra of these classes and the relative distribution of spectral values, the frequency of exceedance of a certain spectral value was determined for each class of events. The overall exceedance frequencies were then determined for various spectral values by adding the contributions from each class of events.

For each selected probability level the so-called "Envelope Response Spectra" were finally constructed by interconnecting discrete spectral values, corresponding to the given level, obtained from the overall exceedance frequency distributions mentioned above. On the basis of empirical relationships between response spectra for various damping ratios, which relationships are also included in some of the above-mentioned Japanese publications, Envelope Response Spectra were also produced for various damping ratios other than 0.05 (Figure 1).

3.6 Generation of synthetic ground motion time-histories

Synthetic time-histories of ground acceleration, velocity and displacement were developed, corresponding to the Envelope Response Spectra (see Figure 2, for example). The time-histories were produced for two perpendicular horizontal directions and for the vertical, one of the horizontal representing the primary principal axis of the ground motion. The basic demands were satisfied as follows:

- The spectra for 5 per cent of critical damping were selected to constitute the primary target spectra.

  As demonstrated in Figure 9 it was possible to attain a good conformity between the response spectra of the time-histories and the target spectra, not only for 5 per cent but also for other damping ratios. Particularly, for the important range f = 1-5 Hz and damping ratios below 0.02, the agreement is remarkably good.

- The time-histories could be given a realistic duration of the various phases of strong motion, implying that they may be used not only for linear but also for non-linear response calculations, without causing any major deviations from a realistic response, e.g. accumulated residual strain and displacements etc.

Since the relation between a velocity response spectrum for zero-damping and the corresponding Fourier acceleration amplitude spectrum is very close, a typical spectrum of the latter type was used as a basis for each iterative procedure of time-history generation. A random phase distribution was assumed. The transient character of the time-history was obtained by multiplying the stationary time-history by an intensity time function, based on empirical data and given as strong motion duration typical of the largest earthquakes of any statistical significance.

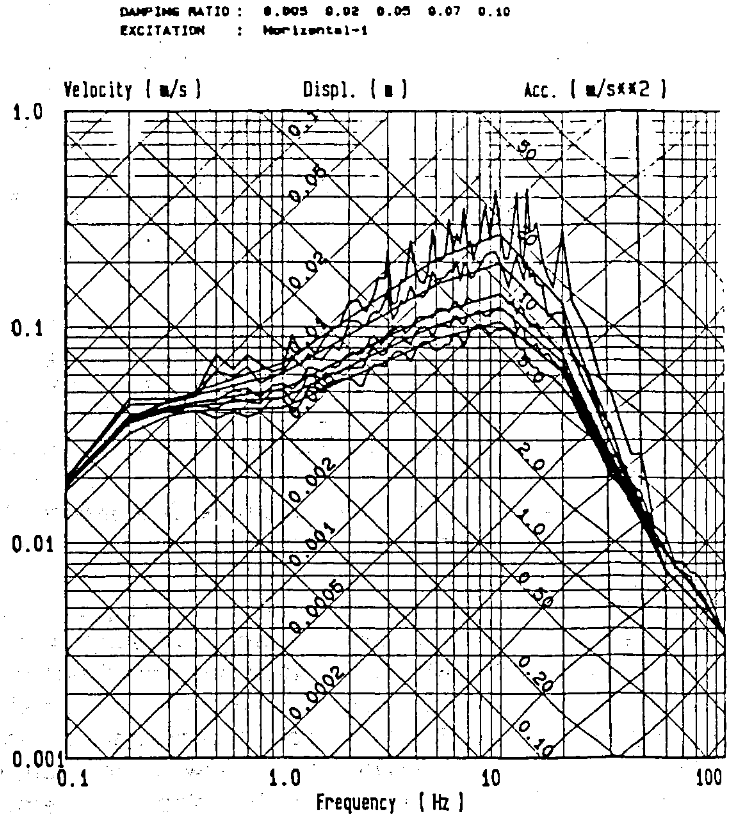


FIGURE 9: Comparison between Envelope Ground Response Spectra, generated by the ground motion time-history displayed in Figure 2, and corresponding target spectra. (Damping ratios 0.005, 0.02, 0.05, 0.07, 0.10)

3.7 Site-specific ground motion characteristics for Barsebäck

Starting out from the ground motion characteristics derived for the "typical hard rock site", the corresponding characteristics were determined for Barsebäck, taking the specific seismological and geological conditions of that site into consideration. Basically two aspects were considered: the seismicity aspect and the wave propagation aspect, the latter being the most obvious concern, since the Barsebäck plant is founded on soil deposits which, though extremely dense, cannot be equalized with hard rock. Furthermore, there is an intermediate 2 km thick layer of sedimentary rocks overlying the hard basement rock below the plant.

In order to investigate whether the "average Fennoscandian seismicity function" could be used as a reasonably conservative basis for the probabilistic considerations relating to Barsebäck, potentially differentiating factors were examined. On the basis of available, fairly detailed, information from site investigations and general geological mapping, the near-field of Barsebäck was scanned with respect to the existence of potential earthquake sources. Hypothetically, the existence, even within the Barsebäck area, of steep fault planes in the basement rock, as discovered in other parts of SW Scania, was considered, and the earthquake catalogues were reviewed, looking for any sign of increased seismicity or connections between the location of the epicentra of historical earthquakes and indicated or suspected faults.

The geological investigations and considerations, as well as the historical records, did not supply any indications, pointing at Barsebäck or SW Scania as a zone deviating significantly from the rest of southern Sweden in respect of seismic hazards. Therefore the "average Fennoscandian seismicity function" was adopted for Barsebäck, most likely implying a portion of conservatism as in its application to the Ringhals site.

The wave propagation effects were assessed by applying the following approach. The sedimentary bedrock and soil strata overlying the basement rock below Barsebäck were modelled by finite elements. Two models were tested as indicated in Figure 10. The transformation of vertically propagating shear and longitudinal waves, when transmitted from the basement through the sedimentary rock and the soil strata, was determined, using the synthetic time-histories of unreflected waves corresponding to the "hard site spectra" to represent the incident waves from the basement rock.

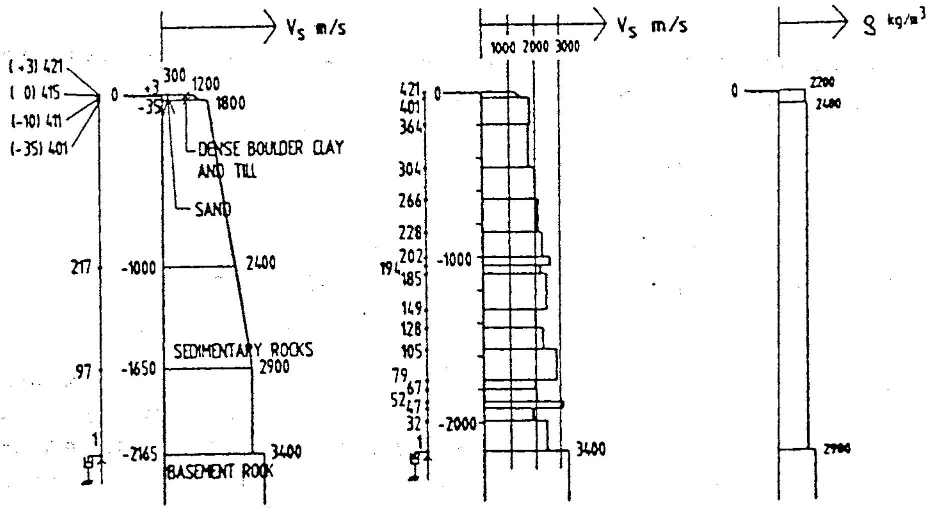


FIGURE 10: Geological models of the Barsebäck site, used for the calculation of the transformation of vertical waves from the basement. The irregular distribution of shear wave velocities is based on data from a deep bore hole at the Barsebäck site.

An example of the results is shown in Figure 11, in the form of Envelope Response Spectra relating to various levels and, for comparison, the corresponding response spectrum relating to outcropping rock at the "typical hard rock site".

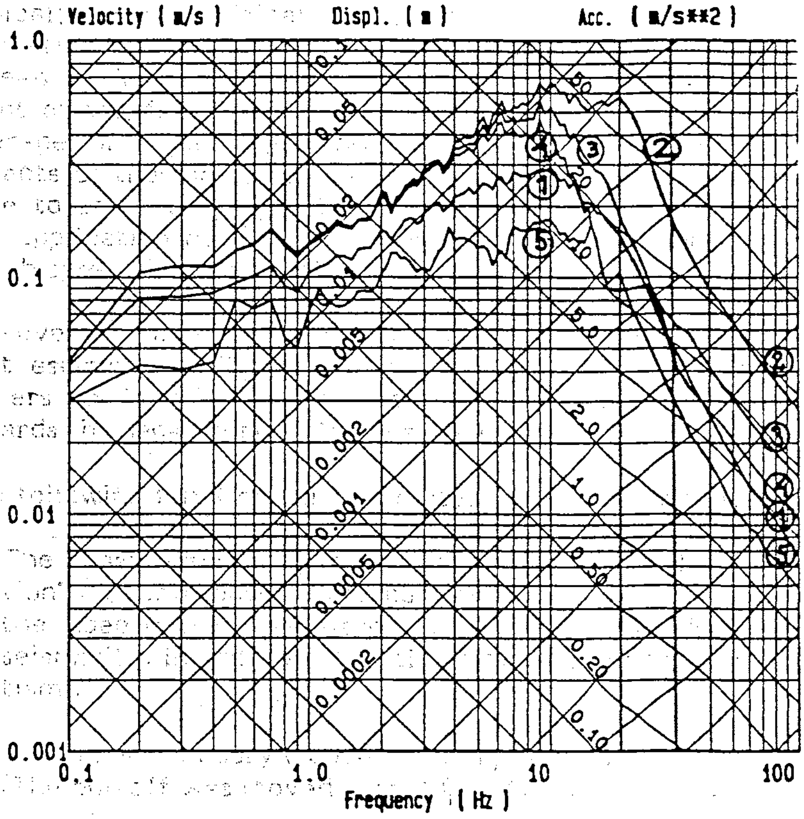


FIGURE 11: Envelope ground response spectra for the probability level 10^{-7}, damping ratio 0.05 and horizontal direction.
Curve 1: "Typical hard rock site"
Curve 2: Barsebäck El. +3 m
Curve 3: Barsebäck El. Zero (MWL)
Curve 4: Barsebäck El. -10 m
Curve 5: Barseväck El. -2165 , (basement)

The effects of amplification due to the wave transmission from hard to softer rocks is evident over the entire spectral frequency range. Within the important frequency range 1-5 Hz this "site amplification" amounts to 30 à 40 per cent. Waves with frequencies exceeding about 4 Hz are additionally amplified when propagating through the soil strata.

The order of amplification was found to be in good agreement with observations from similar sites in Japan (Ref. 26).

4. CONCLUDING REMARKS

4.1 Uncertainty ranges

The ground response spectra developed for the characterization of ground motions in Swedish hard rock have been derived basically from empirical data, including the bases for the transformation from Japanese to Swedish response spectra. The spread of data has been accounted for by a probabilistic treatment of the fundamental parameters, but for other parameters average or other characteristic values have been accepted. Effects of the inevitable spread of such parameter values from case to case are judged to be reasonably well accounted for by the application of a general spread of spectral characteristics, which spread has also been empirically assessed.

However, the averages of the parameter values were assessed by best estimates. Therefore, some of the most important parameters or functions have been selected for examinations as regards the sensitivity of the results to parameter variations.

The following functions or parameters have been studied:

* The "basic seismicity function" or "epicentral density function" (A curve based on "local seismicity" was compared with the spectrum curve based on the average Fennoscandian seismicity, in order to quantify a possible range of conservatism).

* The upper boundary ("cut-off") magnitude or seismic moment. (The cut-off was moved from $M_L = 6.5$ to $M_L = 7.0$.)

* The Japanese response spectrum formulation. (A less conservative formulation, given in Ref. 8, was tested.)

* The characteristic stress drop and the spectral decay factor n. (The ratio SD_S/SD_J was doubled.)

* The "rock quality factor" Q_o and the anelastic attenuation function. (The ratio Q_{oS}/Q_{oJ} was doubled.)

Except for the "seismicity function" and the alternative spectrum formulation, only parameter deviations tending to increase the responses were tested.

The results of the sensitivity tests are summarized graphically in spectral form in Figure 12.

The conclusion is that the sensitivity of the spectral values to parameter variations is moderate and that the proposed spectra appear to have the appropriate position for being regarded as the best estimates when taking all the most probable parameter variations together. Particularly, within the frequency band 2-5 Hz which is of major importance for the reactor buildings and systems, the sensitivity of the spectrum towards the unconservative side appears to be small.

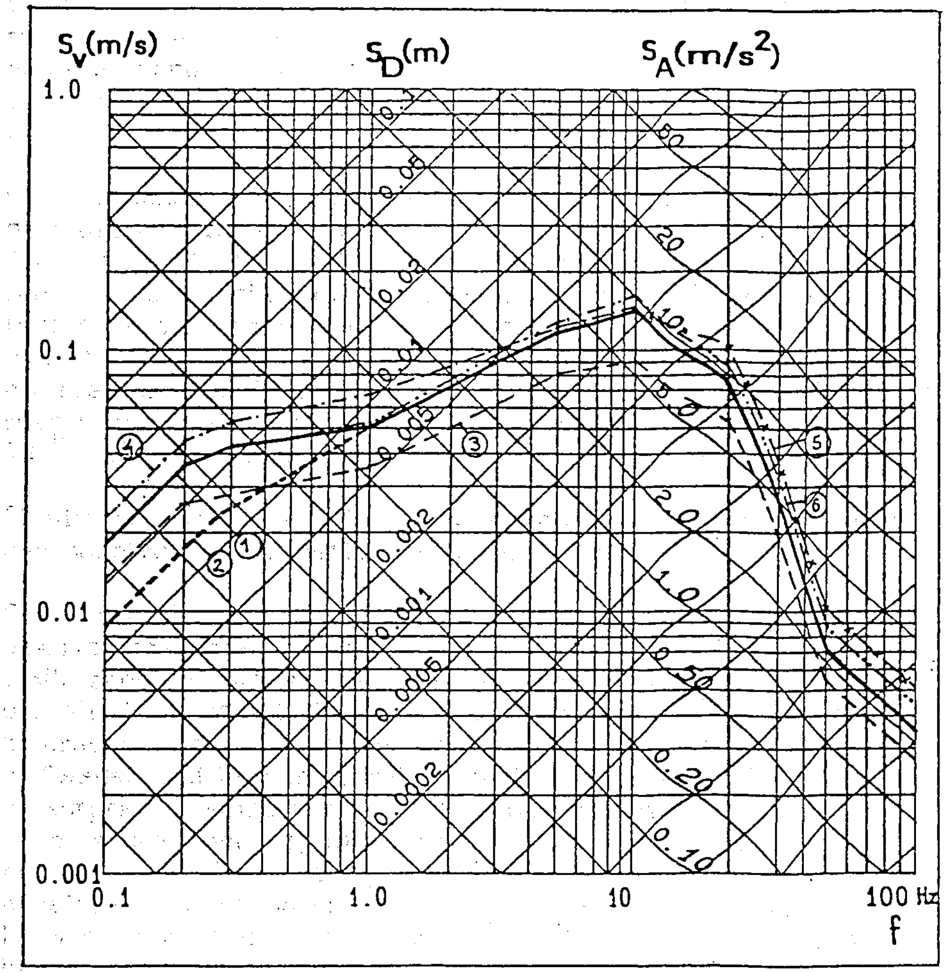


FIGURE 12: Envelope ground response spectrum for horizontal ground motion and structural damping ratio 0.05 (curve 1) compared with spectra adjusted with respect to:

- Alternative Japanese spectrum formulation (curve 2)
- Reduced (local) epicentral density (curve 3)
- Increased cut-off magnitude (curve 4)
- Increased stress drop <u>or</u> increased spectral decay factor (curve 5)
- Increased rock quality factor (curve 6)

4.2 Comparison between the proposed ground response spectra and the original design spectra

In Figure 13 the horizontal Envelope Ground Response Spectrum, (for the damping ratio 0.05) is compared with the design spectrum specified for Forsmark 3 and Oskarshamn 3. This design spectrum was intended to represent the probability level 10^{-5}, and the anchor point of the spectrum, the peak ground acceleration, was therefore assessed with that probability level as a target.

For frequencies exceeding about 10 Hz the agreement is rather good between the original design spectrum and the new spectrum for the level 10^{-5}. For low frequencies the original design spectra are associated with much lower probabilities, not to say that they are unrealistic, even for extreme events. Within the important range 2-5 Hz, (the range of fundamental frequencies of reactor buildings and containments) the original design spectrum appears to correspond to the probability range of 10^{-8} - 10^{-6} annual events per site.

Similar relations are obtained when comparing the original and new spectra for the vertical direction of motion.

Obviously, the specification of a design basis earthquake on the basis of the generalized spectra given in US NRC Reg. Guide 1.60, anchored at a peak ground acceleration, may be quite unrealistic, particularly when the seismic hazard is expected to be predominantly related to near-field earthquakes as is the case in Sweden and in many other intraplate regions. This should not be surprising, since the NRC RG 1.60 Spectra are intended to cover a great variety of seismic events, including large distant earthquakes. The scaling of the spectra to the peak ground acceleration may, however, become quite misleading, particularly when near-field earthquakes give the predominant seismic hazard contribution. In the near-field, before the high-frequency waves have attenuated very much, the peak ground acceleration is determined to a large extent by these waves which are not very strongly related to the lower-frequency waves of a spectrum. Parameters such as the peak ground velocity which are more strongly related to the low frequency waves and thus to the fundamental fault mechanism, constitute more appropriate anchor points.

The most reliable spectrum, corresponding to a certain type of events, is, however, determined on the basis of direct empirical relationships between the whole spectral function and the fundamental event specific parameters, e.g. M_0 and R, as in the present study and in the basis for the Japanese standard spectra.

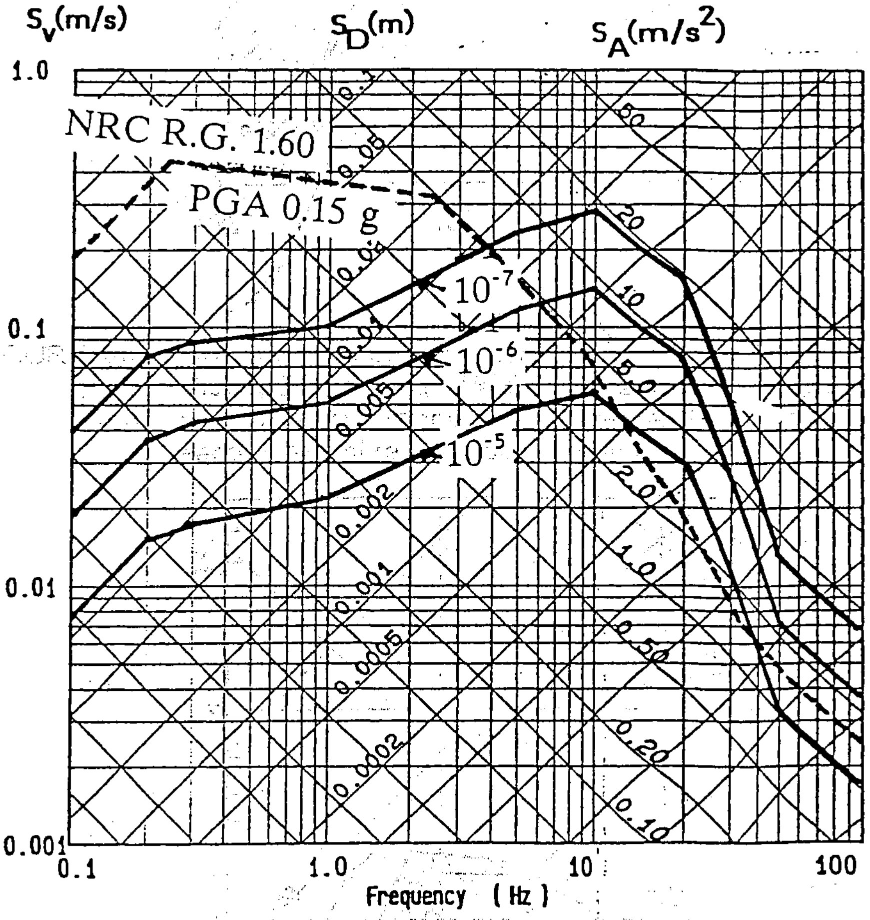


FIGURE 13: The original Swedish design response spectrum, based on RG 1.60 and scaled to PGA = 0.15 g for horizontal acceleration, compared with suggested Envelope Ground Response Spectra for 10^{-5}, 10^{-6} and 10^{-7} annual events per site

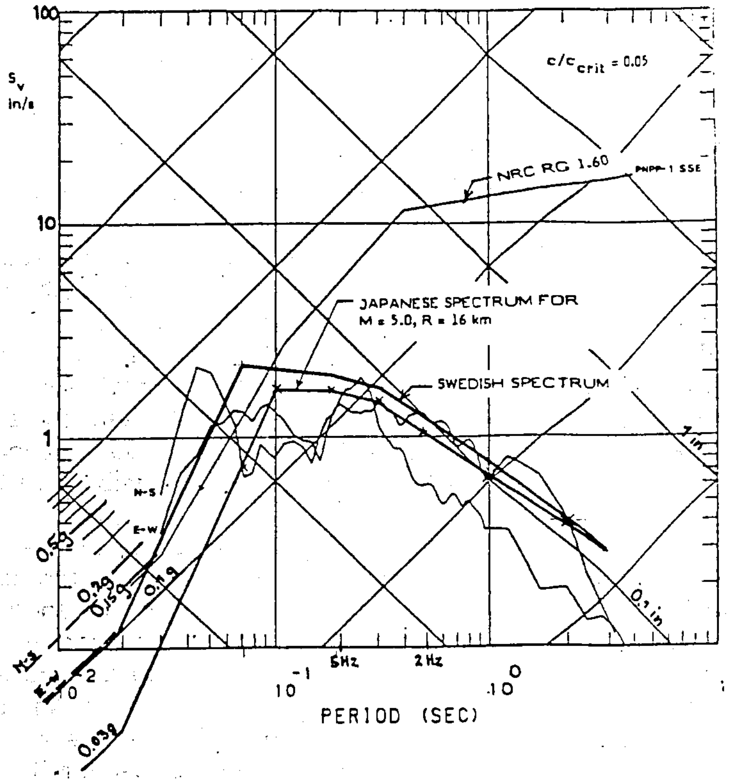


FIGURE 14a: Ground response spectra from the Leroy main shock, January 31, 1986, compared with Japanese and Swedish spectra for the actual estimated earthquake size and focal distance.

