Quality check of the Groningen accelerometer network

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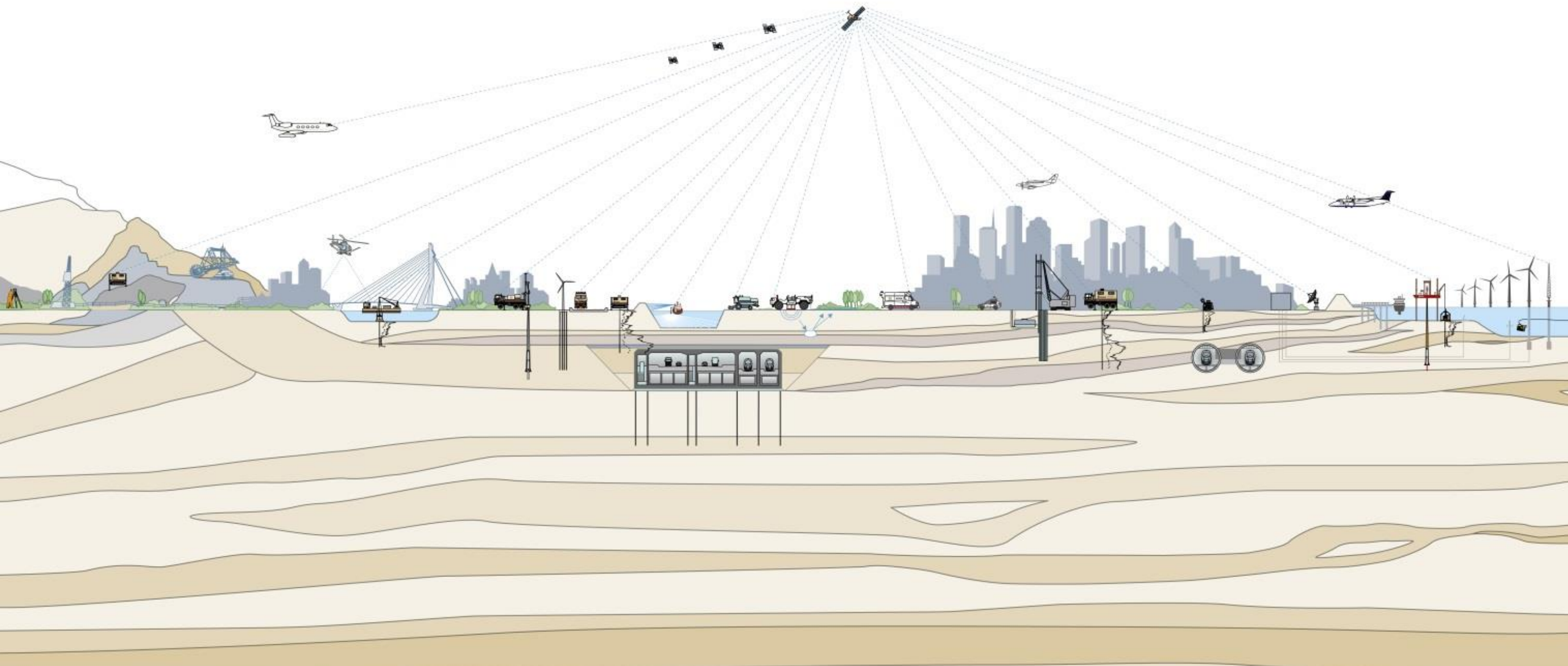

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CONTENTS

1. INTRODUCTION

In February 2019, KNMI published a mistake of the surface motions of the surface G-network that collected data since 2014. For the majority of stations, the presented motion was a factor of 2 underestimated, the rest was a factor of 2 overestimated. Because of the importance of the network and the uncertainties, State Supervision of Mines started several checks of KNMI's network. Part of the checks and inspections were done by Fugro.

The following checks were carried out relating to the KNMI-network in the Groningen field:

1. Testing of B- and G-station-equipment on the shaking table;
2. Study of additional information on B-stations and analysis of potential soil-structure effects: installation documentation etc. to be provided by KNMI and building and foundation information, to be provided by municipalities;
3. Field inspections of selected B- and G-stations to check irregularities and possible influence of setup/ installation/ building and/or ditches;
4. Comparison of CPT's between B- and G-stations;
5. Analysis of consistency between B- and G-station records for induced events in the Groningen gas field.

The quality check is a result of preliminary findings of the Fugro-team during the KEM04-study: the data driven study on seismic structural features of Groningen ground motions. Doubt arose because of inconsistencies of the data. The quality check was done by part of Fugro's KEM04-team: Fugro and its subcontractors Hanze University of Applied Sciences (Groningen) and Seister (France).

1. Testing of B- and G-station-equipment on the shaking table
   For the shake tests of the accelerometers, the facilities of Hanze University of Applied Sciences were used. In consultation with the client, 4 accelerometers were selected to be tested: 2 B-sensors and 2 G-sensors. The following accelerometers were tested: BOWW, BZN1, G190 and G750. Because of irregularities for G190, the accelerometer of G470 was tested additionally. It was necessary to dismantle part of the existing installation in the field to obtain a test environment that is equal to the field installation. The results of the shake-tests are presented in a separate report, see attachment A.
2. Study of additional information on B-stations and analysis of potential soil-structure effects:
   KNMI has provided the reports and photos that were made during installation of the accelerometers. Fugro has collected site data, building data and foundation information from several sources like municipalities. The combined data was interpreted.. This part of the check is presented in the main text of this report.
3. Field inspections
   Fugro and Hanze, together with KNMI, have carried out field inspections on selected B- and G-stations. The dismantling of the selected accelerometers with corresponding equipment was done by KNMI, with assistance of Hanze. The inspections have provided observations which were used for the quality check. The findings of the inspections are presented in the main text and the attachment of this report.
4. Comparison of CPT's between B- and G-stations;
   Fugro has conducted a comparison of soil data (CPT's) to check if differences between B- and G-stations can be (partly) explained by soil differences. The results can be found in attachment C. In

general the CPT's don't support the supposed explanation. A more extensive analysis is possible after execution of SCPT's at G-stations.

5. Analysis of consistency between B- and G-station records for induced events in the Groningen gas field:
   The collected acceleration data from KNMI from adjacent B- and G-stations was compared by Seister. The results can be found in attachment B.

2. PROPERTIES OF BUILDINGS AND FOUNDATIONS OF B-STATIONS

Table 2.1 shows the locations and names of the KNMI measurement stations that are analysed in this report. Figure 2.1 shows the locations and addresses of the B-stations. At each station, a seismic CPT was performed. Not all SCPT's however, were performed next to the stations. The distance can be derived from the coordinates. The year of construction is mentioned, as well as the foundation type. The foundation type was derived from the information and drawings that was collected. Most of the buildings are founded on shallow foundations. For BHAR, BWIN and BWIR, based on the incomplete information, it is not certain which kind of foundation is applicable. Based on the year of construction and the characteristics of the buildings, it is plausible that a shallow foundation is applicable for these stations.

Table 2.1: Names and locations of surveyed KNMI stations

KNMI station	GPS-coordinates SCPT	GPS-coordinates KNMI station	Address	Year of construction	Foundation style
BAPP				1910	shallow foundation
BFB2	N			1906	shallow foundation
BGAR				1920	Spread foundation
BHAR				1910	shallow foundation?
BHKS				1910	shallow foundation
BLOP	N			1890	shallow foundation
BMD2				1657	shallow foundation
BOWW				1903	shallow foundation
BSTD				1936	shallow foundation
BUHZ				1900	Pile foundation
BWIN				1910	shallow foundation?
BWIR				1930	shallow foundation?
BWSE				1960	shallow foundation
BZN1				1960	shallow foundation
BZN2				1972	shallow foundation

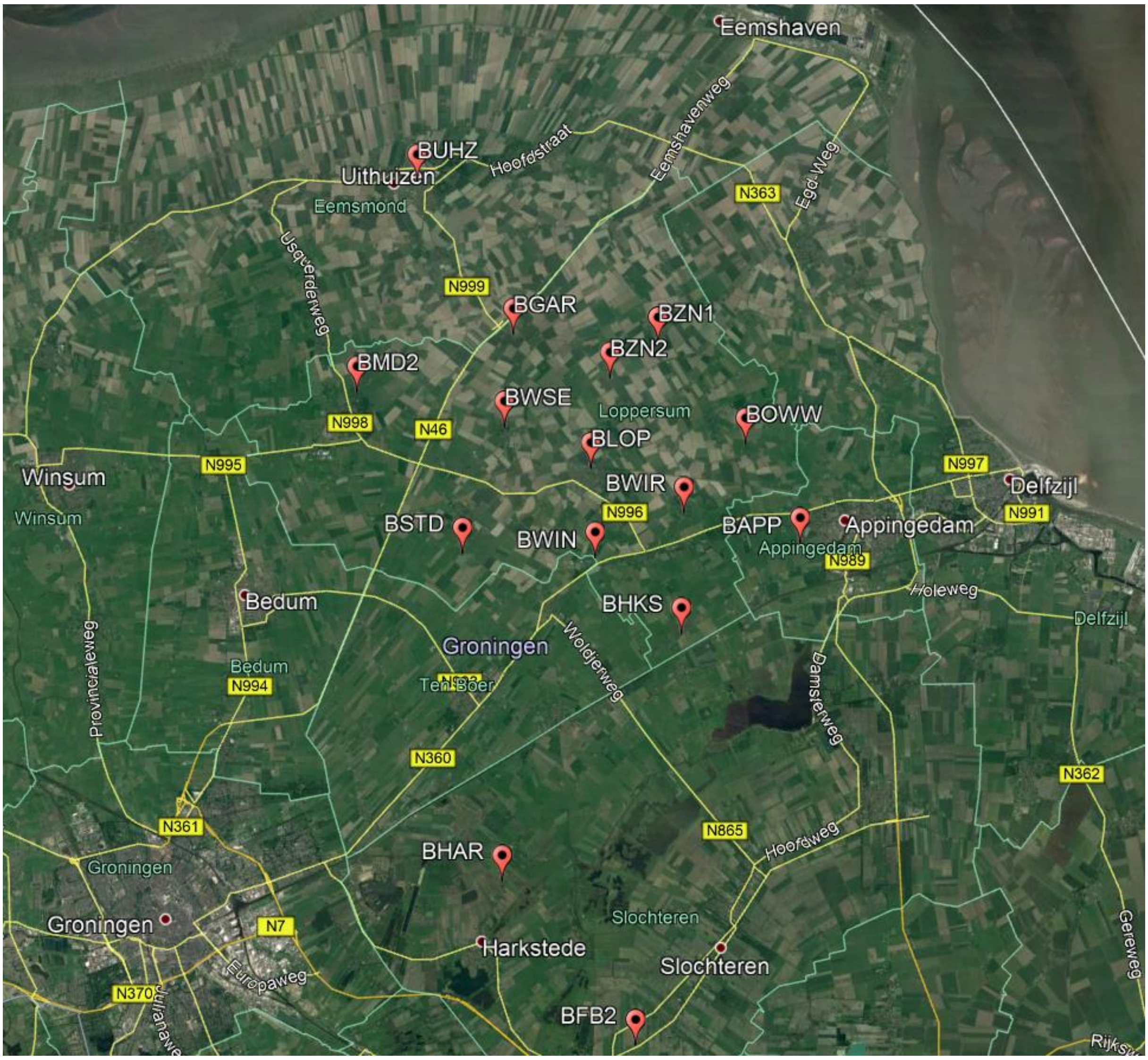


Figure 2.1: Map view of the locations of the KNMI-stations that are analysed in this report (source: Google Earth)

In the following paragraph, the characteristics of each station will be discussed in detail.

2.1 BAPP – Appingedam

The BAPP-station is located in a small shed at the . Drawings of the foundation indicate that the shed is founded on a spread foundation. The building consists of a concrete floor, light (wooden) walls and is covered with roof tiles, see figure 2.2a and b.

Figure 2.2a and b: Shed in which KNMI-station BAPP is located

2.2 BFB2 – Kolham

The BFB2-station is located in a relatively small farm-building (see Figure 2.3a) on Drawings of the foundation indicate that the garage is founded on a spread foundation (see Figure 2.3a).

Figure 2.3a: Farm in which KNMI-station BFB2 is located

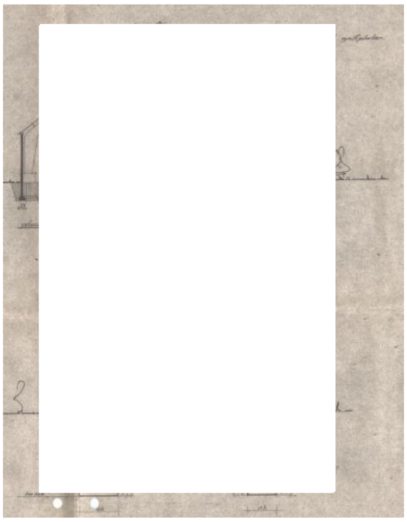
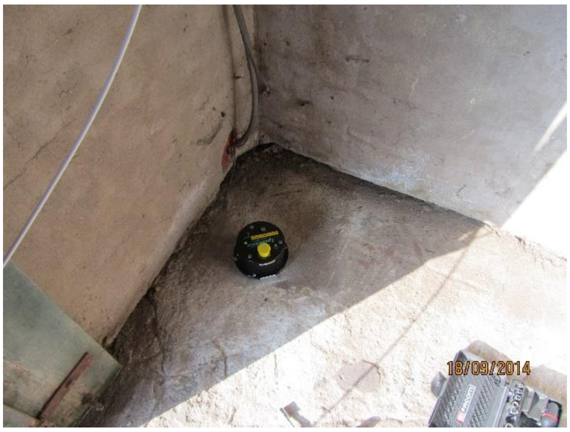



Figure 2.3b and c: Cross sectional drawing of the farm showing its spread foundation and detail drawing of the foundation and photo of the accelerometer.

2.3 BGAR – Garsthuizen

The BGAR-station is located in the shed next to the house (see Figure 2.4) on the . Drawings of the foundation indicate the garage is founded on a spread foundation (see Figure 2.5).

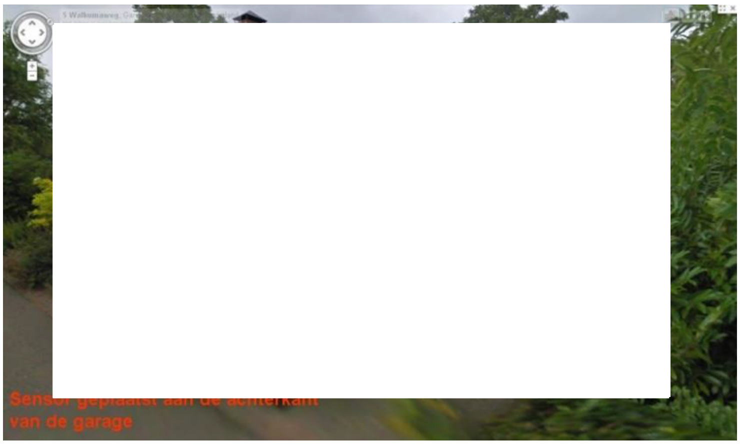


Figure 2.4: Location of the KNMI-station BGAR, back of the garage

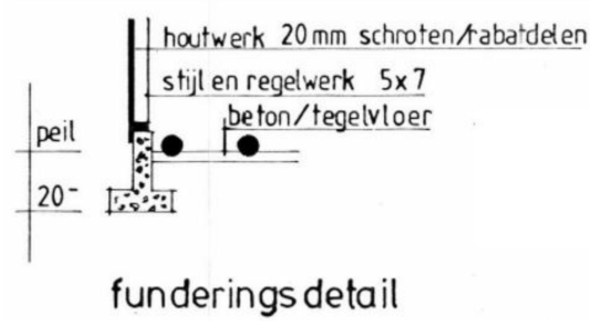


Figure 2.5a and b: Foundation detail of the shed

2.4 BHAR – Harkstede

The BHAR-station is located in a building (see Figure 2.6) that belongs to the house on the . The foundation style of the shed is not known exactly. However, information received from the municipality of Midden-Groningen, which says the foundation material is concrete, in combination with the building style, indicates it is founded on a spread foundation.

Figure 2.6: Building in which KNMI-station BHAR is located

2.5 BHKS – Garrelsweer

The BHKS-station is located under a desk in the farm on the
Drawings of the foundation (see Figure 2.7) show the house is founded on a spread foundation.

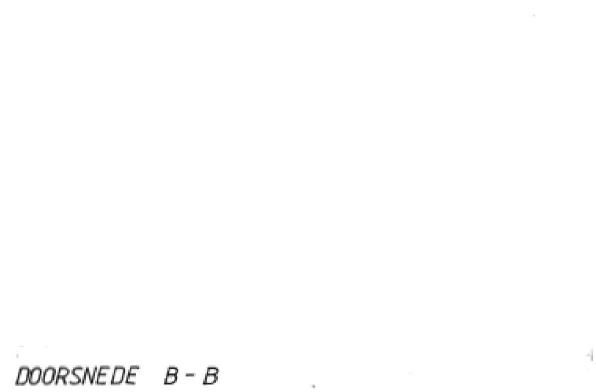


Figure 2.7: Cross sectional drawing of the farm in which KNMI-station BHKS is located, showing the spread foundation.

2.6 BLOP – Loppersum

The BLOP-station is located in the shed (see Figure 2.8) that belongs to the building on the . Constructional drawings of the shed show that it is founded on a spread foundation (see Figure 2.8).

Figure 2.8a: The shed with the BLOP-accelerometer; 2.8b: Cross sectional drawing of the shed showing its spread foundation; 2.8c: location of the accelerometer

2.7 BMD2 – Middelstum

The BMD2-station is located in the shed next to the main building on the . Constructional drawings of the shed show that it is founded on a spread foundation (see Figure 2.9).

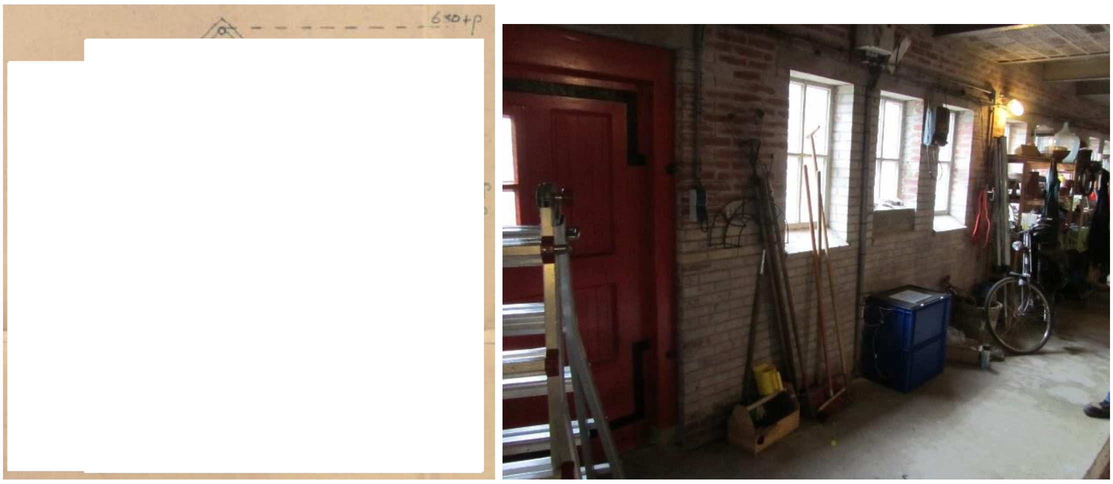


Figure 2.9a: Cross sectional drawing of the shed showing the spread foundation; 2.9b Photo with the location of the accelerometer

2.8 BOWW – Oosterwijtwerd

The BOWW-station is located in the shed (see Figure 2.10) that belongs to the house on the Constructional drawings of the shed indicate that it is founded on a spread foundation (see Figure 2.10), however the characteristics of the real shed deviate from the drawing.

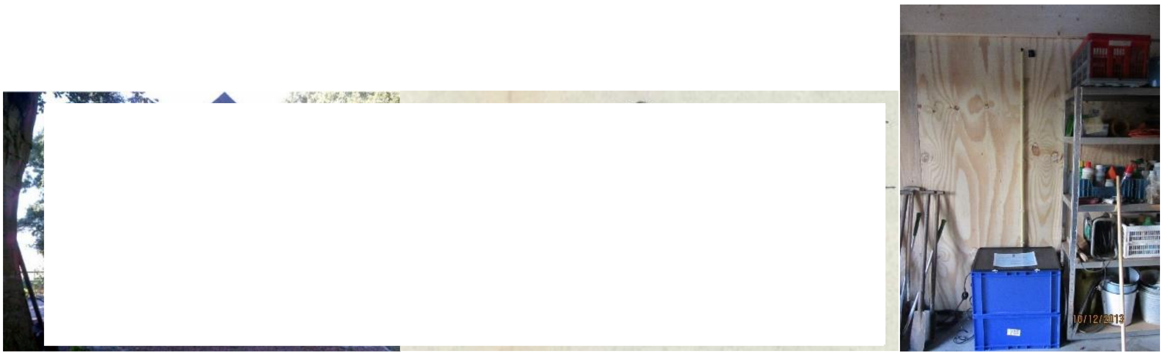


Figure 2.10a: Left: The shed in which the KNMI-station is located. 2.1b: Cross sectional drawing of the shed showing its spread foundation; 2.1c: photo inside the shed with the installation

2.9 BSTD – Stedum

The BSTD-station is located in the house on the . Constructional drawings of the house indicate that it is founded on a spread foundation (see Figure 2.11).

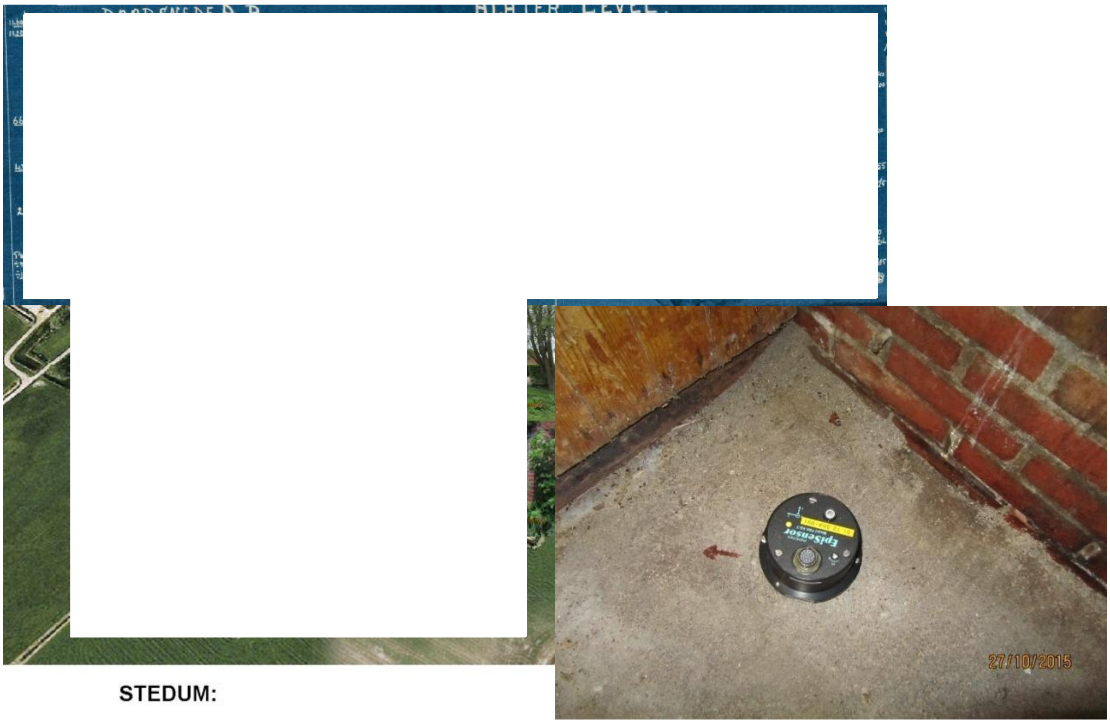


Figure 2.11a: Cross sectional drawing of the building showing its spread foundation; 2.11b location of the accelerometer and 2.11c: photo of the accelerometer

2.10 BUHZ – Uithuizen

The BUHZ-station is located in the bicycle parking in the cellar under the main building of the city hall on the . The bicycle parking is founded on cast-in-situ piles (see Figure 2.12).

