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EXPERIENCE WITH SEISMIC INSTRUMENTATION AND REAL EARTHQUAKE DATA AT NUCLEAR POWER PLANT BEZNAU SWITZERLAND

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ABSTRACT

This paper deals with the aspects of design specification, bid evaluation and, seismic criteria used for the generation of seismic alarms etc. The paper also describes how the recorded data is utilized to check the various assumptions made in conjunction with the seismic plant design and seismic load generation. Out of some 8 seismic events registered so far only one event had the maximum recorded acceleration of approximately 28% of OBE Peak Ground Acceleration (PGA).

From the real earthquakes experienced and the in-situ free-field ground accelerations recorded, the free-field response spectra were calculated. The calculated spectra are compared to the Regulatory Guide 1.60 Design Response Spectra scaled linearly to the site peak ground acceleration. The free field data recording units on the weathered rock and at the top of the soil provided a real data to calculate the site amplification factors. The in-situ amplification calculated is then compared to that used in the seismic design. The recorded acceleration time history at various plant grades were used to generate response spectra. The calculated response spectra were in turn compared to the spectra used in the seismic design.

Keywords: seismic instrumentation, response spectra, free-field, soil-structure interaction

1 INTRODUCTION

1.1 Objectives

The scope of the project was to replace the old analog seismic instrumentation with a state-of-the art digital instrumentation as defined hereafter.

The new system consists of a Central Processing Unit (CPU) and 6 Data Recording Units (DRU). A typical DRU comprises of two instruments; one tri-axial Sensor and one Strong Motion Recorder (GSR). In order to achieve redundancy, the motion signals detected by the sensors are stored first in the local recorders. The seismic instrumentation is continuously running during normal operation and during event downloading. The key components of the seismic instrumentation are also equipped with emergency power supply (sensors with recorder). The 6 tri-axial measuring sensors and recorders have self-monitoring and testing facilities for periodic testing of the entire measurement chain. For each measuring channel the recording threshold and the alarm limit values can be set individually. The GSR has sufficient storage capacity for the complete recording of an event. The alarm transmission and communication between the GSR and the CPU take place via fiber-optic cable. It is also possible to retrieve the data with a laptop computer directly from the GSR. As soon as recording starts the system automatically initiates a pre-defined evaluation. The results of this automatic evaluation are stored in the computer of the CPU in pre-defined files and are printed out automatically. The CPU is housed in an earthquake-safe cabinet, including specified accessories.

The main objectives are that the system has the capability to record the seismic data digitally, should allow an on-line and remote data processing, create pertinent seismic event alarms (in the control room) based on the recorded time history. It should be possible to use the recorded digital data to check the theoretical results (floor response spectra, damping used in the analysis, amplification etc.) with the results calculated from real ground motion.

1.2 Bid Evaluation

Based on our technical specification for the new Seismic Instrumentation System we received quotations from various international vendors. In order to evaluate each quotation to its merit in an objective and effective manner, an expert team was constituted. Their first task was to define the criterion should be used for the bid evaluation. These were grouped together in four main categories. Category Technical included –technical specifications compliance, conformity with the specified and other major industry standards and norms, service life, robustness (exposed to radiation, humidity and, temperature), on-line self testing capability, allowable non-linearity, 16 bit resolution, pre and post seismic activity recording, capability to store over 30 minutes of seismic activity, independent power source, trigger to start recording 0.001g – 0.05g, PC connection, a seismic event is registered with all DRUs simultaneously, can each alarm be set independently, are all the pertinent equipments seismically qualified? Category Finance included - internal and external costs of engineering, hardware manufacturing, hardware transport and installation, acceptance tests, Quality assurance, spare parts and scope options, contractual obligations and warranty. Category Software includes– DRU time history analysis software is qualified, it is compatible with MS WIN (NT), on line and off line application is possible, a seismic event triggers the storage and analysis of the seismic data automatically, a seismic event report is generated automatically, it is possible to recall and reanalyse the stored data with different criterion, trigger value for each sensor can be individually set. Category Service includes – experience (references), expert assistance, location of the vendor, language, receptiveness to our needs and spare parts.

Out of the total of 100 points, depending upon their importance each of the four main categories was allocated certain amount of points. The categories Finance and Technology were found to be equally important and were allotted 35 points each. Category Software was allocated 20 points and 10 points were given the category services. The evaluation was performed individually by each member of the expert team. The team leader mediated different point of views. At the end we feel the best vendor was chosen who was incidentally also the cheapest amongst the bidders.

1.3 Seismic Alarms and the Criterions

The plant protection philosophy distinguishes between a seismic event with Peak Ground Acceleration (PGA) ≥ 0.005 g and < 0.075g at the weathered rock or < 0.128g at the top of the soil, an Operating Bases Earthquake (OBE) with PGA greater than or equal to 0.075g and a Safe Shutdown Earthquake (SSE) with PGA ≥ 0.15g at weathered rock or 0.22g at the top of the soil. For a seismic event to be relevant two DRUs should be triggered. At least one of them should be free field DRU (F1 or F2).

According to the plant operating rules, if following a seismic event alarm no other alarm is activated, the operator in the control room is required to maintain the plant status as it was before the seismic event and inform the plant safety supervisor. Further actions are decided by the safety supervisor.

In the event the PGA registered is equal to or greater than PGA defined for OBE The operator trips the reactor - if required manually - and maintains the plant in the state of hot shutdown. The plant operator in the control room informs the plant safety supervisor on site. It is the plant safety supervisor who decides whether it is an emergency condition or not. In case it is an emergency he mobilises the Technical Emergency Response Team consisting of systems and operation specialists. The shift supervisor puts together a scout team, which checks the condition of the important plant hardware using a predefined checklist.

The Seismic Event Alarm is generated if two DRUs are triggered, the peak fast Fourier transfer value is ≤ 33 Hz and the minimum duration of excitation ≥ 2 s.

The OBE alarm is generated if one of the two free field DRU (F1 or F2) is activated in the frequency range of 2 ... 10 Hz and 5% Damping show that at least one component is ≥ the RSA or RSV ≥ design limits

1...2 Hz and at least one component of CAV is greater than 1570 mm/s.

The SSE alarm is generated if one of the two free field DRU (F1 or F2)is activated in the frequency range of 2 ... 10 Hz and 5% Damping show that at least one component is ≥ the RSA or RSV ≥ design limits 1...2 Hz and at least one component of CAV is greater than 3140 mm/s.

1.4 Location of DRUs and Central Processing Unit (CPU)

The reg. Guide 1.16 requires six DRUs at the following locations:

Free field near to surface
Reactor building foundation
2 DRU in the reactor buildings at higher elevations
1 DRU at the foundation of an independent building
1 DRU at the higher elevations in the same building

The location of DRU at NPP Beznau is chosen considering the NPP Beznau specific needs using the following criteria: .

- The building is seismic qualified. The building can withstand seismic loads caused by an earthquake with accelerations tight over SSE without loss of the stability.
- The building has an independent and seismic qualified emergency power.
- The equipment in surrounding area are fixed earthquake safe. Any Interaction effects between seismic equipment and other equipment induced by earthquakes exist.

The locations are shown in Figure 1. The reg. Guide requirements are fulfilled with two exceptions. Instead of two instrument in an independent building the free field instrument on the weathered rock is kept. Two instruments at the higher elevations in the reactor building located in the unit 1 and unit 2.