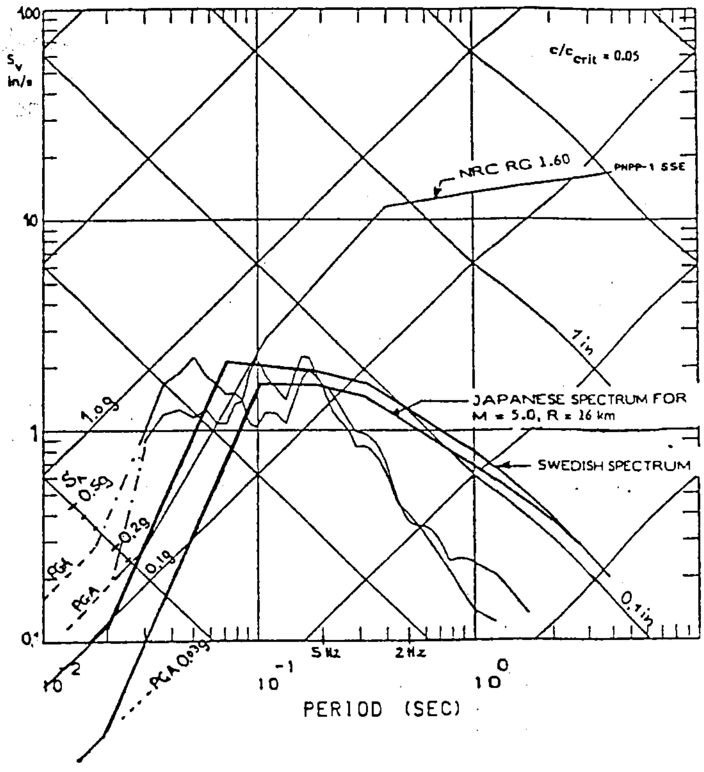


FIGURE 14b Ground response spectra from the New Brunswick aftershock, March 31, 1982, compared with Japanese and Swedish spectra for the actual estimated earthquake size and focal distance.

4.3 Comparison between the proposed spectra and spectra from other intraplate regions

In the long-term perspective the outline of response spectra for Swedish hard rock sites on the basis of data from interplate regions may obviously be regarded as a temporary approach, to be validated and probably improved in the light of an increasing database from intraplate regions which are similar to Fennoscandia from a geological and seismotectonical point of view. A few near-field records from recent earthquakes in Eastern North America have already been compared with Swedish "event-specific" response spectra for the actual seismic moment (about 10^{16} Nm) and focal distance (about 16 km).

As demonstrated in Figure 14 the spectra of the North-American earthquakes do not deviate very much from the proposed Swedish spectra. The content of high-frequency waves in the near-field of the North-American earthquakes was, however, even greater than would be predicted by the Swedish spectra. More data are needed to clarify if this was due to an extreme stress drop or if it shall be taken as an indication that the wave content within this range is still somewhat underestimated.

Stockholm May, 1989

Alf Engelbrektson

Alf Engelbrektson

REFERENCES

1. R. Slunga: Seismicity of Southern Sweden, National Defence Research Institute, Dep. 2 Report C20543-T1, Stockholm, July, 1984.

2. T. Katayama: An engineering prediction model of acceleration response spectra and its application to seismic hazard mapping. Earthquake Eng. and Structural Dynamics, Vol 10, p. 149-163 (1982).

3. S. Okamoto: Introduction to earthquake engineering. University of Tokyo Press (1984).

4. R. Slunga: Seismicity of Southern Sweden. National Defence Research Institute, Dep. 2, Report C20572-T1, Stockholm, April, 1985.

5. N.N. Ambraseys: The seismicity of Western Scandinavia. Earthquake Engineering and Structural Dynamics, Vol. 13, 1985.

6. Seismic hazard characterization of the Eastern United States - Methodology and preliminary results for ten sites. Lawrence Livermore National Laboratory (NUREG CR/37) 1984.

7. P. Norrman, R. Slunga: A seismic hazard study for Ringhals. National Defence Research Institute, Dep. 2., May 25, 1984.

8. T. Hisada, Y. Ohsaki, M. Watabe, T. Ohta: Design spectra for stiff structures on rock.
   Proc. of the Second International Conference on Microzonation for Safer Construction, San Francisco, 1978.

9. Y. Ohsaki: Guideline for evaluation of basic design earthquake ground motion. Appendix to Regulatory Guide for Aseismic Design of Nuclear Power Facilities, Japan, 1979.

10. M. Watabe, M. Tohdo: Analyses on various parameters for the simulation of three-dimensional earthquake ground motions. 5th Int. Conf. on Structural Mechanics in Reactor Technology (SMIRT), Berlin, 1979.

11. T. Ohta, H. Koshida, M. Takemura, S. Hiehata, H. Morishita: Characteristics of seismic motions on rock sites through highly accurate strong motion earthquake observation network. 7th Int. Conf. on Structural Mechanics in Reactor Technology (SMIRT), Chicago, 1983.

12. V.I. Keilis-Borok: On the estimation of the displacement in an earthquake source and of source dimensions, Ann. Geofis., 12, 1959, p. 205-214.

13. J. Boatwright: A spectral theory for circular seismic sources; simple estimates of source dimension, dynamic stress drop, and radiated seismic energy. Bull. Seism. Soc. Am., 70, 1980.

14. P.C. Jennings, G.W. Housner, N.C. Tsai: Simulated Earthquake Motions for Design Purposes. Proc. of 4th World Conf. on Earthq. Eng., 1969.

15. G. Larsson, H. Olsson: Study of the development of the spectral response as a function of time. (Report Nov. 6. 1986 to the Swedish State Power Board in Sweden.)

16. J.H.K. Tang: Characteristics of design earthquakes for CANDU nuclear power plants in eastern Canada. (SMIRT, 1987)

17. R. Slunga: Peak values and amplitude spectra for ground motions of Swedish earthquakes. National Defence Research Institute. Working report to the Swedish Seismic Safety Project, 1988.

18. Won-Young Kim: Simulation of near-field ground motion from a circular fault in a layered crust by using synthetic seismograms. Uppsala University, Seismological Department, Report No. 3-87 (Report to the Swedish Seismic Safety Project.)

19. H.B. Seed, J. Lysmer: The seismic soil-structure interaction problem for nuclear facilities. University of California, Berkeley, April 1980.

20. ADINA program descriptions, i.e. Report AE 83-4, 1983.
ADINA ENGINEERING and SOLVIA ENGINEERING
(Gunnar Larsson, Västerås).

21. B. Löfquist, Kjessler & Mannerstråle Co: Barsebäck site investigation report, Oct. 1967. (In Swedish)

22. Orrje & Co: Barsebäck site investigation reports, Nov. 1969 and July 1976. (In Swedish)

23. L. Tallbacka: OPAP Completion Report, Barsebäck -1, Nov. 1972.

24. B. Ringberg: Description to the quaternary map, Malmö NV. SGU, Stockholm, 1976.

25. K. Aki: Scaling law of seismic spectrum. Journal of Geophysical Research, Vol. 72, No. 4, 1967.

26. M. Watabe et al: Simplified seismic analysis mehtods in Japan. Report to EPRI's Symposium, Dec. 1988, Orlando, Florida.

27. R. Slunga: The earthquakes of the Baltic shield. Swedish National Defence Research Institute. June 1990. Also SKB's Techn. Rep. 90-30.

28. F Ringdal. E. Husebye, H. Bungum, S. Mykkelveit, O. Sandvin: Earthquake hazard offshore Norway. NTNF/NORSAR Contribution No. 302. Feb. 1982.

29. S. Gregersen, P.W. Basham: Earthquakes at North-Atlantic passive margins - Neotectonics and postglacial rebound (Congress proceedings) NATO ASI Series C, Vol. 266. Publ. by Kluwer,1989.

30. R. Arvidson: Seismodynamics of Sweden deduced from earthquake-source and seismic-wave characteristics. Uppsala University 1988.

31. P. Norman, R. Slunga: A seismic study for Ringhals. Report to the State Power Board, May 25, 1984.

32. K-A. Kornfält, K. Larsson: Geological maps and cross-sections of Southern Sweden. SKB Techn. Rep 87-24 (1987).

LIST OF SYMBOLS

Seismic source parameters

Seismic moment	M_O
Local magnitude	M_L
"Swedish local magnitude"	M_{LW}
"Japanese magnitude"	M
Static stress drop	SD
Fault area	A_f
Fault length	l
Fault radius	a
Fault slip	s
Focal depth	Z

Wave path parameters

Focal distance	R
Epicentral distance	X
Angle of direction (from site to source)	ϕ
Wave velocities	v_p, v_s

Ground response parameters

Fourier amplitude spectra	
- general symbol	$F(f)$ or $F(\omega)$
- displacement spectra	$F_D(f)$ or $F_D(\omega)$
- velocity spectra	$F_V(f)$ or $F_V(\omega)$
- acceleration spectra	$F_A(f)$ or $F_A(\omega)$
Response spectra, correspondingly	$S(f)$, $S(\omega)$, $S(T)$
- displacement spectra	$S_D(f)$ etc
- velocity spectra	$S_V(f)$ etc
- acceleration spectra	$S_A(f)$ etc
Duration of ground motion	t_d
Corner frequency	f_c
Peak ground acceleration	PGA
Peak ground velocity	PGV
Peak ground displacement	PGD
Fourier spectral amplitudes	F_D, F_V, F_A
Response spectral amplitudes	S_D, S_V, S_A
High-frequency spectral slope	n
Particle motions, horizontal	$x, \dot{x}, \ddot{x}$
Particle motions, horizontal	$y, \dot{y}, \ddot{y}$
Particle motions, vertical	$z, \dot{z}, \ddot{z}$
(Index G for free-field ground response)	x_G etc
Relative particle motions	$u, \dot{u}, \ddot{u}$
Structural damping ratio	c/c_{crit}

Statistical notations

$N(M_o)$	recurrence frequency, annual number of events within a certain area or volume, exceeding a certain seismic moment.
$\Delta N(M_o)$	incremental occurrence rate, i.e. for increments of M_o.
N_A	recurrence frequency per unit area (sqkm) or "epicentral density" of occurrence.
N_V	$= N_A \times p_Z$ recurrence frequency per unit volume at a certain depth ("volume density" or "hypocentral density" of occurrence), where
p_Z	represents the vertical probability distribution, expressed as the fraction of the events N_A that are expected to occur within each incremental km of depth.

APPENDIX 1

P4672-001
Project
SEISMIC SAFETY

SUMMARY REPORT

CHARACTERIZATION OF SEISMIC GROUND MOTIONS FOR PROBABILISTIC ANALYSES OF NUCLEAR FACILITIES IN SWEDEN

ENVELOPE GROUND RESPONSE SPECTRA FOR A TYPICAL HARD ROCK SITE

E17/15fc-01

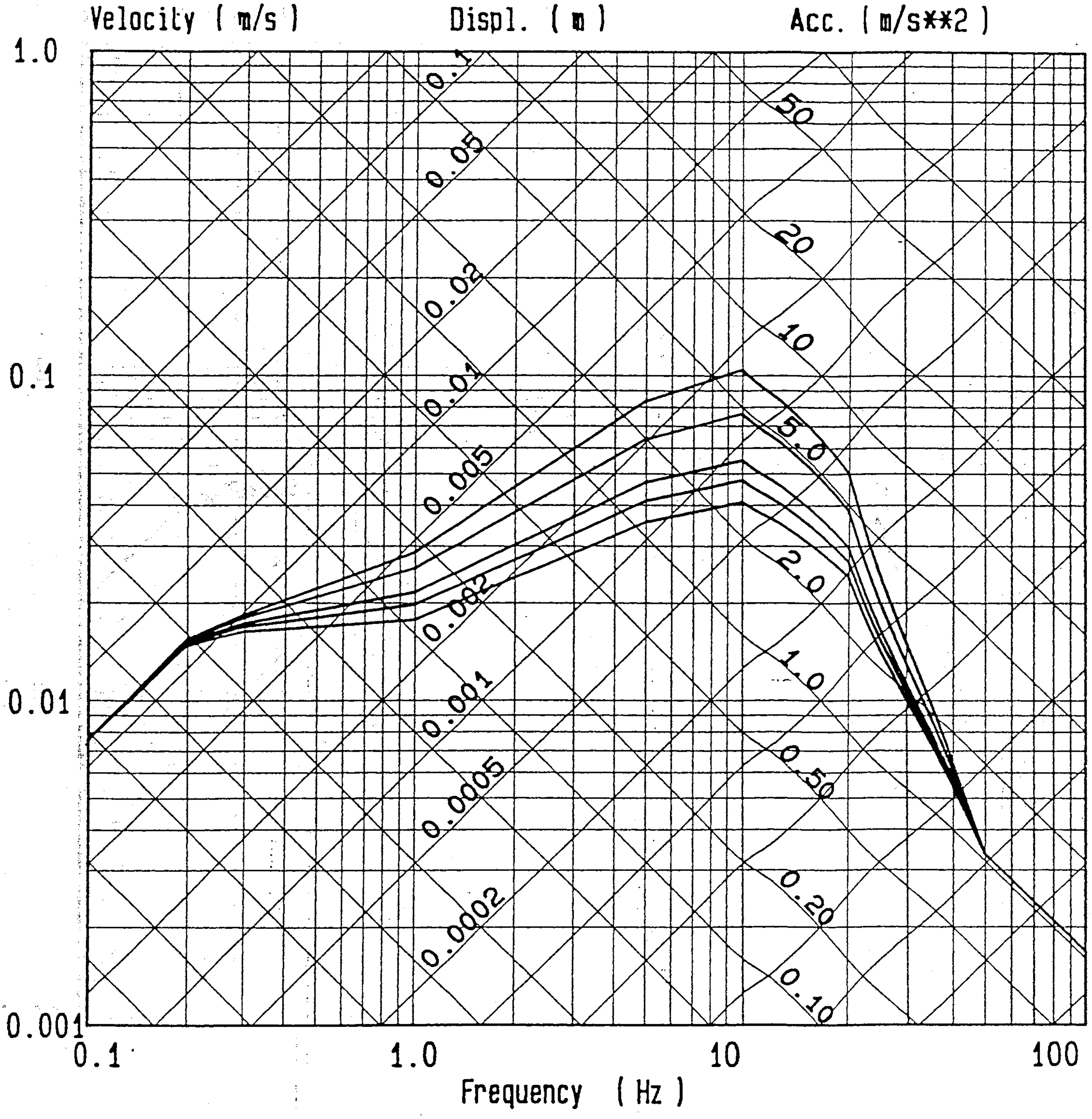
VBB

SEISMIC SAFETY

HORIZONTAL ENVELOPE SPECTRA

PROBABILITY LEVEL: 1.0E-5 DATE: 1988-06-10

DAMPING RATIO : 0.005 0.02 0.05 0.07 0.10



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SEISMIC SAFETY

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PROBABILITY LEVEL: 1.0E-6

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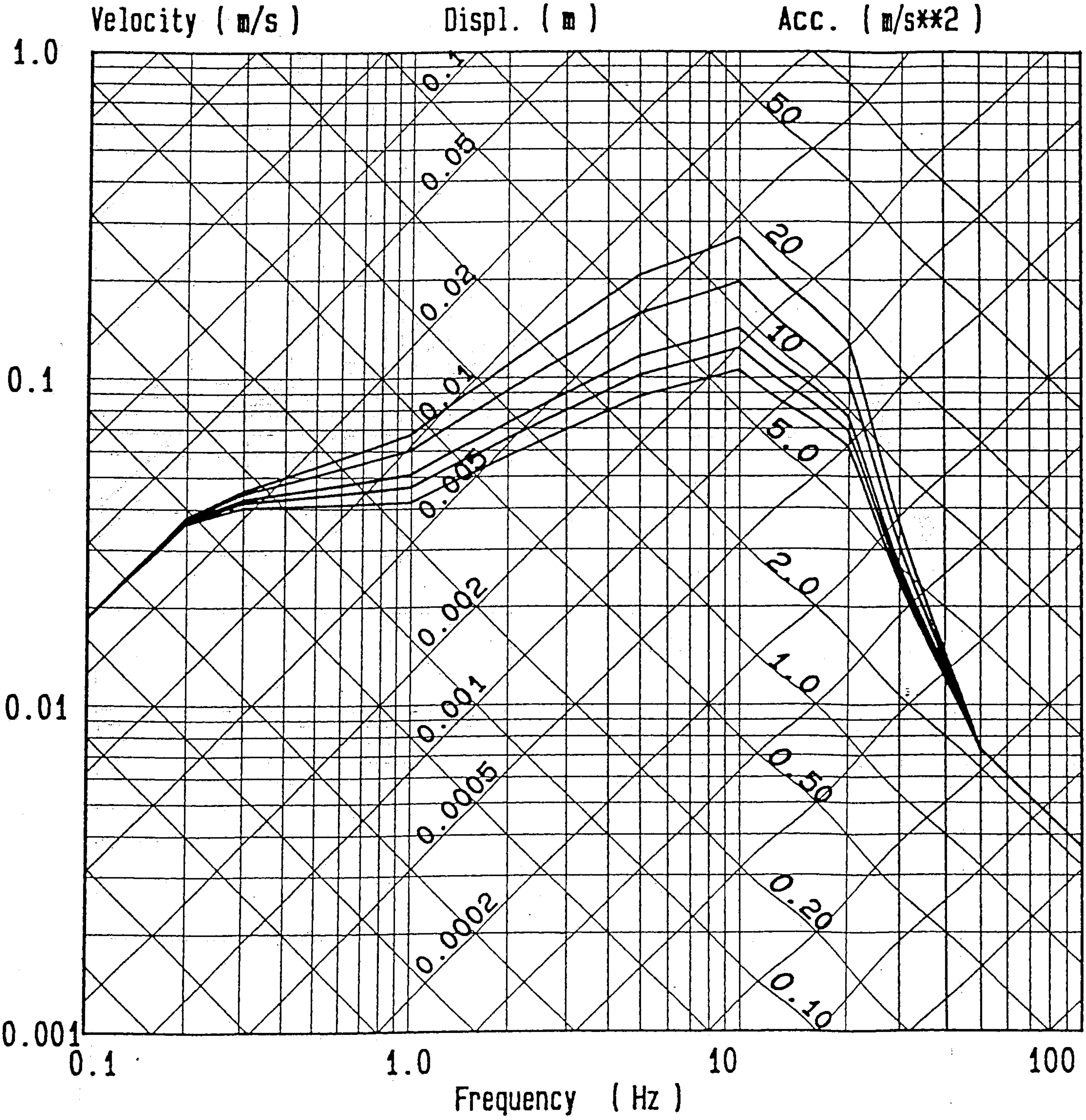

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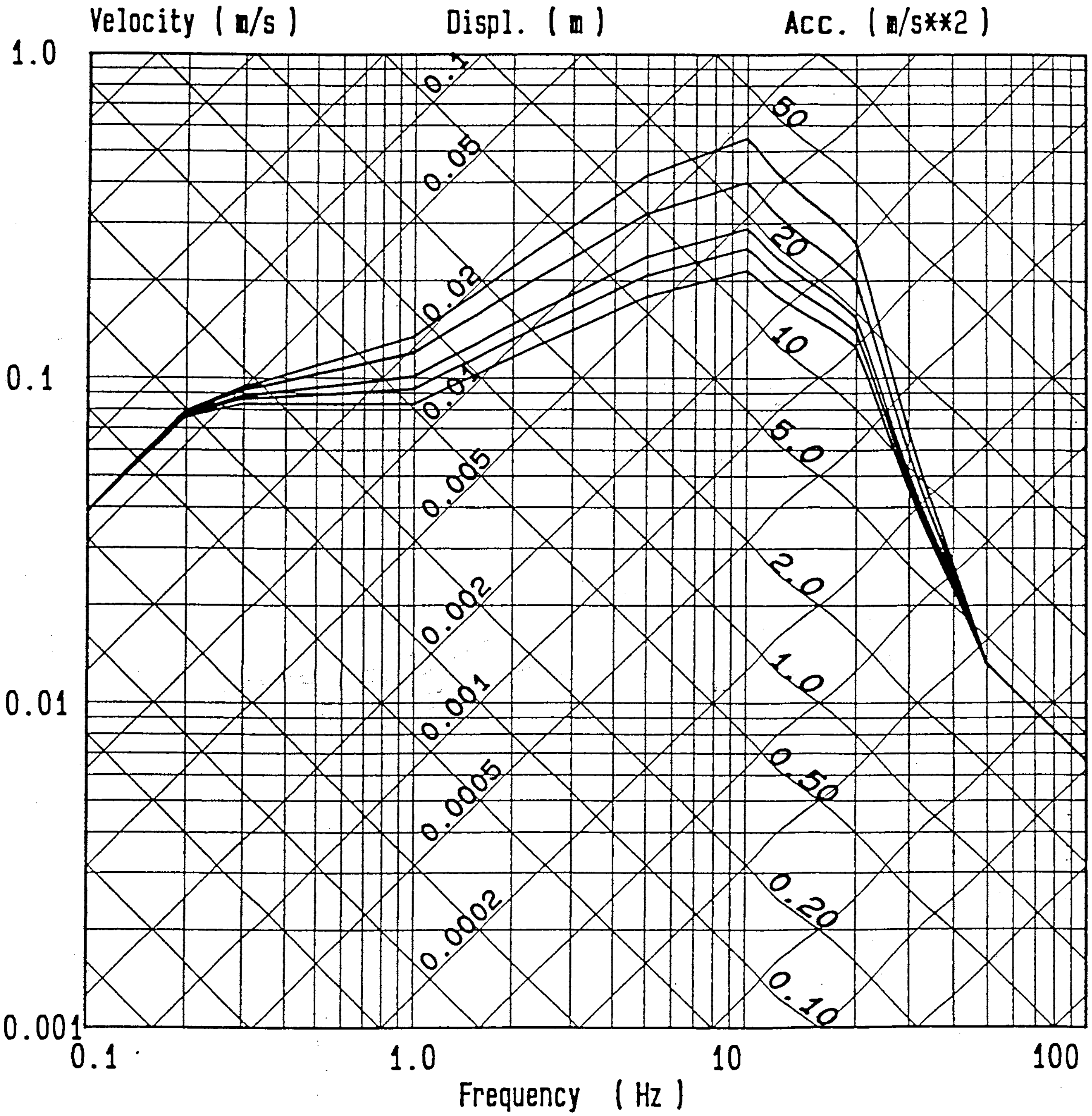
SEISMIC SAFETY