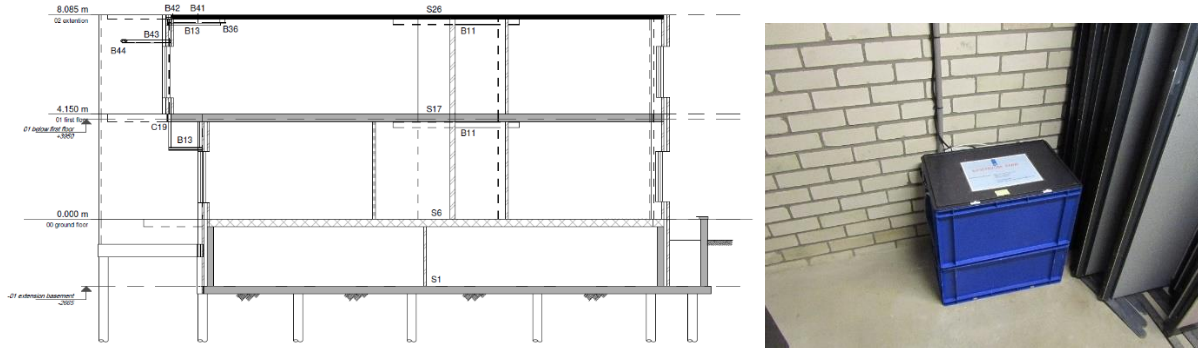


Figure 2.12: Cross sectional drawing of the basement showing the pile foundation and photo of the installation in the cellar

2.11 BWIN – Winneweer

The BWIN-station is located in the basement of the house (see Figure 2.13) on the . The foundation type of this house is unknown; probably a shallow foundation. The accelerometer itself is mounted onto a loose (?) tyle.

Figure 2.13a to c: House in which KNMI-station BWIN is located and 2 photos inside the house

2.12 BWIR – Wirdum

The BWIR-station is located in the shed (see Figure 2.14) that belongs to the house on the . The foundation type of the shed is unknown, probably shallow foundation.

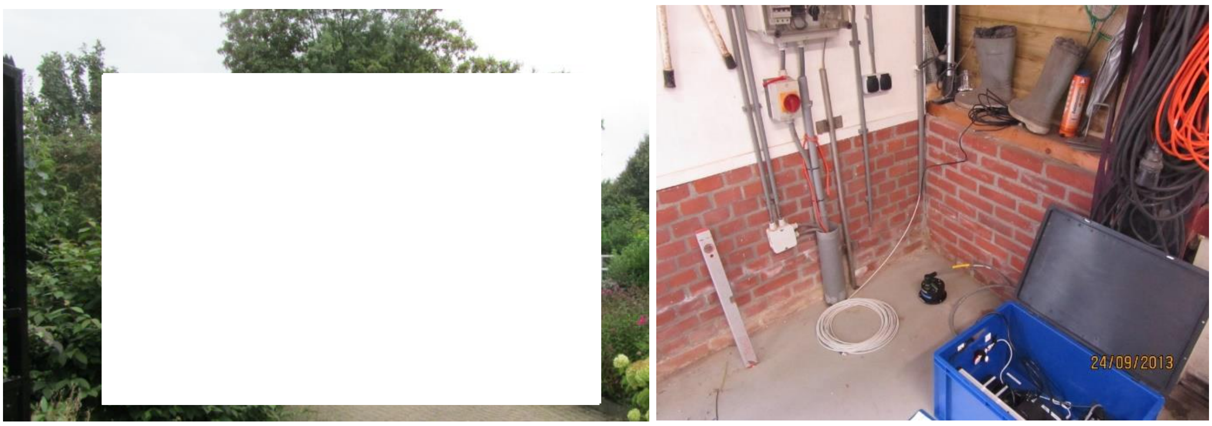


Figure 2.14a: Shed with BWIR and 2.14b: photo of the accelerometer inside the shed

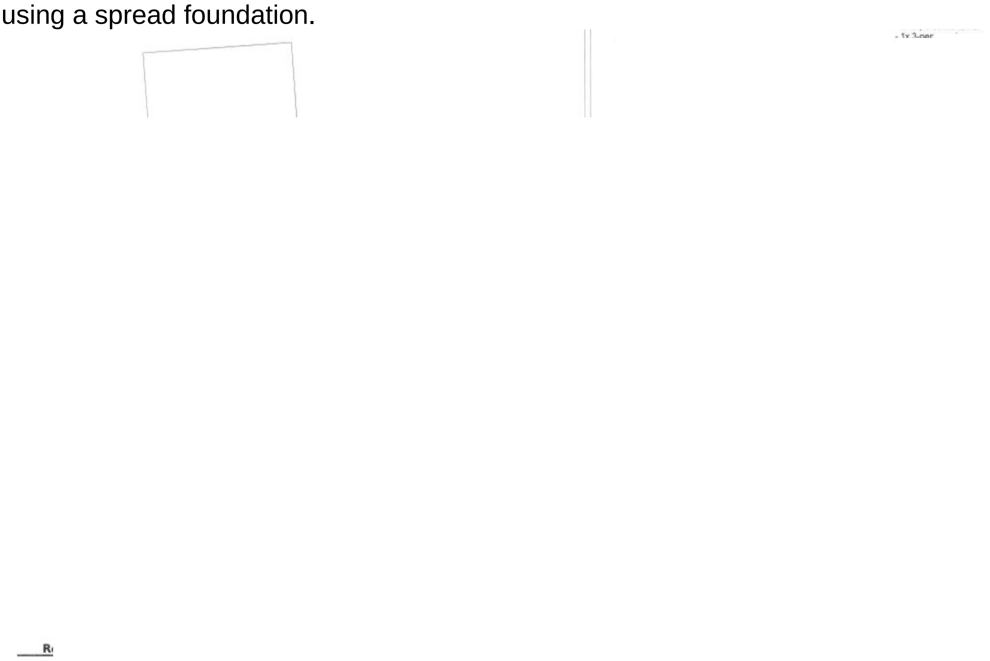
2.13 BWSE – Westeremden

The BWSE-station is located in the shed that belongs to the house on the . Constructional drawings of the shed show that it is founded on a shallow foundation (see Figure 2.15).

Figure 2.15a: Cross sectional drawing of the shed showing its spread foundation. 2.15b: Detailed drawing of the shallow foundation.

2.14 BZN1 – Zeerijp

The BZN1-station is located in the basement of a former municipality building on the . The foundation style is not exactly known, however the annex buildings belonging to the main building are founded using spread foundations. Hence, it is likely the main building is also founded using a spread foundation.



2.15 BZN2 – Zeerijp

The BZN2-station is located in the shed that belongs to the house on the . Constructional drawings of the shed indicate that it is founded on a shallow foundation (concrete plate; see Figure 2.16).

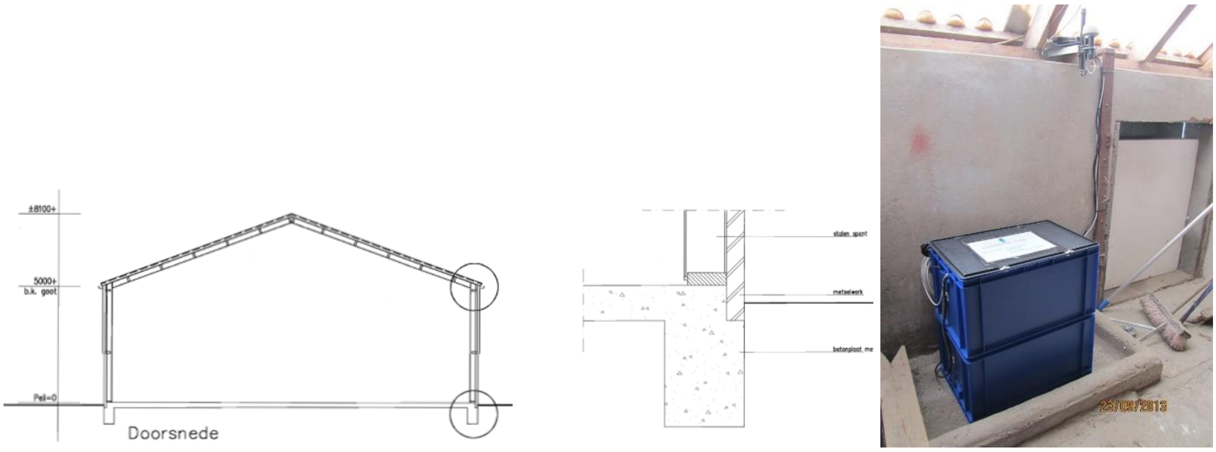


Figure 2.16a: Cross sectional drawing of the shed, showing its spread foundation. 2.16b: Photo inside the building with installation

3. ASSESSMENT OF RELIABILITY OF MOTION DATA OF B-NETWORK

3.1 Comparison of motion data of adjacent B- and G-installations

Seister has processed the motion data of adjacent B- and G-stations as can be read in attachment B. In the attachment you can find the FAS ratios and PSA ratios of B over G records of the horizontal and vertical component.

Based on the characteristics of the G-stations, it is assumed that the G-stations give a reliable representation of the ground motions at the location. The FAS and PSA comparison however show that the motions of the B-stations are significantly lower than the motions of the adjacent G-stations. In general, the following deviations have been identified at B-stations:

- Relatively low deviations at BOWW and BZN2 (especially below 12 Hz resp. 8 Hz)
- Underestimation (-40 to -90%) of ground motions at most B-stations for higher frequencies (frequency higher than 8 Hz but occasionally already above 3 Hz)
- Relative peaks for some frequencies between 7 and 14 Hz, possibly due to natural frequency of buildings, especially at BWIN, BSTD, BZN2, BAPP
- Big/ heavy buildings show relatively big deviations

3.2 Assessment of reliability of B-stations also based on comparison with other data

Fugro, Movares and Royal HaskoningDHV have published a memo: “Het berekenen van de kans op mijnbouwschade door gaswinning in de second opinion van de proef buitengebied” on the 1st of March 2018. In this memo, figure 3.1 shows the differences between ground motions and building motions (as measured at the foundation), both for horizontal as for vertical motions.

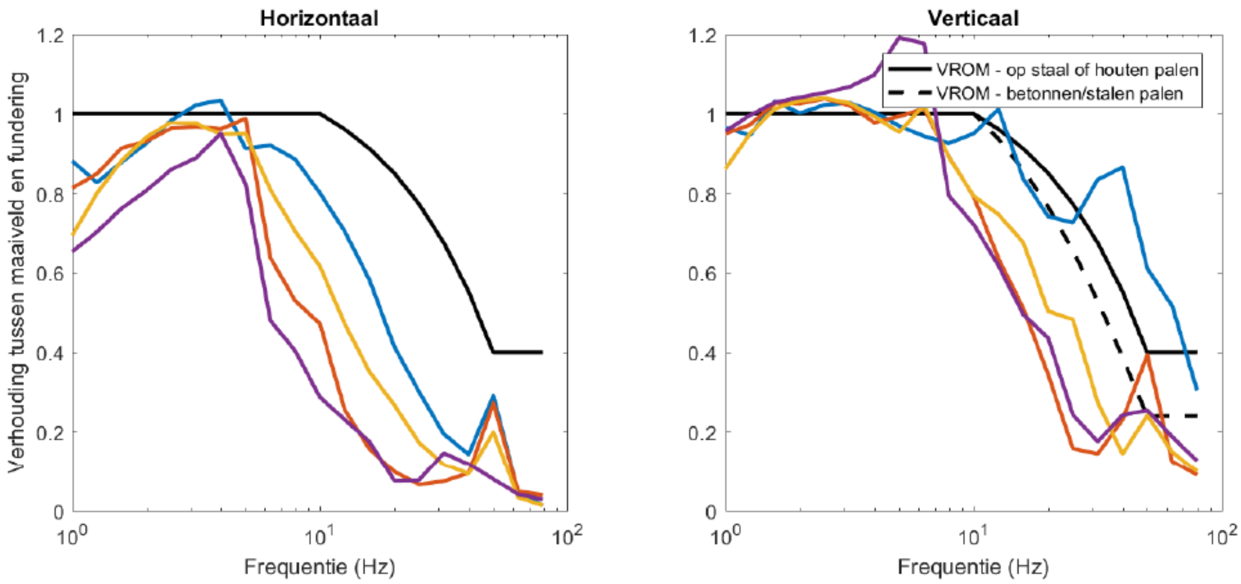


Figure 3.1: Observed building motions over ground motions for 4 (foundations of) houses, both horizontal and vertical component

The memo has to be revised because in the meantime, the KNMI-data is corrected, which affects the published analysis by Fugro, Movares and Royal HaskoningDHV. However the presented damping of ground motions while monitoring on a building supports the deviations that were observed at the B-stations. In general, the B-stations show significant deviations for higher frequencies. The degree of deviation and the frequency which divides reliable data from disturbed data depends on the characteristics of the building (size, weight, weight distribution, stifness), the location of the accelerometer and the soil characteristics. In some cases also the connection (or the absence of it) can affect the results. A more extensive study on disturbance by the buildings is advised.

For the KEM04 study, the data from the B-stations in general is not suitable because of the influence of the buildings.

ATTACHMENTS:

A. KNMI Accelerometers Shake Table Validation Tests, revision R2, Hanze University of Applied Sciences, 30th April 2019

B. Analysis of consistency between B- and G-station records for induced events in the Groningen gas field; final version, Seister 29th April 2019

C. Memorandum: comparison closest available CPT at B- and G-stations, Fugro, 30th April 2019

Hanze
University of Applied Sciences
Groningen

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Built Environment NoorderRuimte

Client:

Staatstoezicht op de Mijnen (SodM)

KNMI Accelerometers Shake Table Validation Tests

Hanze
University of Applied Sciences
Groningen

Research Centre for
Built Environment NoorderRuimte

Prepared by	**Signatures**	
Issue: 08.04.2019 / The First Draft	Document Type: **Technical Report** *Pages: 18*	File_Name: HRGERS_06_KNMI_R2.pdf
Revision: 23.04.2019 / R1		
Revision: 30.04.2019 / R2 This revision is prepared based on the reviewer comments of KNMI on R1. Comments and responses can be found in Appendix 3.		Protocol: HRGERS/06KNMI
Revision:		

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Table of Contents

1. Introduction

Research Group on Earthquake Resistant Structures from Hanze University of Applied Sciences Groningen was commissioned by Staatstoezicht op de Mijnen (SodM) for running a quick check on some of the KNMI stations. Hanze plays a role in the KEM04 project, supporting Fugro and the other team members. This is reason why this additional work presented here was commissioned via the KEM04 contract.

On 21st of February 2019, KNMI has published a note on their website. This note refers to a measurement mistake in KNMI data. The issue has also found place at national and regional media. The note of KNMI states erroneous measurements by KNMI in the recent years regarding their Strong Ground Motion network on the Groningen gas field. The purpose of the presented study is to check some of the stations. This check involves:

- visiting some of the stations and reporting the mounting and storage conditions
- testing sensors and their dataloggers in respect to known input motions, by using the xml files and gain factors corrected and published by KNMI after the recent event on wrong recording

In order to achieve that, 4 stations were visited and the sensors, together with their dataloggers, were removed. Sensor+digitizer couples are kept exactly the same as at the station, apart from G470 for which the digitizer of G190 (the same brand & model) was used. These sensors were then tested at shake table at BuildinG. When noise problems were detected at one of the sensors, an additional sensor was also removed by KNMI and tested. This report presents the findings from the station visits as well as the comparative results of the shake table tests.

This revision is prepared based on the reviewer comments of KNMI on R1. Comments and responses can be found in Appendix 3.

2. Station Visits

Four stations are visited during this study (see Figure 1) on 1st of March, 2019. The team visiting the stations consisted of the following people:

-

The reason BZN1 was selected is because the sensor malfunctioned in some of the past earthquakes. BOWW and G190 were chosen because they are very close to each other, only 420m (see Figure 2).

KNMI stated that the settings were wrong for all G stations, where half the amplitudes were calculated for G010-G700 stations, and they were calculated double for G710-G800 stations. In order to have one G station from each of these two groups, also G750 was added to the stations to be visited.

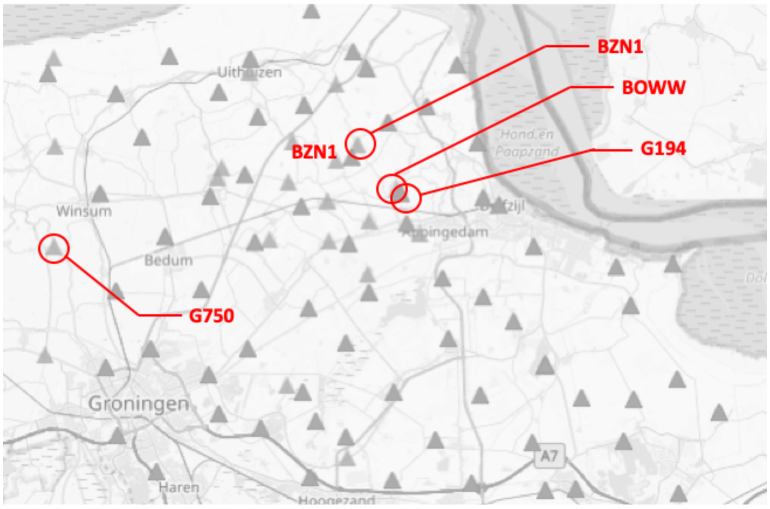


Figure 1. Four KNMI stations visited and the sensors of which are removed and tested on the shake table

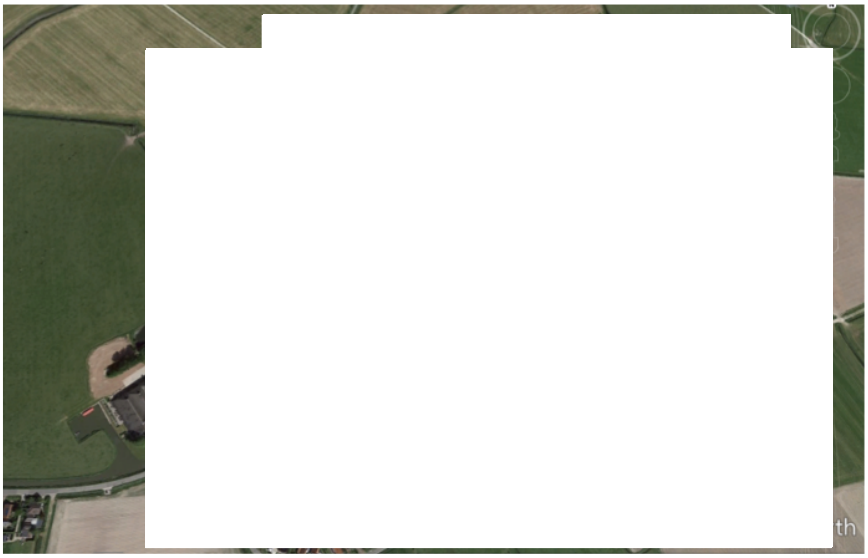


Figure 2. BOWW and G190 stations

Four stations were visited, the host environments and the sensor instalments were photographed. The B-stations are older than the G-stations, and are hosted by public or private buildings. The G-stations fit to the description of free-field, mostly, as they are hosted in the open field by standard metal cabins. Picture of the visited B-stations, BZN1 and BOWW can be seen in Figure 3 and Figure 4, respectively.

The sensors used in all stations is Kinemetrics Epi Sensor accelerometer. Sensor-specific datasheets can be obtained from Kinemetrics website. Sensor specs for each of the tested sensors are obtained from Kinemetrics and presented in Appendix 1.

The B-stations consist of two plastic boxes one freely placed over the other. A schematic cross-section of the mounted sensors at B-stations can also be seen in Figure 5. The sensor itself is connected to the floor via a socket-type moment-free bolt connection. Three levelling screws are then used to level and counter-force the sensor. This is a standard mounting method of the Kinemetrics sensors. After the sensor is placed, a red box is freely (without being connected to anywhere) placed over the sensor. Another blue box is, again freely, is placed on the red one. The blue box contains the power, storage and communication devices. B-stations use “Rock Series Basalt 4X” model dataloggers. The data is stored at the datalogger as well. The serial numbers of the Basalt digitizers were sent to Kinemetrics and the properties are received. The most relevant information are the i) the voltage output range of the digitizer, and b) the resolution. The Basalt digitizers have 20V range and are 24bit. This means the full analog signal is scaled within 20V and counts (divided) to $2^{(24)}$ pieces.

G190 station visited during this study is not only a surface station but also consists of 4 geophones at -50, -100, -150 and -200m depths from the surface. The pictures of the G190 station can be seen in Figure 6. G190 station (and other similar stations of the series G100-G600) use “Rock Series Granite and Granite Expansion” model dataloggers. This specific digitizer works with 20V range and 24bit in the first 3 channels, and 2/5V in the rest of the 12 channels. Only the first 3 channels are used in the verifications tests presented here.

The sensor of G190 is placed on a concrete base as seen in the pictures. G190 is next to a ditch, but rest of the arrangement is pretty much a free-field setup. The host environment and the mounting conditions of G750 are pretty similar to that of G190. Picture of the G750 station can be seen in Figure 7. G750 station does not have deep geophones. “Rock + Series Obsidian 4X” model datalogger is used. G750 is also right next to a ditch. When the serial number of the Obsidian digitizers was shared with Kinemetrics, they were not able to find the specs of the digitizer. Considering all their digitizers are 24bit, the only unknown remains as the voltage output. We assumed 20V output range also for this digitizer but we also did cross-correlation tests by using the same sensor with different digitizers. KNMI needs to return the Obsidian to factory defaults or check the software/settings. This has already been communicated with KNMI.

Figure 3. Host environment and the sensor placement of BZN1 station

Figure 4. Host environment and the sensor placement of BOWW station

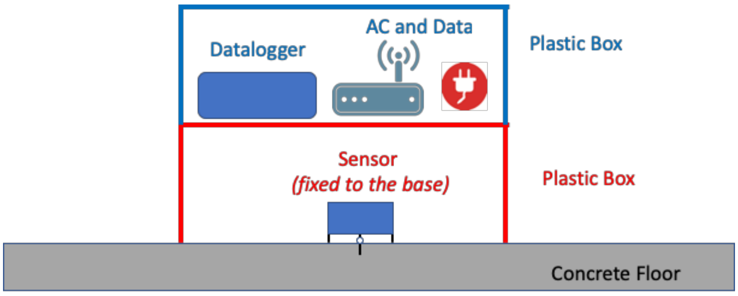


Figure 5. Schematic cross-section of the sensor placement of B-stations

The sensors of the B-stations are not protected from water. Furthermore, they are not stable if the motion is high. The sensor is directly placed on the concrete floor of the host environment. There is a water pump right next to the BZN1 sensor, for example, and there are signs of water intrusion. Metal mounting bracket of the BZN1 station is corroded, which is another sign of possible regular water intrusion. G stations are protected from water and other environmental conditions (not floods). Chemical bids are placed against insects and ants.

Figure 6. Host environment and the sensor placement of G190 (and 191-192-193-194) station

Figure 7. Host environment and the sensor placement of G750 station

Although all the sensors are the same brand and model, they have different settings that yield to 3 different calibration parameters. The sensor-specific technical datasheets are given in Appendix 1. Critical parameters are listed in Table 1.

Table 1. Voltage and acceleration ranges of the tested sensors

Station	Sensor Serial Number	Voltage Output	Range
G190	ES-T 6543	2.5V Differential	+-2g
G470	ES-T 6516	2.5V Differential	+-2g
G750	ES-T 7440	10V Differential	+-2g
BOWW	ES-T 5484	10V Differential	+-4g
BZN1	ES-T 5483	10V Differential	+-4g

In case of BOWW and BZN1, the sensor output matches. Please note that "10V Differential" means +-10V, that is equal to a 20V range in total. Considering that 24bit means 16,777,216 counts (pieces), a range of +-4g is spread over that many counts. When the recorded seed file provides 8,388,607 counts (one count per side goes to zero-crossing) this means that the sensor is recording at full range, at 4g. Every 2,097,152 counts recorded by BOWW and BZN1 stations reflects 1g.

In case of G series stations, this is different. In G750 station, the full range of +-2g (4g in total) spread over 16,777,216, meaning that every 4,194,304 counts recorded in the seed files represents 1g.