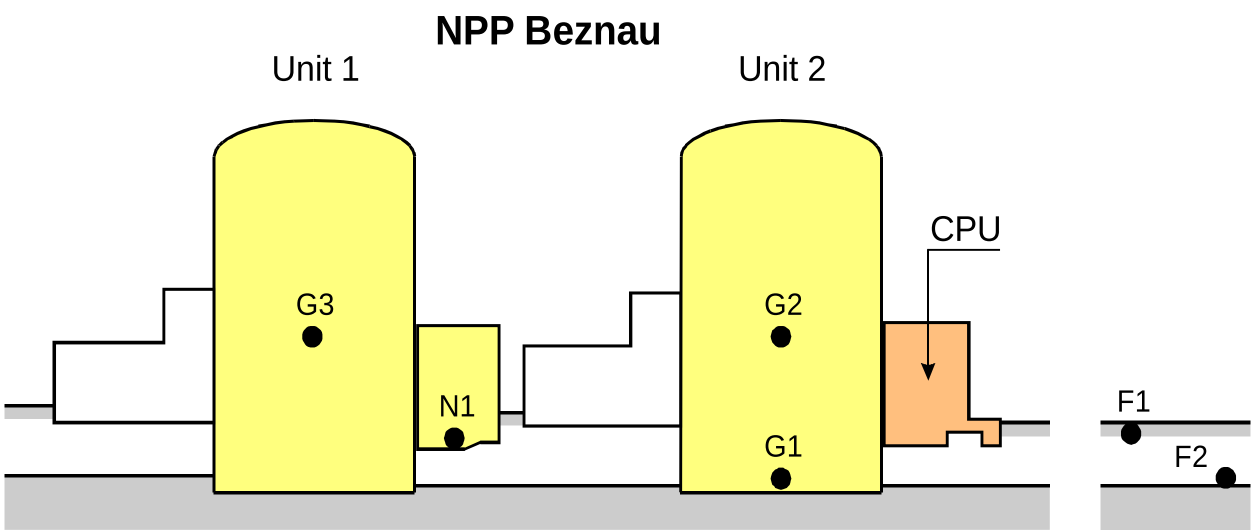

Figure 1. Location of DRUs and CPU

1.5 Recorded events

During the operation of seismic instrumentation, from 1970 to 2005 eight strong motions were recorded. The Figure 2 contains the location of all epicentres

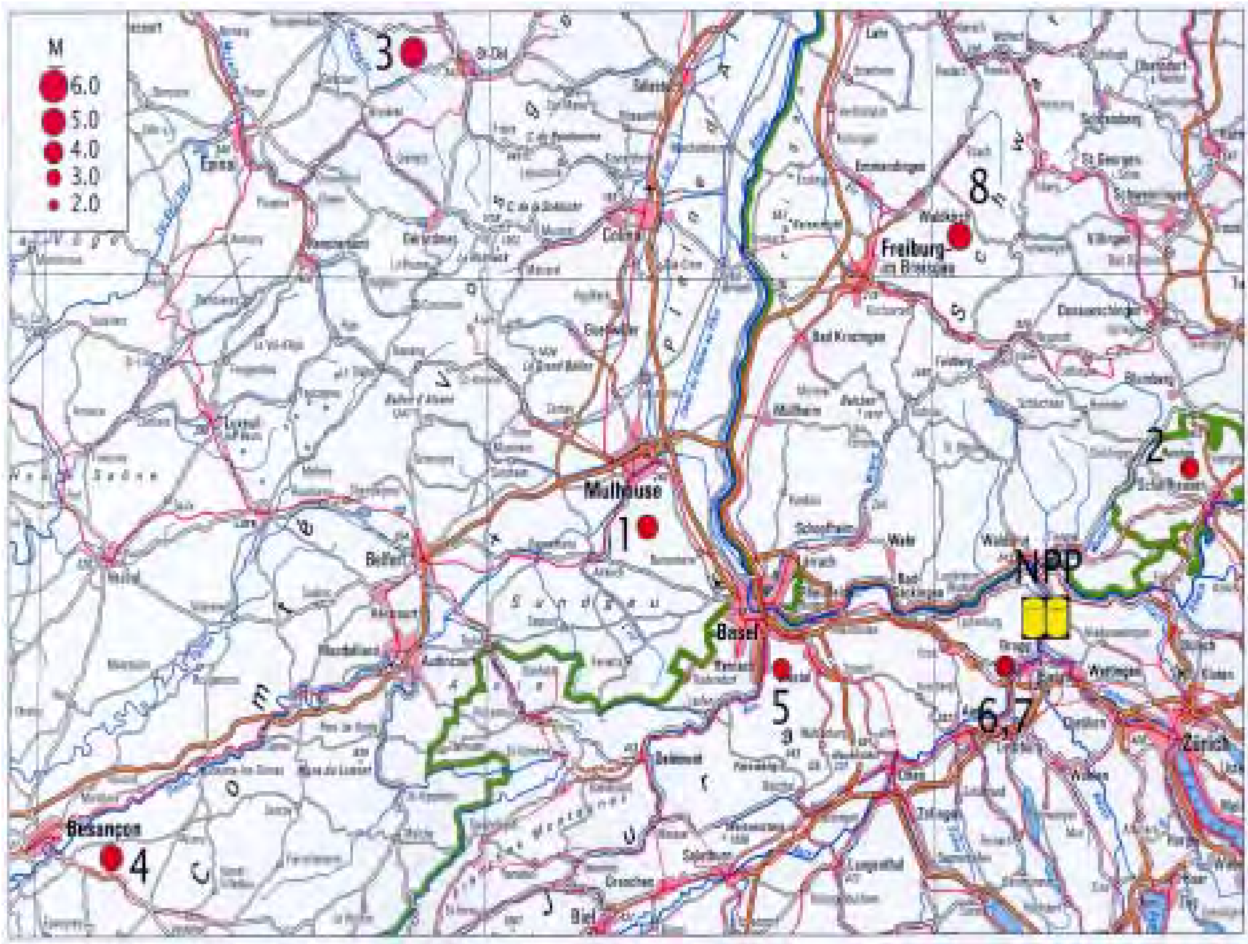

Figure 2: Location of epicentres of recorded events

The recording happened due to very low trigger value (0.001g) of acceleration at free field instrument. This value was chosen intentionally to check the functionality of the seismic instrumentation and to gather seismological data at the NPP site. An overview of all registered events is given in the table 1.

The peak ground acceleration (PGA) as well as the max spectral amplitude for acceleration response spectra for 5% damping with the related frequencies are given in this table. According to Swiss Seismological Services local magnitude of registered earthquakes varies between 2.7 to 5.4 and epicentre distances from 6 km to 159 km. All recorded earthquakes with the exception of the last one were largely observed by persons living close to the NPP site. Therefore the intensity at site could be more than 4 according to European Macro Seismic scale /6/. The first three events between 1970 and 2003 were registered by the old seismic instrumentation and last five events by the new one. The records from the DRU F2, which located on the weathered rock allow a interpretation of seismic data for a broad band of events including far and near earthquakes in the last three decades.