HORIZONTAL ENVELOPE SPECTRA

PROBABILITY LEVEL: 1.0E-7 **DATE: 1988-06-10**

DAMPING RATIO : 0.005 0.02 0.05 0.07 0.10



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SEISMIC SAFETY

VERTICAL ENVELOPE SPECTRA

PROBABILITY LEVEL: 1.0E-5

DATE: 1988-06-10

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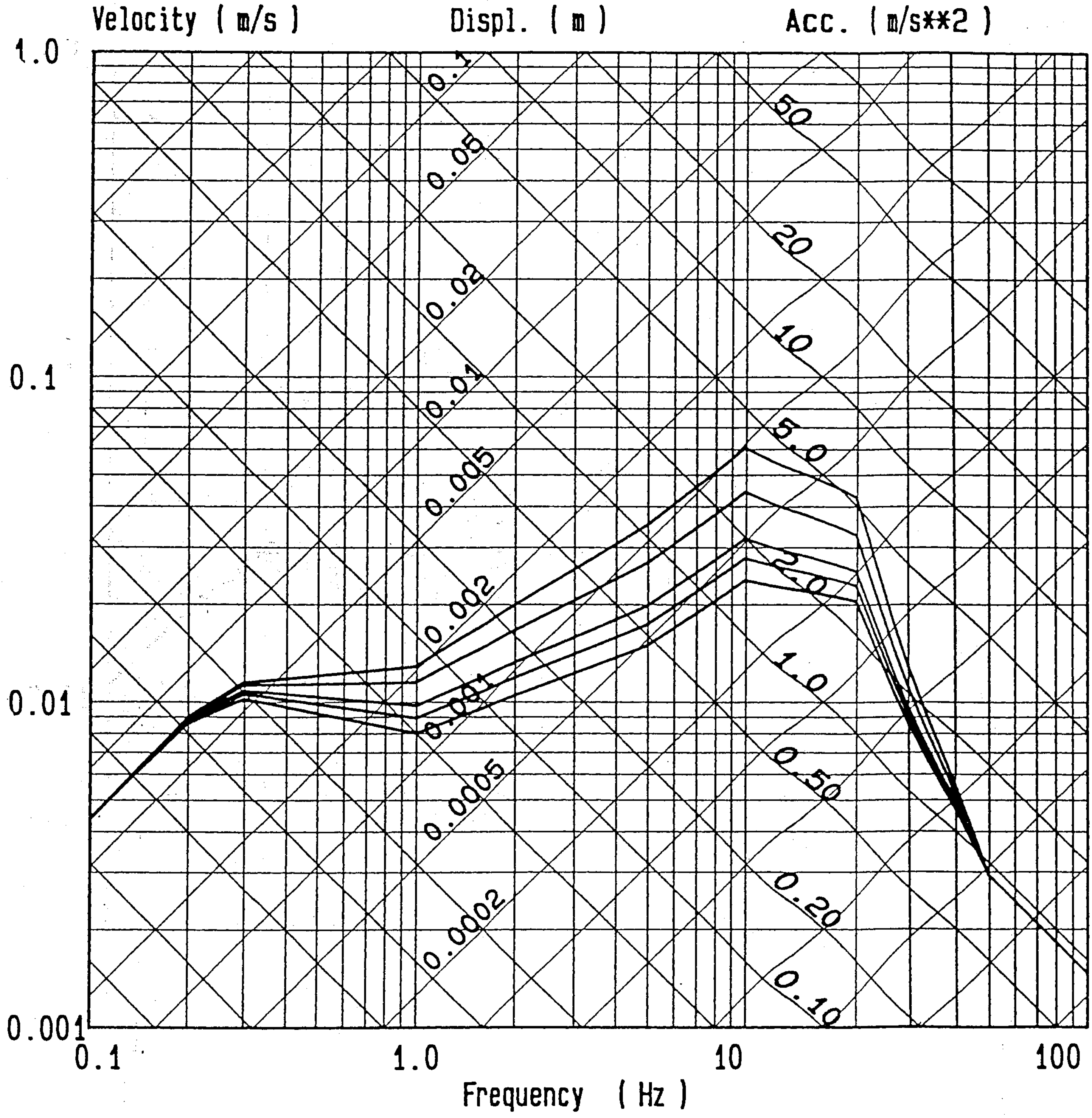

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SEISMIC SAFETY
VERTICAL ENVELOPE SPECTRA
PROBABILITY LEVEL: 1.0E-6

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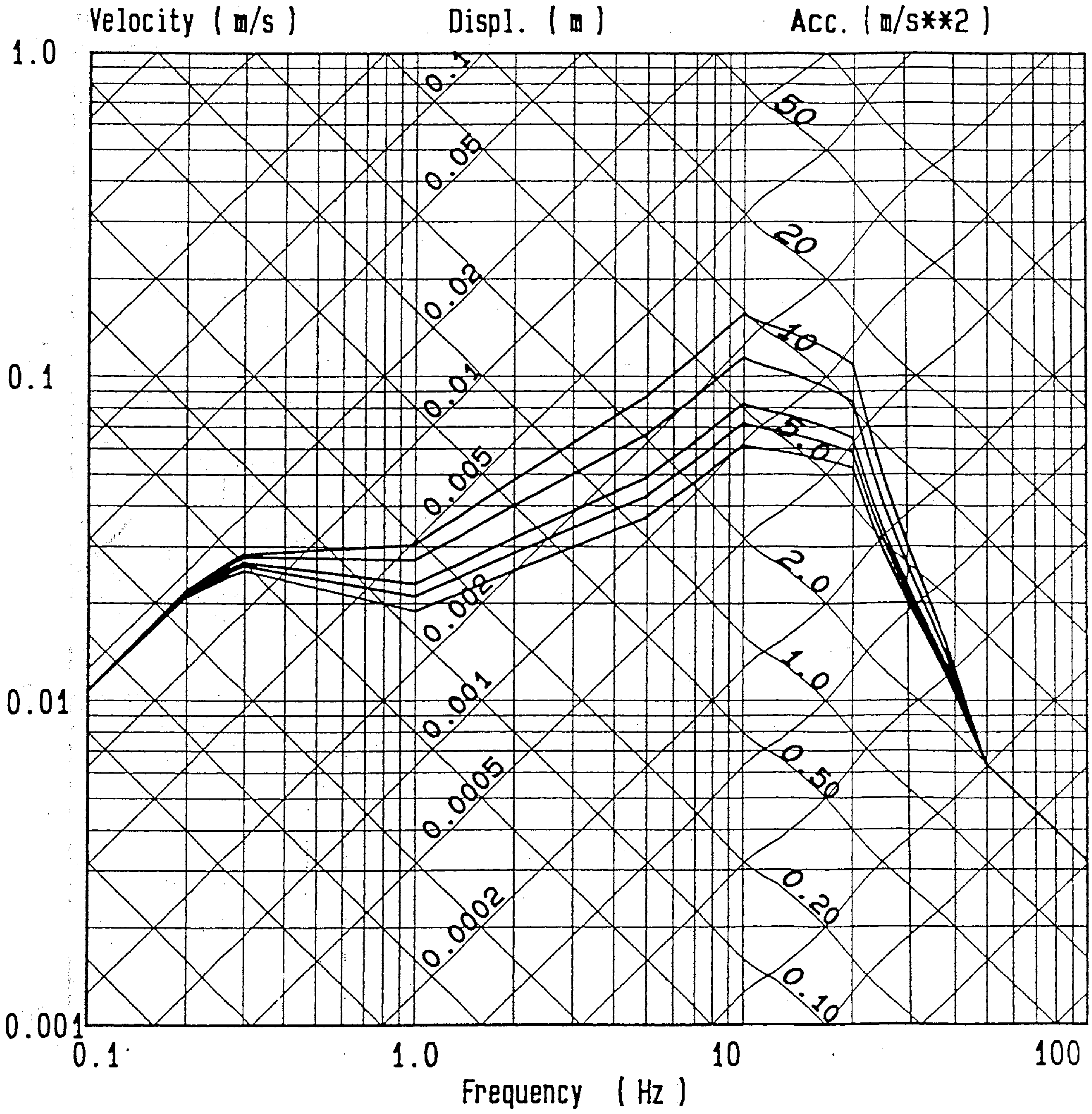

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SEISMIC SAFETY

VERTICAL ENVELOPE SPECTRA

PROBABILITY LEVEL: 1.0E-7 DATE: 1988-06-10

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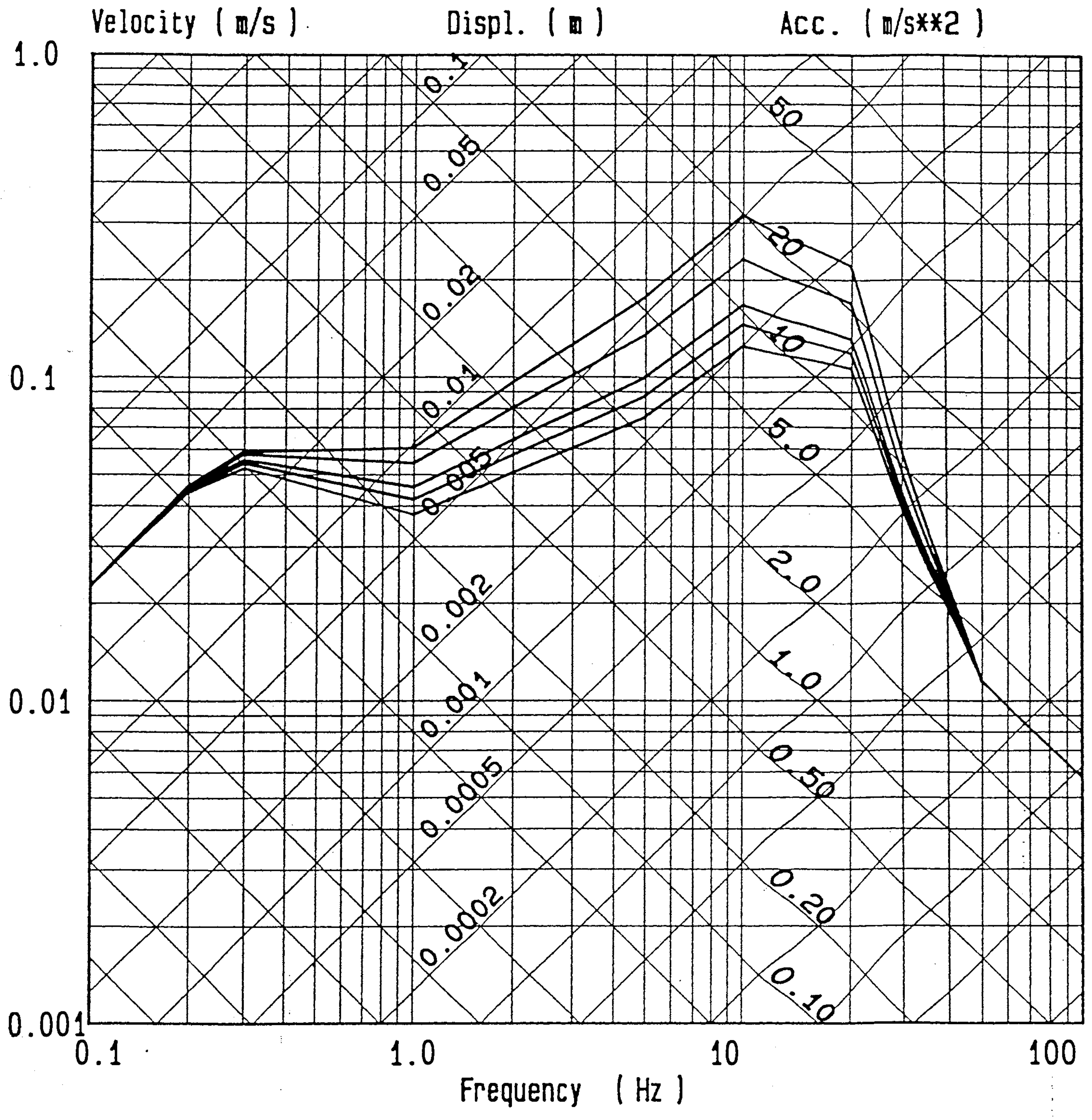


P4672-001
Project
SEISMIC SAFETY

SUMMARY REPORT

CHARACTERIZATION OF SEISMIC GROUND MOTIONS FOR PROBABILISTIC ANALYSES OF NUCLEAR FACILITIES IN SWEDEN

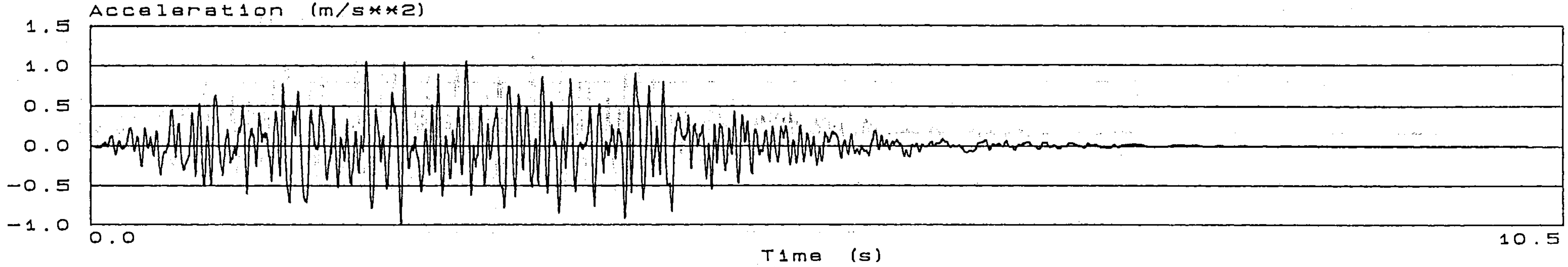
SYNTHETIC GM TIME-HISTORIES FOR A TYPICAL HARD ROCK SITE

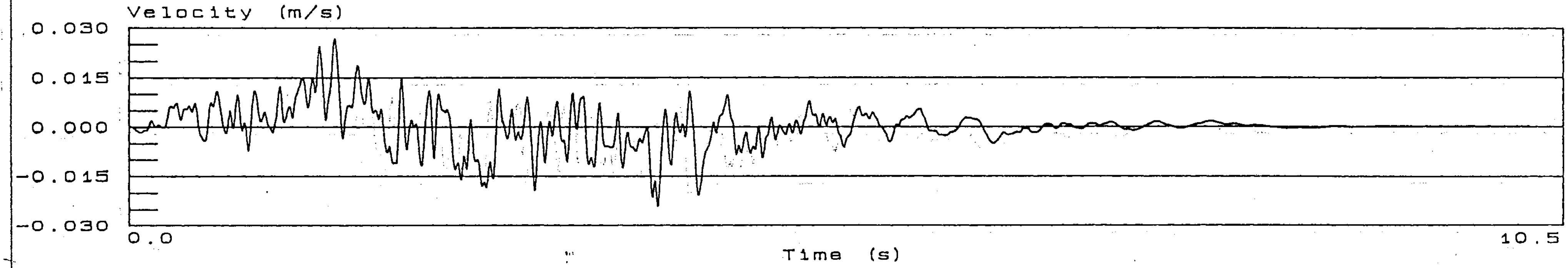
E17/15fc-01

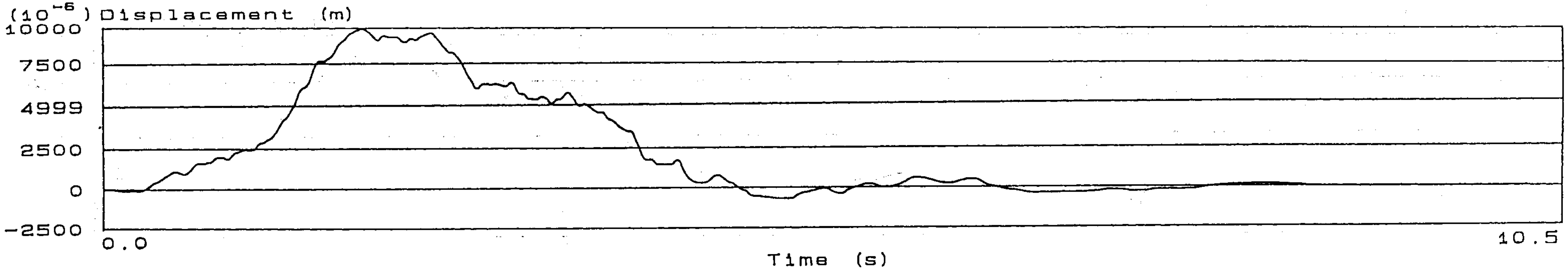
TIME HISTORY BASED ON ENVELOPE SPECTRA

GM direction: Horizontal 1
Envelope spectrum exceedance freq. E-5

DATE: 1988-06-12







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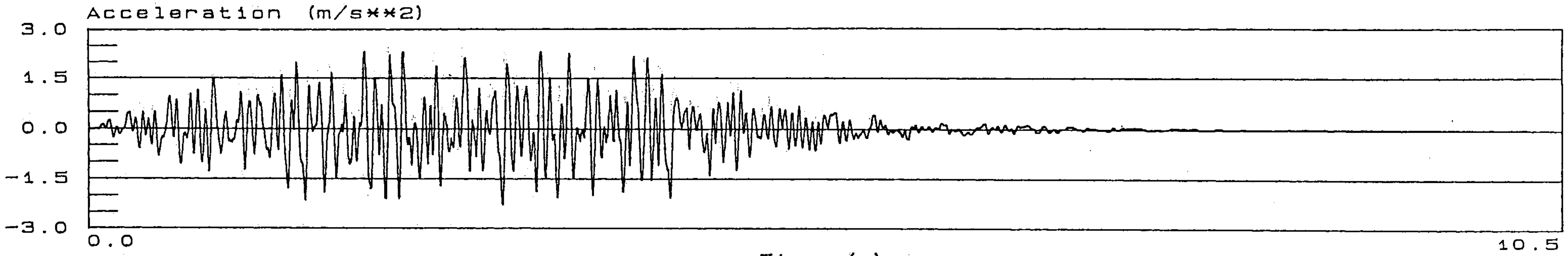
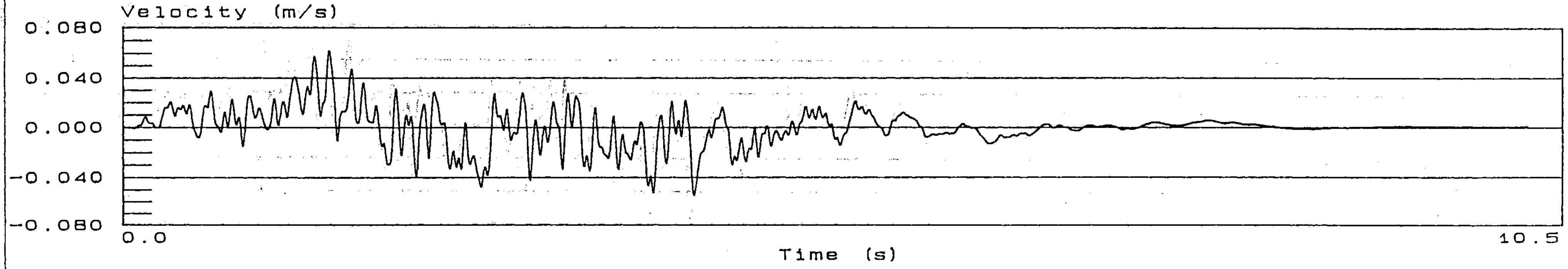
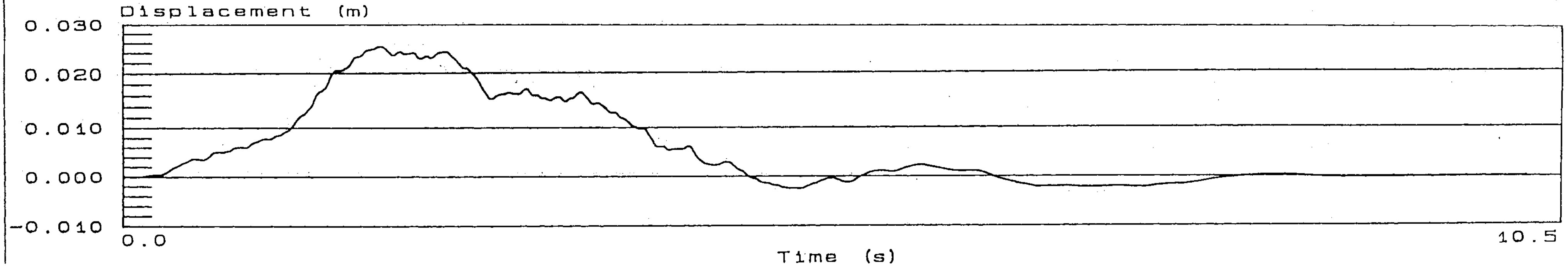
TIME HISTORY BASED ON ENVELOPE SPECTRA