G190 and G470 are also different because the sensor output voltage does not match the digitizer voltage. In this case, there normally are two ways: i) use an amplifier to match the two voltages, ii) use only a portion of the full range of the datalogger. Our communications with the producer, Kinemetrics, proved that the latter was preferred for the tested G190 and G470 station. In this case the count outputs of these two stations need to be divided with the voltage different, that is 20/5=4.

3. Gravity and Shake Table Tests

The sensors of the 4 stations visited were removed (Figure 8) and tested at BuildinG in Groningen. Due to the noise problems at G190 sensor, another one from the G100-G600 series, G470, was removed and tested. The tests were conducted by using sinus waves with frequencies from 0.3 to 15Hz. It should be noted that the shake table used for the tests is not designed for precise sensor calibrations. This is reason why there are small differences among the sensors in terms of peak response. This is because of the high-frequency that is mobilised when the table is moving, tilt and rotation of the moving table. The level of accuracy the table could provide found to be adequate for the purposes of this study.

All 4 sensors and 4 dataloggers were removed. The 5th sensor, G470, was removed alone and tested with the Granite digitizer of G190. The picture of all the removed equipment can be seen in Figure 8. Sensor-to-datalogger data cables and the power adapters were removed only from BZN1 and BOWW, but they are also used for G stations since these are typically the same in all three types of dataloggers. A socket of the Granite datalogger was removed (see the top left item in Figure 8) to be able to connect the data cables of the Basalt dataloggers. Both Basalt and Granite dataloggers use the same datalogger-to-PC LAN cable, while Obsidian has its own connection cable that was used.

The dataloggers turn on in approximately 2-3 minutes when they are plugged to electricity. After that the recording starts. In all dataloggers, the data was extracted by using SSH file protocols, directly from the memory of each datalogger.

Tests were done 2 sensors at a time since the number of sensor-to-datalogger cables was not enough to test all sensors simultaneously.

GPS antennas were difficult to be removed so they were not taken to the laboratory. Internal clock of the dataloggers was used. Synchronisation of various sensors was not used for the purposes of this study, so GPS was not needed anyways.

Figure 8. Sensors, cables and dataloggers removed from the 4 stations

3.1. Gravity Tests

The EPI sensors have the range of DC-200Hz for measurements. This means that they can properly record waves between these two frequencies (DC means 0 Hertz). Because the gravity is mathematically treated as a motion with infinite wavelength (infinite period, thus zero frequency), sensors that have a frequency bandwidth starting from DC are able to detect 1g when they are placed parallel to the gravity. EPI Sensors, like many others, have a -1g offset when they are placed horizontally, this is reason why they will record 0g normally (this is usually done not to lose the measurement range).

As a first test, the sensors are placed in a way that one of the horizontal components will be parallel to gravity. The reason why a horizontal component is tested is because there is no counter off-set in horizontal components. The reason why a single component is tested is because all components have the same gain, thus testing one is enough to verify the gain level. The results are presented in Figure 9. It can be seen that the gravity tests confirmed that the sensors record correctly.

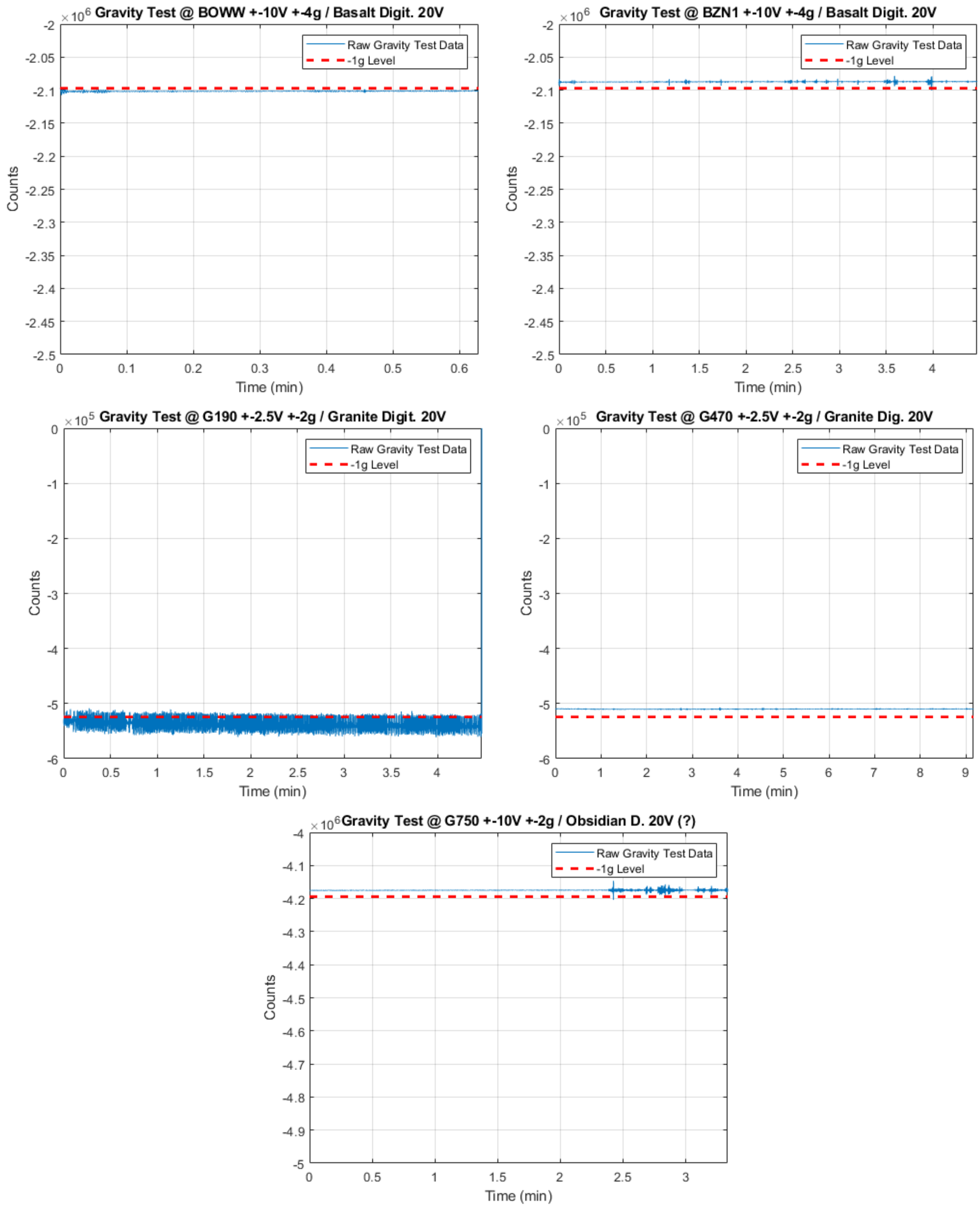


Figure 9. Gravity test results for all 5 sensors

3.2. Setup

The test setup consists of the following components:

- Shake-table
- Geophones used in the flexible network measurements by NAM (Figure 10)

- KNMI sensors and the dataloggers (Figure 10)
- Reference accelerometers (two types) used for calibration (Figure 10)
- Reference lasermeter used for measuring the table displacements (Figure 10)
- Laser device for alignment (Figure 10)

The KNMI sensors were mounted directly on the table, using the exact same method that is originally used for mounting on site. The table has threaded holes for M10 bolts, so the head of M10 bolts were modified to fit the metal mounting bracket at the bottom of the sensor (Figure 12). The tested axis of the sensors are all aligned by using a laser device that produces two lines, parallel and perpendicular to the direction of the gravity. The vertical laser line is aligned with the holes on the table where the sensors are placed, then the X and Y axis lines on the sensors are aligned with that laser line (Figure 13). The vertical alignment is done by fitting the air bubble (bull's eye spirit level) on the sensor.

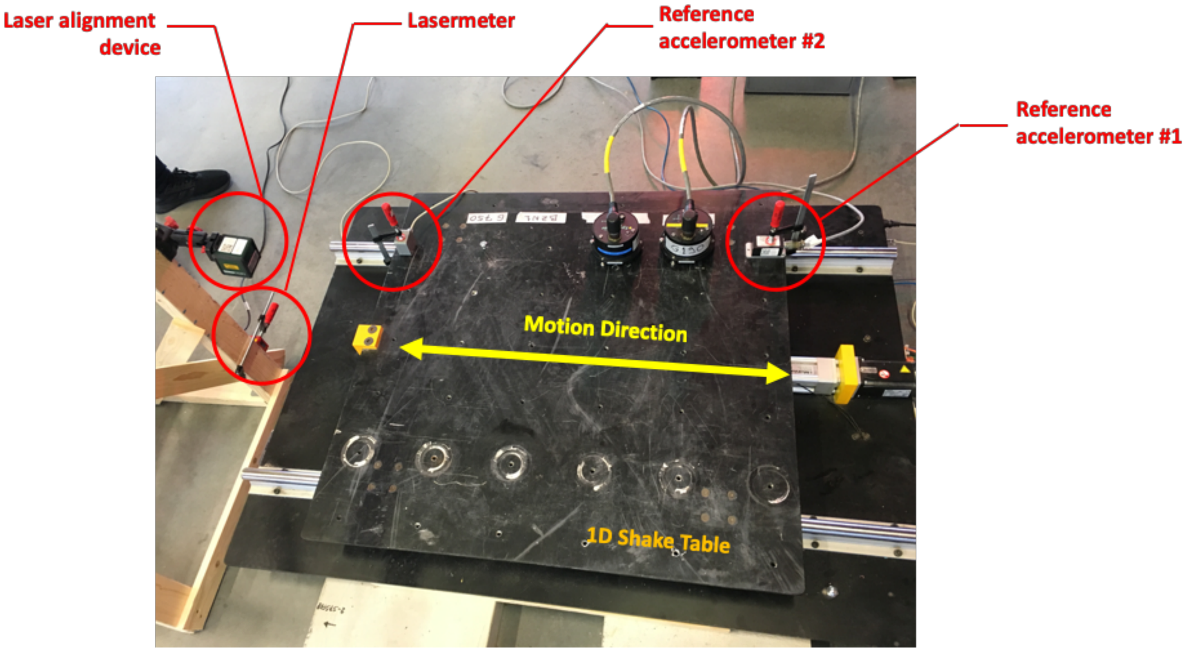


Figure 10. Shake table and the reference sensors

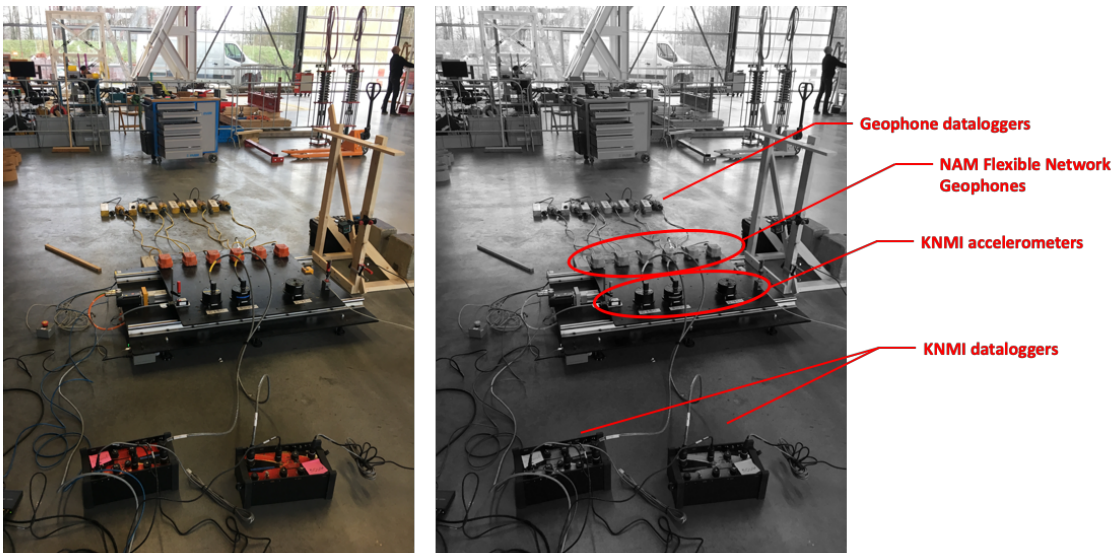


Figure 11. General view of the test setup, NAM geophones and KNMI sensors placed on the shake table

Both the KNMI sensors and the reference sensors recorded with 200Hz sampling rate. KNMI sensors were not connected to GPS as no time synchronisation was used. Reference sensors were all connected to one datalogger and the data was recorded directly on the computer. KNMI sensor data was first recorded into the dataloggers and then retrieved by using SSH protocols, after the test.

6 geophones, previously used by NAM for the flexible network measurements, were tested. 2 stations of these NAM sensors were 0dB and 4 stations were 18dB. Each station was a 3-component geophone. 0deg and 90deg horizontal components are tested. The sensors were provided and installed by Rossingh. The data of these sensors are still being processed and will be submitted as a separate report. Geophones were also aligned horizontally via a laser line and vertically via the air bubble. They are designed for field applications, thus the data was sent to Rossingh servers during the test automatically and was recovered by Rossingh personnel afterwards.

Figure 12. Mounting bolts modified from M10 for mounting the KNMI sensors on the table

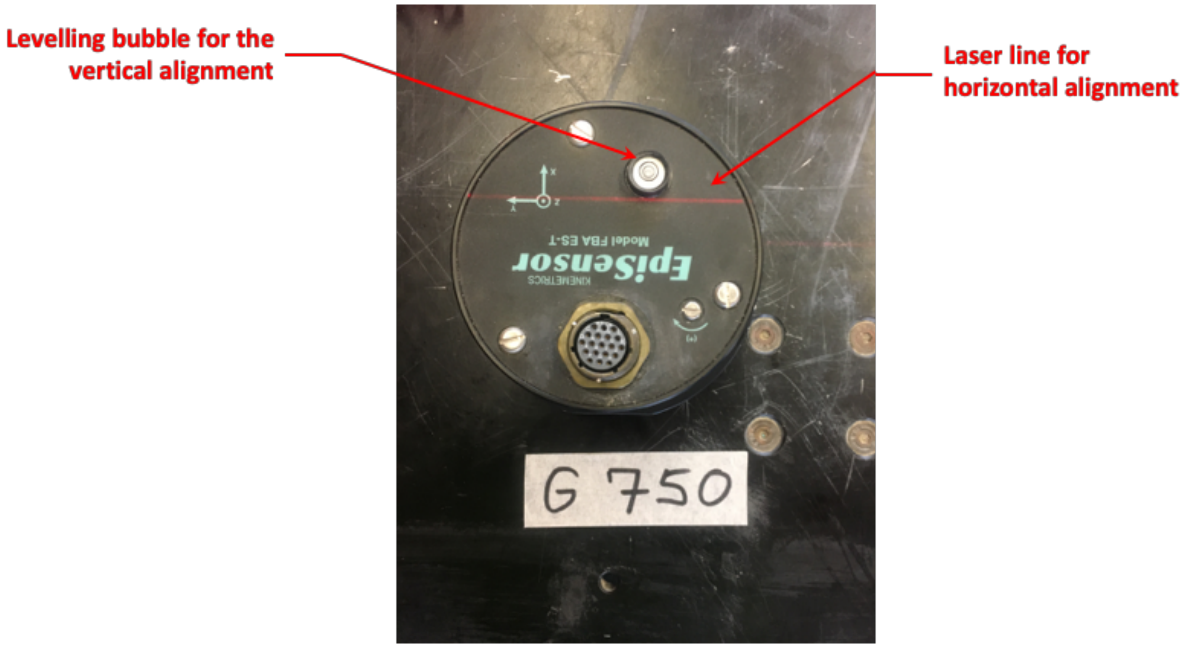


Figure 13. Example for vertical and horizontal alignment of a sensor

3.3. Test Procedure

Sinus wave was used for testing the sensors. 10 stable cycles, with 5 ramping up and 5 ramping down cycles, as shown in Figure 14, were used in the tests. Amplitude of the stroke of the motion varied from 0.6mm to 10mm. The frequencies ranged from 0.3Hz to 15Hz. The table tends to resonate when reached to high frequencies (above 15Hz) with no payload, thus 15Hz was not exceeded. Also smaller amplitudes of strokes were used in higher frequencies in order to prevent triggering high-frequency peaks on the table. The tests performed are as below, once for the 1st horizontal direction and once more for the 2nd horizontal direction :

Test No	Stroke	Frequency	# of Stable Cycles
1	5mm	0.3Hz	10 cycles
2	5mm	0.6Hz	10 cycles
3	5mm	1Hz	10 cycles
4	10mm	1Hz	10 cycles
5	1mm	6Hz	10 cycles
6	10mm	2Hz	10 cycles
7	5mm	3Hz	10 cycles
8	1mm	9Hz	10 cycles
9	5mm	4Hz	10 cycles
10	3mm	6Hz	10 cycles
11	1mm	12Hz	10 cycles
12	0.6mm	15Hz	10 cycles

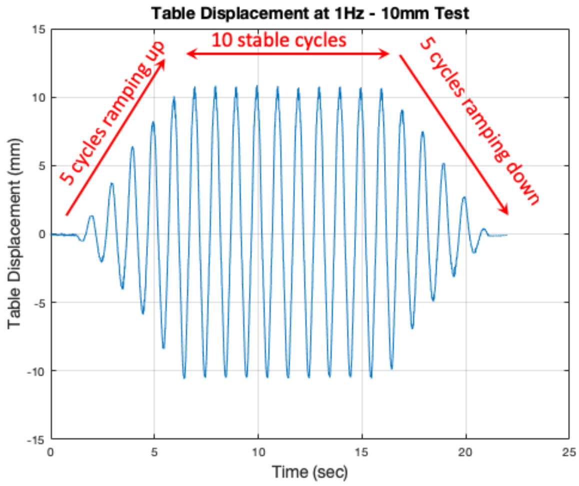


Figure 14. An example table displacement time history measured during the tests by the lasermeter

4. Results

The results are processed as the PGA (Peak Ground Acceleration). The PGA value for each sensor and for each test was calculated as the average of 10 stable peaks in positive and negative directions. The reason why a single peak is not used for the PGA calculations is because there are high-frequency peaks inside the sensor measurements which alter the peak value in each stable cycle slightly, in positive or negative direction. This is reason why an averaging procedure is applied to obtain more smooth results and a better overall comparison.

The results of the reference sensors are produced as TDMS files and directly multiplied with a single calibration factor, linearly modifying the voltage measurements to accelerations. The KNMI data were produced as seed format and the latest XML files, published on the KNMI website (last checked in in March 2019), were used for each station. The results of the KNMI sensors were obtained by using ObsPy Python code. A high-pass low-pass band filter between 0.1 and 25Hz was also applied within ObsPy. The reference sensor results are processed in Matlab and a similar bandpass filter was also applied.

G190 station was also tested during this campaign but the results were not usable. The reason for this is an unusual high background noise. Both BOWW and G190, very close to each other (420m distance) recorded a small earthquake the night before their removal. The earthquake was on 28th of February at 23:14:35 UTC. The unfiltered measurements of the two sensors for the same earthquake can be seen in Figure 15and in Figure 16. The unusually high noise of G190 is evident. This noise can be filtered out up to a certain degree, but the filtering process was intervening with the sinus wave measurements conducted on the table. This is the reason why G190 is taken out from the test results and G470 is added.

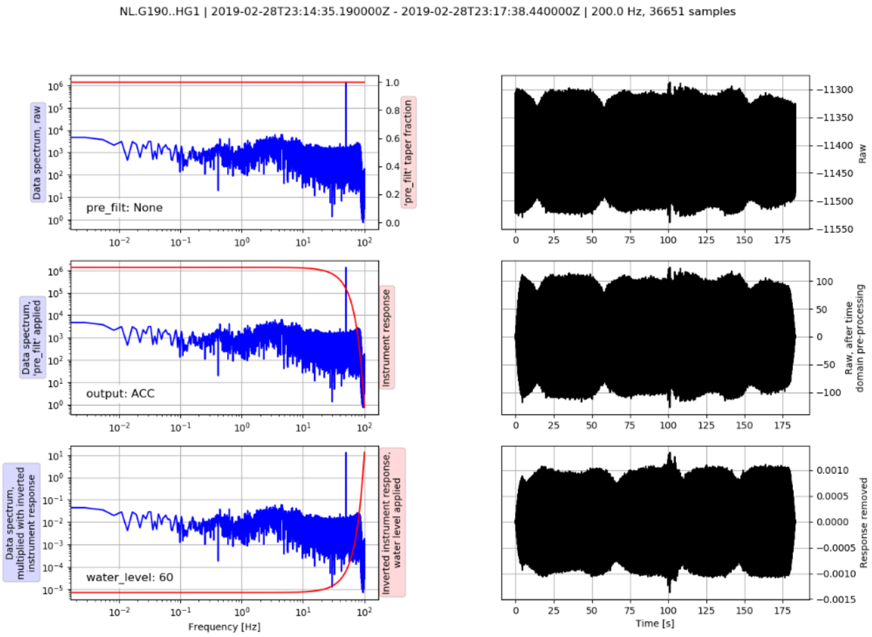


Figure 15. Unfiltered G190 East Component for the 28th of February 2019 earthquake

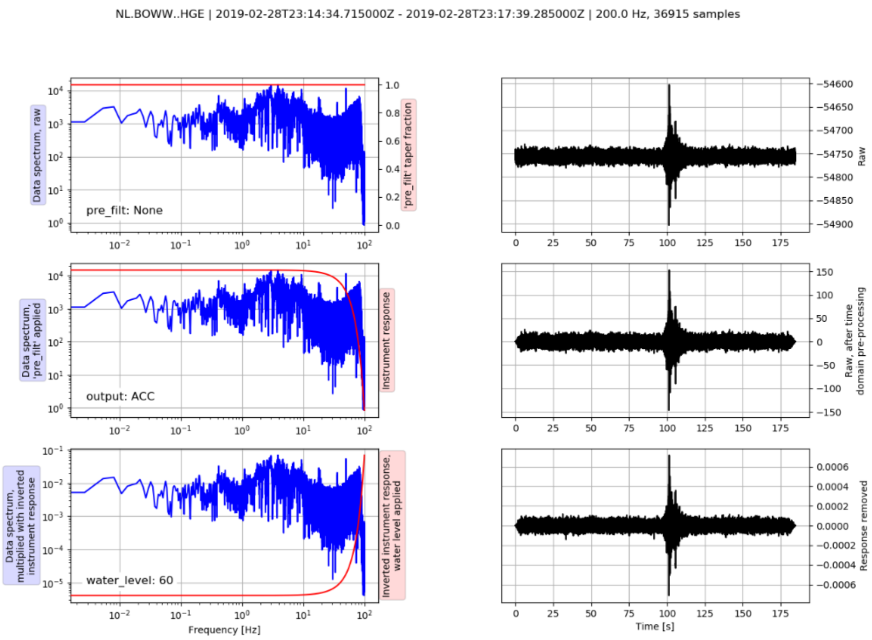


Figure 16. Unfiltered BOWW East Component for the 28th of February 2019 earthquake

The results of the averaged PGA (i.e. averaged from 10 stable cycles) can be seen in Figure 17 to Figure 20. These results belong to the two horizontal component tests. KNMI sensors are consistent with each other and they are also in agreement with the reference accelerometer. One exception to that is the test of f=6.0Hz and Δ=+-3mm for the BOWW station. The reason for this anomaly was not found but attributed to a mounting issue that may be triggered at 6Hz frequency only in that particular test, also because it cannot be observed in the tests in perpendicular direction. Apart from that, the results of the KNMI sensor tests with the latest XML files and calibration factors published on the KNMI website (last checked in in March 2019) are correct for the tested stations. G190 and G470 sensors output voltage mismatches the datalogger voltage. We are not aware of any amplifiers or different hardware settings for taking care of this mismatch for G470, thus KNMI should make sure that the sensor-digitizer mismatch for G190 and G470, as well as sensors with similar range properties, is correctly addressed.