Table 1: Overview of recorded events

Event number Date Location	ML: Local Magnitude H: Epicentral Depth D: Distance		PGA in g		Max. spectral response for 5% damping				Sa(f)/PGA		PGA(F1/F2)
					Frequency	Sa in g	Frequency	Sa			
			F1 (Surface)	F2 (Rock)	F1 (Surface)		F2 (Rock)		F1	F2	
1 15.07.1980 Habsheim	ML= 4.4	X		0.001700			20 Hz	0.005507		3.24	
	H = 15 km	Y		0.003200			22 Hz	0.025696		8.03	
	D = 54 km	Z (vert.)		0.000600			11 Hz	0.001848		3.08	
2 30.12.1992 Wutöschingen	ML = 3.9	X		0.006000			25 Hz	0.034627		5.77	
	H = 25 km	Y	not available	0.006000	not available		22 Hz	0.025696	not available	4.28	not available
	D = 21 km	Z (vert.)		0.005000			28 Hz	0.024694		4.94	
3 22.02.2003 St. Dié	ML = 5.4	X		0.002900			2.3 Hz	0.007856		2.71	
	H = 10 km	Y		0.002300			2.9 Hz	0.008246		3.59	
	D = 159 km	Z (vert.)		0.001100			4.8 Hz	0.004107		3.73	
4 23.02.2004 Besancon	ML =4.8	X	0.003114	0.002135	12.6 Hz	0.01159	8.4 Hz	0.010430	3.72	4.89	1.46
	H = 22 km	Y	0.003203	0.001439	8.4 Hz	0.01454	7.1 Hz	0.007260	4.54	5.05	2.23
	D =147 km	Z (vert.)	0.001690	0.000999	6.7 Hz	0.00521	13.3 Hz	0.004550	3.08	4.55	1.69
5 21.06.2004 Sissach	ML = 3.8	X	0.003954	0.004720	11.2 Hz	0.02039	7.1 Hz	0.014970	5.16	3.17	0.84
	H = 22 km	Y	0.004094	0.002356	11.2 Hz	0.02021	9.4 Hz	0.012270	4.94	5.21	1.74
	D =40 km	Z (vert.)	0.002658	0.002574	15.8 Hz	0.00952	15.0 Hz	0.008020	3.58	3.12	1.03
6 28.06.2004 Frick	ML = 4.0	X	0.018290	0.021800	7.9 Hz	0.07235	7.1 Hz	0.063000	3.96	2.89	0.84
	H = 21 km	Y	0.030710	0.020650	21.1 Hz	0.09042	10.6 Hz	0.064820	2.94	3.14	1.49
	D = 6 km	Z (vert.)	0.012080	0.011040	12.6 Hz	0.02781	15.0 Hz	0.027450	2.30	2.49	1.09
7 29.06.2004 Frick	ML = 2.7	X	0.001472	0.001215	37.6 Hz	0.005622	10.0 Hz	0.003179	3.82	2.62	1.21
	H = 21 km	Y	0.001502	0.000756	26.6 Hz	0.005194	9.4 Hz	0.002692	3.46	3.56	1.99
	D = 6 km	Z (vert.)	0.001973	0.001108	39.8 Hz	0.005882	16.8 Hz	0.002898	2.98	2.62	1.78
8 05.12.2004 Waldkirch	ML=5.1	X	0.016500	0.014150	7.1 Hz	0.06426	7.1 Hz	0.063210	3.89	4.47	1.17
	H=10 km	Y	0.021880	0.014070	4.2 Hz	0.08305	6.0 Hz	0.058080	3.80	4.13	1.56
	D=60 km	Z (vert.)	0.013180			0.04605	7.1 Hz	0.031000	3.49	3.28	1.39

2. CHECK ASSUMPTIONS FOR SEISMIC DESIGN LOADS

2.1 Seismic Design Assumptions

SSE annual probability of non-exceedance 10^{-4}
Peak Ground Acceleration (PGA)-values on the weathered rock for SSE hor. X direction = 0.15g
Hor. Spectrum shape in accordance with US-NRC 1.60 /4/
PGA-values on the weathered rock for SSE hor. Y direction = 0.15g
PGA-values on the weathered rock for SSE vertical direction= 0.10g
Vert. Spectrum Shape is according to /4/ modified by moving PGA values to 50 Hz.
SSI-Analysis performed using FLUSH, Floor response Spectra with 3-D Stick Models of Structures and Reactor Coolant Loop Piping and Components.
PGA values free field surface according to free field analyses with SHAKE /5/. The SSE horizontal components (X and Y) = 0.22g and vertical component Z = 0.16g
OBE =1/2 SSE on the weathered rock, PGA in X und Y = 0.075g and Z = 06g
PGA-values free field surface OBE X = 0.128g, Y = 0 0.124g and. Z = 0.089g

2.2 Spectral Amplitudes

The acceleration response generated using the recorded data by DRU F2 in the plant Y-direction on the weathered rock is shown in Figure 3. The spectra form is remarkable different for far and near field earthquakes. Far earthquakes contain low frequencies, near field earthquake has high frequencies. The frequency content of all response spectra from earthquakes with the epicentres in a 40 km distance from the site is very similar. The amplitudes of those spectra vary with magnitude and distance.

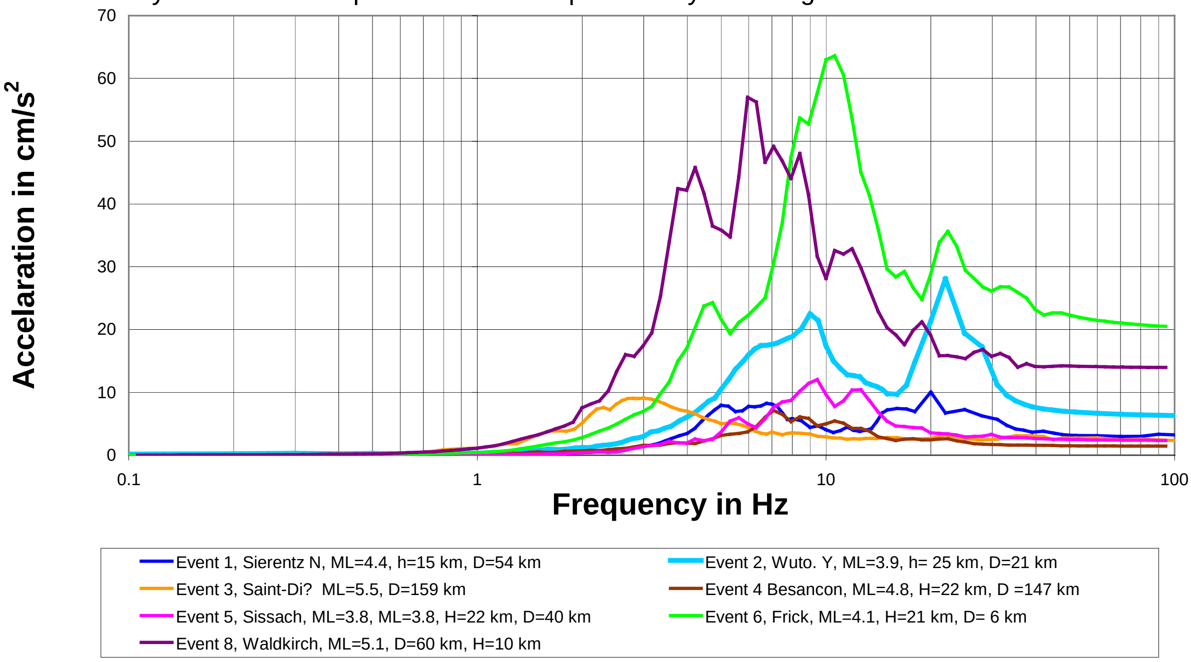

Figure 3: Acceleration Response Spectra in Plant Y-Direction (-17° to north direction) from recorded data by DRU F2 on the weathered rock for 5% damping

The highest acceleration values recorded at site were caused by the near earthquake (event 6) with a magnitude of 4.1 The resulting response spectra from DRU F1, Free field at the top of soil, are compared with the design spectrum in Figure 4. The US-NRC Spectrum scaled with free field PGA-accelerations was used as design spectrum. As it can be seen spectral amplitudes of the recorded event are very low in comparison to OBE-Design Spectra.