GM direction: Horizontal 1
Envelope spectrum exceedance freq. E-6

DATE: 1988-06-12





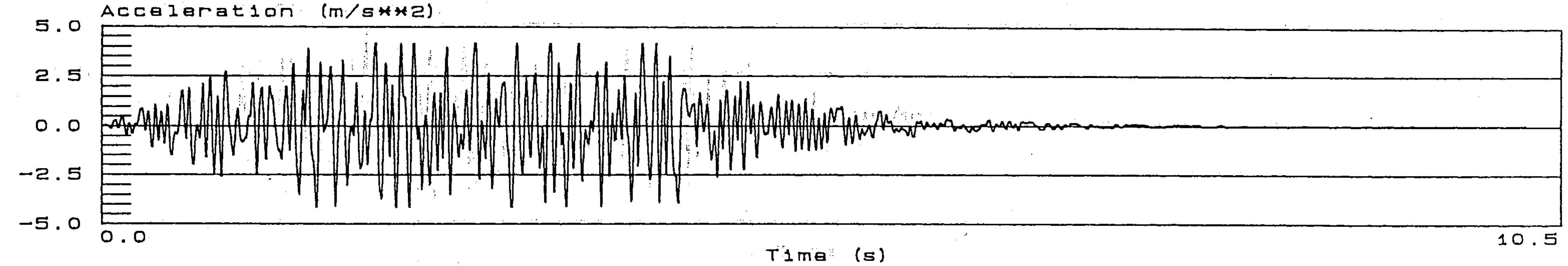


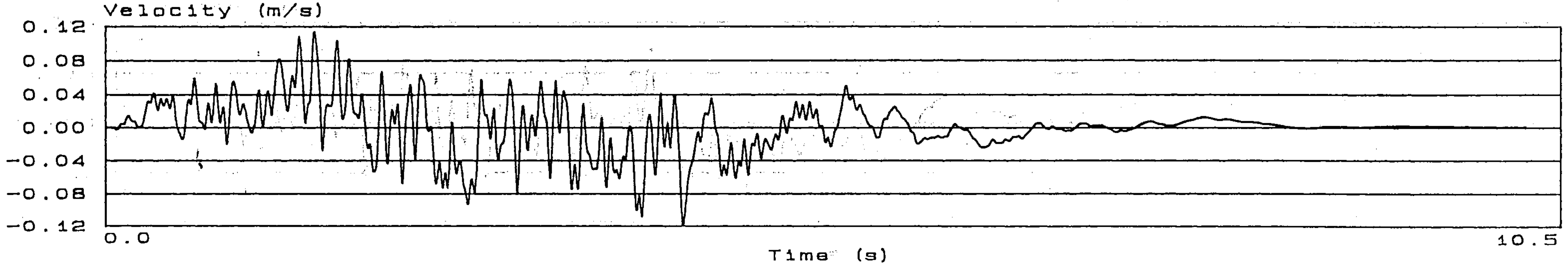
TIME HISTORY BASED ON ENVELOPE SPECTRA

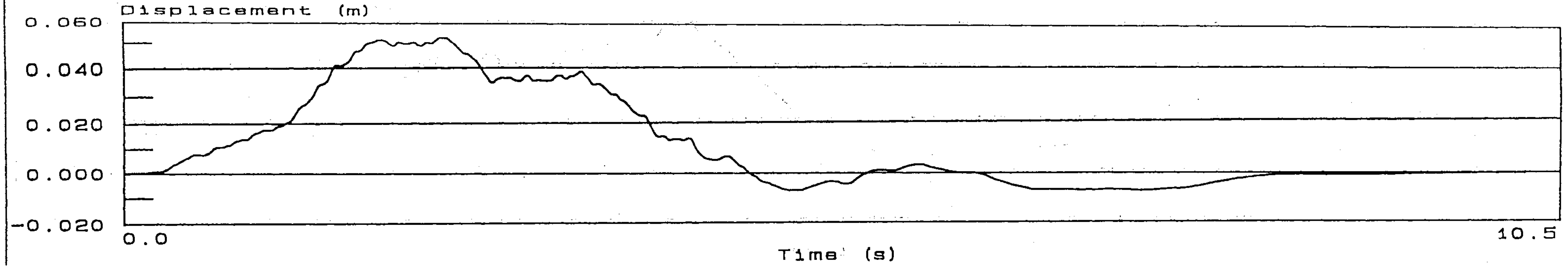
GM direction: Horizontal 1

Envelope spectrum exceedance freq. E-7

DATE: 1988-06-12





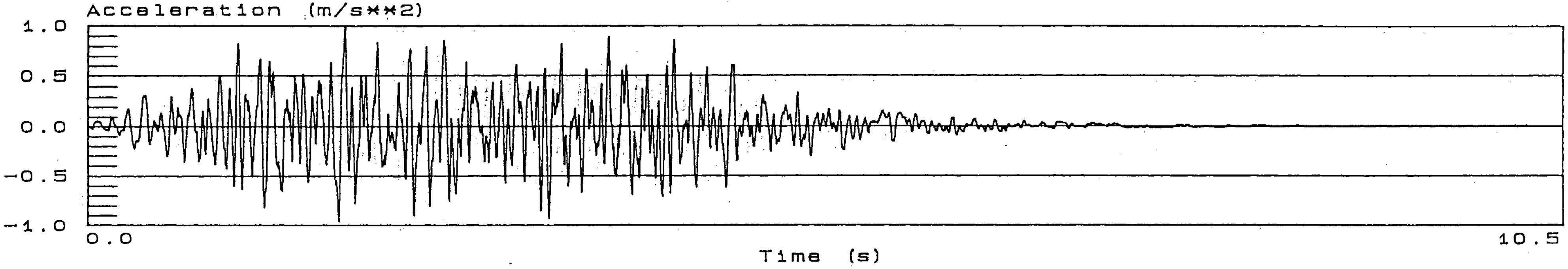


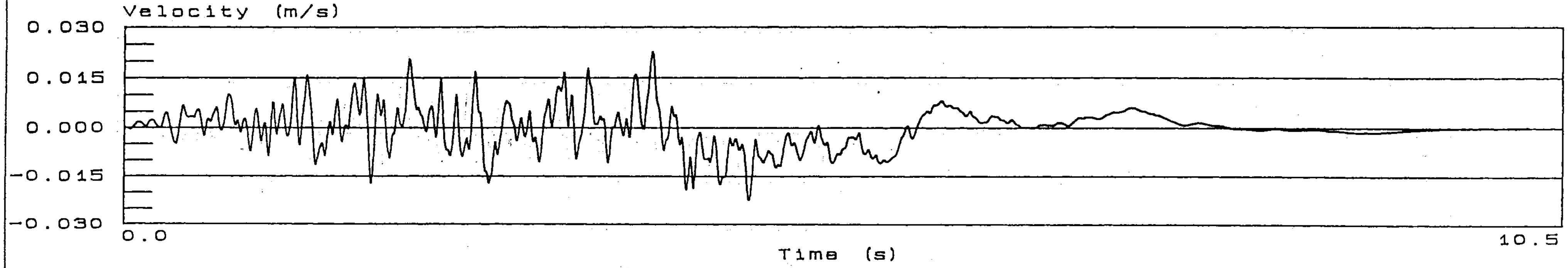
TIME HISTORY BASED ON ENVELOPE SPECTRA

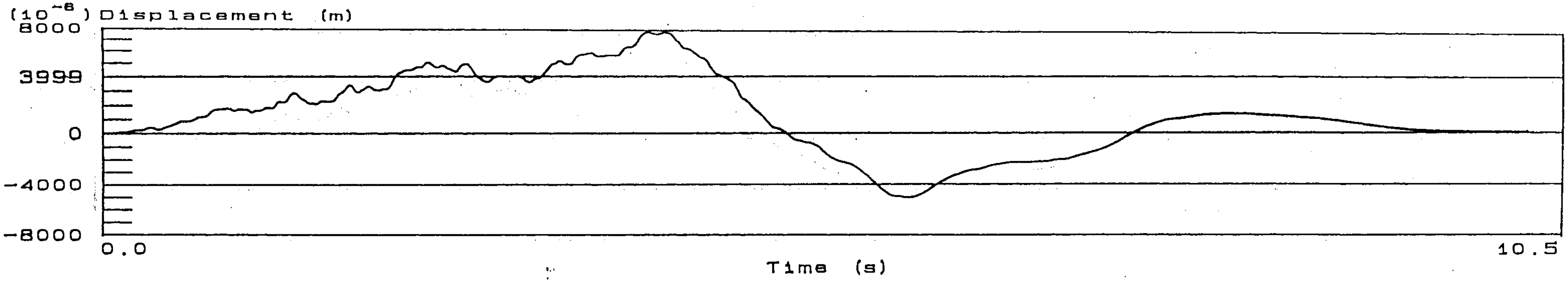
GM direction: Horizontal 2

Envelope spectrum exceedance freq. E-5

DATE: 1988-06-12





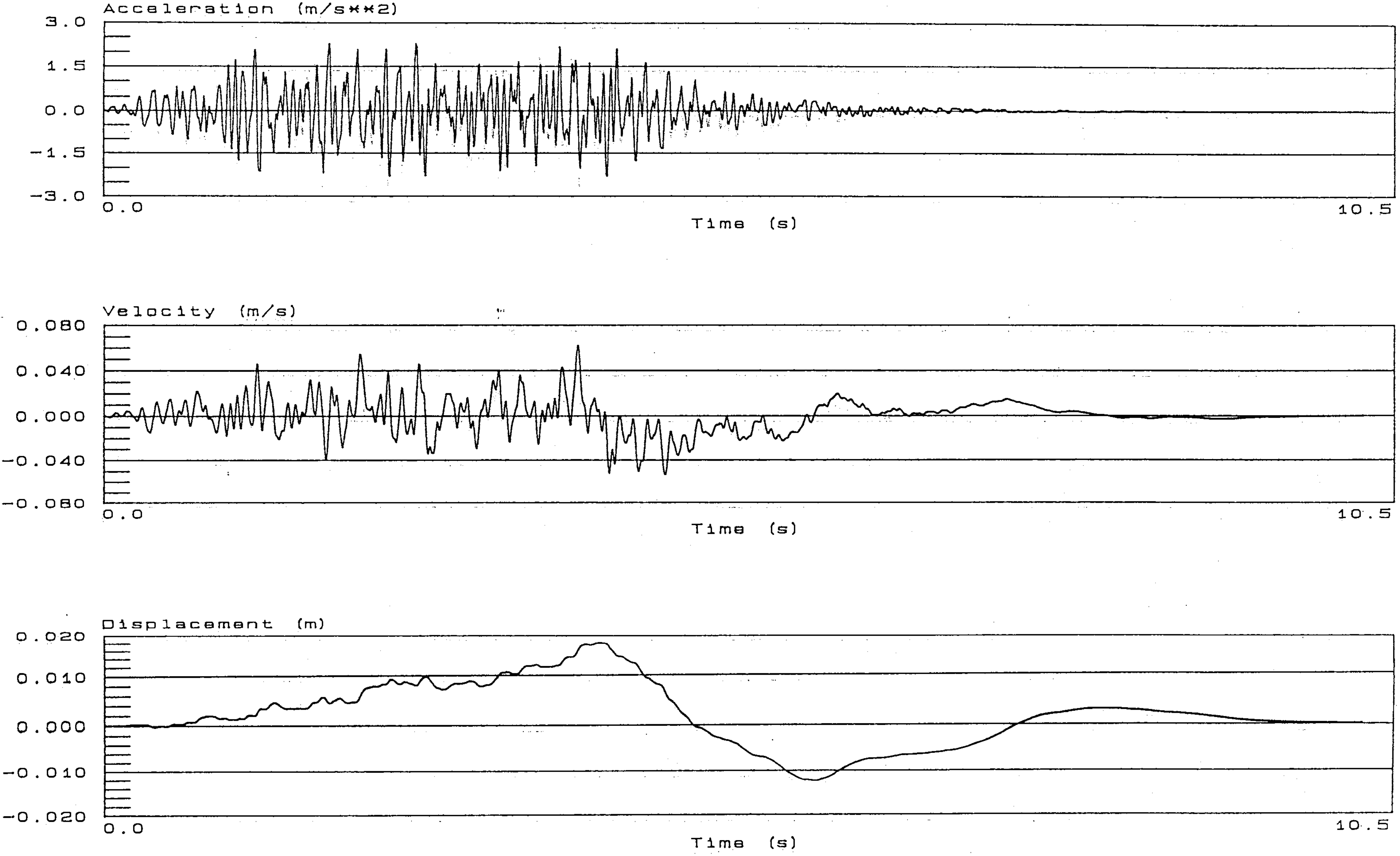


VBB

TIME HISTORY BASED ON ENVELOPE SPECTRA

GM direction: Horizontal 2
Envelope spectrum exceedance freq. E-6

DATE: 1988-06-12



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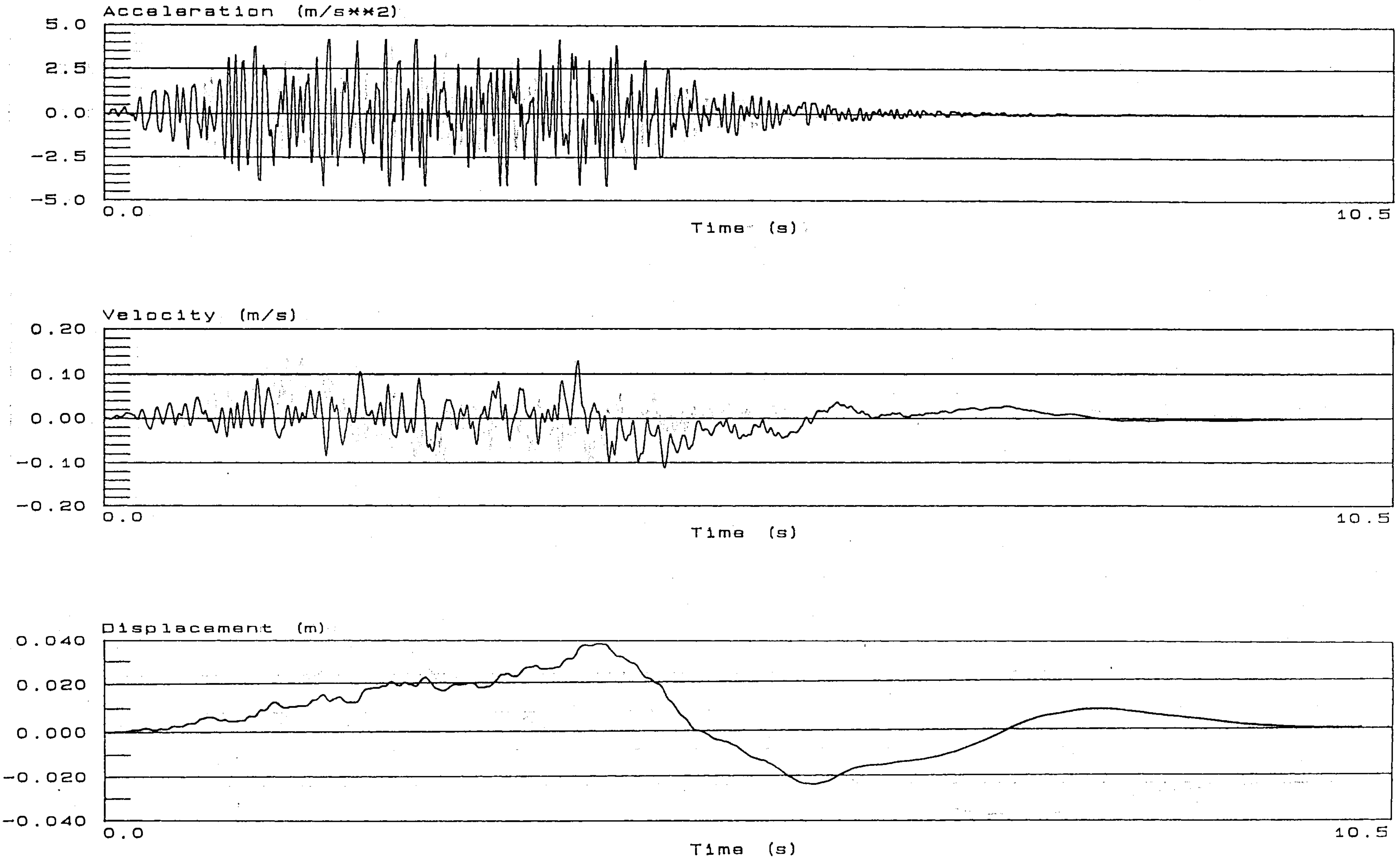
TIME HISTORY BASED ON ENVELOPE SPECTRA

GM direction: Horizontal 2

Envelope spectrum exceedance freq. E-7

DATE: 1988-06-12



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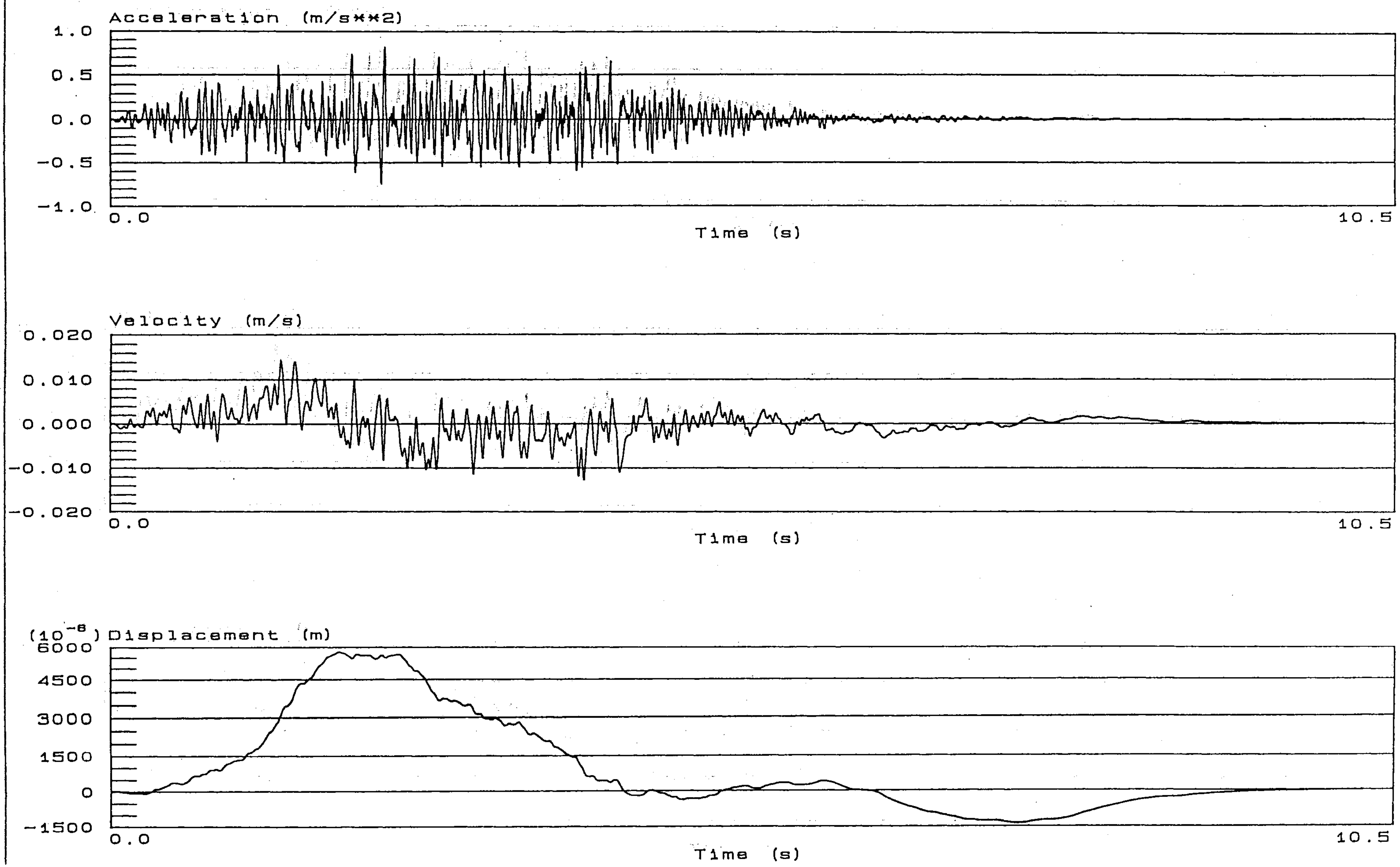
GM direction: Vertical