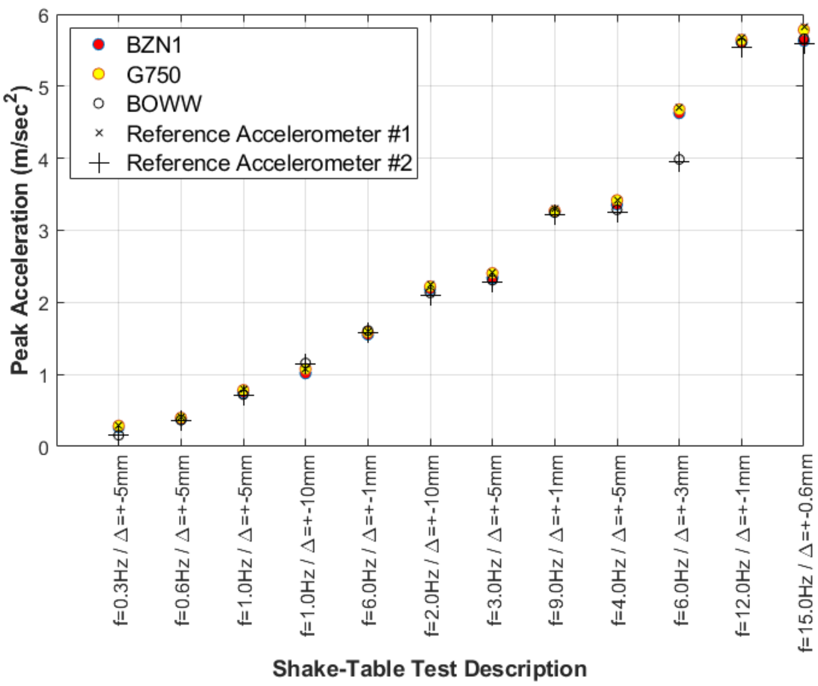


Figure 17. PGA values recorded by the KNMI sensors in respect to the reference sensors in Direction 1

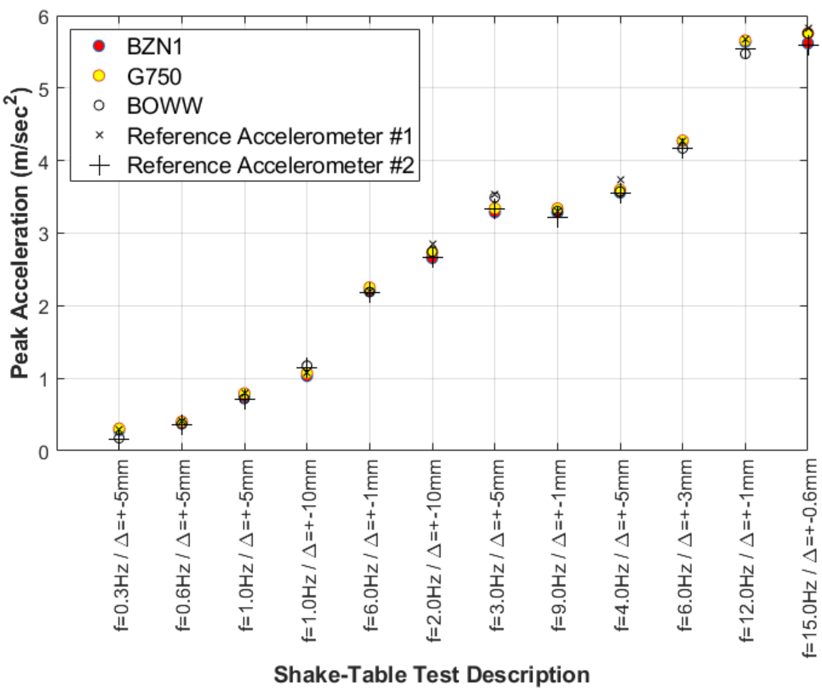


Figure 18. PGA values recorded by the KNMI sensors in respect to the reference sensors in Direction 2

Finally, we were not able to check the G470 sensor with its original cable and the digitizer. We cannot make 100% sure in which range this sensor behaves because we do not have the original digitizer of this sensor (it was not removed from the site). This needs to be clarified by KNMI since it would directly affect the gain factor.

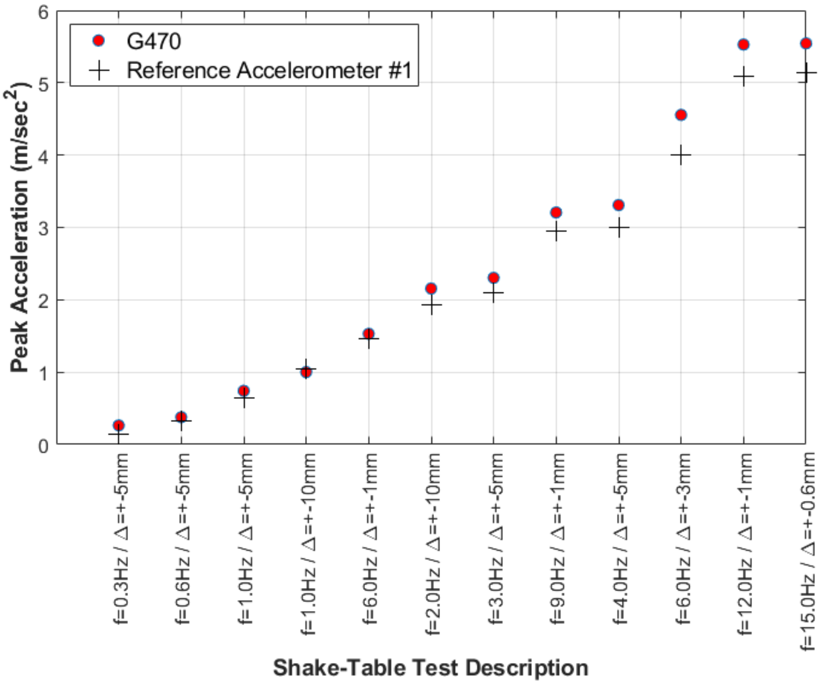


Figure 19. PGA values recorded by the KNMI sensor G470 in respect to the reference sensors in Direction 1

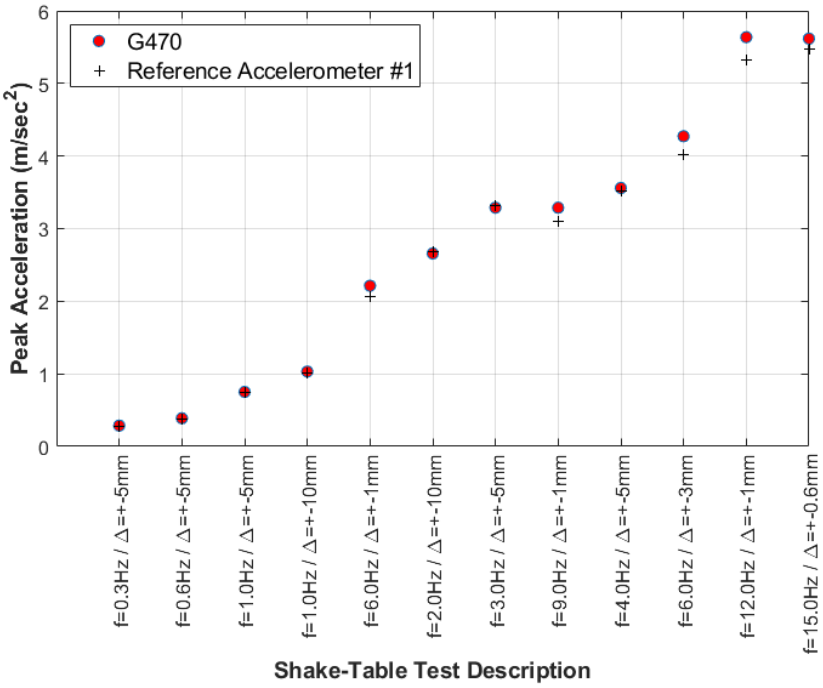


Figure 20. PGA values recorded by the KNMI sensor G470 in respect to the reference sensors in Direction 2

5. Suggestions for Improvement

As a result of the site visits and tests conducted, we share some comments for improving the network.

- G190 and/or its digitizer exhibits high noise and needs to be checked.
- The range of the Obsidian digitizer of G750 could not be detected. The producer suggests a factory defaulting. KNMI personnel should evaluate this.
- BZN1 station is known to have issues. These issues may be related to water intrusion, an issue that needs to be confirmed.
- Mounting and storage conditions of B stations need to be improved in overall. This improvement includes sensor mounting. An inappropriate mounting example from BWIN station can be seen in Figure 21.
- The sensor storage is also not appropriate in B stations. A proposal for storage and boxing is given below in Figure 22. A station does not consist only of a sensor, but it needs power, data transfer and data storage. If any of these components fails, the recording does not take place. In KNMI B-stations, the sensor is fixed on the floor per manufacturer's instructions. All other equipment other than the sensor, however, is placed on plastic boxes which are not fixed anywhere (i.e. freely moving), on top of another plastic box covering the sensor and is also not fixed anywhere.
- All the stations of the Groningen SGM (Strong Ground Motion) network should be visited regularly, preferably once in a year. We understood during the site visits that some of the B stations were not visited for very long time.

Figure 21. An inappropriate sensor mounting from BWIN station

Figure 22. An example station from Canterbury (NZ) SGM network

Appendix 1

Technical Specifications of the KNMI Sensors

(Obtained from the Producer)

KINEMETRICS

EpiSensor

FBA ES-T Calibration Data & Configuration

Sales Order Number	**320899**	
QA Date		
Unit Serial Number	**5484 (BOWW)**	
Oscillator Board Serial Number	**3624895**	
	Yes	**No**
Feedback Adapter	**X**	
Ground Jumper Board	**X**	
Isolated Supply	**X**	
Power Supply Type	+/-12V Supplies	+12V Single Supply Option
		X
Current	+12V /mA	-12V /mA
	96.06	
Sensor Output Voltage Level	2.5V	10V
		X
Standard or Low Noise Output	Standard	Low Noise
		X
Output Type	Single Ended	Differential
		X
Sensitivity	**5 V/G**	
Final Setup Check by	**QT**	
Test Date	**7.01.2013**	

	Serial Number	**Range Set**	**Sensitivity Check**
X Axis Module	**46699**	**4G**	**5.003**
Y Axis Module	**46700**	**4G**	**4.994**
Z Axis Module	**46701**	**4G**	**5.001**

This data sheet reflects the factory-set configuration of this EpiSensor. If you wish to change the configuration, refer to the User Guide included with your EpiSensor. Data for the individual modules is included in the following pages.

Kinemetrics Inc.
222 Vista Avenue
Pasadena
California 91107
USA

(626) 795 2220
www.kinemetrics.com

KINEMETRICS

EpiSensor

FBA ES-T Calibration Data & Configuration

Sales Order Number	320899	
QA Date		
Unit Serial Number	5483 (BZN1)	
Oscillator Board Serial Number	3624828	
	Yes	No
Feedback Adapter	X	
Ground Jumper Board	X	
Isolated Supply	X	
Power Supply Type	+/-12V Supplies	+12V Single Supply Option
		X
Current	+12V /mA	-12V /mA
	97.24	
Sensor Output Voltage Level	2.5V	10V
		X
Standard or Low Noise Output	Standard	Low Noise
		X
Output Type	Single Ended	Differential
		X
Sensitivity	5 V/G	
Final Setup Check by	QT	
Test Date	7.01.2013	

	Serial Number	Range Set	Sensitivity Check
X Axis Module	46748	4G	4.995
Y Axis Module	46749	4G	4.992
Z Axis Module	46750	4G	4.995

This data sheet reflects the factory-set configuration of this EpiSensor. If you wish to change the configuration, refer to the User Guide included with your EpiSensor. Data for the individual modules is included in the following pages.

Kinemetrics Inc.
222 Vista Avenue
Pasadena
California 91107
USA

(626) 795 2220
www.kinemetrics.com

KINEMETRICS

EpiSensor

FBA ES-T Calibration Data & Configuration

Sales Order Number	**340323-7**	
QA Date	8.07.2014	
Unit Serial Number	**6543 (G190)**	
Oscillator Board Serial Number	**1345841**	
	Yes	**No**
Feedback Adapter	**X**	
Ground Jumper Board		**X**
Isolated Supply		**X**
Power Supply Type	+/-12V Supplies	+12V Single Supply Option
	X	
Current	+12V /mA	-12V /mA
	34.36	**31.77**
Sensor Output Voltage Level	2.5V	10V
	X	
Standard or Low Noise Output	Standard	Low Noise
		X
Output Type	Single Ended	Differential
		X
Sensitivity	**2.5 V/G**	
Final Setup Check by	**QT**	
Test Date	**4.06.2014**	

	Serial Number	Range Set	Sensitivity Check
X Axis Module	**60494**	**2G**	**2.495**
Y Axis Module	**60495**	**2G**	**2.496**
Z Axis Module	**60497**	**2G**	**2.506**

This data sheet reflects the factory-set configuration of this EpiSensor. If you wish to change the configuration, refer to the User Guide included with your EpiSensor. Data for the individual modules is included in the following pages.

Kinemetrics Inc.
222 Vista Avenue
Pasadena
California 91107
USA

(626) 795 2220
www.kinemetrics.com

KINEMETRICS

EpiSensor

FBA ES-T Calibration Data & Configuration

Sales Order Number	**340323-7**	
QA Date	25.06.2014	
Unit Serial Number	**6516 (G470)**	
Oscillator Board Serial Number	**1345836**	
	Yes	**No**
Feedback Adapter	**X**	
Ground Jumper Board		**X**
Isolated Supply		**X**
Power Supply Type	+/-12V Supplies	+12V Single Supply Option
	X	
Current	+12V /mA	-12V /mA
	34.67	**32.13**
Sensor Output Voltage Level	2.5V	10V
	X	
Standard or Low Noise Output	Standard	Low Noise
		X
Output Type	Single Ended	Differential
		X
Sensitivity	**2.5 V/G**	
Final Setup Check by	**QT**	
Test Date	**3.06.2014**	

	Serial Number	Range Set	Sensitivity Check
X Axis Module	**54199**	**2G**	**2.495**
Y Axis Module	**60383**	**2G**	**2.493**
Z Axis Module	**60384**	**2G**	**2.506**

This data sheet reflects the factory-set configuration of this EpiSensor. If you wish to change the configuration, refer to the User Guide included with your EpiSensor. Data for the individual modules is included in the following pages.

Kinemetrics Inc.
222 Vista Avenue
Pasadena
California 91107
USA

(626) 795 2220
www.kinemetrics.com

KINEMETRICS

EpiSensor

FBA ES-T Calibration Data & Configuration

Sales Order Number	**360248**	
QA Date	11.05.2016	
Unit Serial Number	**7440 (G750)**	
Oscillator Board Serial Number	**666716**	
	Yes	**No**
Feedback Adapter	**X**	
Ground Jumper Board	**X**	
Isolated Supply	**X**	
Power Supply Type	+/-12V Supplies	+12V Single Supply Option
		X
Current	+12V /mA	-12V /mA
	98.62	
Sensor Output Voltage Level	2.5V	10V
		X
Standard or Low Noise Output	Standard	Low Noise
		X
Output Type	Single Ended	Differential
		X
Sensitivity	**10 V/G**	
Final Setup Check by	**QT**	
Test Date	**29.03.2016**	

	Serial Number	Range Set	Sensitivity Check
X Axis Module	**65922**	**2G**	**9.987**
Y Axis Module	**65923**	**2G**	**9.998**
Z Axis Module	**65924**	**2G**	**9.993**

This data sheet reflects the factory-set configuration of this EpiSensor. If you wish to change the configuration, refer to the User Guide included with your EpiSensor. Data for the individual modules is included in the following pages.

Kinemetrics Inc.
222 Vista Avenue
Pasadena
California 91107
USA

(626) 795 2220
www.kinemetrics.com

Appendix 2

Technical Specifications of the Reference Sensors

SENSEBOX 7001/02/03

HIGH SENSITIVIY ACCELEROMETER SERIES (2-400 G)

These accelerometers are very low noise sensors which are based on nitrogen damped MEMS technology and named as SENSEBOX7001/02/03 depending on the number of axis included.

This series is an ideal solution for, forced vibration dynamic identification, shake-table tests, machinery health monitoring and Structural Health Monitoring of relatively less rigid structures such as bridges under Ambient Vibration as well,offering an excellent performance at a relatively lower cost.

They can be used for Structural Health Monitoring of bridges or high storey buildings where vibration levels are relatively higher.

This series provide powerful, stable, practical solutions for applications that require sensitive vibration measurements such as railway tests, vehicle dynamics, high speed train testing,vibration tests in vehicles for safety and comfort, machine/ balance tests, explosion & impact tests, tilt monitoring, crash tests and robotics.

DIGITIZER AND SOFTWARE SUPPORT

TESTBOX2010 / e-QUAKE-DIGI / EASYTEST-NETWORK / eQ-LAB

SUB VERSIONS

7001-Uniaxial / 7002-Biaxial / 7003-Triaxial

TECHNICAL SPECIFICATIONS

	SENSEBOX 7001/02/03
Number of Axis	1/2/3
Type	MEMS – nitrogen damped
Maximum Acceleration Measurement Range	+-2g to +-400g
Output Noise Density	5 µg / √Hz - ±2 g version
Frequency Bandwidth	0 - 400 Hz - ±2 g version
Sensitivity	2000 mV/g - ±2 g version
Shcok Resistance	2000 g - ±2 g version
Excitation Voltage	+5VDC / 8 mA
Operating temperature	-55°C ~ +125°C
Enclosure	Field type / laboratory type IP 65 protection class (contact us for other options)

Teknik Destek Grubu

SENSEBOX 7001/02/03

HIGH SENSITIVIY ACCELEROMETER SERIES (2-400 G)

1328. Sokak 5/6 Aşağı Öveçler 06460 Çankaya / Ankara / TURKEY
Tel: +90 312 473 97 91-92 - **Fax:** +90 312 473 97 93
info@teknikdestek.com.tr - www.teknikdestek.com.tr

Teknik Destek Grubu

- 5 µg / √Hz Low Noise
- MEMS Technology
- High Stability
- Wide Selection Options from +-2g-400g Measurement Range and 0-4000 Hz Bandwidth
- Natural Frequency Detection on Bridges
- Ideal for Forced Vibration and Shake-Table Tests
- Factory Vibration Monitoring
- Structural Health Monitoring of Machines, Balancing, General Vibration Analysis
- Railway / High Speed Train / Vehicle Dynamics
- Explosion Effects
- Crash Tests / Robotics

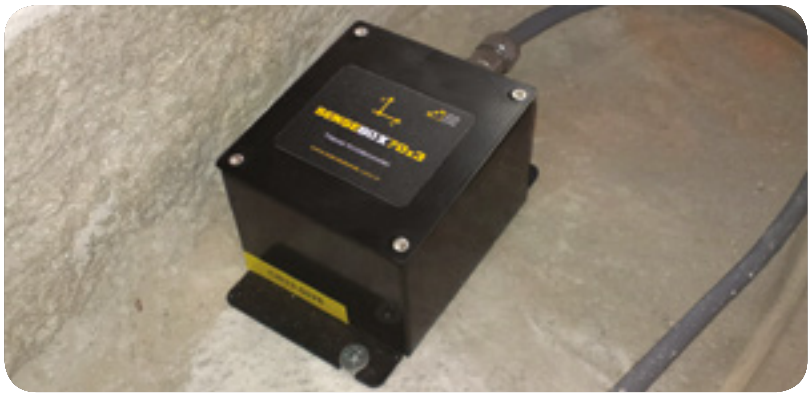
www.teknikdestek.com.tr

SENSEBOX 702x/703x

ULTRA SENSITIVE SEISMIC ACCELEROMETER SERIES

These accelerometers are ultra low noise sensors which are based on force balance / electro-dynamic feedback technology and named as SENSEBOX7021/22/23+ and 7031/32/33 depending on the number of axis included.

This series is an ideal solution for Seismic Strong Ground Motion Monitoring, Ambient Vibration and Structural Health Monitoring applications, offering an impressive performance at a relatively lower cost.



DIGITIZER AND SOFTWARE SUPPORT

TESTBOX2010 / e-QUAKE-DIGI / EASYTEST-NETWORK / eQ-LAB

SUB VERSIONS

7021-Uniaxial / 7022-Biaxial / 7023-Triaxial
7031-Uniaxial / 7032-Biaxial / 7033-Triaxial

SENSEBOX 7021/22/23+

SENSEBOX 7031/32/33

TECHNICAL SPECIFICATIONS

	SENSEBOX 7021/22/23+	SENSEBOX 7031/32/33
Number of Axis	1/2/3	1/2/3
Type	Force/ electro-dynamic feedback (FBA- Force Feedback)	
Maximum Acceleration Measurement Interval	±3 g	±0,8 g
Noise Density	130 ng√Hz	70 ng√Hz
Frequency interval	0,1-120 Hz	
Sensitivity	2400 mV/g	6000 mV/g
Shock Resistance	2000 g	
Excitation Voltage	+6....±15VDC	
Operating temperature	-40°C ~ +65°C	
Enclosure	Standard: IP65/ field type metal boxing (contact us for other options)	

SENSEBOX 702X/703X

ULTRA SENSITIVE SEISMIC ACCELEROMETER SERIES

Teknik Destek Grubu

SENSEBOX 702X/703X

ULTRA SENSITIVE SEISMIC ACCELEROMETER SERIES

1328. Sokak 5/6 Aşağı Öveçler 06460 Çankaya / Ankara / TURKEY
Tel: +90 312 473 97 91-92 - Fax: +90 312 473 97 93
info@teknikdestek.com.tr - www.teknikdestek.com.tr

CE ISO 9001 TÜRK MALI ® TÜR

Teknik Destek Grubu

- 70-130 ng / √Hz Ultra Low Noise
- +-3g Range
- FBA (Force Balance)-Force Feedback
- Impressive Performance
- Cost Advantage

- Seismic Strong Ground Motion Measurements
- Structural Health Monitoring
- Ambient Vibration
- Operational Modal Analysis

www.teknikdestek.com.tr

Appendix 3

Response to Reviews

We have received the reviewer responses from KNMI for the report cited below:

KNMI Accelerometers Shake Table Validation Tests, by (HRGERS_06_KNMI_R1)

We respond to the reviewer comments in this document. Some changes have been made on the report based on these reviews. Responses and modifications are listed here.

Our responses are given in Black while the KNMI reviewer comments are given in *Italic/Blue*. Modified parts of the main report are given in Black/Yellow Highlighted.

Comment 1

This document describes the results from a shake table test of selected sensors operated in Groningen by the KNMI.

Conclusion of the test is that KNMI sensors are consistent with each other and in agreement with a reference accelerometer. Suggestions are given for improvement of the network.

General comment:

The current version of the document requires more explanation on different statements made and we also found in some cases incorrect statements. We detail our comments below.

Comments:

The reason of performing the tests is not clear. In the introduction it is stated that the reason is "check some of the stations". Why? Are there reasons to assume that the sensors do not have the specs as provided by the manufacturer? Is it the purpose to check whether the sensors have degraded over time and are currently not in accordance with factory settings? Only when the purpose of the test is clear, a sensible test can be thought out.

Response 1

The introduction has been modified as below:

…The purpose of the presented study is to check some of the stations. This check involves:

- visiting some of the stations and reporting the mounting and storage conditions
- testing sensors and their dataloggers in respect to known input motions, by using the xml files and gain factors corrected and published by KNMI after the recent event on wrong recording

In order to achieve that, 4 stations were visited and the sensors, together with their dataloggers, were removed. Sensor+digitizer couples are kept exactly the same as at the station, apart from G470 for which the digitizer of G190 (the same brand & model) was used. These sensors were then tested at shake table at BuildinG. When noise problems were detected at one of the sensors, an additional sensor was also removed by KNMI and tested. This report presents the findings from the station visits as well as the comparative results of the shake table tests.

Comment 2

In the introduction it is stated that the purpose is to test the sensors. For a sensor test, the common procedure would be to attach (different) sensors to the same datalogger. From Hanze we got the request at KNMI to also remove 4 different dataloggers from the field. As a consequence, 4 stations are not in operation for multiple months. It seems like the purpose was to replicate exact sensor+datalogger configurations as in the field, i.e., changing two variables at the same time. We do agree that the digitizer is not so much a variable in this case. The different dataloggers can be set such that they yield exactly the same digitization. Hence, although two variables were changed at the same time, we still appreciate the results in this report as valid sensor tests. In the introduction please describe the actual purpose of the test and how this connects to the approach taken.

Response 2

We have added some more explanation in the introduction, as shown yellow highlighted above.

We thought that the purpose of the tests was clear to KNMI as these tests were proposed by other scientists (not by Hanze) in a meeting on 13th of February at EBN in Utrecht, where KNMI was also present and did not object. In any case, the purpose of the tests is indeed to replicate the exact sensor+datalogger combination on the site, but this time recording motions where the amplitude and frequency are controlled and known. This is the only way to see if, when the recorded count values are turned into accelerations by using the KNMI-declared gain values, the results are correct. We thought that the gain values declared by KNMI was the problem, and we thought (as suggested by other scientists during the Utrecht meeting), a shake table test could answer this question. If KNMI has/had other expectations from these tests, this should be communicated to SoDM and we will look into it.