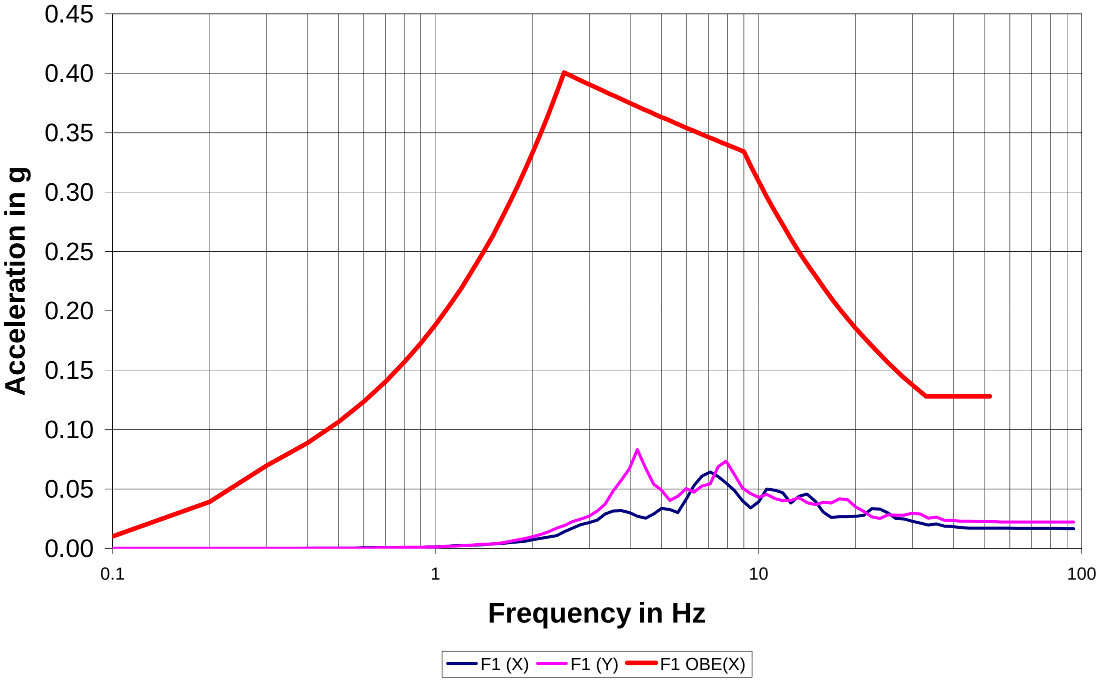

Figure 4: Comparison of acceleration response from Free field DRU at Surface (F1) from Event 6 with the OBE-Design spectrum

2.3 Spectrum Shape

The comparison of the spectral shape by scaling all spectra to unit PGA in horizontal plant directions is shown in Figure 5 and 6. In general for frequencies less than 6 Hz the design spectra shape envelopes all the spectra from recorded events. The spectra from event 3 in Y-direction is an exception. The spectra from earthquakes closest to site in 6 to 40 km distance have high frequencies. Since the first eigenfrequencies of the structures are laying between 2.0 and 6.0 Hz, the peaks at high frequencies are not relevant for structures. The structures will damp out these frequencies and not transfer to the components and equipment inside the buildings.

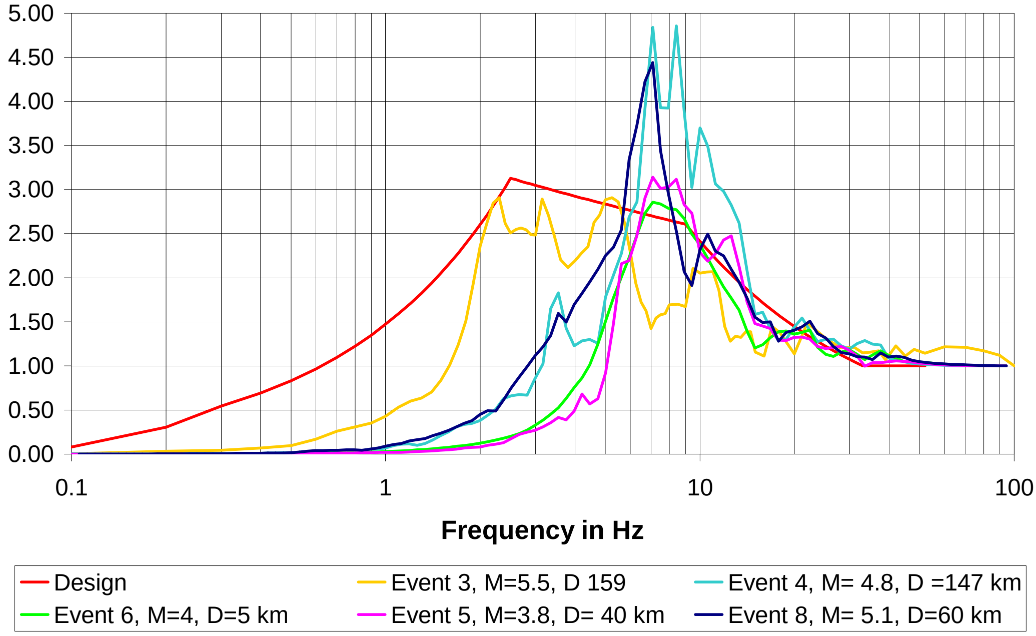

Figure 5 :Comparison of spectral shape from recorded events in horizontal X-direction by DRU F2 on the weathered rock with those for the design