Envelope spectrum exceedance freq. E-5

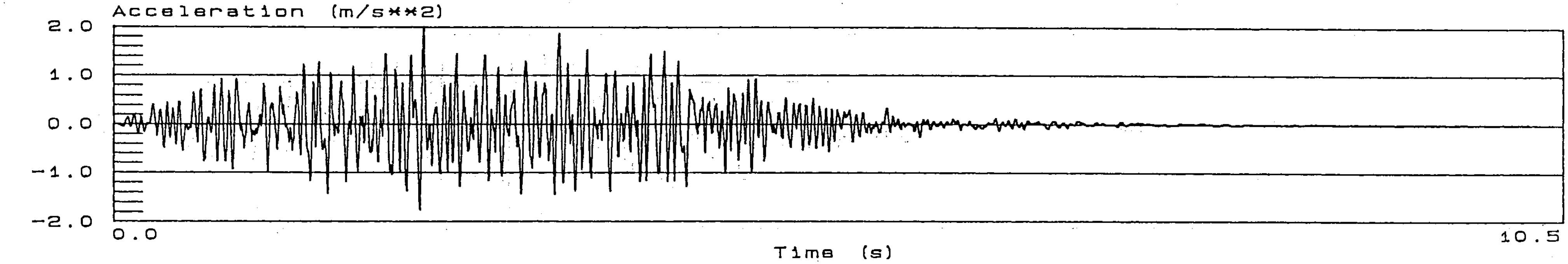
DATE: 1988-06-12

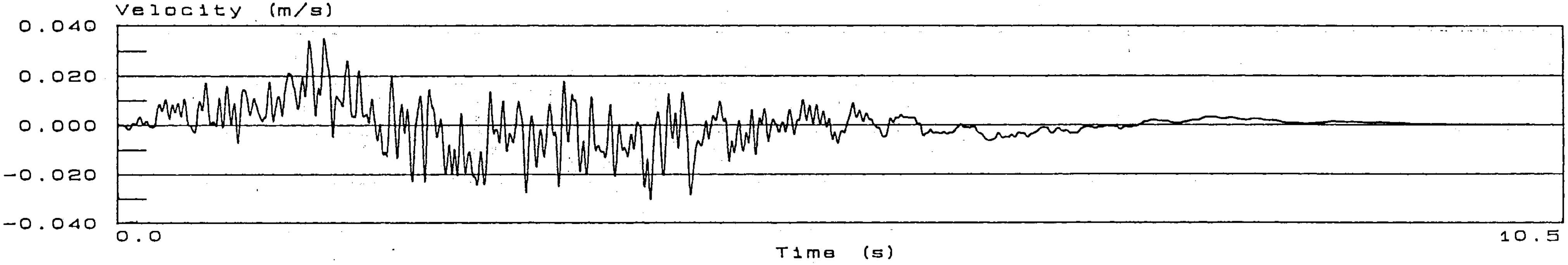


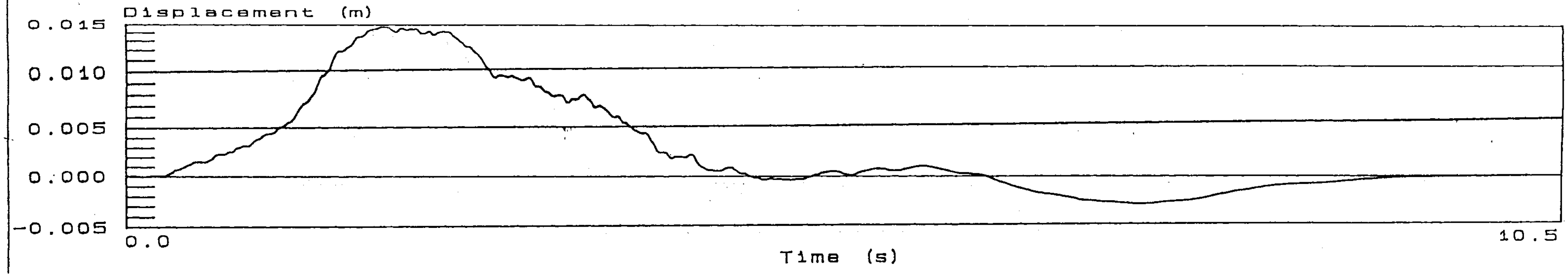
TIME HISTORY BASED ON ENVELOPE SPECTRA

GM direction: Vertical
Envelope spectrum exceedance freq. E-6

DATE: 1988-06-12



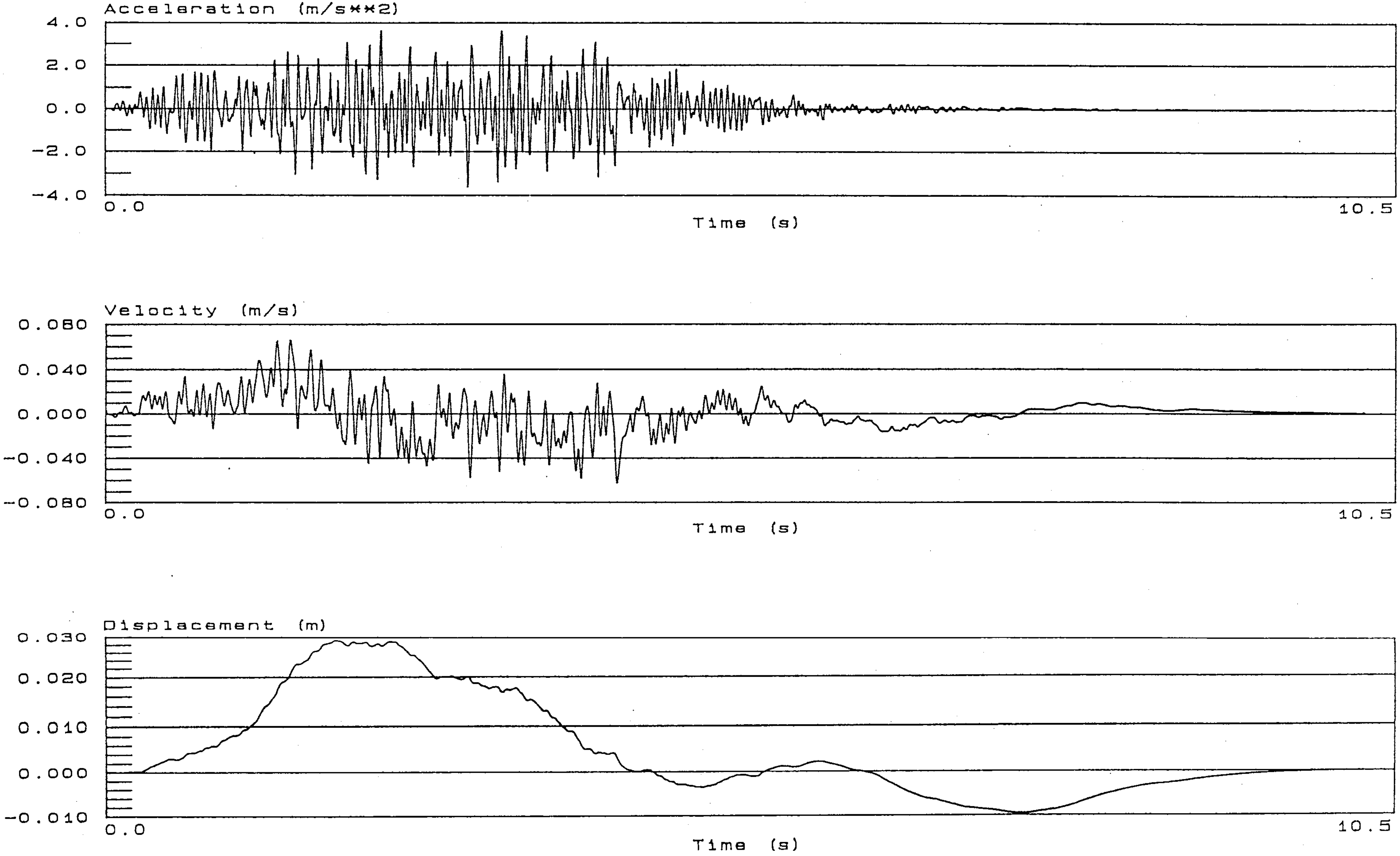




TIME HISTORY BASED ON ENVELOPE SPECTRA

GM direction: Vertical
Envelope spectrum exceedance freq. E-7

DATE: 1988-06-12



P4672-001
Project
SEISMIC SAFETY

SUMMARY REPORT

CHARACTERIZATION OF SEISMIC GROUND MOTIONS FOR PROBABILISTIC ANALYSES OF NUCLEAR FACILITIES IN SWEDEN

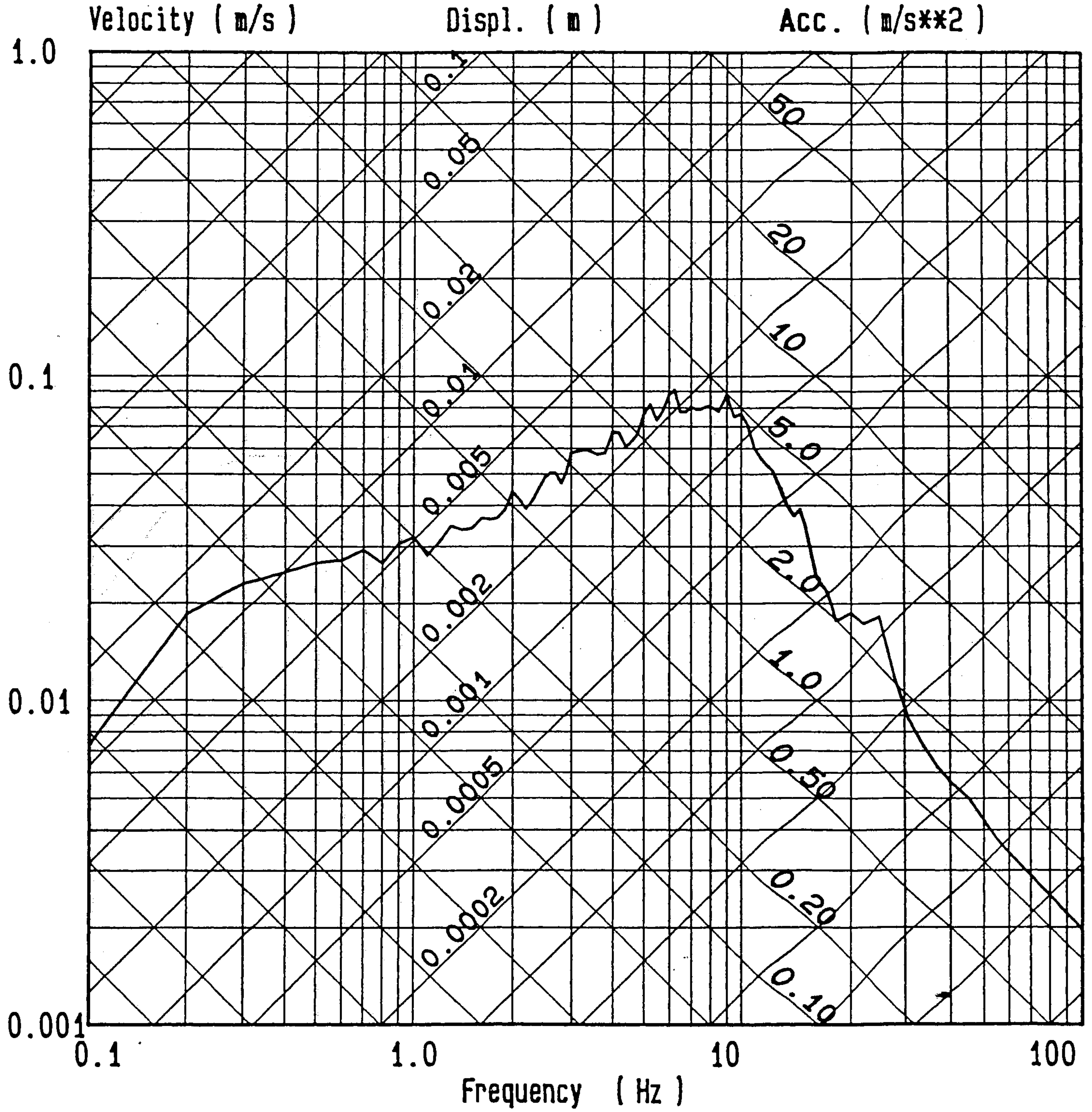
ENVELOPE GROUND RESPONSE SPECTRA FOR BARSEBÄCK

VBB

SEISMIC SAFETY

SITE SPECTRA: Barsebaeck 10 m below MWL
PROBABILITY LEVEL: 1.0E-5 **DATE: 1989-01-12**

DAMPING RATIO : 0.05
EXCITATION : Horizontal-1



VBB

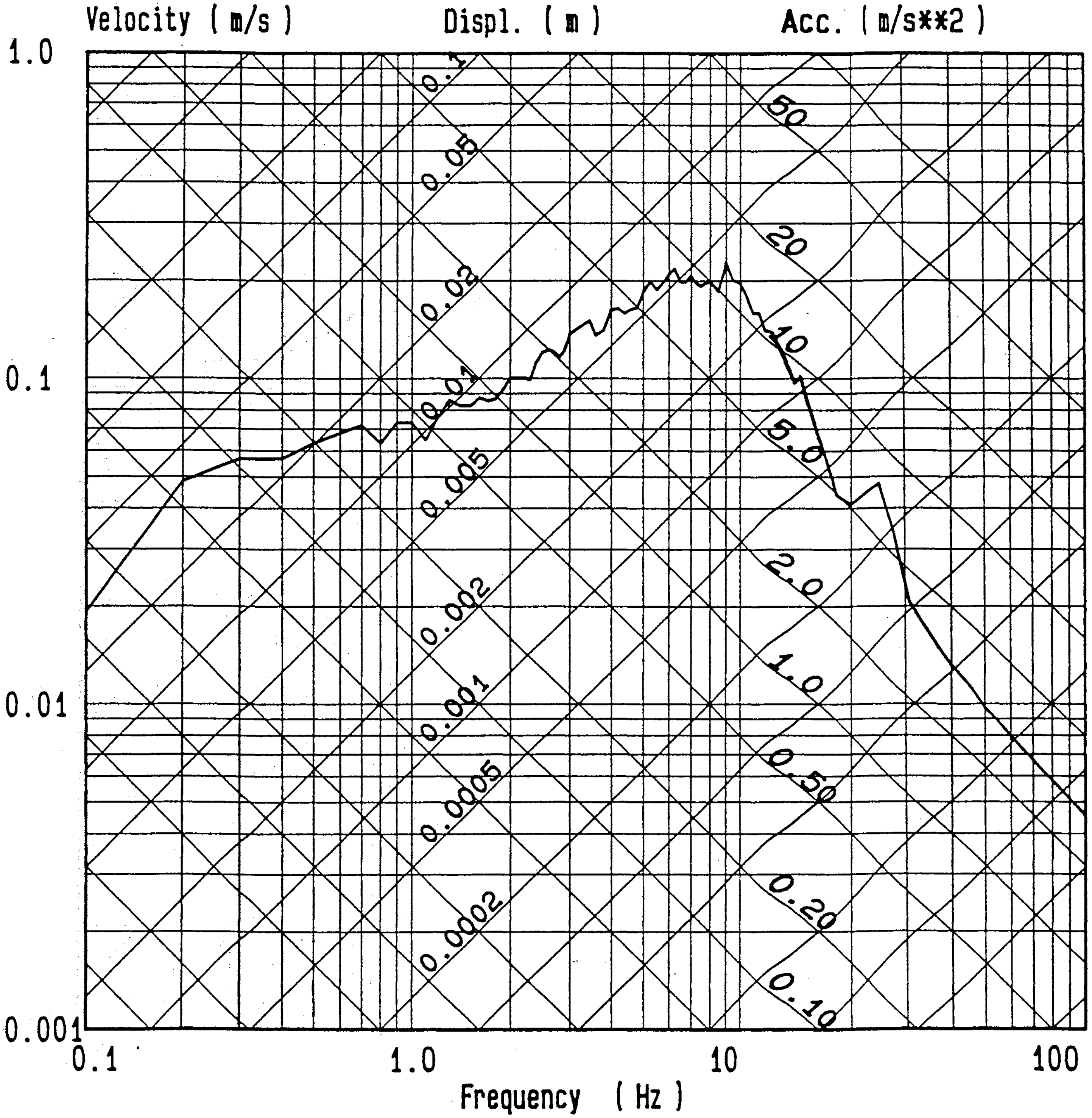
SEISMIC SAFETY

SITE SPECTRA: Barsebaeck 10 m below MWL

PROBABILITY LEVEL: 1.0E-6 DATE: 1989-01-12

DAMPING RATIO : 0.05

EXCITATION : Horizontal-1



SEISMIC SAFETY

SITE SPECTRA: Barsebaeck 10 m below MWL

PROBABILITY LEVEL: 1.0E-7 **DATE: 1989-01-12**

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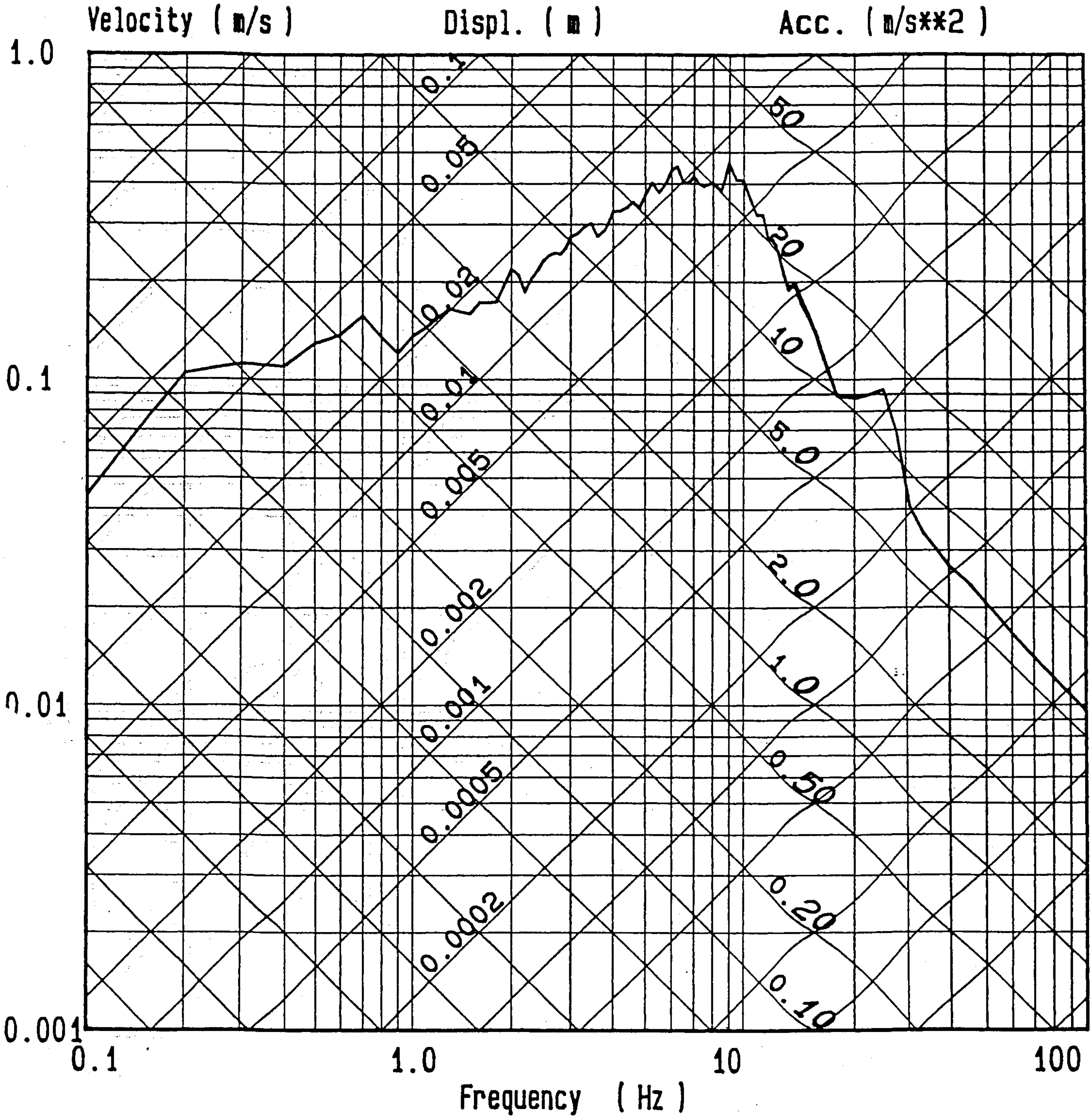
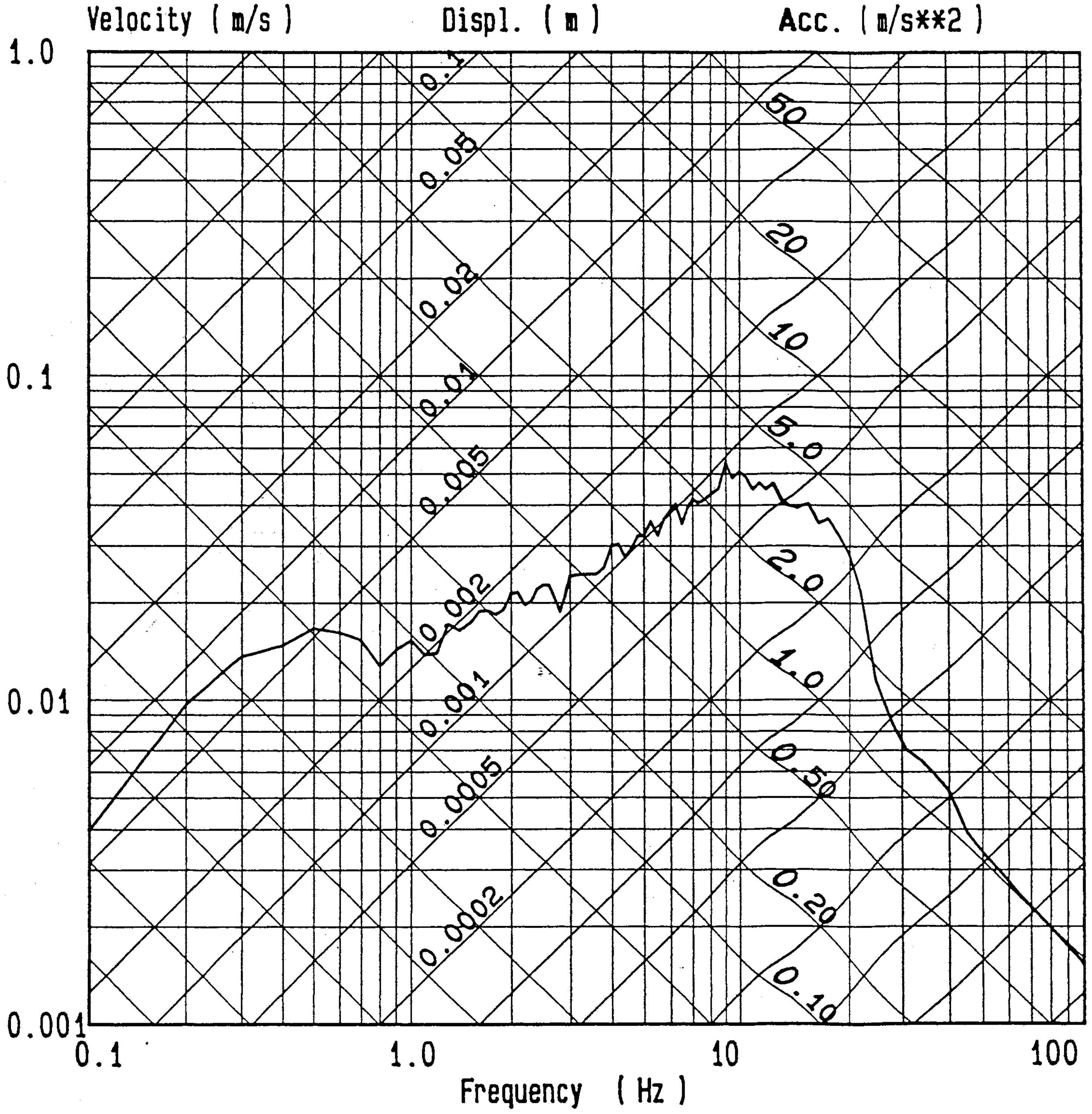
EXCITATION : Horizontal-1



VBB

SEISMIC SAFETY
SITE SPECTRA: Barsebaeck 10 m below MWL
PROBABILITY LEVEL: 1.0E-5 DATE: 1989-01-12