We disagree with the statement that “two parameters are changed at the same time”. We kept two dominating parameters, the sensor and the digitizer, exactly the same as at the recording station. The only parameter that changed as compared to the installation conditions is the data cable between the digitizer and the sensor, and the reason was that it was difficult to remove the cables from the tested G stations.

We also disagree with the statement that “the digitizer is not so much a variable in this case”. G190 and G470 sensors have voltage output (2.5V) different than the rest of the sensors (10V) and this outage does not match that of the digitizer. It makes a lot difference (to the level of factor of 4) how the digitizer is set to handle this difference.

Regarding the comment on “4 stations are out of operation for multiple months”; for the record, we would like to remind the reviewer(s) the timeline of the events:

- 1st of March, 2019: Sensors from 4 stations were removed. Dataloggers from 3 stations were removed the same day, but KNMI did not want to remove the Granite datalogger from G190 station for two reasons, a) the same job could be done by using other dataloggers and no reason to shut down also the geophones at the same station, and b) it is difficult to remove the large Granite datalogger.
- 7th of March, 2019: We finished testing 2 stations, run into issues with BOWW datalogger and the use of Obsidian for G190, instead of the original Granite datalogger. KNMI changed opinion and suggested to come back to Groningen and remove the G190

original datalogger, the Granite. The correspondence can be seen in "Correspondence #1" below.

- 8th of March, 2019: We informed KNMI that we are done with the two stations (G750 and BZN1) and they can be installed back. We received the response on "Correspondence #2" given below, suggesting placing all the stations back when they are all done.
- 11th of March, 2019: We received the Granite datalogger.
- 14th of March, 2019: We run into some noise problems with G190 and communicated this to KNMI (see "Correspondence #3"). We suggested removal of another G100-G600 sensor.
- 28th of March, 2019: We informed all parties, including KNMI, that we finished the tests and the equipment could be placed back (see Correspondence #4).
- 12th of April, 2019: KNMI delivered G470, the 5th sensor, and did not replace back the stations we were done with (see Correspondence #5).
- 23rd of April, 2019: We informed KNMI that we are done with the tests and the equipment can be taken back (see Correspoendence #6). As of writing of this response document, we have not heard anything back from KNMI yet .

Correspondence #1 ---

From: ' l>
Subject: Re: Sensor tests
Date: 7 March 2019 22:49:43 EET
To: '
Great, monday it is...

>>>
Op 7 mrt. 2019 21:42 schreef '
, I will be in Utrecht on Monday but are here. Actually they are the ones who run the tests, so they can handle the case. I will be in contact with them anyways, and I can always check the setup and the results afterwards, when I am back.
Conclusion is that Monday is OK.
The tests take place at BuildinG that is at

I will inform them.
Best,

>>>
On 7 Mar 2019, at 21:34,
wrote:

I was planning, taking into account the urgency, to go tomorow. But i would have to change some meetings for that though. If it is all the same to you, monday is more confenient for me.
Let me know what you prefer. On monday I can go to G19 quite early, as I can skip going to KNMI first. So I would probably be at your office before lunch.
Regards
>>>
Op 7 mrt. 2019 21:26 schreef
hi, that would be great!
Do you mean you will come to Groningen tomorrow (Friday) ? My group and myself do not work on Fridays but I can arrange that. Please let me know if this is the case.
Regards,

>>>
On 7 Mar 2019, at 21:18,
wrote:

Dear l
After reading your last mail, I see no other option than to remove the granite from G19 and bring it to you. I can than also configure the BOWW datalogger to store the miniseed on disk, like the other dataloggers.
Tomorow morning I first have to go to KNMI, but my suggestion is that I make the trip to Groningen soon after that and retrive

the granite from G19. Subsequently I can come by your office to make sure we are all set for the shake test.
Please let me know if this would work for you.
Warm regards,

>>
Op 7 mrt. 2019 13:47 schreef '
Dear , thank you for the detailed explanations so far.
After reading your note and discussing it with the people in the project, we decided that the existing setup is not reliable to continue the tests on BOWW and G190. These two stations are the closest to each other, which are used for immediate comparisons of the two stations groups (i.e. B and G). This is reason why we need to make sure what we are recording at the lab is correct as we cannot bear a mistake at this point. In order to do that, and based on your explanations, we need the following:
1. The datalogger of the G190 station at the lab, despite the practical difficulties
2. Either the small PC collecting the data at the station to be brought to the lab for the BOWW, or a personnel from KNMI to stream the data during our tests
Thank you for your help.
I will communicate this with the rest of the group.
Regards,

>>
On 7 Mar 2019, at 12:00,

Ahhh, good point...
let me think on that a bit.
The basalt digitzers are all configured the same and as the episensors from BZN1 and from BOWW also have the same jumper settings, there will be no problem there, just renaming the miniseed files will suffice.
For G750 and G190 there is a difference in the jumper setting for the sensor, so using the same digitizer will result in a factor 4 difference in amplite (I assume). For the rest it should not matter at all.
Cheers

Van:
Verzonden: donderdag 7 maart 2019 11:54:02
Aan:
CC:
Onderwerp: Re: Sensor tests

So in this process of using different dataloggers for different stations, the only issue is the naming right? Do we have issues related to the calibration factors of the dataloggers of different types? I am asking this question especially for G190 that uses Granite normally but we will test it with Obydian.
Thanks,
.
>>
On 7 Mar 2019, at 11:49,

about BOWW, unless you get the seelink client from obspy running, I do not see how we can get the data for BOWW with the logger from BOWW. You could of course use the logger from BZN1, but as the logger is configured fr BZN1, the miniseed files under /data/continuous will be named BZN1 instead of BOWW. This is not a problem, you just have to keep track of the file names. Of course you can rename them afterwards.
The same holds for G19. If you attach the sensor to the obsidian of G750, or the basalt from BZN1, the miniseed files from this test will have the name G750 or BZN1 respectively. Again, not a problem, when you take the files from the logger, you can rename them. If you use obspy, you can even change the station name inside the miniseed records.
I have never used the miniseed client from obspy before, so I would have to look into the manual, just as you.
Hope this helps,

>>
Van:

Verzonden: donderdag 7 maart 2019 11:26:33
Aan:
CC:
Onderwerp: Sensor tests
hi,
We did tests on BZN1 and G750 stations yesterday by using the dataloggers originally taken from these stations. Today we would like to run the tests on:
- BOWW sensor with BOWW datalogger
- G190 sensors with G750 datalogger
We will start these tests in the afternoon. We need your help in two issues:
1. How to stream BOWW (Dimitris tried with ObsPy yesterday but did not manage, and there was no enough time for trials)
2. What we need to take care in testing G190 sensor, because actually we are using a different type of datalogger (Obsydian instead of Granite) which belongs to another station
Please contact us when you can.

Regards,

Correspondence #2 --

On 8 Mar 2019, at 12:52,

We are aware of the problems with BZN1. Most likely I will send that back to the manufacturer. I suggest we first do the test on G190 and BOWW, so that we can pick up the 4 sites at once and return them to the field. I have to check my schedule (or a technician)
Let's get back to that after the tests are finished
Groet
>>
Op 8 mrt. 2019 11:46 schreef '
hi again,
We are done with the two stations (G750 and BZN1). Would you like to place them back? Please let us know how to organize that.
I would strongly suggest to have a look at the sensor of BZN1 and make a maintenance, since it has been providing questionable data and we found traces of water and flood in that basement. There were also some rust on the sensor's metal connector.
Regards,
.

Correspondence #3 --

From: '
Subject: RE: Problem with the G190 sensor
Date: 15 March 2019 10:23:09 EET
To: "
Cc: '

Dear
Thank you for sharing the results from station BOWW and G190.
We do see at some stations the 50 Hz disturbance that is obviously present at G190 and thought this had to do with the field installation (50 Hz induced by the local electricity cables).
Although we are not happy with this disturbance, it does not affect our processing, since it is a very sharp noise peak and we can use a notch filter to compensate or alternative filters.
Apart from the noise peak, the spectra are quite similar and the same applies to the recorded event data (see enclosed plots)
The fact that you also see this disturbance now at a laboratory installation reduces the origin of the noise peak to the instrument itself and we will ask the manufacturer what the cause may be.
Best regards

>>
Van:
Verzonden: donderdag 14 maart 2019 09:32

CC:
Onderwerp: Problem with the G190 sensor
Dear
We looked more closely into the problem we have been facing with the G190 sensor, after the Skype meeting yesterday. We observe unusually high self-noise when we do the shake-table tests with G190. We tried it with different combinations (cable-sensor-datalogger), but the result was the same.
In order to understand if the problem occurred after we removed the sensor, we checked the last earthquake recorded on site. We used the KNMI data on the website for this purpose. There was an earthquake of M1.6 just the night before we removed the sensors. Below are the processed acceleration data from BOWW and G190, the two closest B&G stations. You can see below that G190 was recording with extremely high noise even when installed on the field. Our conclusion is that this problem is associated to the sensor itself (i.e. not to the datalogger), clearly existed before the removal, but the total duration of the problem is yet unknown to us.
Please let us know if there is anything we can do with this sensor. We will, unfortunately, need to remove another G100-G600 sensor instead, if the problem persists.
Regards,

Correspondence #4 --
From: '
Subject: RE: Calibrations test on the shake-table at BuildinG
Date: 28 March 2019 14:40:06 EET
To: ' >
Cc:

Dear all,

The shake tests of BZN1, BOWW, G190 and G750 have been completed and the data has been processed and interpreted. Reporting is underway.
We advised KNMI to have BZN1 to be checked by the manufacturer, since it has been providing questionable data and we found traces of water and flood in that basement. There was also some rust on the sensor's metal connector.
Additionally, G190 shows too much noise, and after filtering still doesn't give proper results. Also this accelerometer should be checked by/on behalf of KNMI.
All equipment that was removed from the stations and is now in the test facility Building of Hanze, is now available to be collected and checked and/or re-installed by KNMI. , could you please make an appointment with Ihsan Bal?
Because of the poor results for G190, we advise to test a 5th sensor. Is it possible KNMI provides the equipment from another G-station? (G100-G600).
If you have any questions or remarks, please contact me or
Kind regards,

Business Development Manager Earthquakes
| www.fugro.com
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Veurse Achterweg 10, 2264 SG Leidschendam | P.O. Box 9440, 9703 LP Groningen, The Netherlands
Trade Register nr 27114147 | VAT nr NL005621409B08

Correspondence #5 --

From: '
Subject: Re: cables for the Granite
Date: 8 April 2019 10:29:39 EEST
To: '
Cc: '
Dear
I will be going to Groningen coming Friday, April 12 (hope not to inconvenient for you) to pick up a EpiSensor from the filed en bring it to you for the shake-test. If possible, I will NOT pick up the other equipment, I hope to plan one trip, after you have finished all the tests, to pick up and put all equipment back into the field.
Let me know if Friday is possible for you....
Thanks,

Van:
Verzonden: woensdag 3 april 2019 13:48:49
Aan:
CC:
Onderwerp: cables for the Granite
hi,
Please note that we need the connection cables for the Granite. We have been using the cables of Basalt dataloggers but you will probably take them back. We need:
- the power cable
- sensor-to-datalogger data cable
- datalogger-to-PC ethernet LAN cable
Please remember this when you will be visiting us next week.
Thanks,

Correspondence #6 --

From:
Subject: Returning the KNMI sensors back
Date: 23 April 2019 10:49:29 EEST
To: '
Cc: '

G
We are done with the sensors and the digitizers. Can you arrange to pick them up from BuildinG?
Please let us know if you need our help for placing them back.
Regards,

Comment 3

For the testing a reference sensor is used. It is not mentioned what the specs of this sensor are, nor arguments are given why this would be a reference that is to be trusted as such.

Response 3

We used two reference sensors, different brand, different model, different properties. Please see Appendix 2 (added in this version) for the technical specifications of the reference sensors. Please also note that we applied sinus wave with known frequency and amplitude, meaning that we can and we did cross-check all measured values with the calculated peak accelerations.

Comment 4

P4: G100 – G600 → G010 – G700

Response 4

Corrected.

Comment 5

P4: G700 – G800 → G710 – G800

Response 5

Corrected.

Comment 6

P4: Appendix 1 is mentioned, but not included, also not in the table of contents. Are there multiple appendices planned?

Response 6

Added.

Comment 7

On P5 it is mentioned that "KNMI needs to return the Obsidian to factory defaults or check the software/settings. This has already been communicated with KNMI". No argument is given why KNMI would need to do this. The settings of all digitizers in the KNMI Groningen network were checked in the autumn of 2018. All Obsidian dataloggers digitize the incoming signal from -10 to +10 V, which is consistent with the -10 to +10 V output range of the EpiSensors in the G710 – G800 network.

Response 7

This was suggested by the Manufacturer (Kinemetrics) when we sent them the config file and config data of the Obsidian. Please see Correspondence #7.

Correspondence #7 --

From:
Subject: Re: Epi Sensors - question on measuring the gravity
Date: 16 April 2019 22:58:37 EEST
To:
Cc:
No. As of right now, G75 is not operational.
It looks like that system was built somewhere in early 2016, so whatever configuration changes have been made in the intervening 3 years since it shipped that may have affected the configuration are unknown to us.
It will have to be defaulted to make it operational.

Best regards,

>>>>>>>>>>>>>>>>>>>>

On Tue, Apr 16, 2019 at 12:54 PM PDT, wrote:
Thank you for the answers.
I cannot change the settings (i.e. restore to default) of the digitizers. We are commissioned to check the equipment, thus intervening with how they function could cause potential problems for the client. Is there any other way of learning the voltage range of G75?
Thank you.

>>>

On Tue, Apr 16, 2019 at 12:49 PM PDT, wrote:
Count range on our digitizers is always +/-
BZN1 is set to 20V input range on all channels.
G19 is set to 20V input range on channels 1-3, but set to 2.5V on channels 4-16
- These can be changed from the "Hardware" section of the instrument's web page
G75 has no channels defined. I suggest you factory default the unit (from Linux) with the following commands:
rock stop
cd /usr/rock/SMARTSDist/bin
./rhfactoryrestore
Best regards,

Comment 8

On P6 it is mentioned that B-stations are not protected from water. This is a generalization that cannot be made. Though there is earthquake damage in the B-network area, most buildings with B-stations are water proof and have no issues with internal sources of water.

Response 8

The sensor is placed directly on the floor (on a tile in one case at BWIN). If, by any chance, there is water on the floor, then it will get into contact with the sensor. That is pretty much the case in BZN1 (manifested by the water pump next to it, rusty connector, and also reported by the owner during our visit) and for BWIN (see Figure 21 in our report). We thus disagree here with the reviewer(s).

Comment 9

On P6 it is mentioned that the B stations are not stable if the motion is high. This is an unproven assumption that in fact is contradicted by the way the shake table test is performed. As mentioned in the report, the B-station sensors in houses are connected to the floors following instructions from Kinemetrics (with a moment-free bolt connection, see P4). A reasonable assumption to make then is that with such a connection California type strong motions exceeding 1 g can stably be recorded. On P11 it is described that for the shake table test, exactly the same connection was used. Why would this setup be used if it were unstable?

Response 9

The mounting of the accelerometers is not the problem in this case, but the electronics of the accelerometer are not stable. See Response 21 below.

Comment 10

P8, chapter 3, line 2: a reference to noise problems for G190 was given, but not previously discussed. Please be specific on this issue, since from the spectra in Figure 15 it becomes clear that there is a 50Hz noise source, but no other problems *seem to be detected. If there are other problems, please be specific. Also the discussion in chapter 4, 3rd paragraph only mentions unusual high background noise. A clear underpinning of the high noise argument, other than the 50 Hz is required.*

Response 10

See Response 18 below.

Comment 11

P9, line 1: "cables were not enough"? long enough or not enough cables?

Response 11

Modified as:

Tests were done 2 sensors at a time since the number of sensor-to-datalogger cables was not enough to test all sensors simultaneously.

Comment 12

P10+11: maybe we missed, but is there a description of the reference accelerometers (type, manufacturer, calibration details, etc.)?

Response 12

See Appendix 2.

Comment 13

P12: it is not clear what is meant with "2 stations were 0 dB and 4 stations were 18 dB.

Response 13

This is for the NAM geophones, not for the KNMI sensors. We modified the text anyways:

2 stations of these NAM sensors were 0dB and 4 stations were 18dB.

Comment 14

P14: the abbreviation PGA is not introduced

Response 14

We added it for the non-technical reader.

Comment 15

P15+16: "the voltage mismatch is not reflected in the KNMI XML files." This statement is incorrect. If the voltage mismatch between the sensor output and the digitizer input for the G010-G700 accelerometers were not well taken care of in the XML files, this would result in wrong acceleration outputs. Also in this report it is shown that correct acceleration values are obtained when using the corrected XML files. The user needs to know how to compute acceleration from counts. This is the total sensitivity that is stated in the XML files. For the G010 – G700 accelerometers the sensitivity is a factor of 4 lower than for the G710 – G800 sensors, due to 2 unused bits (which are used to digitize the unused voltage range between 2.5 and 10 V). Obviously, the digitizers can be set to the -2.5 to +2.5 V range to improve the sensitivity of the instruments. In the current environment, however, we feel restricted in making any changes to the digitizers and inventory.

Response 17

We had not correctly phrased this part of the report. We have removed the sentence below, keeping the rest of the statements the same :

However, the voltage mismatch is not reflected in the KNMI XML files and the gain factors reported there.

Comment 16

P17: "G470 sensor behaves like a +- 4g sensor". This statement comes without argumentation. In fact, this statement is contracted in the same report on Figure 9, in which it is shown that both G190 and G470 yield an output in counts that is consistent with a 2g setting.

Response 16

It was not possible to report the "as installed" situation of G470 since we do not have the original digitizer and the original cable. We only made an assumption, as explained in the report, thus Figure 9 is based on that assumption.

The comment of "G470 may be behaving like +-4g sensor" comes from the manufacturer. See Correspondence #8 below.

We have also slightly modified this part of the report as below:

Finally, we were not able to check the G470 sensor with its original cable and the digitizer. We cannot make 100% sure in which range this sensor behaves because we do not have the original digitizer of this sensor (it was not removed from the site). This needs to be clarified by KNMI since it would directly affect the gain factor.

Correspondence #8 ---

From:
Subject: Re: Epi Sensors - question on measuring the gravity
Date: 24 April 2019 00:13:37 EEST
To:

My colleague and I were discussing your concerns with sensor SN 6516 further and he mentioned that the sensors use a differential signal connection.
So if the sensor is mis-wired such that only one side of the signal is connected to the digitizer that you would see exactly the behavior you are reporting.
In other words, "half" the signal would make the 2g sensor behave like a 4g sensor.

Comment 17

In the same paragraph it is implied that the actual hardware setting of the sensor cannot be tested because the digitizer at station G470 was not available to Hanze. Here we need to reiterate that the output of a sensor can in principle be tested with any digitizer.

Response 17

The purpose of the tests is not to test only the sensors. The same sensor vs station confusion of the reviewer(s) is evident also here. What we tested is the sensor+digitizer “as installed” and the gain values reported by KNMI. Please see Response 1.

Comment 18

Comments on the suggestions for improvements:

- “G190 and/or its digitizer exhibit high noise and need to be checked”. Please refine this conclusion by adding the sensor to another digitizer. If this is a sensor test, one needs to be able to conclude whether it is in fact the sensor, not the digitizer, that picks up heavy 50 Hz distortion (as well shown in Figure 15).

Response 18

50Hz is the “usual” noise since it comes from the frequency of electricity used in Europe. What we are talking about is the unusual noise, that we cannot see in BOWW, for example. When G190 sensor is connected to the Granite, by using the cables of the B-stations, we get very high noise in the raw data. This is what we reported and commented. That is pretty much evident in Figure 15 in the raw data. It is not in our scope to go further.

Comment 19

- “the range of Obsidian ...”. This range can be detected and has been detected.

Response 19

See Response 7 above.

Comment 20

“BZN1 station is known to have issues”. Please give arguments. In Figure 17 it is shown that in fact BZN1 yields good output.

Response 20

Our argument, given below in Correspondence #9, comes from KNMI itself.

Correspondence #9 --

From: "
Subject: Re: Important - BZN1 and BGAR stations data
Date: 23 October 2018 15:32:15 EEST
To: "

Dear I
To make sure, we had another check of the data quality for accelerometers BGAR en BZN1. Attached are distribution functions

of the power-spectrum density recorded the week prior to the Zeerijp event. It can be seen that BGAR records realistic ground motions in the different frequency bands and for the 3 components, whereas BZN1 has instrumental issues for all 3 components. Hence BZN1 is not be used for data analysis.
Also attached is the 3C recording of the Zandeweer event by BGAR. Also this event registration looks fine. Hence, there is no reason to dismiss data from BGAR from further analysis. The S-wave arrival has much larger amplitudes on the East component than on the North component. This is related to radiation pattern of the source.
For all KNMI stations, data quality and availability can be checked
on

ORFEUS - Data

Observatories & Research Facilities for European Seismology
Best regards,

From:
Sent: Friday, October 19, 2018 12:12:41 PM
To:
Subject: Important - BZN1 and BGAR stations data
Dear
We have been working on the Groningen data produced by KNMI. We are about to publish a SCI paper in which we reported conclusions based on public KNMI data. You may remember that in the NAM workshop at Schiphol, organized by on 22-24th of May, I presented polarity plots for BZN1 station and the unusual extreme polarity observed there.
had the comment (the others further agreed) that this station did not function properly during the Zeerijp Earthquake. A fact that may be related to this is that we cannot find the vertical component from that event at BZN1 station at KNMI website, but there is a component downloading when ObsPy is used. We also observed a similar unusual response at BGAR station from the 5th of November 2014 Zandeweer event (see attached)
Because we are using public data and our results need to be reproducible, for obvious academic reasons, we would like to properly address this issue in the paper. We were planning to report the problem in the paper text and remove these data from the dataset, but we need to justify this (we also had a comment from the Reviewer for further confirming this with the data producer).
Could you please let us know about your views on the reliability of the two horizontal components (HGE and HGN) of these two records (please see attached figure) ?
Thank you for your help.
Regards,

Professor in Earthquake Resistant Structures
Hanze University of Applied Sciences Groningen
Research Centre for Built Environment NoorderRuimte
Zernikeplein 11 | P.O. Box 3037, 9701 DA GRONINGEN| The Netherlands

Comment 21

"B stations need to be improved overall". Please give arguments how the current B-station acceleration recordings are affected by the setup. Should we not use the installation procedure anymore as suggested by Kinematrics? What makes the Canterbury box better than the KNMI instrument box?

Response 21

We do not think that the mounting of BWIN station (see Figure 21 in the report) is according to Kinematrics' instructions. We would be very much surprised if it is so.

At B-stations there are multiple causes for not showing the correct ground motions. In this report we focus on detecting any problems with the accelerometer and the installation as a whole. Influence of the building can also be relevant but is not investigated by Hanze.

Please note that a station does not consist only of a sensor, but it needs power, data transfer and data storage. If any of these components fails, the recording does not take place. In KNMI B-stations, the sensor is fixed on the floor per manufacturer's instructions, and our objection is not to that. All other equipment other than the sensor, however, is placed on plastic boxes which are not fixed anywhere (i.e. freely moving), on top of another plastic box that is also not fixed anywhere and covering the sensor. That is one strange way of creating a SGM (strong ground motion) station. Canterbury box, that was only one example, is a compact box fixed to the floor, protecting all equipment in the same place.

We rephrased the conclusions as below:

- B stations need to be improved in overall. This improvement includes sensor mounting. An inappropriate mounting example from BWIN station can be seen in Figure 21.
- The sensor storage is also not appropriate in B stations. A proposal for storage and boxing is given below in Figure 22. A station does not consist only of a sensor, but it needs power, data transfer and data storage. If any of these components fails, the recording does not take place. In KNMI B-stations, the sensor is fixed on the floor per manufacturer's instructions. All other equipment other than the sensor, however, is placed on plastic boxes which are not fixed anywhere (i.e. freely moving), on top of another plastic box that is also not fixed anywhere and covering the sensor.

Comment 22

"All the stations of the SGM network should be visited regularly, …". Why would stations in the UK be visited?