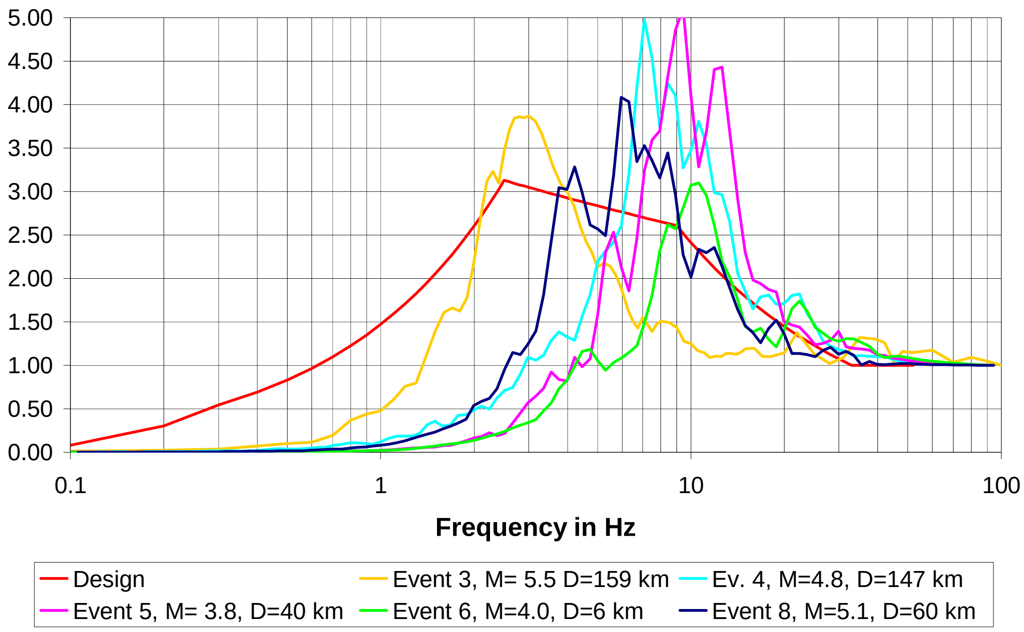

Figure 6: Comparison of spectral shape from recorded events by DRU F2 on the weathered rock in horizontal Y-direction with those for the design

Figure 7 and 8 contain the spectral shape for DRU G2 which located at the operating floor in the reactor building. As it can be seen in those figures peak spectral values at low frequencies in the input motion exist no more in the response. These are filtered through SSI-effects. Since design input has no high frequency content the design response spectrum does not show any peaks at those frequencies. At high ground motion levels it is expected that soil stiffness will be reduced and consequently lower response frequencies result. At same time the peaks will be damped out due to non-linearities in the soil and in the structure. It is well known that accelerations in higher frequency range cause little structural damage. Since the deflections are small and damping effects can significantly reduce the response. Well below that predicted by linear elastic analyses.

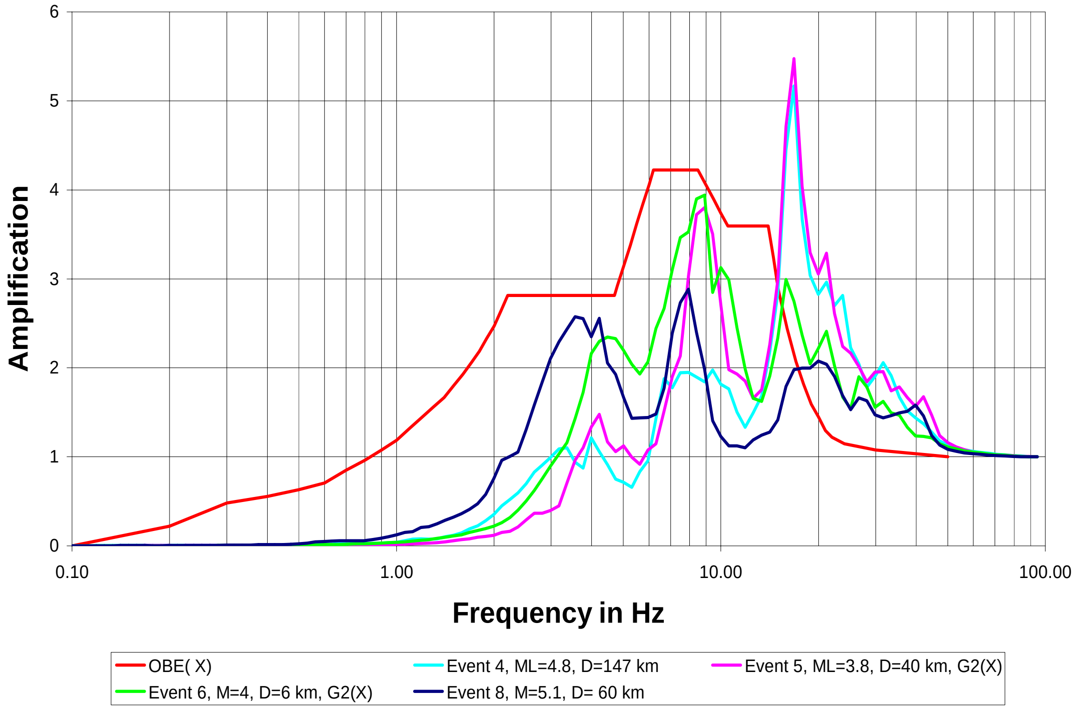

Figure 7: Comparison of spectral shape from recorded events in horizontal X-direction by DRU G2 on the operating Floor with those for the design

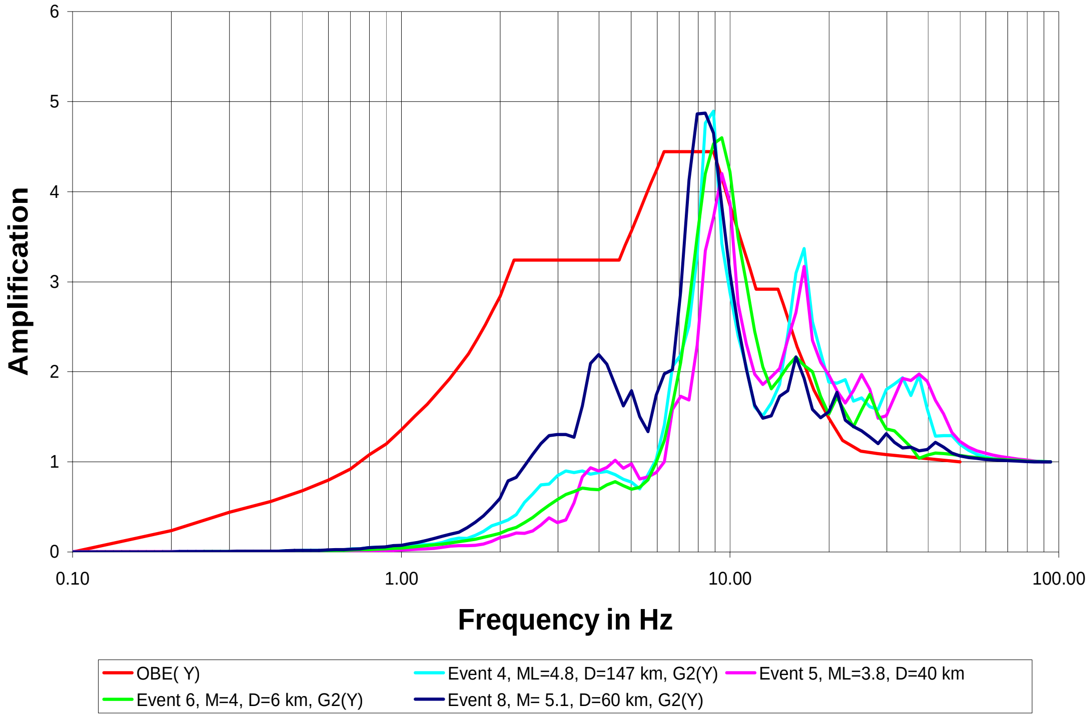

Figure 8: Comparison of spectral shape from recorded events in horizontal X-direction by DRU G2on the operating floor with those for the design

2.4 Ratio vertical / horizontal

The ratio vertical/horizontal is evaluated for two strongest events, i.e. for event 6 and event 8. Event 6 represents a near earthquake, event 8 an earthquake in a medium distance. Figure 9 shows the ratios of vertical spectral amplitudes to horizontal spectral amplitudes in X and Y directions. The ratio of vertical component to horizontal X or Y component of ground motion was assumed as 0.67 in the seismic requalification study. This assumption is valid for the frequencies less than 9 Hz.