DAMPING RATIO : 0.05
EXCITATION : Vertical



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SEISMIC SAFETY

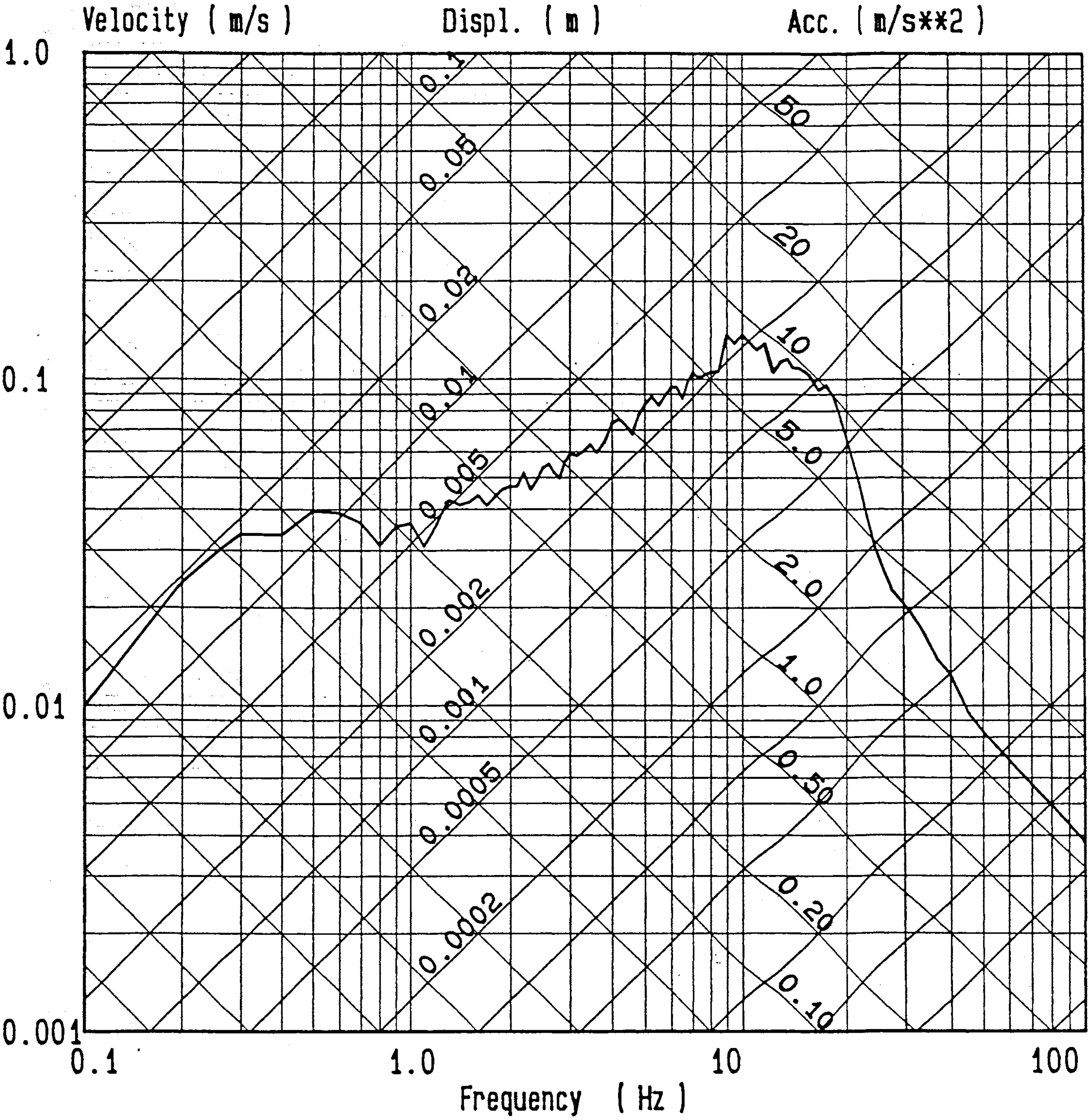
SITE SPECTRA: Barsebaeck 10 m below MWL

PROBABILITY LEVEL: 1.0E-6

DATE: 1989-01-12

DAMPING RATIO : 0.05

EXCITATION : Vertical



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SEISMIC SAFETY

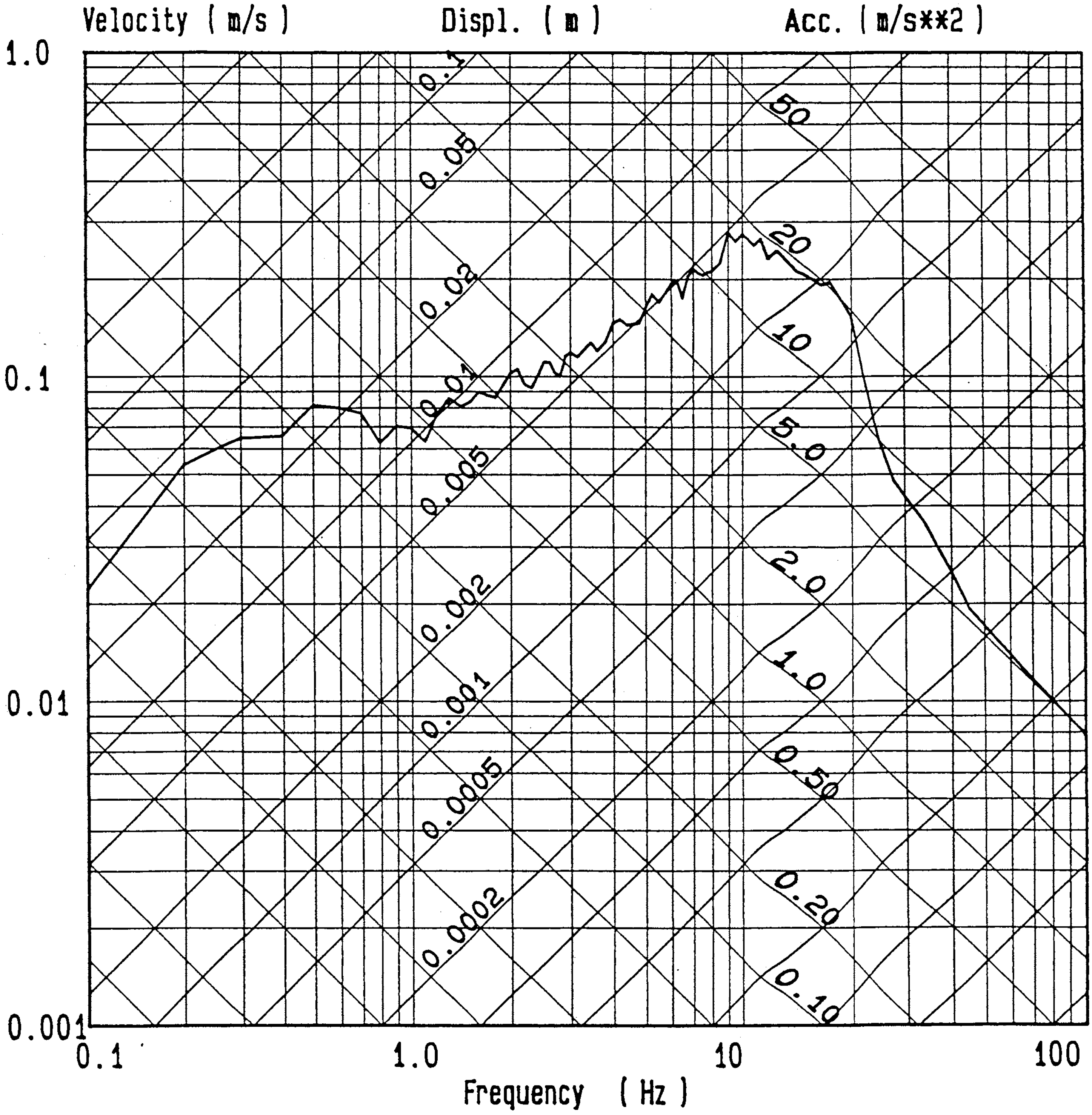
SITE SPECTRA: Barsebaeck 10 m below MWL

PROBABILITY LEVEL: 1.0E-7

DATE: 1989-01-12

DAMPING RATIO : 0.05

EXCITATION : Vertical



P4672-001
Project
SEISMIC SAFETY

SUMMARY REPORT

CHARACTERIZATION OF SEISMIC GROUND MOTIONS FOR PROBABILISTIC ANALYSES OF NUCLEAR FACILITIES IN SWEDEN

SYNTHETIC GM TIME-HISTORIES FOR BARSEBÄCK

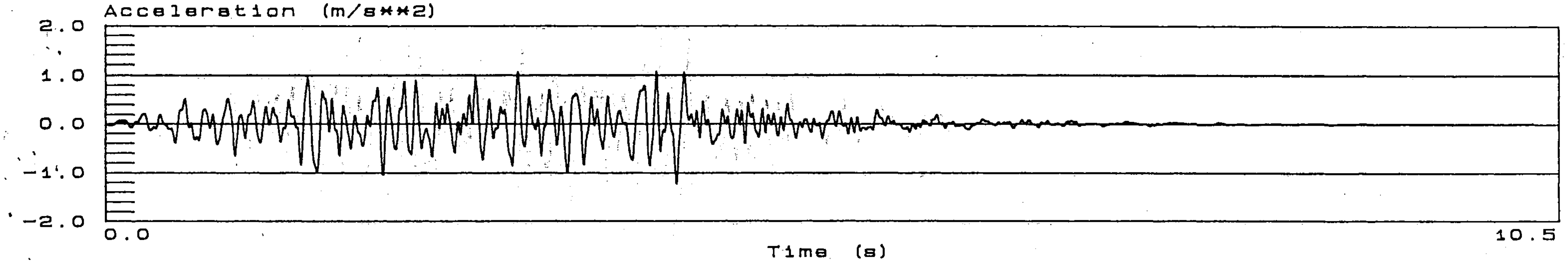
E17/15fc-01

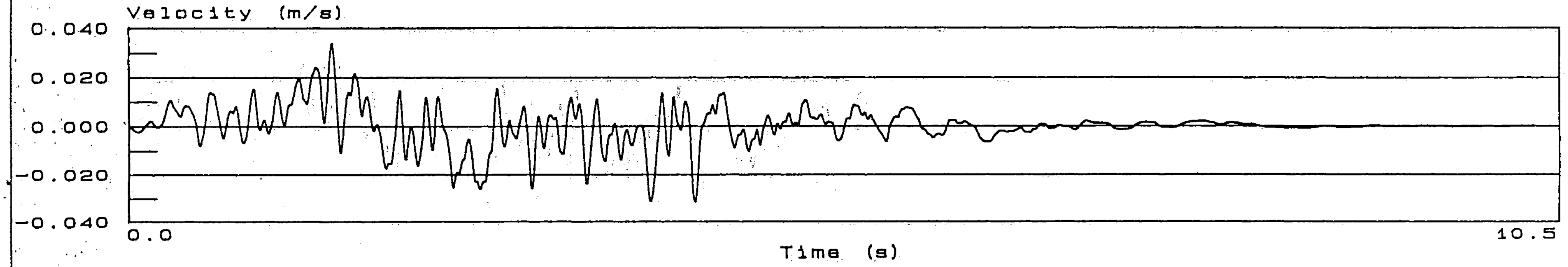
SITE TIME HISTORY: Barsebaeck 10 m below MWL

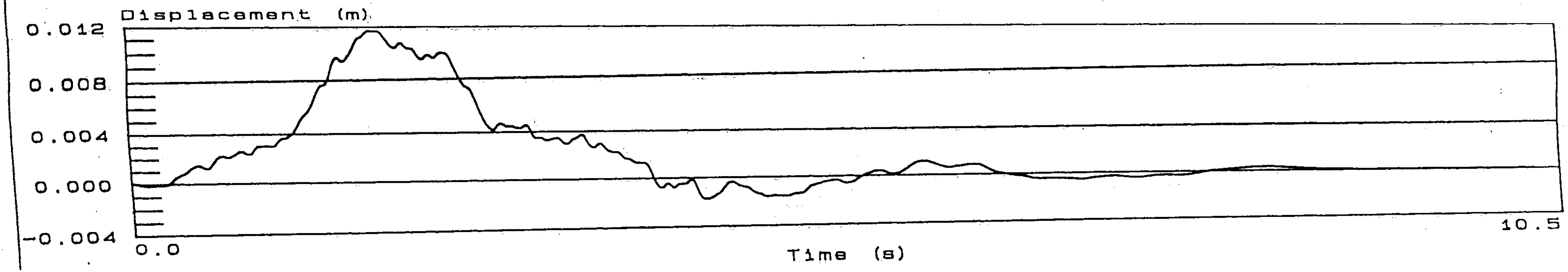
GM direction: Horizontal 1

Envelope spectrum exceedance freq. E-5

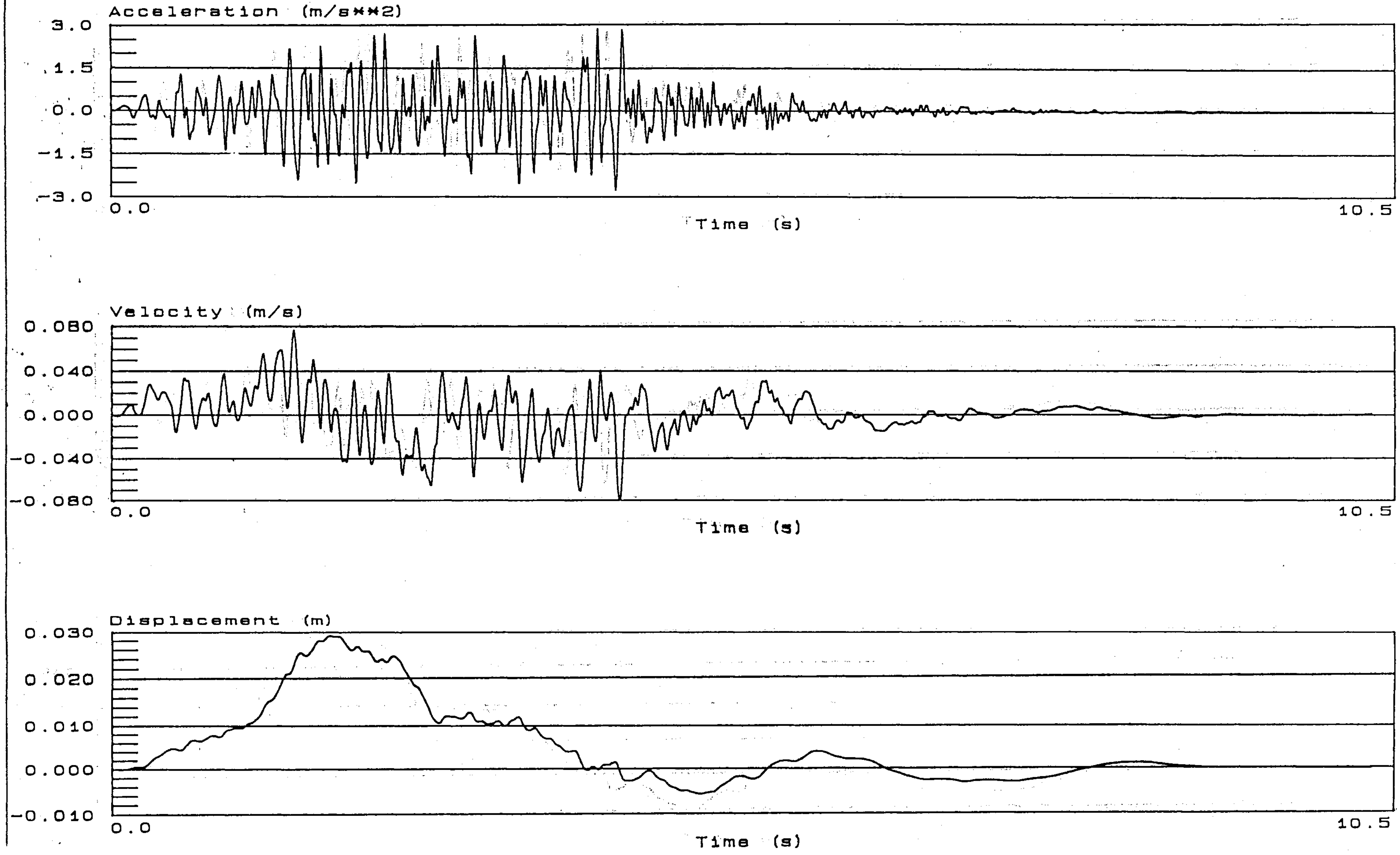
DATE: 1989-01-12







SITE TIME HISTORY: Barsebaeck 10 m below MWL
GM direction: Horizontal 1
Envelope spectrum exceedance freq. E-6
DATE: 1989-01-12

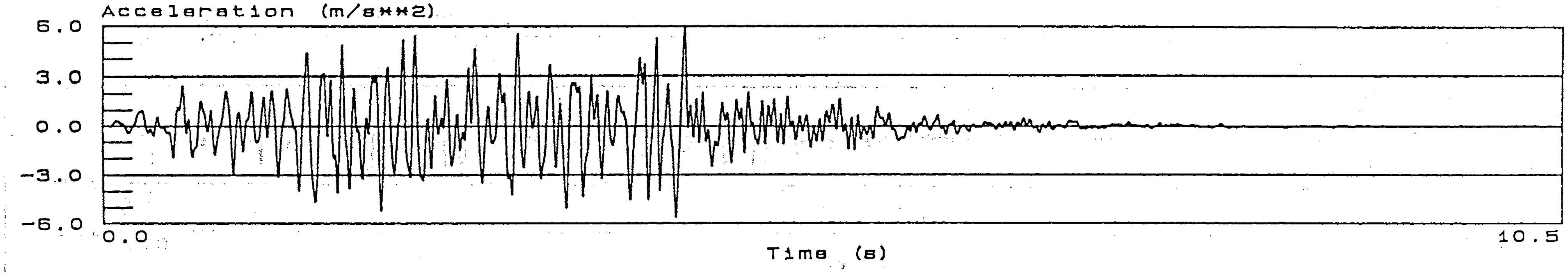


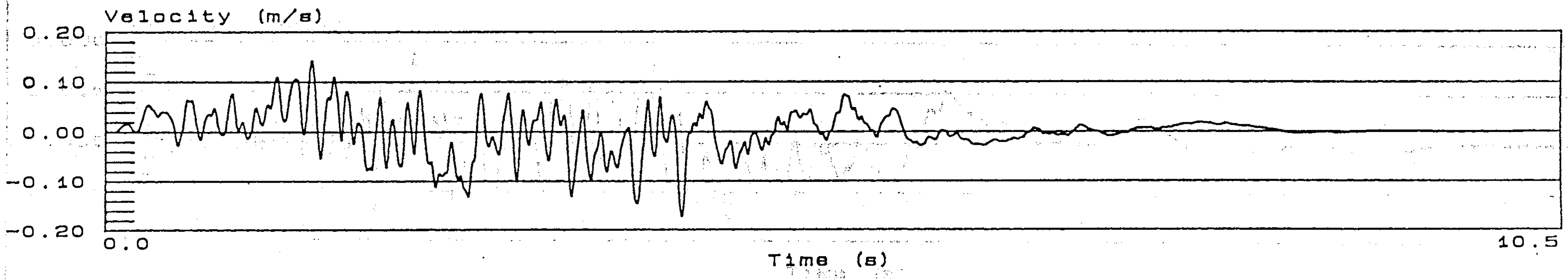
SITE TIME HISTORY: Barsebaeck 10 m below MWL

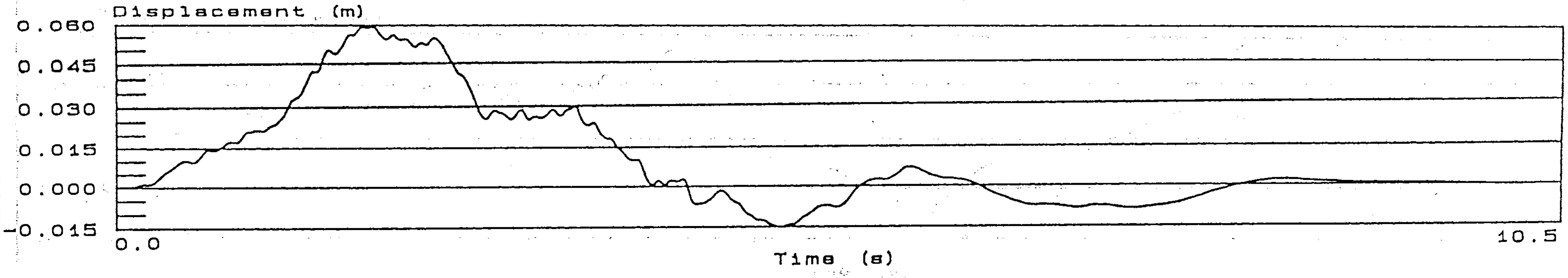
GM direction: Horizontal 1

Envelope spectrum exceedance freq. E-7

DATE: 1989-01-12





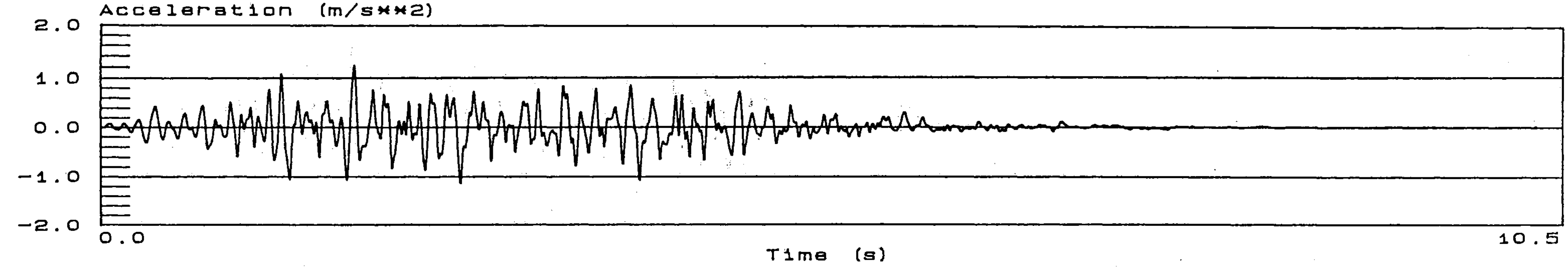


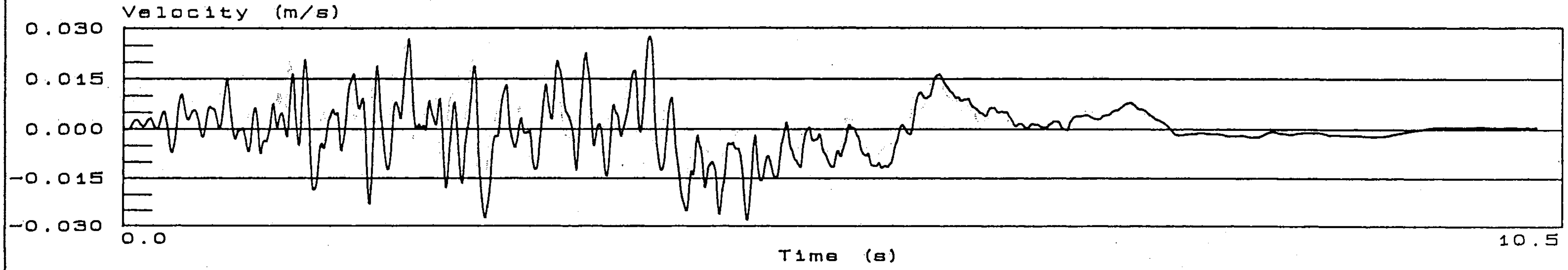
VBB

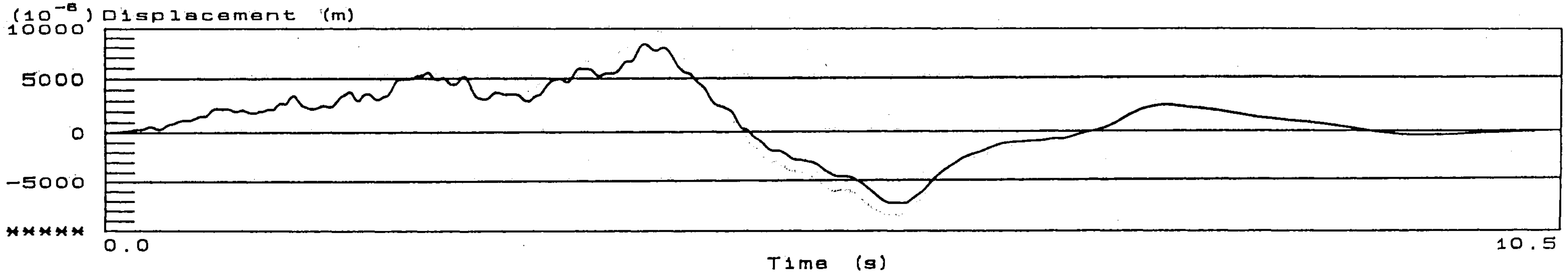
SITE TIME HISTORY: Barsebaeck 10 m below MWL