Response 22

We could not understand this comment, but in any case, as very well known in the earthquake engineering world, SGM stands for "Strong Ground Motion" and it has nothing to the with the UK (?). We rephrased this sentence for the non-technical readers as below:

All the stations of the Groningen SGM (Strong Ground Motion) network should be visited regularly, preferably once in a year. We understood during the site visits that some of the B stations were not visited for very long time.

Analysis of consistency between B- and G-stations records for induced events in the Groningen gas field.

Final Report

Document N° : STR_FUG_18P17_01

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FUGRO

Analysis of consistency between B- and G-stations records for induced events in the Groningen gas field.

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Table of contents

1. Introduction and objectives

Within the framework of the KEM04 project "Data driven study on seismic structural features of Groningen ground motions", an important task is the collection and analysis of the recorded ground motions for the induced events in the field. The induced earthquakes are recorded at the KNMI stations consisting of two networks: the B and G networks. These data are publicly accessible from the KNMI website and have been downloaded by the project team. The B network consists of accelerometers at the surface (EpiSensor starting from 2014) whereas the G stations consists of a vertical array of 1 accelerometer (EpiSensor) at the surface (called G0) and 4 geophones at 50m, 100m, 150m and 200m depth. Only records at the surface are considered in this Report.

Records from these networks are used in the project to:

1. Investigate the features of the Groningen ground motion records (spatial variability, vertical motion, attenuation);
2. Calibrate and validate the 3D simulations of wave propagation performed using the SPEED code;
3. Test the GMM V5 in order to assess its performance in reproducing the observed ground motion records.

The reliability of recorded motions at these stations is thus of paramount importance for the project.

A consistency analysis between recordings at closely located B and G0 stations was presented in the MEMO N° 18P17_05022019 in February 2019 (hereafter referred to as MEMO) based on data downloaded from the KNMI portal on late November 2018. One of the conclusions of the MEMO was that there was a systematic difference between ground motion recorded at B and G0 stations that was probably related to instrumentation issues.

After the MEMO and the following discussions, KNMI communicated that an error was found in the parameterization of the G0 sensors that caused recordings of such sensors being about a factor of 2 smaller than what they should be. The G0 data were corrected by KNMI *on December 17, 2018* and they are available from their portal.

The objective of this document is to repeat some of the analyses performed in the MEMO using the corrected G0 data in order to evaluate the effect of the correction. Some additional analyses are also performed (e.g., considering acceleration response spectra) upon request from The Dutch State Supervision of Mines (SodM). All the analyses are performed using Matlab and related functions.

2. Records processing

The raw data were downloaded from the KNMI portal (http://rdsa.knmi.nl/dataportal) on March 2019 (after that the correction to the G0 stations was applied by KNMI). We considered the following set of data:

- Magnitude $M_L \geq 2$ (29 events after 09/2013);
- Stations located within 5 km buffer from Groningen gas field
- Horizontal and vertical components
- Surface and borehole records (only surface records are discussed in this document)

The records are processed based on PEER/RESORCE (Akkar et al., 2014) processing scheme (Figure 2-1).

The processing includes a filtering step. The identification of the low- and high-cut frequencies is based on the analysis of the signal-to-noise ratio (SNR). First, noise, P-wave and S-wave windows are identified based on manual picking of P- and S- arrival times and on the scheme defined in Kishida et al. (2014) and modified for the Groningen region (Figure 2-2 left). In particular the end time of the S-wave window was automatically selected using an assumed S-wave duration and is expressed as follows:

$$Ds = Td_{rup} + Td_{prop}$$

where Td_{rup} is related to the rupture (source) duration and Td_{prop} is the duration through the propagation of the S-wave to the site and to scattering along the path. According to Kishida et al. (2014) Td_{rup} is found to be larger than the theoretical source duration. We considered Td_{rup} = 2s and Td_{prop} =0.18 Rh , where Rh is the hypocentral distance. The 0.18 coefficient for Td_{prop} is slightly larger than the one proposed by Kishida et al. (2014) but it was found appropriate for the Groningen recordings based on visual inspection of selected windows.

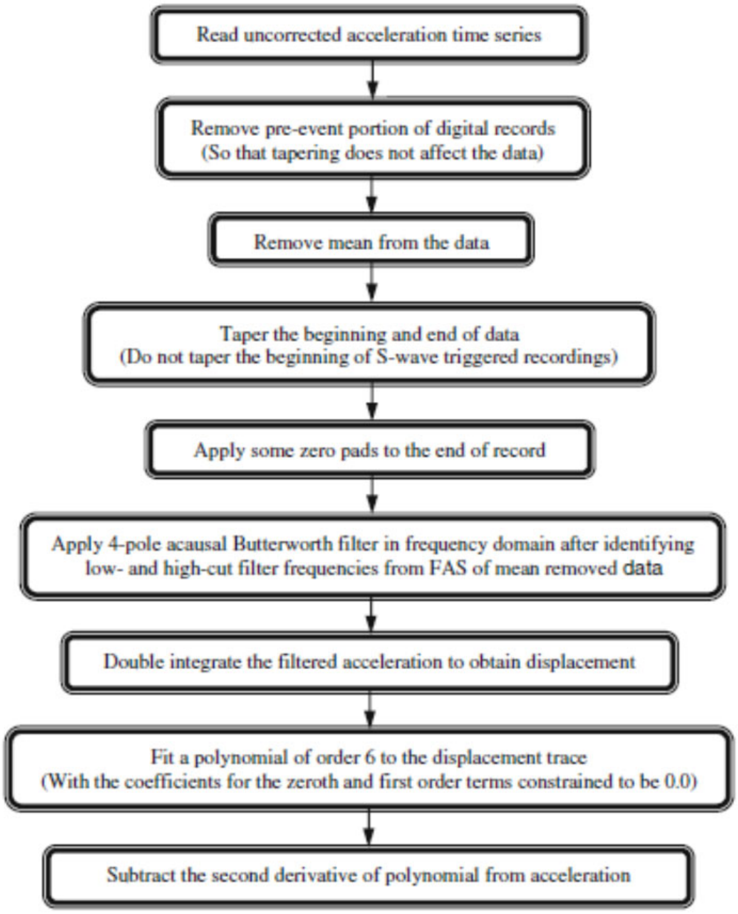

Figure 2-1 : Flow-chart of the processing used for the Groningen records also used in the RESORCE and PEER strong-motion database (from Akkar et al., 2014).

Fourier spectra are computed for the noise window as well as for the S-wave window, and for the total record duration defined as the S-waves arrival time + 25 s (Figure 2-2 middle). SNR are computed from the S-wave and the noise windows, and the frequency band with an SNR≥3 is identified (Figure 2-2 right). The full waveform is then filtered between the low- and high-cut frequencies identified. Note that a minimum threshold of 0.2 Hz is imposed to the low-cut frequency of the filter in order to avoid low-frequency trends not removed by the previously detailed procedure. The following exclusion criteria are applied to the records (meaning that the records are discarded and not used in subsequent analyses):

- maximum $f_{low\text{-}cut}$ for the 3 components is higher than 5.0 Hz;
- minimum $f_{high\text{-}cut}$ for the 3 components is lower than 5.0 Hz;
- minimum bandwidth $f_{low\text{-}cut}$ - $f_{high\text{-}cut}$ for the 3 components is lower than 5.0 Hz .

Examples of the results of this step of the processing are shown in Figure 2-2 and Figure 2-3 for two stations with different level of noise.

In order to optimize the procedure, the manual picking of P- and S-waves is done for the Zeerijp recordings only and, based on such results, simple functions for estimating the arrival times are developed and used for the other events (Figure 2-4). Because the relatively small extension of the gas field, the close source-to-site distances and the relatively homogenous velocity structure, we believe that such approximation is appropriate for this study. In any case, a visual screening is performed for each record based on plots as in Figure 2-2 in order to assess the appropriateness of the windows.

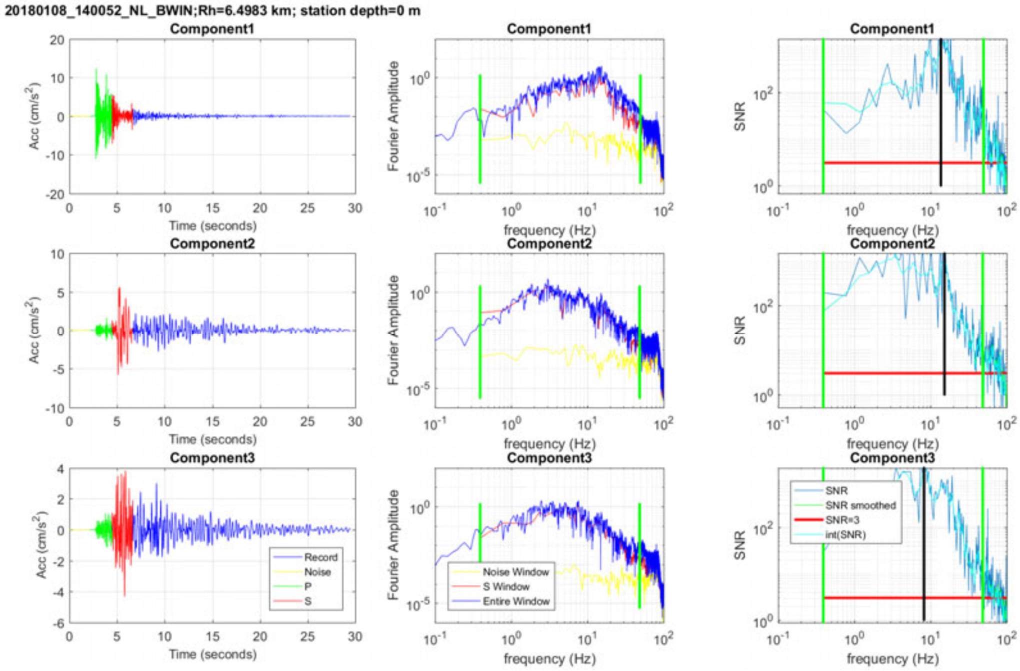

Figure 2-2 : Event 20180108_140052, station BWIN. Example of identification of P-waves, S-waves and noise windows, calculation of signal to noise (SNR) ratios and identification of high-cut and low-cut frequencies of the filter. The black line (right graphs) represents the frequency corresponding to the largest SNR.

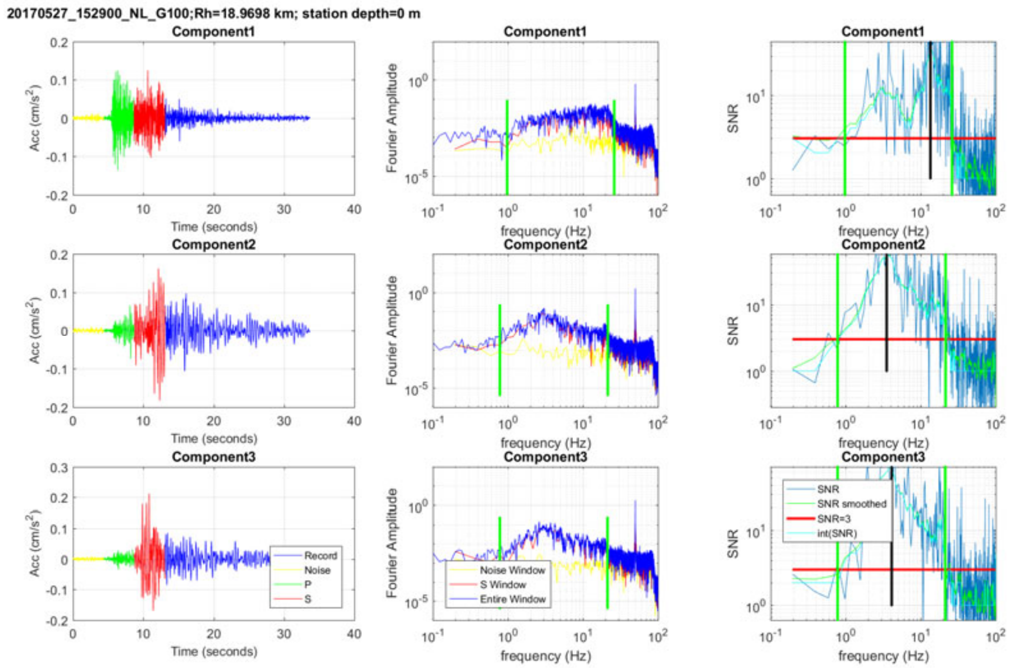

Figure 2-3 : Event 20170527_152900, station G100. Example of automatic identification of P-waves, S-waves and noise windows, calculation of signal to noise (SNR) ratios and identification of high-cut and low-cut frequencies of the filter. The black line (right graphs) represents the frequency corresponding to the largest SNR.

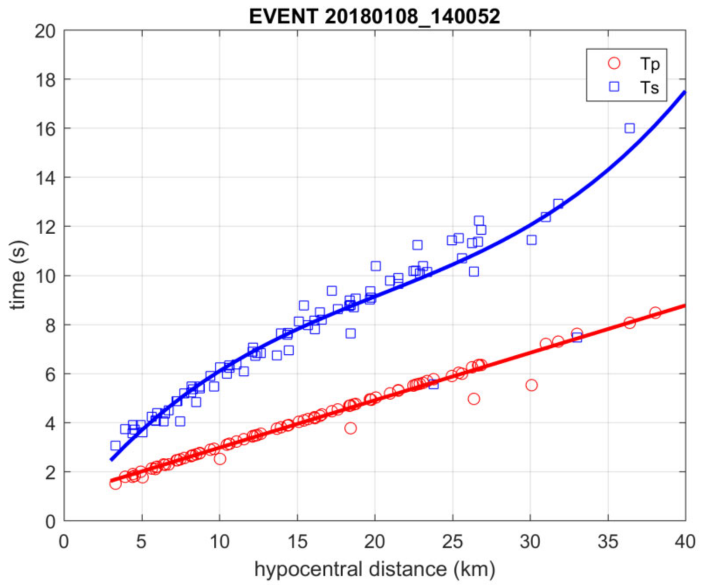

Figure 2-4 : Arrival times of P-waves (red circles) and S-waves (blue squares) based on manual picking of recordings for the Zeerijp event. The curves show the derived polynomial functions used to infer P and S arrival times for the other events.

3. Comparison of recordings at B and G stations

Several B and G stations are located very close to each other, having an inter-station distance of few hundred meters up to about 1.5 km. As a consistency analysis, similarly to what done in the MEMO, we selected pairs of B and G stations located close to each other and compared the records from the recorded events (Figure 3-1). On average, we expected to observe similar ground motions because of the similar wave propagation from the source to the two stations and relatively homogenous local site conditions.

The comparison is performed in terms of B-to-G spectral ratios from the records of each event, both in terms of acceleration Fourier amplitude spectra (FAS) and acceleration response spectra (PSA).

Table 3-1 reports the considered B-G station pairs, their inter-station distance and the number of records available for each pair (after the record processing).

We note that for some pair (i.e., BHKS-G290 and BZN1-G140) only one or two records are available and thus the results are not significant and are only presented for completeness. Other B stations (e.g., BONL, BGAR, BWSE, BWIR) are relatively far from a G station and the calculation of spectral ratios is not meaningful for the purpose of checking the consistency among B and G stations. In this case, other techniques (e.g., generalized inversion approaches, Ameri et al., 2011) may be applied to highlight the differences between B and G stations taking into account the relative source-to-site distance and considering a common reference site condition.

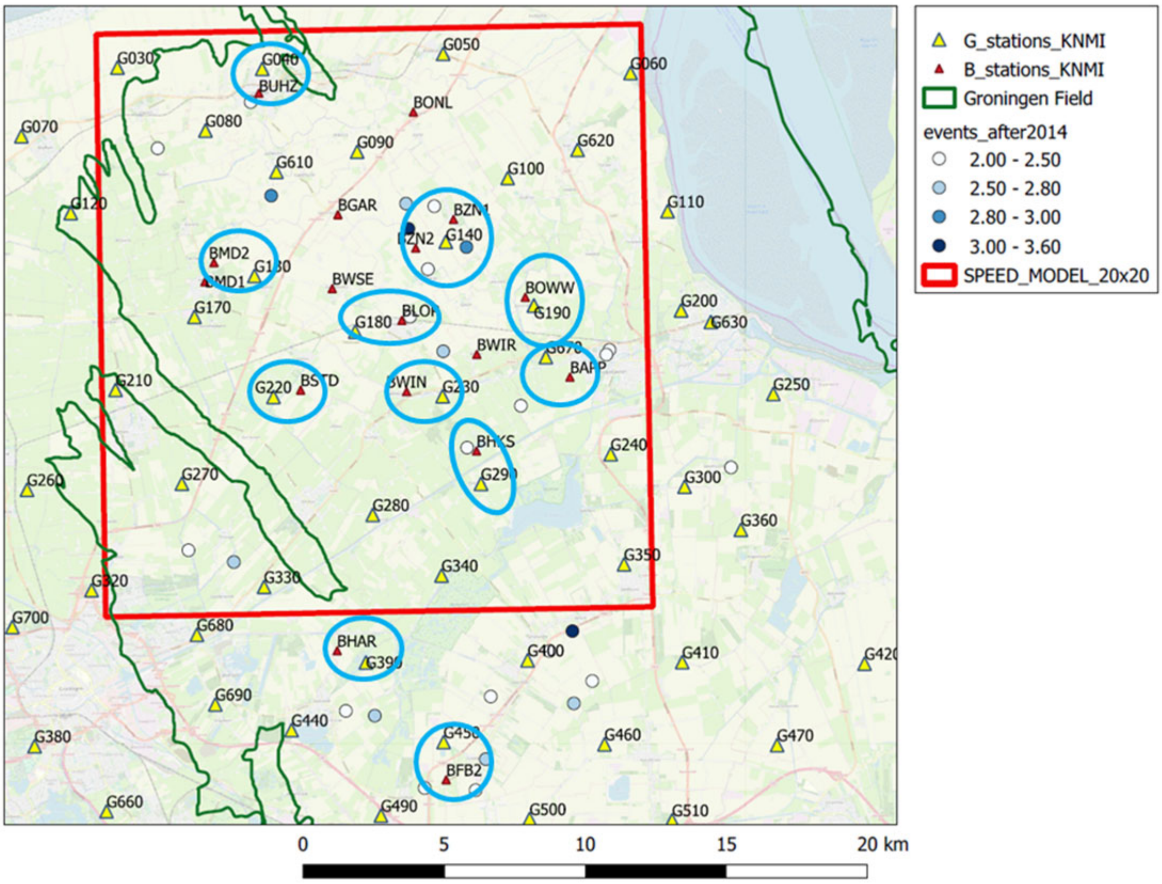

Figure 3-1 : Selected pairs of B and G0 stations in the Groningen field.

Table 3-1: B-G stations pairs considered in the analyses. Relative inter-station distance and number of available records are reported.

B-G pair	Inter-station distance (km)	N. of available records (FAS)	N. of available records (PSA)
BOWW-G190	0.43	9	8
BWIN-G230	1.29	8	7
BSTD-G220	0.99	13	10
BUHZ-G040	0.86	5	2
BZN2-G140	1.09	5	5
BMD2-G130	1.50	6	3
BHAR-G390	1.10	10	8
BAPP-G670	1.11	8	7
BFB2-G450	1.34	14	10
BLOP-G180	1.70	10	8
BHKS-G290	1.18	1	1
BZN1-G140	0.84	2	2

3.1 B-to-G ratios of acceleration Fourier amplitude spectra (FAS)

This section presents the comparisons in terms of acceleration Fourier amplitude spectra (FAS), similarly to what done in the MEMO (here we consider all available recorded events). Ratios between FAS recorded at adjacent B and G stations are calculated for the each event providing recordings at both stations. This is done for the horizontal (geometric mean of as-recorded horizontal components) and vertical components. As described in section 2, the records are processed and filtered and only Fourier spectra within the usable frequency band are considered for calculating the spectral ratios. FAS are smoothed using the Konno-Ohmachi (1998) algorithm with the b-parameter set equal to 40.

Figure 3-2 and Figure 3-3 show B to G stations FAS ratios for the considered pairs, for the horizontal and vertical components, respectively.

For the horizontal component, we observe that for some pairs (i.e., BOWW-G190, BZN2-G140) the mean ratios oscillate around 1 over the considered frequency range, as expected. However, for several other pairs (e.g., BWIN-G230, BHAR-G390, BSTD-G220) the ratios are around 1 in the low-frequency range (up to about 3Hz) and then they decrease to values significantly smaller than 1 towards higher frequencies. In other words, the accelerations recorded at several B stations are significantly smaller than those at the adjacent G stations in the high-frequency range.

Looking at FAS ratios for each recorded events (gray curves in Figure 3-2) we note that there is a general consistency of the spectral ratios and despite some variability, the FAS ratios for each event confirm the observations above. Some variations can be observed for certain pairs and are likely related to the fact that one station could be closer to one or more events event than the other station. This is the case for example of BLOP-G190 where the spectral ratios larger than 1 in the low-frequency range are related to the events in the Zeerijp region closer to BLOP station (see Figure 3-1).

For the vertical components (Figure 3-3) the FAS ratios are on average around 1 for most of the station pairs, although some deviation is visible particularly in the high-frequency range for some pair (e.g., BZN2-G140, BWIN-G230, BAPP-G670). These deviations are, on average, at higher frequencies with respect to what observed for the horizontal component.

Figure 3-4 and Figure 3-5 show the ratios for all events and all pairs of stations for the horizontal and vertical components, respectively. These figures further illustrate that, on average, over all the considered stations pairs, there is a systematic decrease of the horizontal B-to-G FAS ratios towards high frequencies with the average ratio being about 1 up to 3 Hz and decreasing to about 0.5 at 30 Hz. This effect is not visible on the vertical component where the B-to-G FAS ratios are on average around 1 over the considered frequency range.

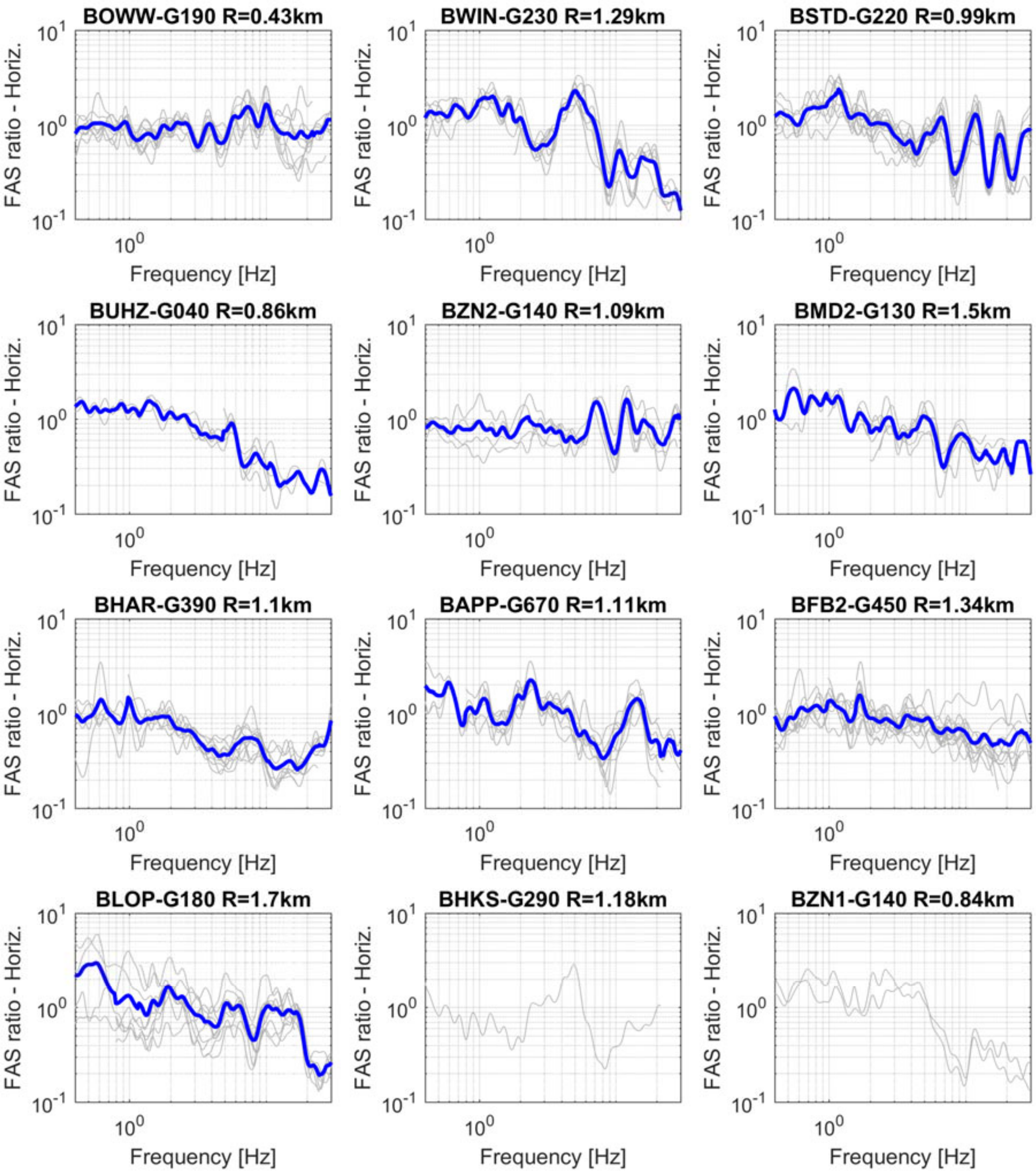

Figure 3-2 : Horizontal B-to-G Fourier Amplitude Spectra (FAS) ratio plotted for each pair of stations and for each recorded event (in gray). The geometric mean of horizontal components is considered. Mean ratios (only for pairs with at least 3 recordings) are shown in blue. The inter-station distance is shown in the graphs. Only FAS within the usable frequency band are plotted and considered for calculating the mean spectral ratios.