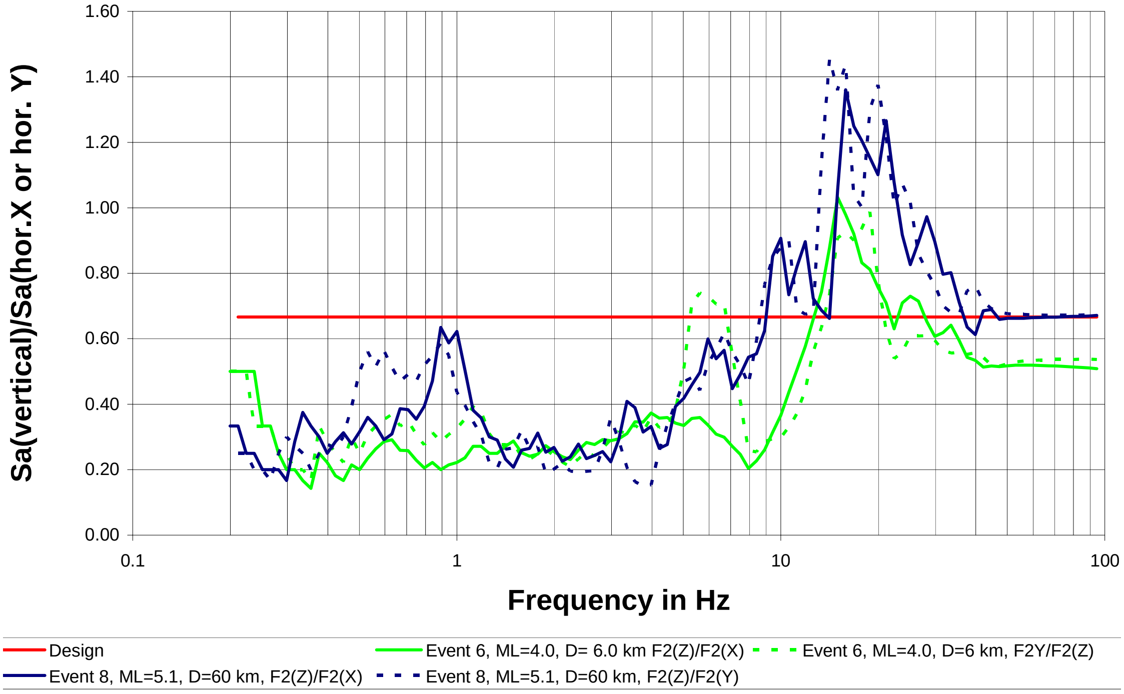

Figure 9: V/H Ratio on the weathered rock

2.5 Amplification from weathered rock to surface

Two free field DRUs provide sufficient data to evaluate the amplification from weathered rock to the surface. The ratios of spectral acceleration from DRU F1 and F2 in horizontal X-direction are shown in Figure 10. The free field analyses which were executed for 1-D vertical propagating shear waves gave an amplification factor of 1.4 for SSE and 1.7 for OBE. This factor for SSE is less than for SSE due to non-linearities in the soil for high ground motion levels. As it can be seen in the Figure 10 the amplification factor for OBE is not exceed below 11 Hz. Since the design spectrum is an US-NRC spectrum with low frequency content no amplifications at high frequencies resulted. In consequence of high frequency contents of near earthquake higher amplification factors results. At higher ground motion levels these peaks will be damped out as a result of non-linearities in the soil. Therefore they are not relevant.

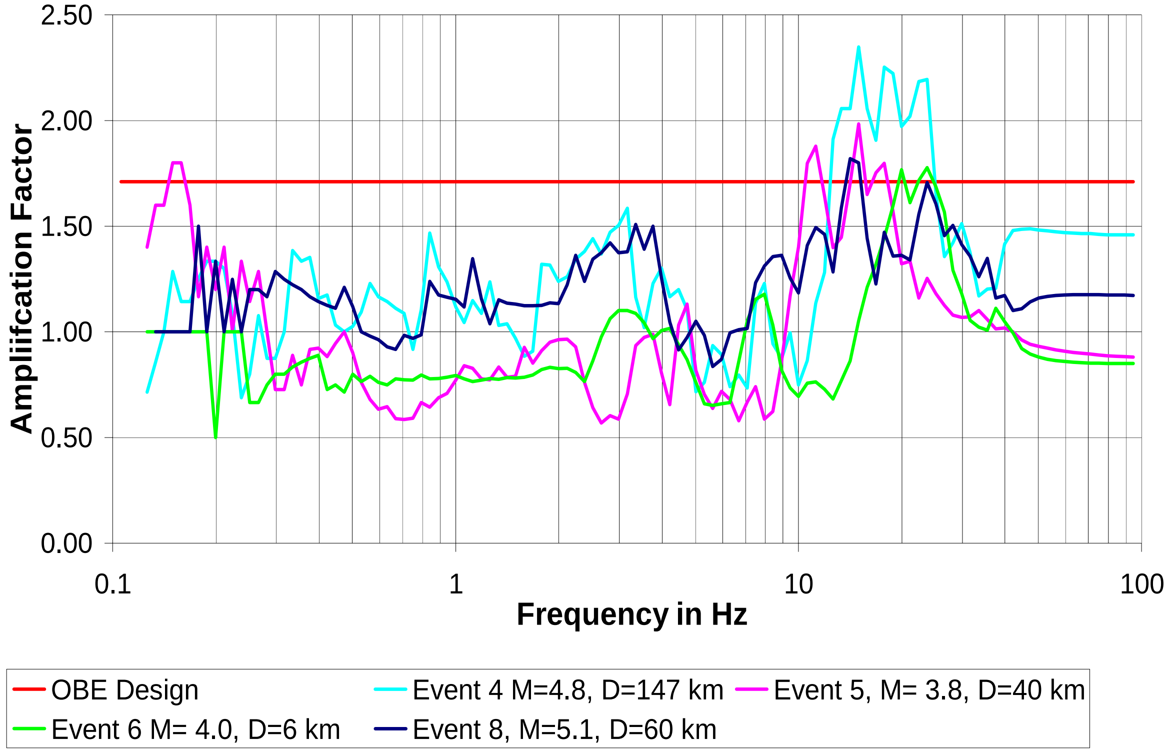

Figure 10: Amplification of Spectral accelerations from weathered rock to surface in X-direction

3. CHECK DYNAMIC MODELS OF STRUCTURES

The following comparisons are carried out for the near field earthquake from 28. June 2004. The epicentre was at a distance of 6.0 km from the NPP site.