GM direction: Horizontal 2
Envelope spectrum exceedance freq. E-5

DATE: 1989-01-12





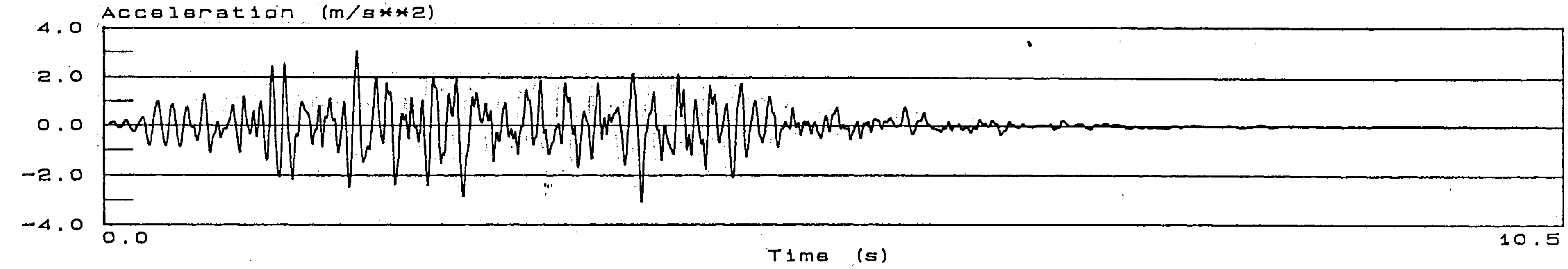


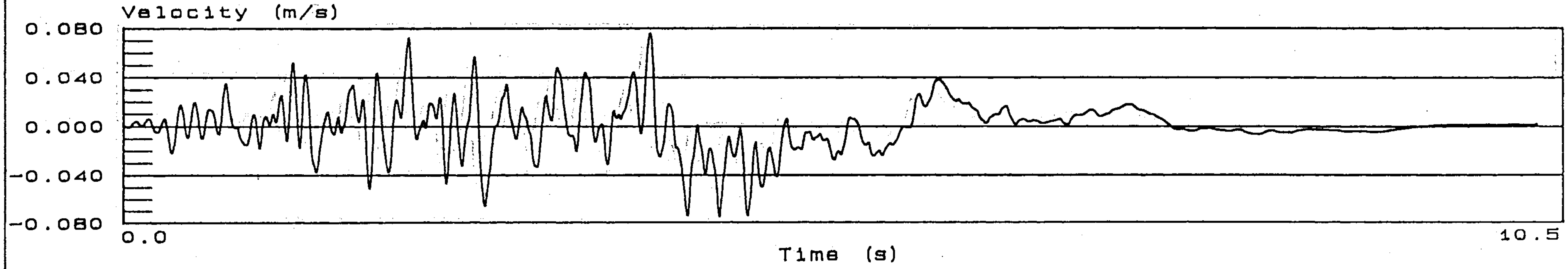
SITE TIME HISTORY: Barsebaeck 10 m below MWL

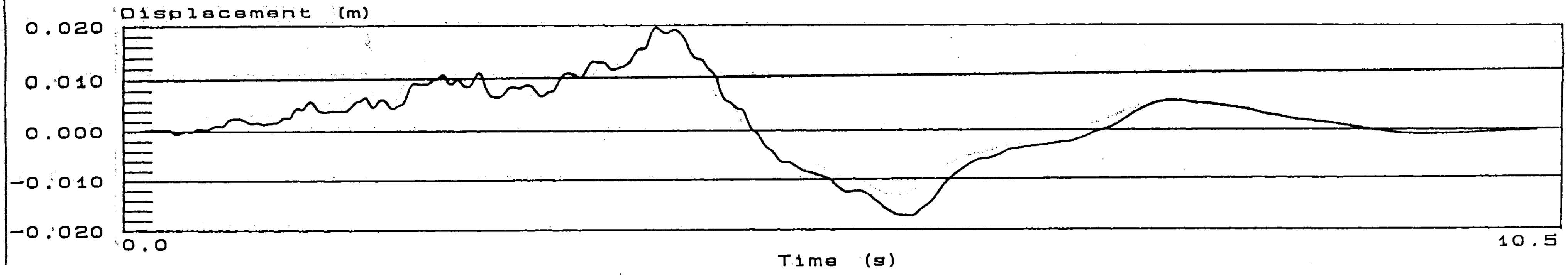
GM direction: Horizontal 2

Envelope spectrum exceedance freq. E-6

DATE: 1989-01-12





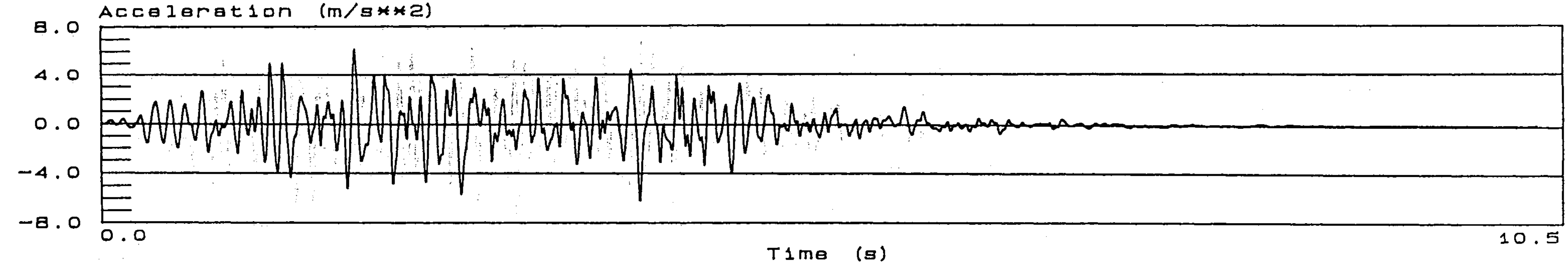


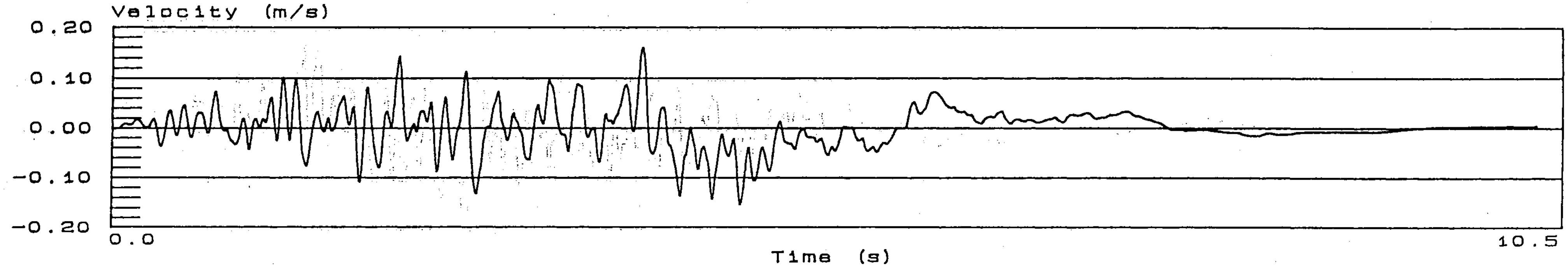
VBB

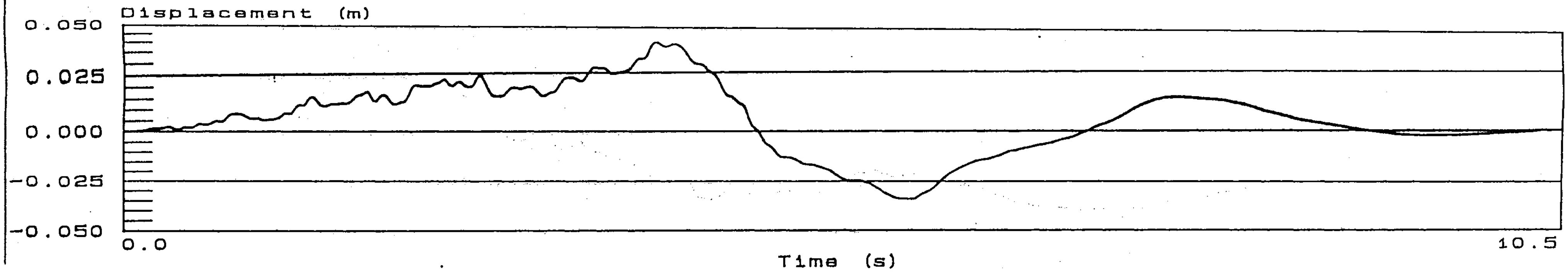
SITE TIME HISTORY; Barsebaeck 10 m below MWL

GM direction: Horizontal 2
Envelope spectrum exceedance freq. E-7

DATE: 1989-01-12



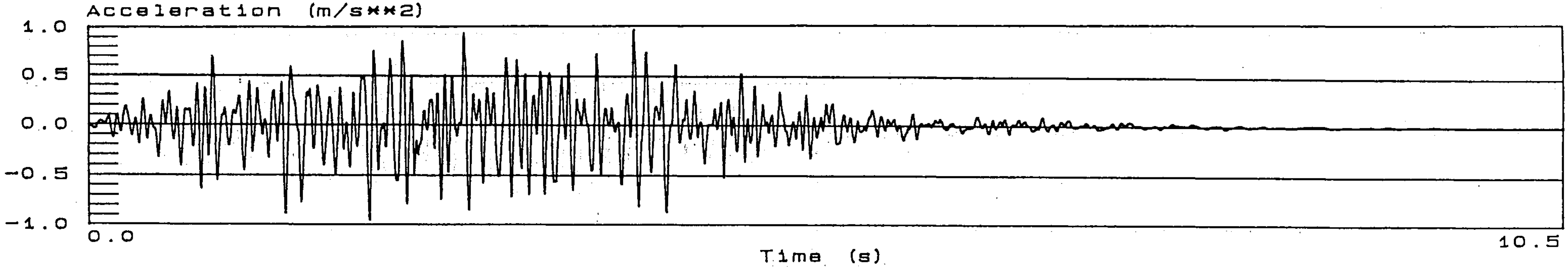


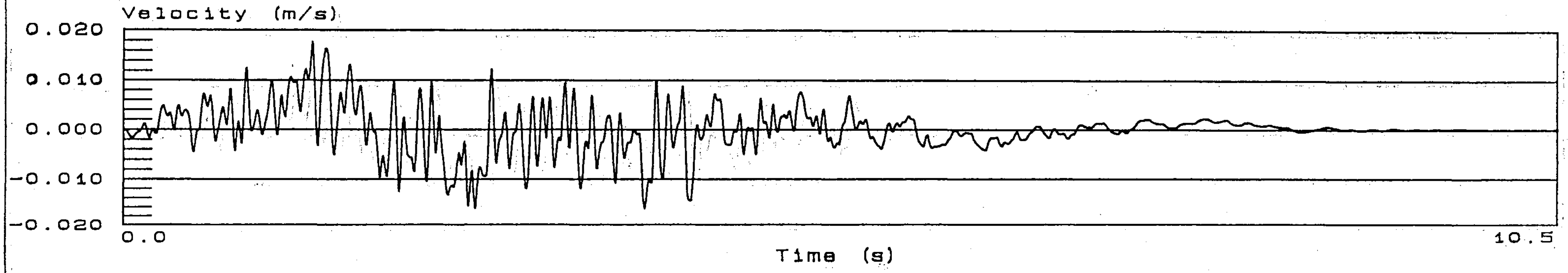


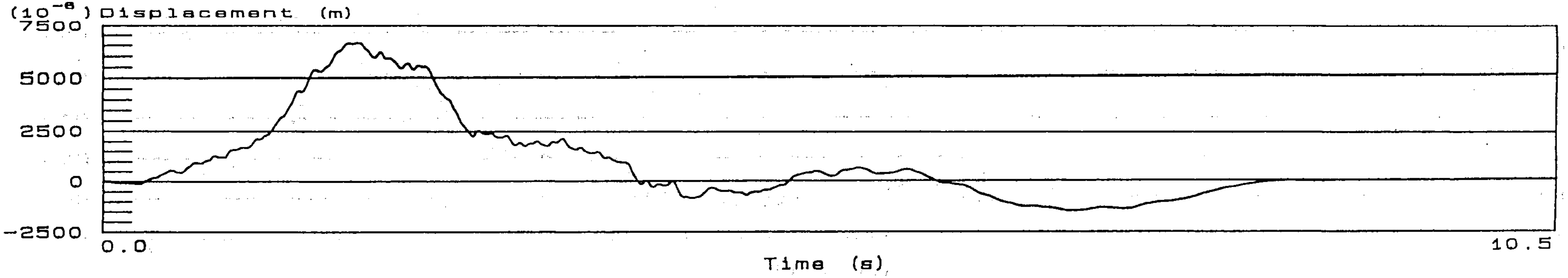
SITE TIME HISTORY: Barsebaeck 10 m below MWL

GM direction: Vertical
Envelope spectrum exceedance freq. E-5

DATE: 1989-01-12







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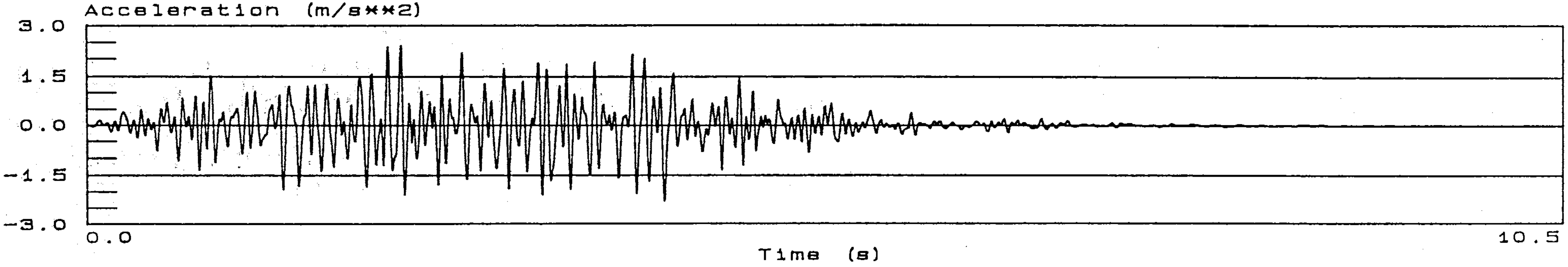
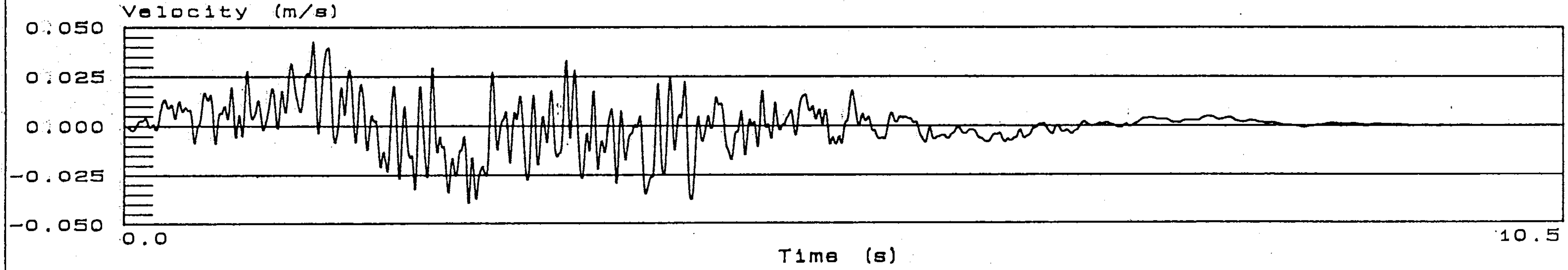
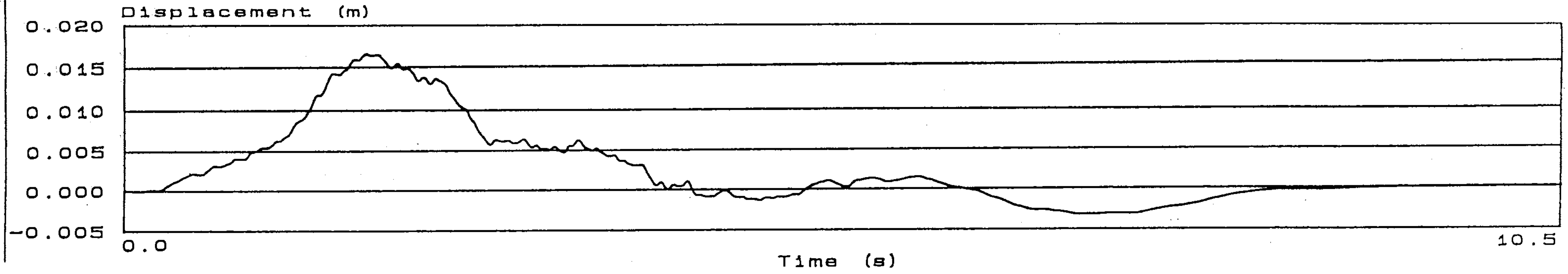
SITE TIME HISTORY: Barsebaeck 10 m below MWL

GM direction: Vertical
Envelope spectrum exceedance freq. E-6

DATE: 1989-01-12







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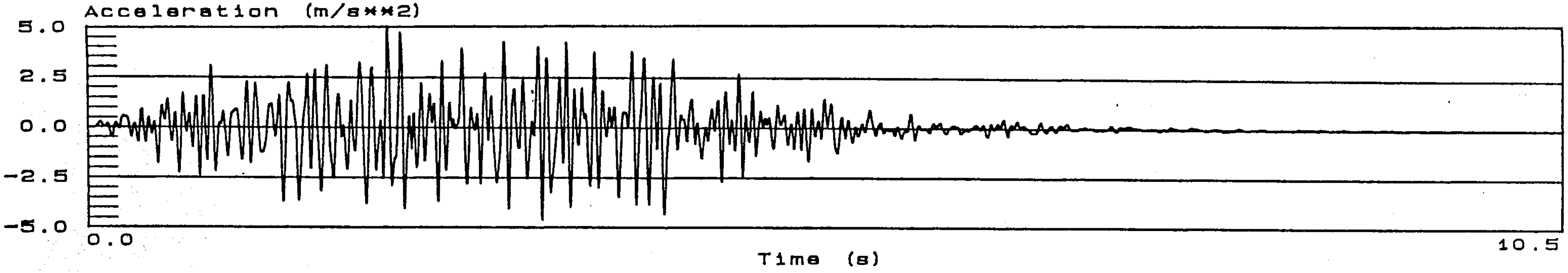
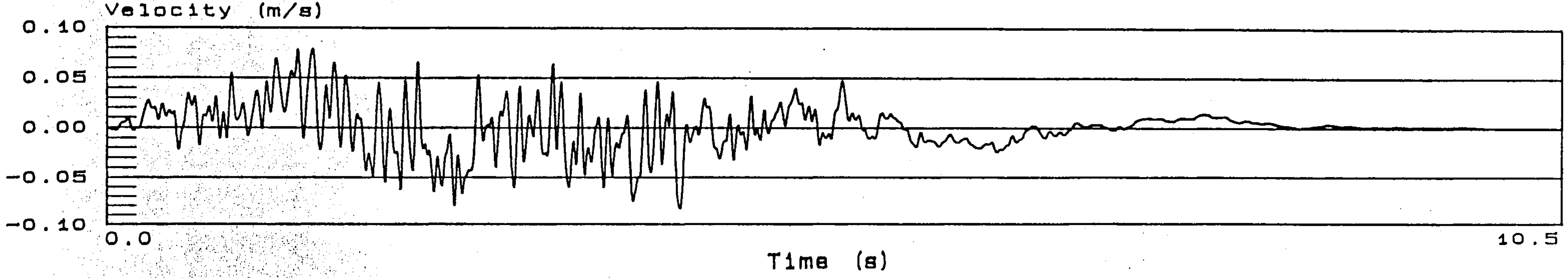
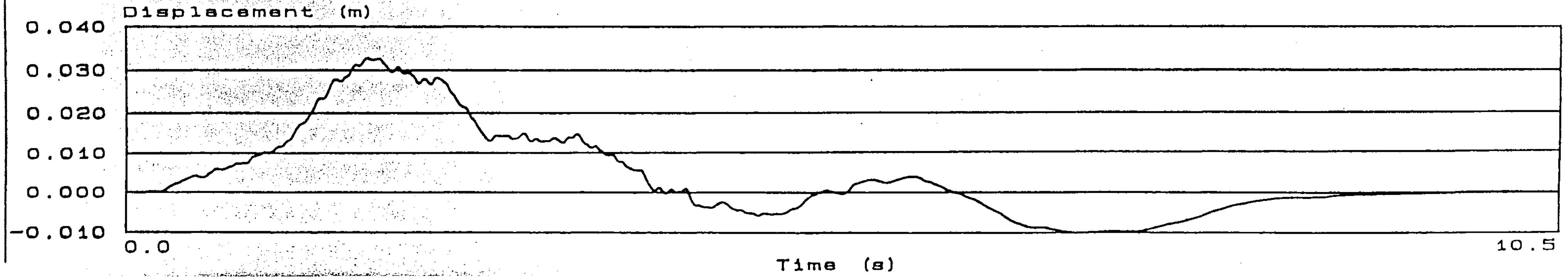
GM direction: Vertical
Envelope spectrum exceedance freq. E-7

DATE: 1989-01-12







VBB

Report to
the 10th International Conference
on STRUCTURAL MECHANICS
IN REACTOR TECHNOLOGY (SMIRT 89)
Anaheim, California, August 1989

Project SEISMIC SAFETY

Characterization of seismic ground motions for probabilistic safety analyses of nuclear facilities in Sweden

The project SEISMIC SAFETY
is sponsored and directed by
the SWEDISH NUCLEAR POWER INSPECTORATE (SKI)
with the assistance of
the SWEDISH STATE POWER BOARD,
SYDKRAFT and OKG

Project management: VBB

CHARACTERIZATION OF SEISMIC GROUND MOTIONS FOR PROBABILISTIC SAFETY ANALYSES OF NUCLEAR FACILITIES IN SWEDEN

A. Engelbrektson
VBB/SWECO, Stockholm
Manager of the project SEISMIC SAFETY, sponsored and directed by

- the Swedish Nuclear Power Inspectorate
- the Swedish State Power Board
- SYDKRAFT
- OKG

ABSTRACT

In 1986 the Swedish Nuclear Power Inspectorate and concerned power utilities initiated the study project SEISMIC SAFETY, aiming at a deepened seismic risk assessment for the nuclear facilities in Sweden. In order to establish a reliable basis for structural response calculations and subsequent risk evaluations, a metodology was outlined for probabilistic assessments of seismic ground motions (GM) at the plant sites. This methodology, though it contains established elements, is partly novel. Improvements are envisaged, and international responses are welcomed.