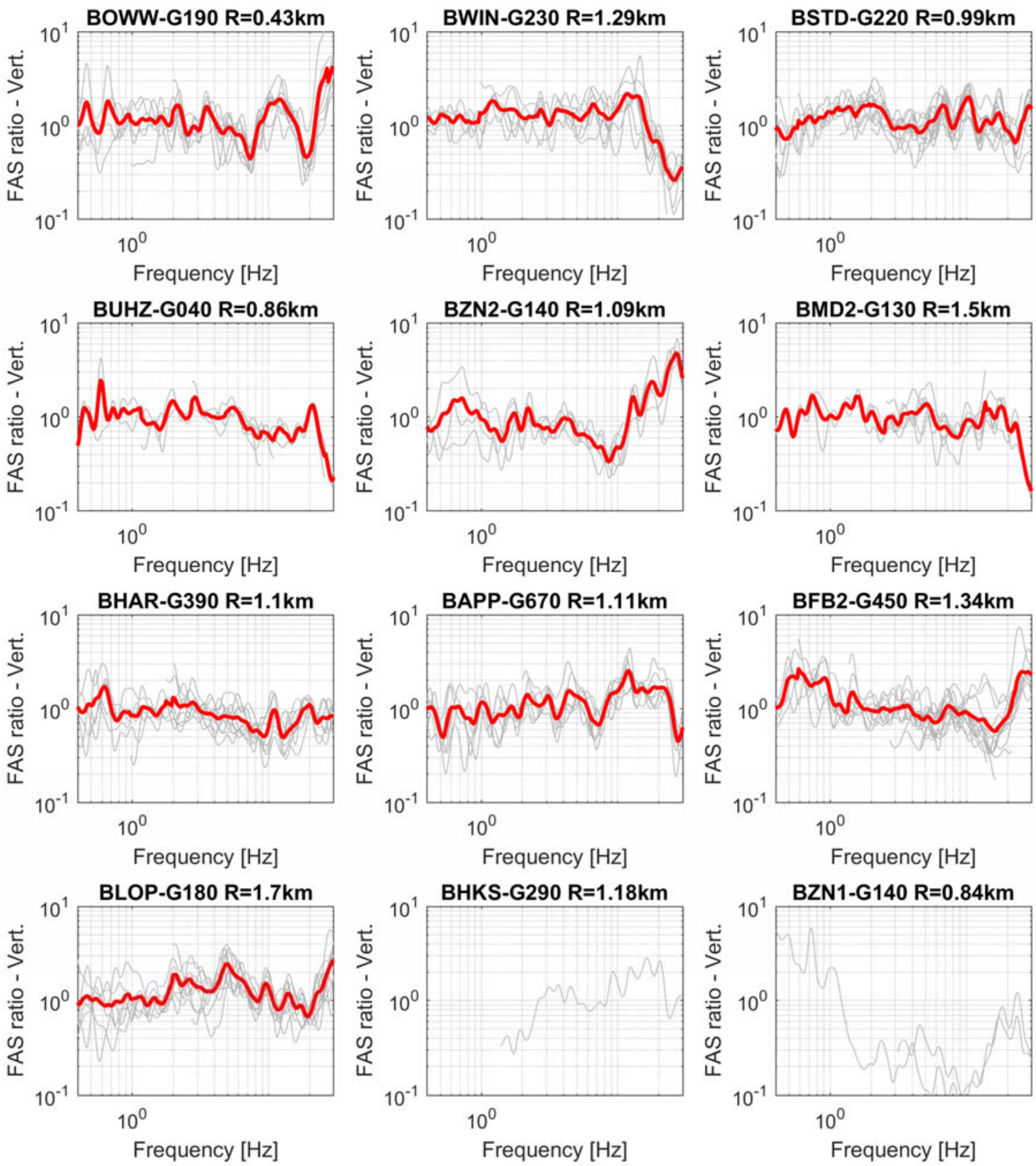

Figure 3-3 : Vertical B-to-G Fourier Amplitude Spectra (FAS) ratio plotted for each pair of stations and for each recorded event (in gray). Mean ratios (only for pairs with at least 3 recordings) are shown in red. The inter-station distance is shown in the graphs. Only FAS within the usable frequency band are plotted and considered for calculating the mean spectral ratios.

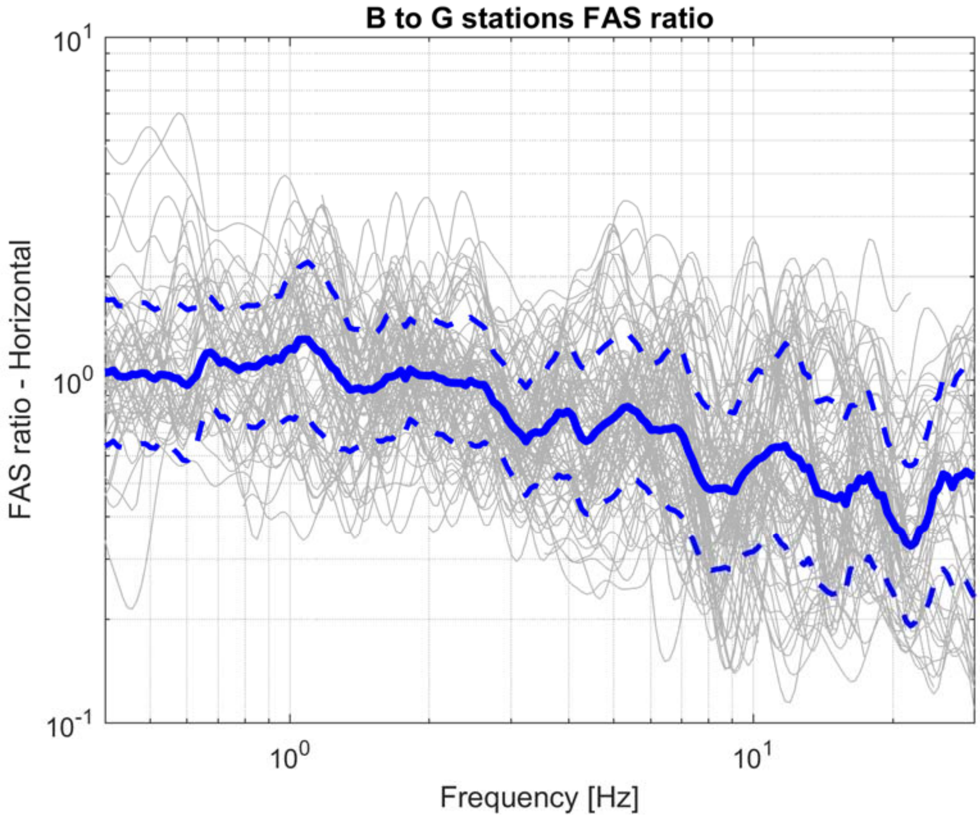

Figure 3-4 : Horizontal B-to-G Fourier Amplitude Spectra (FAS) ratio plotted for all considered pairs of stations and all events. The median ratio and its standard deviation are shown in blue.

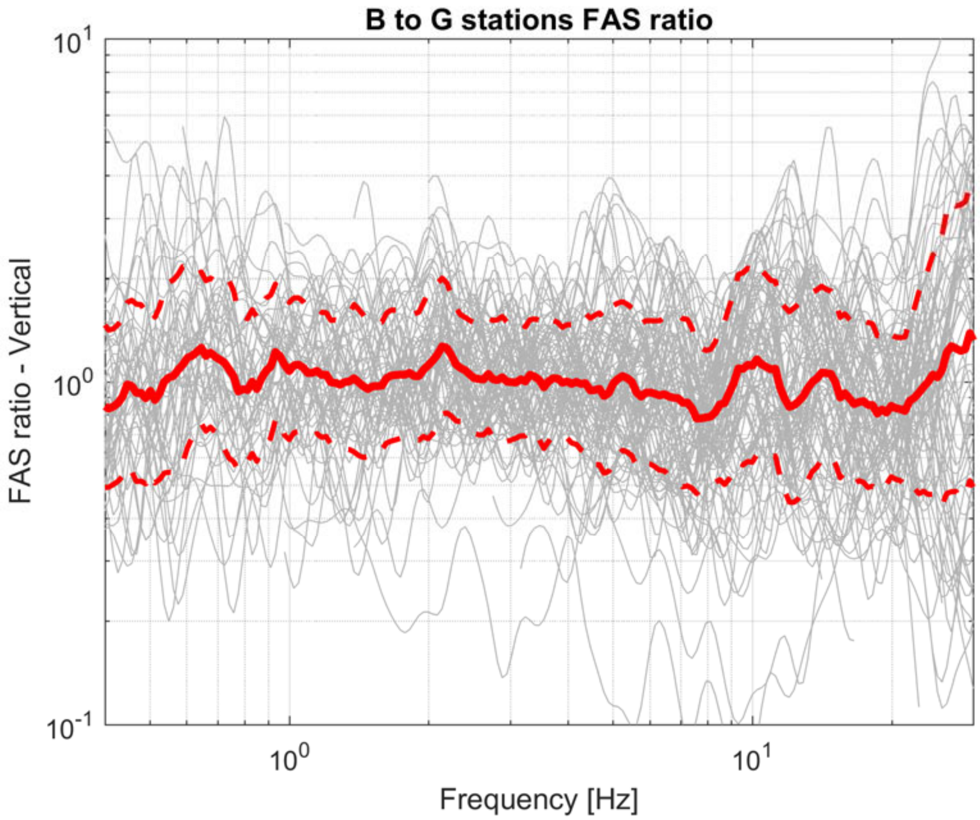

Figure 3-5 : Vertical B-to-G Fourier Amplitude Spectra (FAS) ratio plotted for all considered pairs of stations and all events. The median ratio and its standard deviation are shown in red.

3.2 B-to-G ratios of acceleration response spectra (PSA)

The comparison presented in the previous section are repeated here in terms of pseudo-spectral acceleration (PSA), at 5% damping, which is the measure used in the GMM V5 (and previous versions) for the hazard and risk calculations. This is done upon request of SodM.

Also in this case, the spectral ratios are computed considering the usable frequency band that we defined based on the filter cut-off frequencies during the processing phase of the records (section 2). However, because response spectra are sensitive to the filtering also in proximity to the applied cut-off frequencies, different usable frequencies are identified with respect to the FAS case. In particular, the minimum usable frequency is defined as 1.1*f_lowcut (the frequency of the low-cut filter), also consistent with recommendations of Akkar and Bommer (2006) and to what done in the GMM V4-V5 development. The maximum usable spectral frequency is defined as 100 Hz but only records with f_highcut >= 20 Hz (the frequency of the high-cut filter) are used for the calculation of the PSA ratios in order to have a reliable comparison of PGA (F=100 Hz).

Figure 3-6 and Figure 3-7 show B to G stations PSA ratios for the considered pairs, for the horizontal (geometric mean of as-recorded horizontal components) and vertical components, respectively.

Figure 3-8 and Figure 3-9 show the PSA ratios for all events and all pairs of stations for the horizontal and vertical components, respectively.

The comments made above considering the FAS ratio apply also to the PSA ratios although the shape of the spectral ratio is of course different. Moreover, due the necessary limit imposed to the f_highcut, a smaller number of records is available for certain pairs when considering response spectra compared to FAS consequently reducing the robustness of the results for PSA.

Figure 3-8 depicts, similarly to the FAS case, the systematic decrease of the horizontal B-to-G PSA ratios towards high frequencies with the average ratio being about 1 up to about 2 Hz and decreasing to about 0.6 at 100 Hz. This effectively means that recorded PGA at the considered B stations is on average 40% lower than that recorded at the considered G stations.

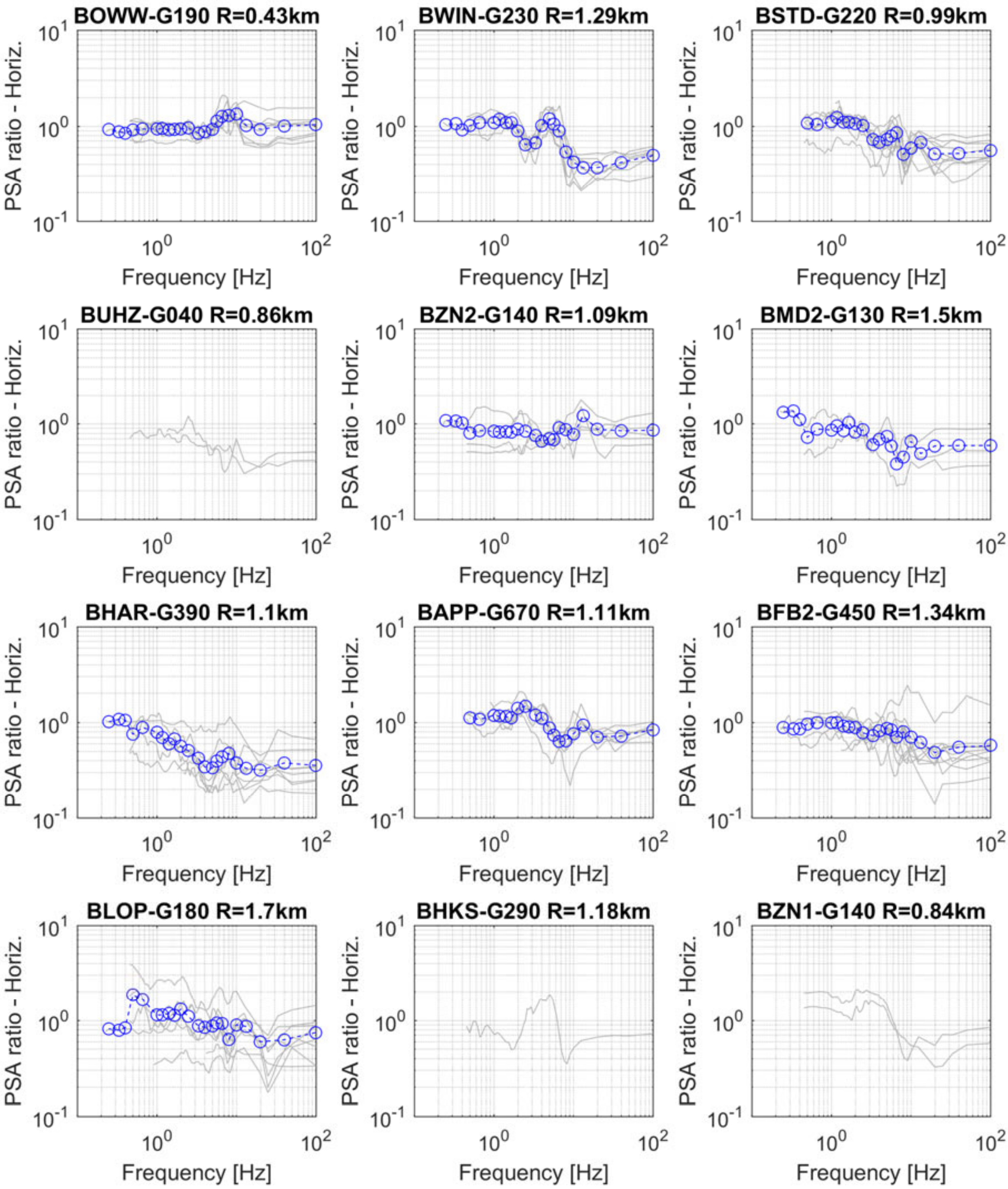

Figure 3-6 : Horizontal B-to-G spectral acceleration (PSA) ratio plotted for each pair of stations and for each recorded event (in gray). The geometric mean of horizontal components is considered. Mean ratios (only for pairs with at least 3 recordings) for the 23 spectral frequencies of the GMM V5 are shown in blue. The inter-station distance is shown in the graphs. Only PSA within the usable frequency band are plotted and considered for calculating the mean spectral ratios.

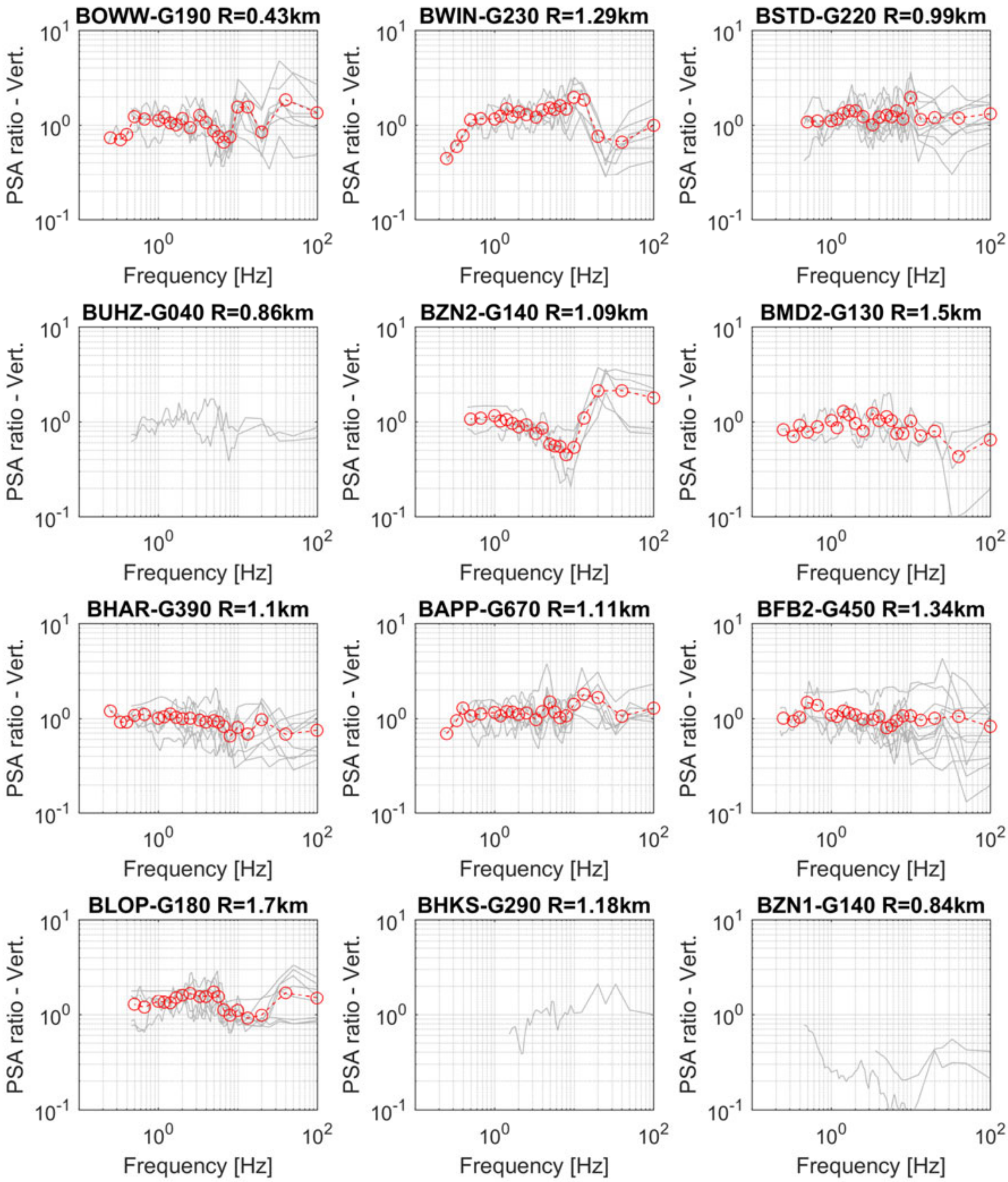

Figure 3-7 : Vertical B-to-G spectral acceleration (PSA) ratios plotted for each pair of stations and for each recorded event (in gray). The vertical component is considered. Mean ratios (only for pairs with at least 3 recordings) for the 23 spectral frequencies of the GMM V5 are shown in red. The inter-station distance is shown in the graphs.

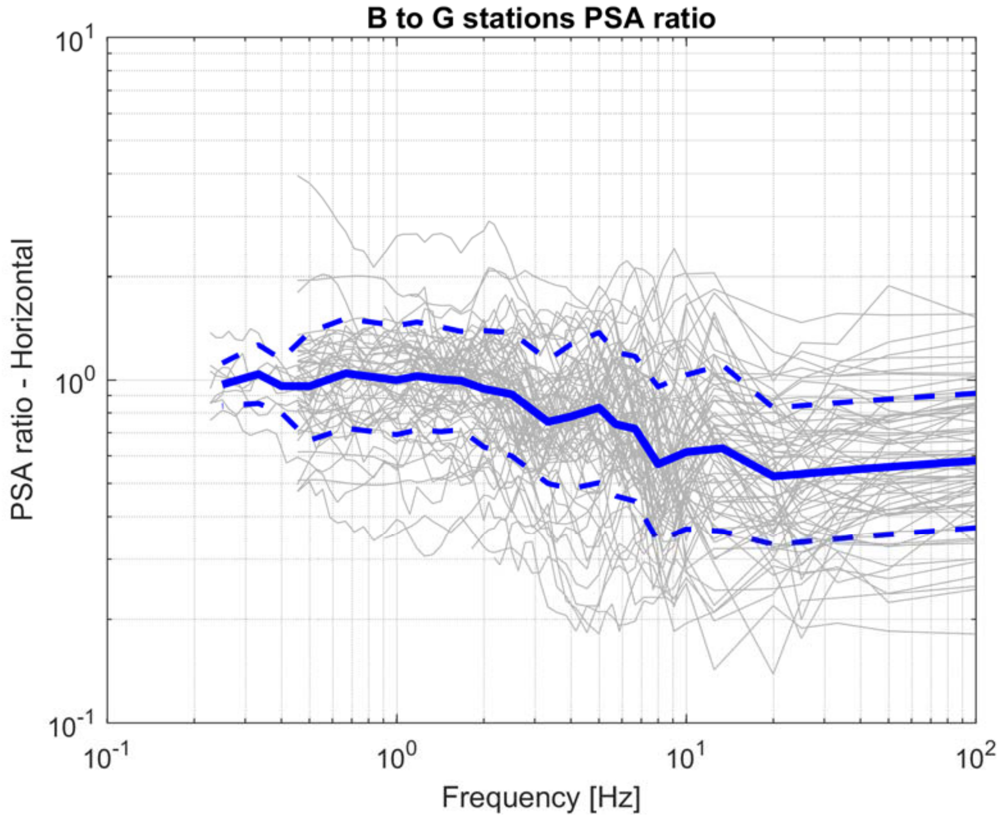

Figure 3-8 : Horizontal B-to-G spectral acceleration (PSA) ratios plotted for all considered pairs of stations and all events. The median ratio and its standard deviation are shown in blue.