3.1 Soil-Structure Interaction at the Reactor Building

The ratio between the horizontal spectral amplitudes of DRU G1 on the foundation of reactor building to those of free field instrument F2 on the weathered rock as well as the ratio for OBE-Design spectrum is plotted in the Figure 11 to visualize the SSI effects. As shown in this figure the ground motion in the building is reduced through SSI effects. The reduction is higher at high frequencies since the relevant eigenfrequencies of the structure and soil diverge from each other. This means the effects of near earthquake with high frequency content are not relevant for the components and equipments in the reactor building. The design is conservative since the ratio for design spectra envelope the curves from real earthquake.

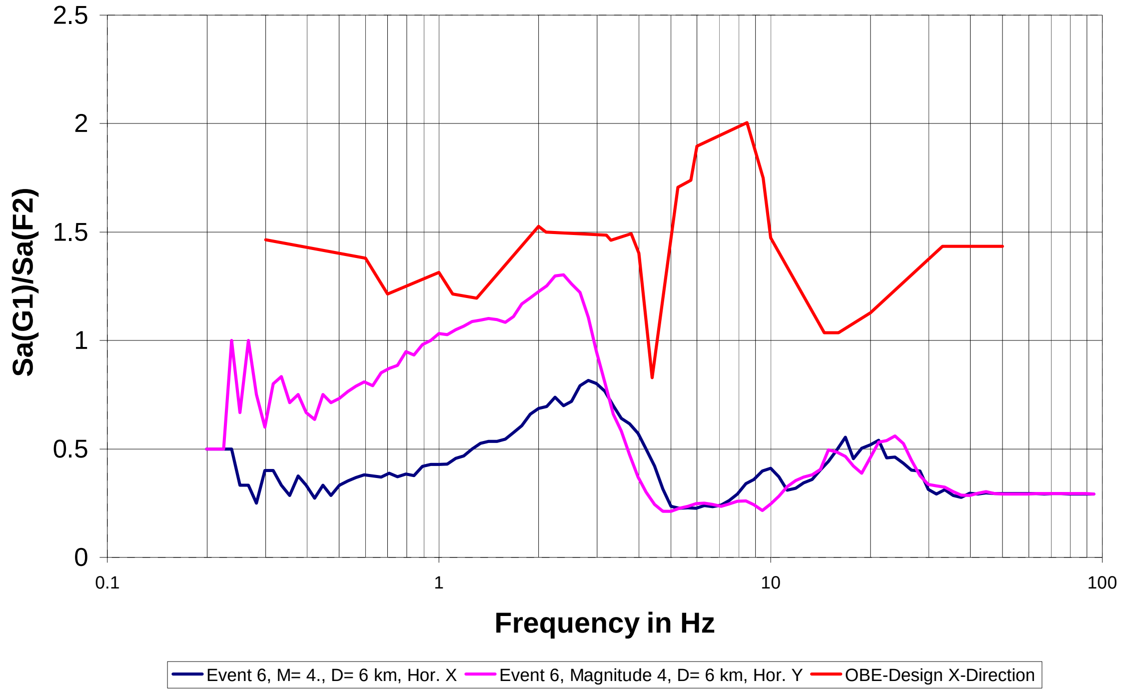

Figure 11: SSI effects in the reactor building

3.2 Soil-Structure Interaction at the Emergency Building

Similar to the reactor building the ratios between horizontal spectral amplitudes of DRUs N1 on the emergency building Foundation and Free field DRU F1 are generated and shown in Figure 12. There is also in this building strong SSI- effects can be observed. These effects lead to 40% reduction of accelerations in the emergency building. The same ratio for design can be seen in the same figure. The conservative design assumptions lead to increase the accelerations instead of decrease.

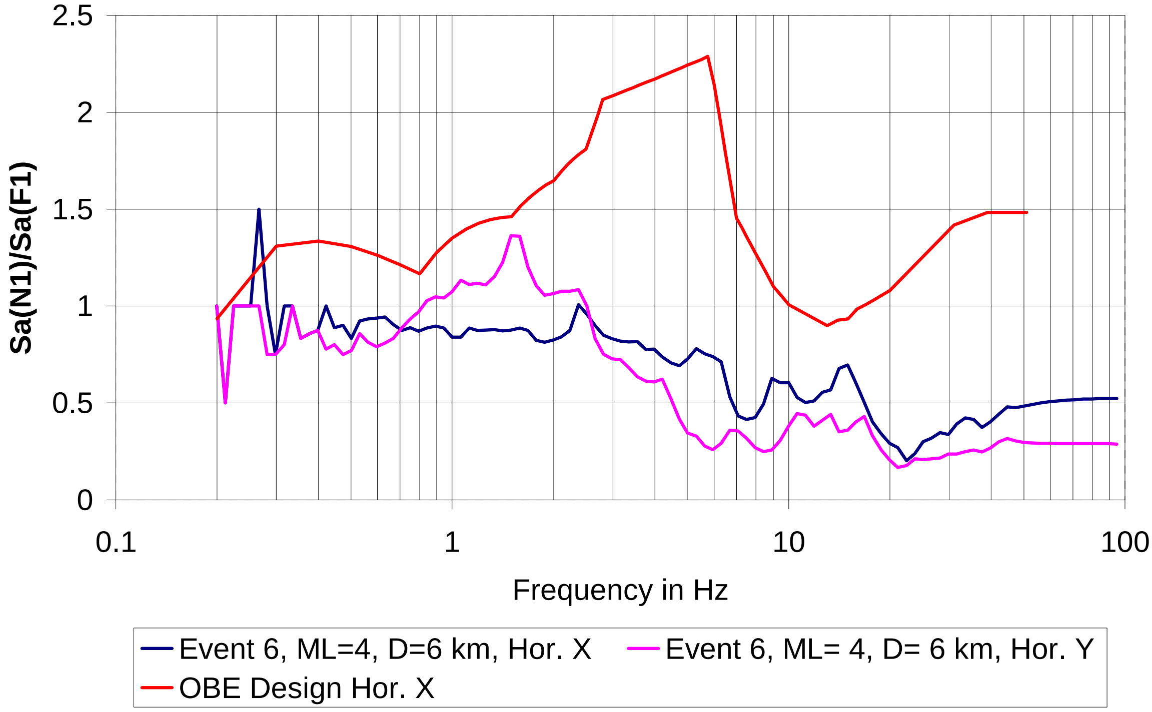

Figure 12: SSI effects in the emergency building.

3.3 Amplification in the Reactor Building

In the Figure 13 ratios of spectral amplitudes in X-direction between DRU G2, installed on he operation floor building and DRU G1, installed on the foundation are shown and compared with those from OBE. To take into account the differences on the structural damping for OBE and real earthquake with very low level accelerations OBE design values are increased by a factor of Since the damping for structural materials are close to zero for vibrations with very low amplitudes the OBE design values increased by a factor of 2.