METHODS AND RESULTS

Basically, the applied methodology can be structured in the form of the following tasks, further commented below.

(1) to assess the joint occurrence frequencies for all significant events, grouped in discrete classes and characterized by the fundamental source and wave path parameters,
(2) to establish "Event-specific Response spectra" for generalized hard rock site conditions, the spectral ordinates being expressed as functions of the most important seismic source and wave path parameters,
(3) to assess the spread of spectral ordinates around the averages,
(4) to determine, on the basis of results from the above, the exceedance rates for the spectral ordinates and to construct "Envelope Response Spectra" for various selected probability levels ("uniform risk spectra"),
(5) to generate synthetic GM time-histories corrresponding to the Envelope Spectra,
(6) to characterize, on the basis of the outcome of the above, site-specific ground motions, considering effects of local rock and soil strata (not dealt with in this report).

The outcome of the above tasks has been presented in a series of working reports, from which certain parts, judged to be of general interest, are summarized in the present report.

(1) Occurrence frequency distributions of seismic events

* Over the entire range of significant sizes and locations historic earthquakes were categorized in respect of the seismic moment M_o and the focal distance R. The widths of the classes were determined to be approximately equal in respect of the ratios between GM values at the upper and lower boundaries of each class.

* Large scale seismicity zoning and seismotectonic considerations resulted in the choice of an average Fennoscandian function of epicentral density, directly applicable to at least two nuclear plant sites and, without major modifications, to the other plants (Figure 1). The epicentral density function was derived from available catalogues, covering stronger earthquakes in Fennoscandia during a period of almost 500 years.

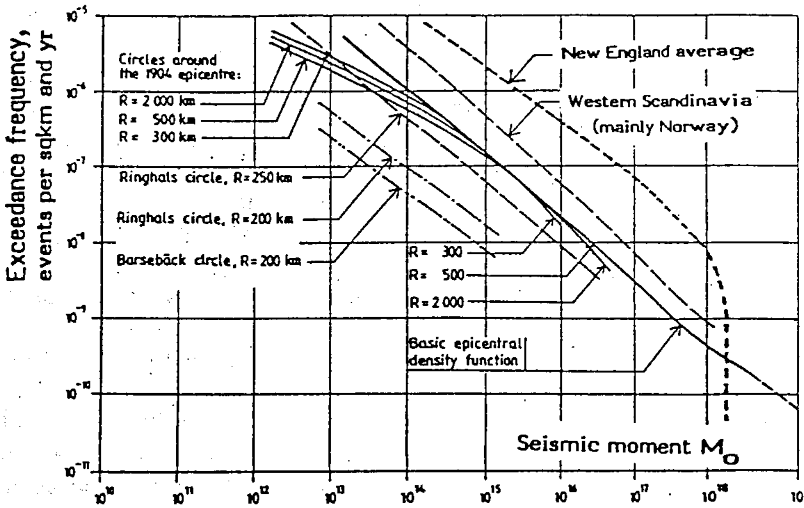


Figure 1:
The "average Fennoscandian epicentral density function", compared with local seismicity functions from Scandinavia and Eastern US (the latter is an approximate average of various experts' predictions for the New England region).

* For each volume element of the crustal model (Figure 2), the occurrence rates of the various classes of events were determined on the basis of the epicentral density function and the probability density distribution of focal depths. The result of this first step of the probabilistic assessment was a matrix of occurrence frequency values for each selected class of events.

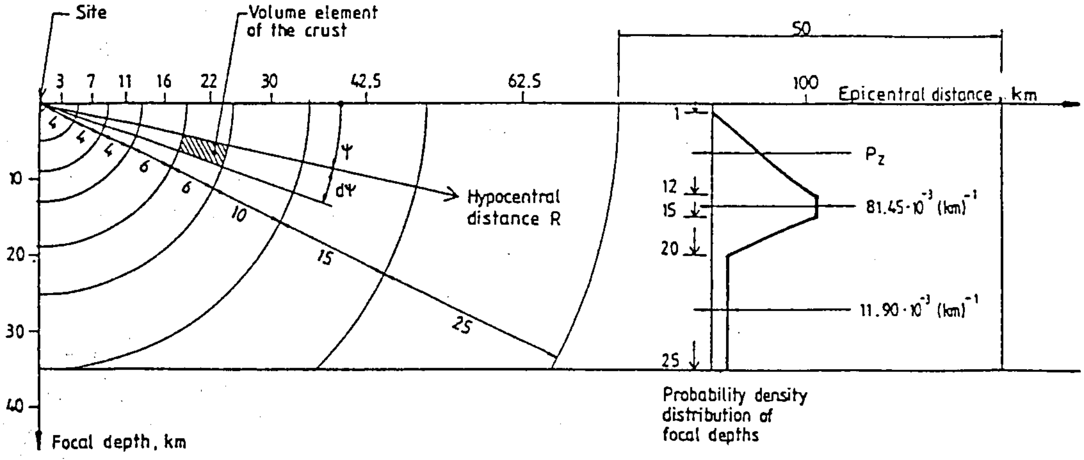


Figure 2: The basic seismicity model: Geometry and distribution of focal depths

(2) Ground response spectra for each class of M_0 - R

* The model used for the development of "event-specific" ground response spectra is based on the processing of empirical data from more seismic regions to suit the typical conditions in Sweden. The main rationales for the choice of this approach are the obvious lack of sufficient local strong motion data corresponding to the extremely low probability levels considered in the risk analysis of nuclear facilities, and the observation that effects of differential geological and seismological conditions have a moderate influence on the shapes of the ground response spectra. The fairly comprehensive and well-defined database given in Ref. 1-3 in the form of empirical ground response spectra, mainly from Japan, was taken as the basis for the first approach of a spectral characterization.

* The characteristic response spectra for Swedish hard rock conditions were thus obtained by modifications of the corresponding Japanese spectra with respect to the influence factors that are expected to affect the spectra differently. These factors are associated with differences of source parameters such as stress drop and fault area, and of wave propagation effects such as anelastic attenuation. Since the resulting differences are moderate, the transformation of the Japanese spectra could be based on generalized, best-estimate values of the influence factors. The following spectral formulae, (based on Aki, 1967) constituted the basis for the transformation.

$$F_d = \text{Const}\ \ F_{do}\ \ (1 + (f/f_c)^{2n})^{-1/2}\ \ A(f,R)$$

where the displacement wave amplitude F_d is a function of the "zero frequency amplitude" F_{do}, the "corner frequency" f_c and the "anelastic attenuation" function A(f,R). Since these parameters can be related to other source and wave path parameters, viz. stress drop, fault displacement area, seismic moment, fault distance and shear modulus, the effects of differential conditions in Sweden and Japan could be assessed based on generalized empirical relationships.. The Japanese spectra for each selected class of magnitudes and focal distances, were thus modified to acccount for

- differential (characteristic) stress drop,
- differential (average) fault area and strong motion duration,
- differential rock quality, rock stiffness and anelastic attenuation.

* The results of the transformation of a Japanese "Standard spectrum" are demonstrated in Figure 3 and compared with spectra based on observations of an earthquake in the Easterns US, where the geological conditions are similar to those prevaling in Sweden.

* It appeared that the influence of the differential properties was moderate, but significant, for frequencies exceeding 1 Hz, whereas, for the lower-frequency range, the effects of differential stress drop and differential duration balanced each other. For the spectral range of higher frequencies, the higher stress drop and lower attenuation significantly increases the spectral ordinates of near-field earthquakes in Sweden compared with Japanese earthquakes of corresponding magnitudes and focal distances.

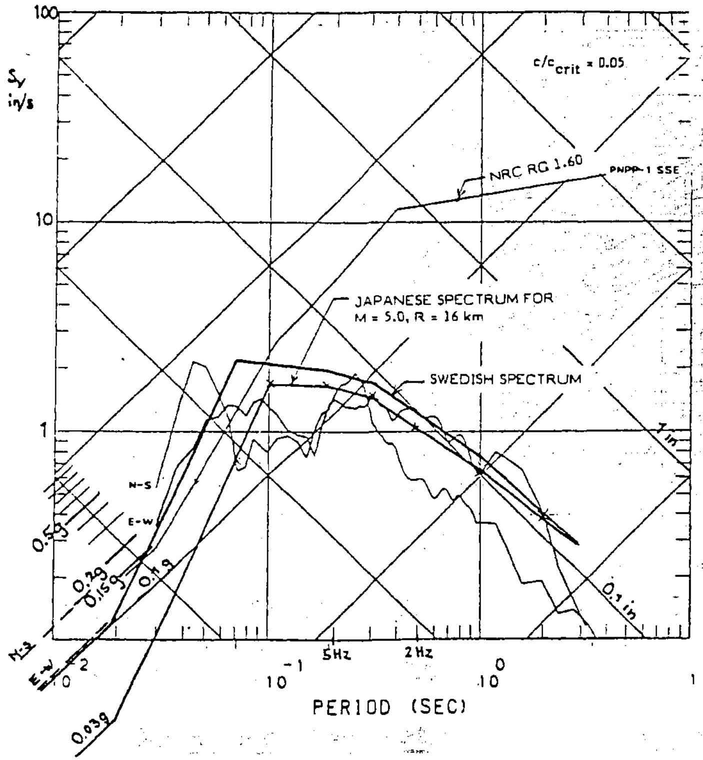


Figure 3:
A Japanese standard response spectrum and the corr. Swedish spectrum for the Japanese magnitude M=5 (est.$M_o=5\times10^{16}$ Nm) and hypocentral dist. R=16 km, comp. with data from the Leroy main shock, recorded at the Perry NPP, Jan. 31, 1986 (m_b=4.9, R=16 km, $M_o=10^{16}$ Nm, approx.)

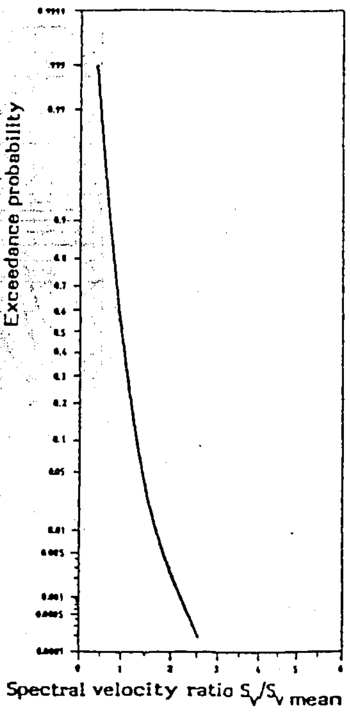


Figure 4:
Cumulative distribution of spectral ordinates around the average

(3) Assessment of the spread of spectral values

Since the various selected events and their corresponding characteristic response spectra have been classified only with respect to the "fundamental parameters" M_0 and R, it is not surprising that there is a considerable spread of spectral values around the average. This spread was assessed in a generalized way, once more on the basis of Japanese data (Ref. 4), reprocessed to suit the conditions pertaining to the Swedish model. Thus the combined effects of other parameters than M_0 and R were considered, though without identifying their individual contributions, that would not be possible at the present state-of-the-art. A considerable part of the spread is probably due to errors in the data acquisition and processing systems, including the uncertainty associated with the use of various magnitude scales and transformations between such scales. On the basis of the Japanese data a generalized distribution function, normalized to the mean spectral value as unity and independent of the frequency of vibration, was thus developed. (Figure 4)

(4) Construction of Envelope Ground Response Spectra

* On the basis of the derived occurrence frequency distributions for discrete classes of events, the event-specific spectra of these classes and the relative distribution of spectral values, the frequency of exceedance of a certain spectral value was determined for each class of events. The overall exceedance frequencies were then determined for various spectral values by adding the contributions from each class of events.

* For each selected probability level envelope spectra or so-called uniform risk spectra were finally constructed by interconnecting discrete spectral values, corresponding to the given level, obtained from the overall exceedance frequency distributions of spectral values. On the basis of empirical relationships between response spectra for various damping ratios that are also included in Ref. 2 and 3, envelope response spectra were also produced for various damping ratios other than 0.05 (Figure 5).

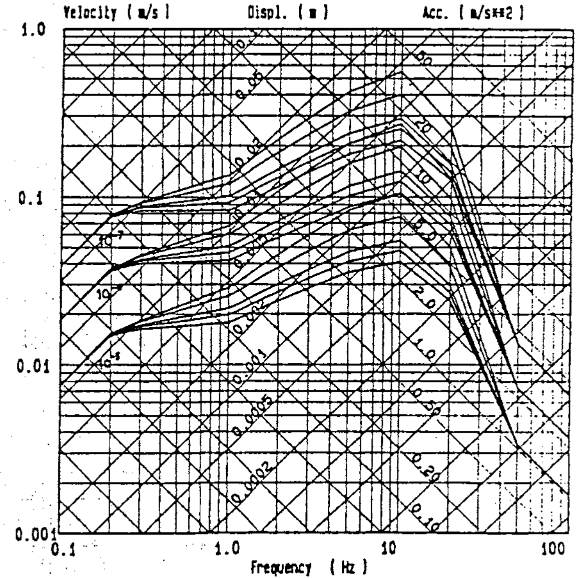


Figure 5: Envelope Ground Response Spectra for horizontal ground motions of outcropping hard rock. Annual exceedance frequencies 10^{-5}, 10^{-6} and 10^{-7}. Damping ratios 0.005, 0.02, 0.05, 0.07 and 0.10.

(5) Generation of synthetic ground motion time-histories

* Synthetic time-histories of ground acceleration, velocity and displacement were developed, corresponding to the envelope response spectra. The time-histories were produced for two perpendicular horizontal directions and for the vertical, one of the horizontal representing the primary principal axis of the ground motion.

* The spectra for 5 per cent of critical damping were selected to constitute the primary target spectra. It was possible to attain a good conformity between the response spectra of the time-histories and the target spectra, not only for 5 per cent but also for other damping ratios. Particularly, for the important range f = 1-5 Hz and damping ratios exceeding 0.02, the agreement is remarkably good.

* The time-histories could be given a realistic duration of the various phases of a strong motion, implying that they may be used not only for linear but also for non-linear response calculations, without causing any major deviations from a realistic response, in the form of accumulated residual strain, displacements etc.

COMMENTS

Uncertainty ranges

Although effects of the inevitable spread of parameter values from case to case are judged to be reasonably well accounted for by the introduction of a probability distribution of spectral characteristics, several averages of the parameter values were assessed only by best estimates. Therefore, some of the most important parameters or functions have been selected for examinations as regards the sensitivity of the results to parameter variations:

- The "basic seismicity function" or "epicentral density function": (A curve based on "local seismicity", representing the lower limit of likelyness as regards earthquakes in south-west Sweden, was compared with the spectrum curve based on the average Fennoscandian seismicity, in order to quantify a possible range of conservatism).
- The upper boundary ("cut-off") magnitude was increased from $M_L = 6.5$ to $M_L = 7.0$.
- The Japanese response spectrum formulation obtained from Ref. 1 was used for comparison with the (more conservative) formulation in Ref. 2 which has constituted the basis for the Swedish spectra.
- The characteristic stress drop.
- The "rock quality factor" Q_o and the anelastic attenuation function.

Except for the "seismicity function", only parameter deviations tending to increase the responses were tested. The results of the sensitivity tests are summarized graphically in a spectral form in Figure 6. It appears that the sensitivity of the spectral values to parameter variations is moderate and that the proposed spectra have the appropriate position for being regarded as being the best estimates when taking all the most probable parameter variations together. Particularly, within the frequency band 2-5 Hz the sensitivity of the spectrum towards the unconservative side appears to be small.

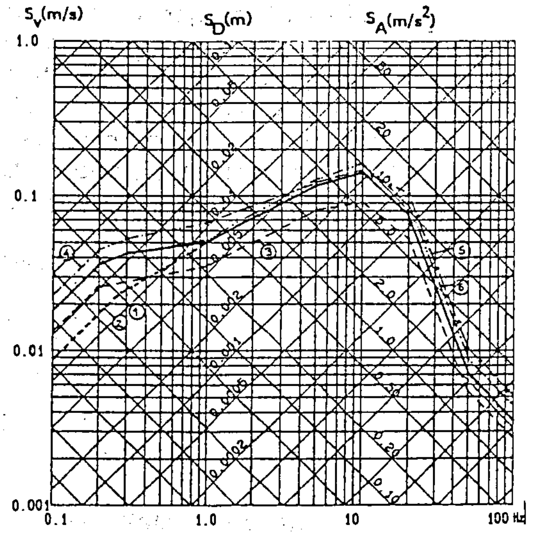


Figure 6:
Envelope Ground Response Spectrum for horizontal ground motions and damping ratio 0.05 (Curve 1), adjusted with respect to an alternative Japanese spectrum formulation (Curve 2), a possible overestimate of the seismicity (Curve 3), increased cut-off magnitude (Curve 4), increased stress-drop or spectral decay factor (Curve 5), increased rock quality factor (Curve 6).

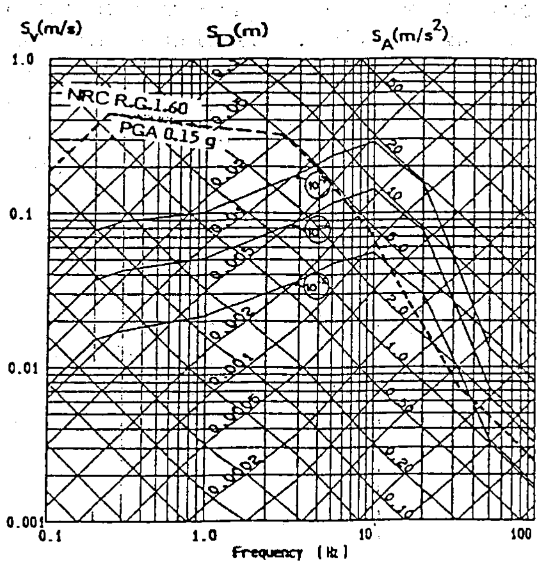


Figure 7:
The new Swedish design response spectra for horizontal GM, damping ratio 0.05 and the exceedance rates 10^{-5}, 10^{-6} and 10^{-7}, compared with the original design spectrum based on US NRC R.G.1.60

* Within a region with an essentially uniform seismicity the predominant seismic hazard contribution comes from the nearfield. In terms of "uniform risk" response spectra, the near-field predominance is stronger the higher the vibration frequencies are. In intraplate regions such as Fennoscandia, the spectra are particularly up-lifted within the high-frequency range, due to the relatively low anelastic attenuation and high stress drop. This up-lift includes the peak ground acceleration, set to a large extent by the high-frequency components of the ground motions.

* The entire shapes of the "uniform risk" spectra for regions with an essentially uniform seismicity differ strongly from the shapes of commonly used envelope design spectra, such as those given in the US NRC Reg.Guide 1.60. As demonstrated in Figure 7, the original Swedish design spectrum, obtained by scaling of the NRC spectrum to PGA=0.15 g and intended to represent the annual exceedance rate of 10^{-5} per year and site, greatly exaggerates the response in the low and intermediate frequency range, viz the range of major significance to the nuclear facilities. Obviously, if aiming at a "uniform risk" assessment, the NRC spectra might be used for areas with a much higher seismicity in the far-field than in the near-field but should not be used for regions with a uniform seismicity. The scaling of the spectra to PGA might be quite misleading, particularly if the choice of PGA is influenced by near-field observations. Figure 3 is also referred to with respect to this matter.

* Parameters such as the peak ground velocity which are more strongly related to the low frequency waves and thus to the fundamental fault mechanism, constitute more appropriate anchor points. The most reliable spectrum, corresponding to a certain type of events, is, however, determined on the basis of direct empirical relationships between the whole spectral function and the fundamental event-specific parameters, e.g. M_0 and R, as in the present study and in the bases for the Japanese standard spectra.

* In the long-term perspective the outline of response spectra for Swedish hard rock sites on the basis of data from interplate regions may obviously be regarded as a temporary approach, to be validated and probably improved in the light of an increasing database from intraplate regions which are similar to Fennoscandia, from a geological and seismotectonical point of view. A few near-field records from recent earthquakes in Eastern North America have already been compared with Swedish "event-specific" response spectra as demonstrated by an example indicated in Figure 3. It appears that the spectra of the North-American earthquakes do not deviate very much from the proposed Swedish spectra.

REFERENCES

1. T. Hisada, Y. Ohsaki, M. Watabe, T. Ohta: Design spectra for stiff structures on rock. Proc. of the 2nd Int. Conf. on Microzonation, San Francisco, 1978.

2. M. Watabe, M. Tohdo: Analyses on various parameters for the simulation of three-dimensional earthquake ground motions. SMIRT, 1979.

3. M. Watabe et al: Simplified seismic analysis methods in Japan. Report to EPRI's Symposium, Orlando, Florida, Dec. 1988.

4. T. Katayama: An engineering prediction model of acceleration response spectra and its application to seismic hazard mapping. Earthq. Eng. and Struct. Dyn., 1982.

5. Seismic hazard characterization of the Eastern United States. NUREG CR/37 1984.

6. K. Aki: Scaling law of seismic spectrum. Journal of Geophysical Research, Vol. 72, 1967.

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