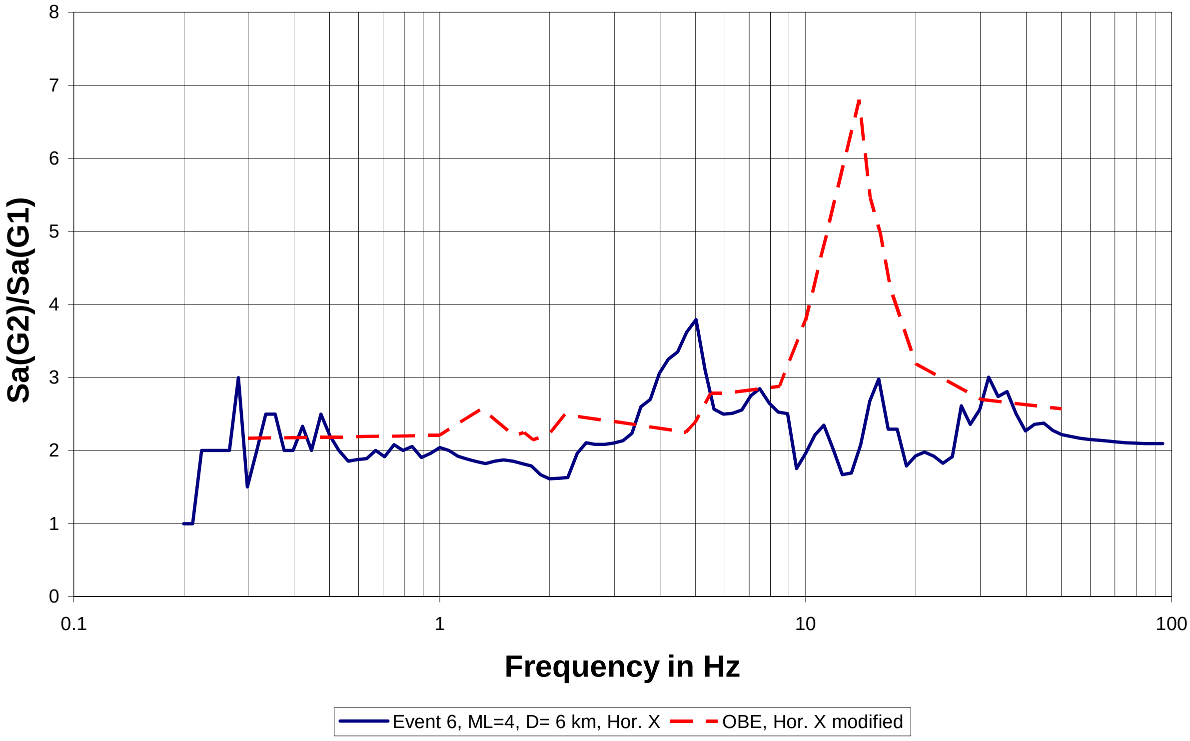

Figure 13: Amplification of the accelerations from foundation at elev.-15.0 m to operating floor + 13.00 m in the reactor building

3. 4 Comparison of Dynamic Behaviour of Reactor Buildings Unit 1 and 2

Two units of NPP Beznau has the same structural properties. During earthquake the unit 2 was in the operating, unit 1 was shut down for the revision purposes and reactor cavity was filled with water.. The acceleration response Spectra of DRU G2 and G3 for horizontal direction are compared in the Figure 14. The horizontal RSA is evaluated as SRSS of acceleration responses in X-. and Y-direction. As it is shown in this figure the RSA's are very similar. For the frequencies higher than 6.0 Hz the spectrum from unit 2 envelopes those from unit 1.The peak values at 4.5 Hz indicates to the first natural frequency of the building. This is consistent with calculated value of 5.0 Hz with fixed boundary conditions. Since for lower ground motion the soil stiffness is closer to the fixed conditions the dynamic model of the reactor building is realistic Light different amplifications in Unit 1 and 2 at that frequency is observed. If this is caused by light different soil layer thicknesses under base mat or caused by additional water masses in the Unit 1 during earthquake need to be clarified by means of dynamic analysis. According to the analysis PGA value amplifies 3.0 times between frequencies 2 ... 5 Hz. The measured values show an amplification of factor 1.8. So for this earthquake the Floor Response Spectra are lying on the secure side.

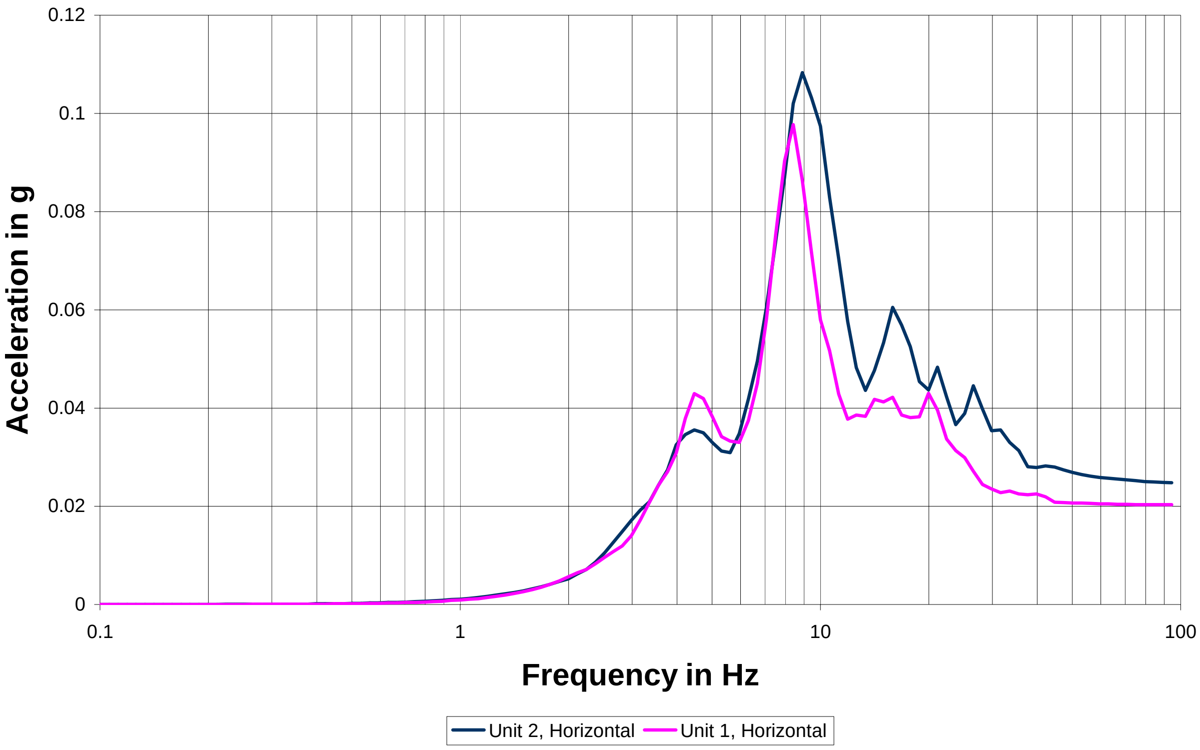

Figure 14: Comparison of the Horizontal Spectra from DRU G2 in Unit 2 and G3 in Unit 1 on the operating floor

4. CONCLUSIONS

The seismic instrumentation fulfils the requirements with respect to its functionality. The registered data from free field DRUs is valuable for further seismological investigations like: check the attenuation laws and to specify soil profiles for site response analysis. Such observations can lead more realistic site specific design assumptions. The evaluation of data showed that the seismic design assumptions are conservative. The data which recorded by DRUs in the structures can be used to generate more realistic and less conservative models of soil-structure parameters. Such events offer both plant operators and engineers an opportunity to deal with real earthquake situations. The experience gained is useful to improve the overall seismic safety of the plant.

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