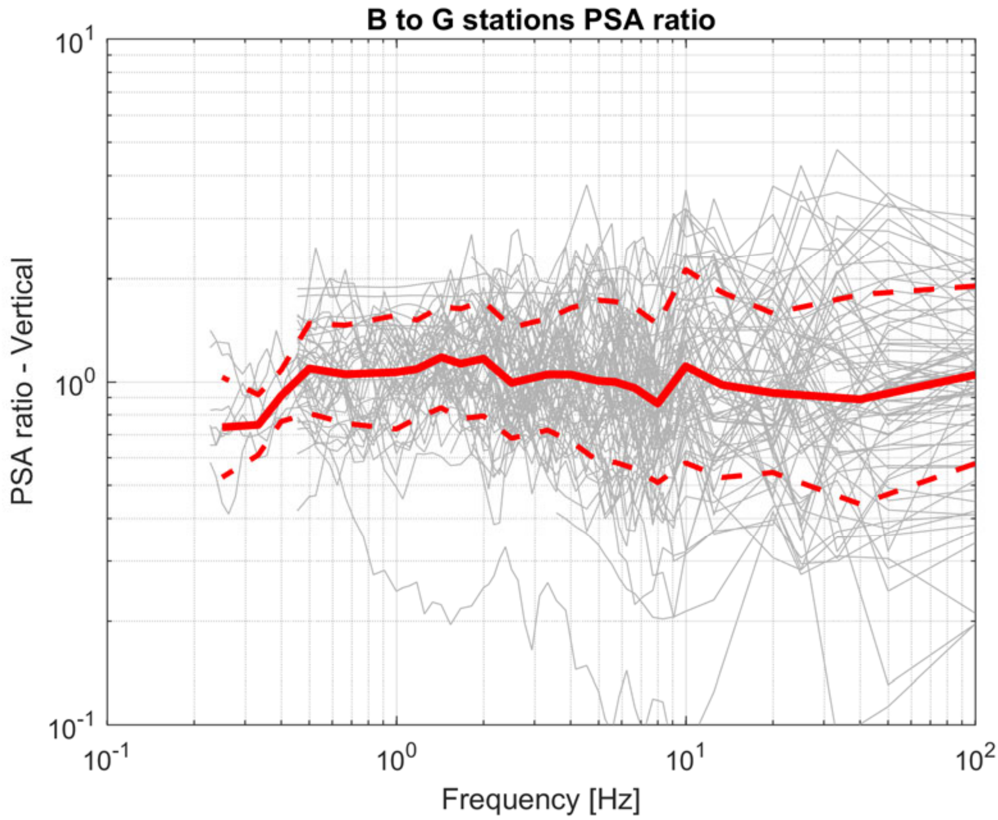

Figure 3-9 : Vertical B-to-G spectral acceleration (PSA) ratios plotted for all considered pairs of stations and all events. The median ratio and its standard deviation are shown in red.

4. Comparison of recordings among G stations

In order to better understand the origin of the unexpected amplitude differences between records at B and G stations at high frequencies, we performed the same comparison for pairs of G stations. In this case, the inter-station distance is larger and we can expect larger variations of the spectral ratios. However, if a sufficiently large number of pairs and records are considered we would expect, also in this case, to observe spectral ratios on average around 1. The selected pairs of G0 stations are shown in Figure 4-1 and their interstation distance and number of records are reported in Table 4-1.

As we can see, the pairs of G0 stations have much larger inter-station distance compared to the B-G pairs and the spectral ratios are not always meaningful when analyzed at single pairs (because large or small ratios may be just due to the local soil differences or to one station being much closer to the epicenter). For this reason only figures showing the spectral ratios for all events and all pairs together are shown in this report. Moreover, the purpose here is not to investigate specific G stations but simply to check whether we observe the same overall effect when considering all G stations pairs and all recorded events.

Figure 4-2 and Figure 4-3 show the G-to-G stations FAS ratios for all events and all pairs of stations for the horizontal and vertical components, respectively. The same is shown in Figure 4-4 and Figure 4-5 in terms of PSA.

Despite the larger inter-station distance between pairs of G stations, we do not observe any systematic effect and the median ratios are around 1 (slightly larger at high frequencies for the horizontal component probably related to local differences in the uppermost soil layers). We also note that, compared to the B-to-G ratios, the G-to-G ratios show larger dispersion around the median which is consistent with the larger inter-station distance of the pair of G stations.

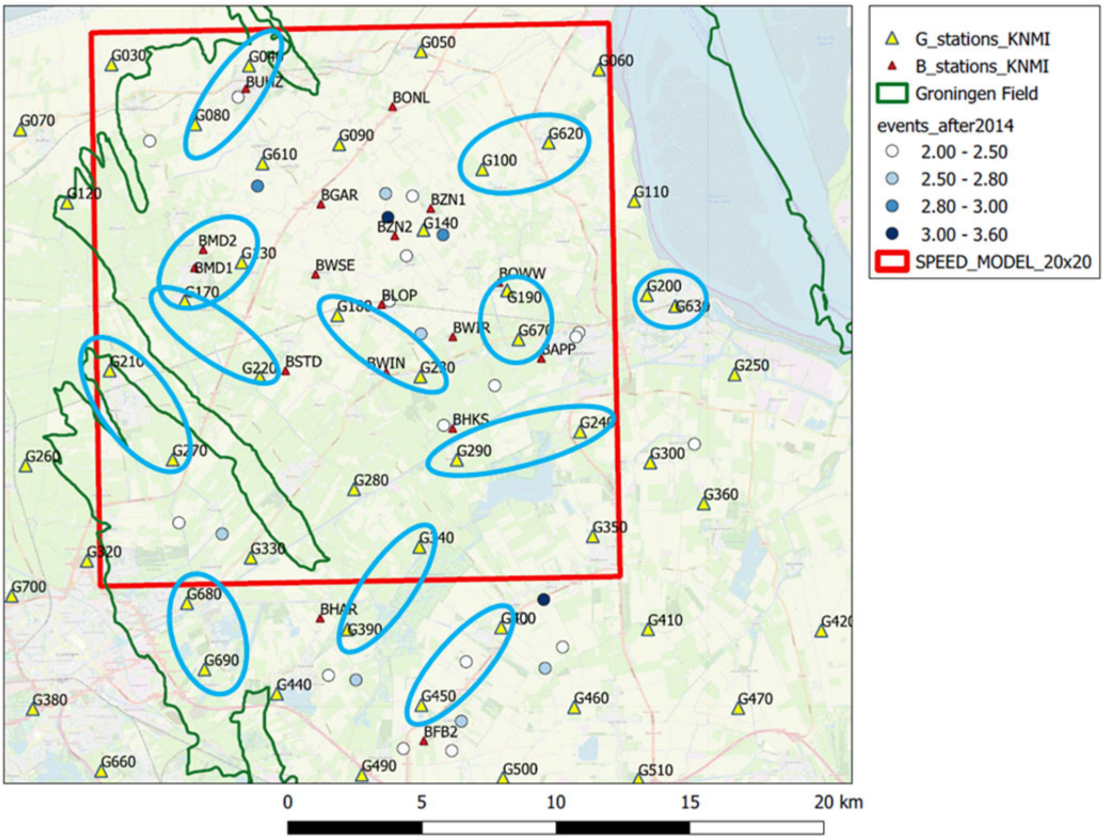

Figure 4-1 : Selected pairs of G0 stations in the Groningen field.

Table 4-1: G0 stations pairs considered in the analyses. Relative inter-station distance and number of available records are reported.

G-G pair	Inter-station distance (km)	N. of available records (FAS)	N. of available records (PSA)
G670-G190	1.87	10	7
G230-G180	3.85	10	9
G220-G170	3.97	11	6
G040-G080	2.96	5	2
G200-G630	1.13	9	7
G130-G170	2.57	9	4
G390-G340	4.08	10	9
G450-G490	3.42	11	8
G620-G110	3.84	6	2
G240-G290	4.70	4	4
G210-G270	4.06	8	3
G680-G690	2.55	3	1

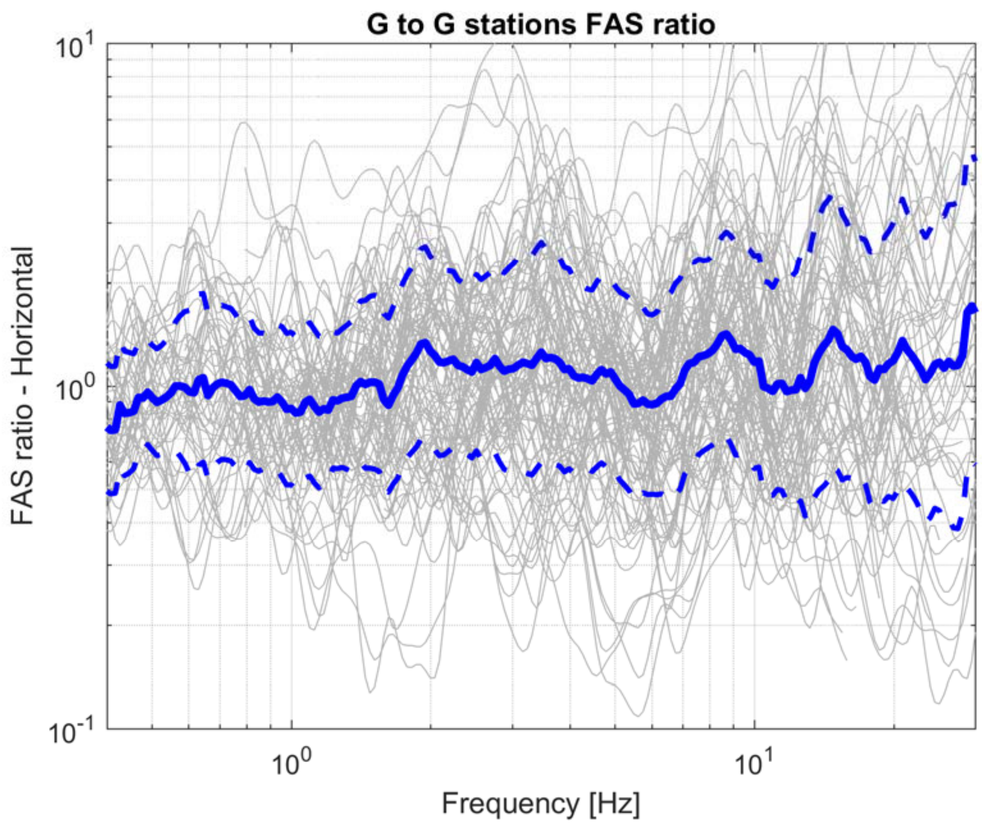

Figure 4-2 : Horizontal G-to-G Fourier Amplitude Spectra (FAS) ratio plotted for all considered pairs of stations and all events. The median ratio and its standard deviation are shown in blue.

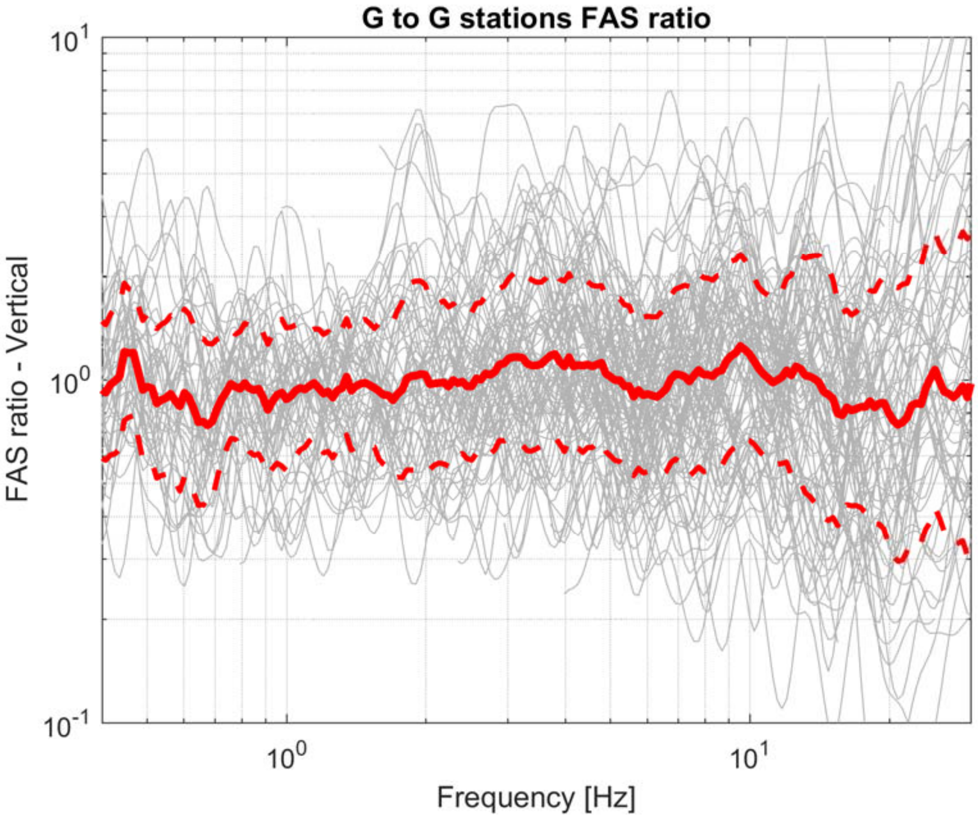

Figure 4-3 : Vertical G-to-G Fourier Amplitude Spectra (FAS) ratio plotted for all considered pairs of stations and all events. The median ratio and its standard deviation are shown in red.

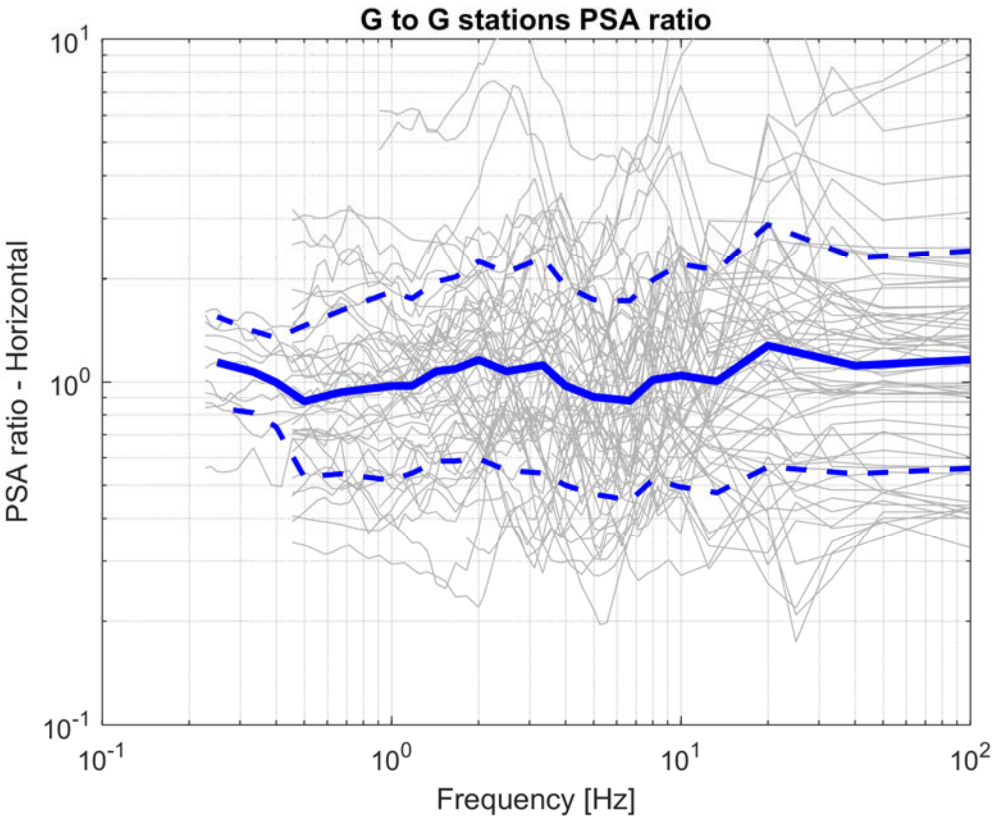

Figure 4-4 : Horizontal G-to-G spectral acceleration (PSA) ratios plotted for all considered pairs of stations and all events. The median ratio and its standard deviation are shown in blue.

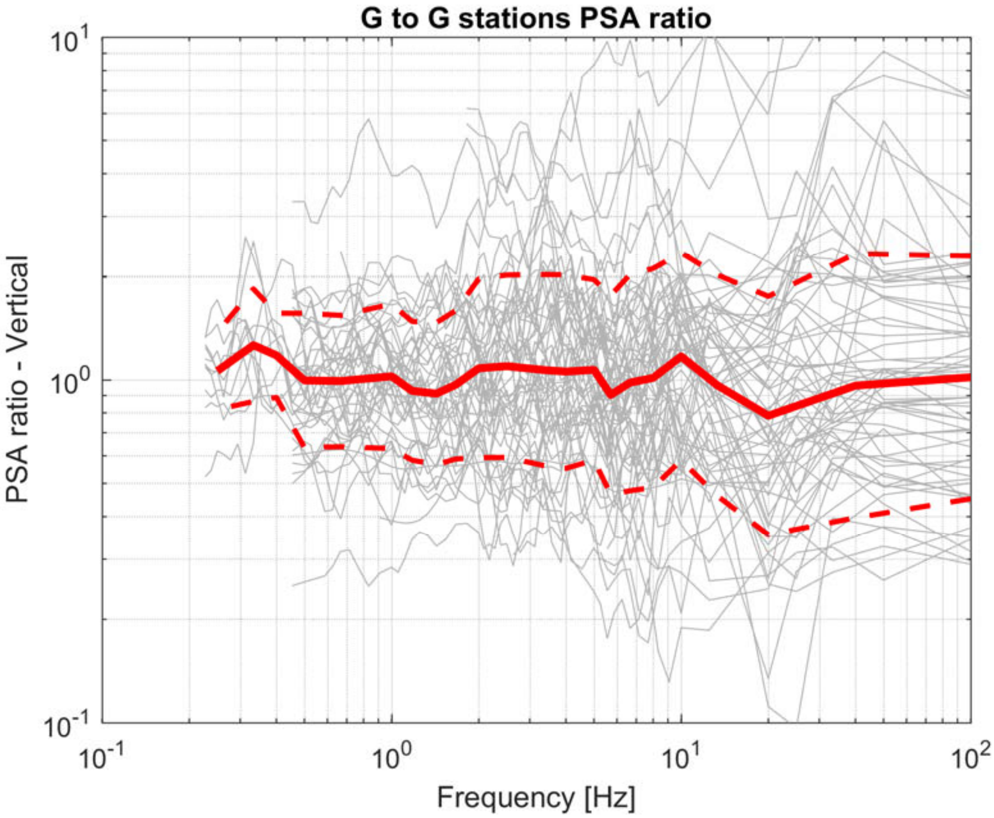

Figure 4-5 : Vertical G-to-G spectral acceleration (PSA) ratios plotted for all considered pairs of stations and all events. The median ratio and its standard deviation are shown in red.

5. Conclusions and implications for KEM04 project

Based on the results presented in this report in terms of B-to-G spectral ratios for relatively close station pairs supported by analyses of G-to-G spectral ratios (with larger interstation distance), we conclude that there are significant differences in the horizontal high-frequency ground motion recorded at most of the investigated B stations compared to that recorded at G stations. Because G stations are in most cases installed in free-field whereas B stations are installed within structures (e.g., buildings, garages), we suggest that this may be due to contamination by the structure or by artificial soil on which the sensor is installed. This is qualitatively supported by the photos of B-stations installations provided by KNMI in which the stations installed in light structures (e.g., BOWW) show on average consistent amplitudes with respect to adjacent G stations whereas stations installed within large/heavy structures (e.g., BUHZ, BMD2) depict the reduction in the high-frequencies accelerations compared to the free-field G stations.

Possible explanations that have been discussed within the KEM04 team are:

- Soil-foundation kinematic interaction that may have a filtering effect on the high-frequency ground motions, particularly on the horizontal component and in case of large structures that may require deep foundations.
- Velocity inversions caused by stiff artificial soils (e.g., concrete, pavement) on which the sensor is posed. As shown by (2009) using noise measurements, the velocity inversion caused by such artificial soil can have a direct effect on the noise spectra and, in particular, the horizontal spectra are lowered in the high-frequency range whereas the vertical spectra are unaffected. Figure 5-1 (taken from , 2009) shows an example of such effect for two simultaneous noise recordings taken respectively on natural

and artificial soil at a distance of 2 m with two instruments of identical response. The vertical component is mostly unaffected while the horizontal ones fall considerably above 5 Hz.

Further investigating the causes of the differences between B and G stations records is beyond the current scope of KEM04 project but we suggest that additional effort is needed in order to better understand and clarify the causes and the potential effects on the GMM V5.

In the KEM04 project, decision has been taken to not consider the B-station records in the continuation of the project, particularly for the calibration of the 3D numerical simulation model. B-station records will potentially be used in the comparison with the forward simulated ground motions for selected events in specific frequency bands (below 3 Hz) where a good consistency with G stations is found.

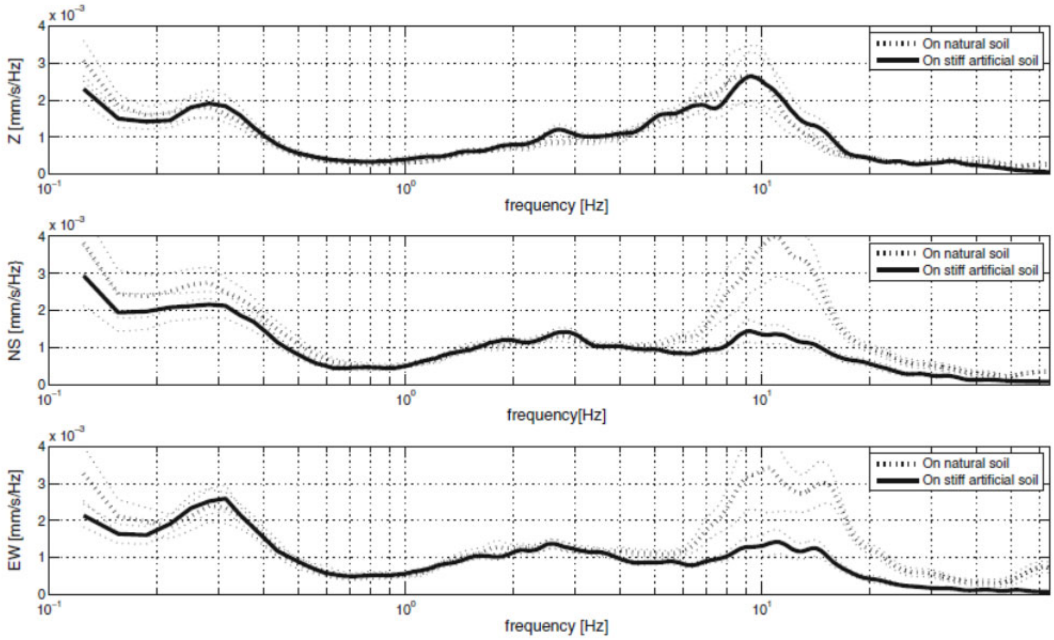

Figure 5-1 : Comparison between single spectral components recorded on natural soil vs. stiff artificial soil at the same time at two very close sites. The drop of the horizontal components is evident. (from Castellaro and Mulargia, 2009)

6. References

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7. Annex 1 : Review from KNMI scientists

A review of the draft report was performed by KNMI scientists and received from H. de Waal (SodM) on the 26th of April 2019. The comments and questions from KNMI as well as our replies are attached in the next pages.

Draft report: Analysis of consistency between B- and G-stations records for induced events in the Groningen gas field (STR_FUG_18P17_01)

This report investigates the consistency of data from B- and G-network data by looking at ratios of acceleration Fourier Amplitude spectra (FAS) and Pseudo Spectral Acceleration (PSA) at 5% damping.

The results show that for higher frequencies the FAS and PSA values for several B-stations are significantly smaller than recordings of adjacent G-stations. This could be due to the influence of the buildings in which the B-stations are located.

We thank the KNMI scientists for taking the time to provide comments on this study. Our replies are provided in red in the following.

General comments:

1] One of the assumptions in the study is a “relatively homogeneous local site condition” between two stations. We know that variation in P velocity is small over the network, but variation in shallow shear velocity is much higher. This is implemented in GMM development in a zonation for Groningen. Did the authors check for each station pair if the stations belong to the same zonation? The effect of the different zonation is taken into account in an amplification function, so amplitudes could be corrected for this effect.

Figure 1 below reports the zonation used in the GMM V5 and the considered B-G stations pairs. As can be seen, most of the pairs (8 out of 12) belong to the same zone whereas others belong to different zones. There is however no apparent correlation between the B-to-G spectral ratios and the fact that two stations of a pair are located or not in the same zone. For example the two pairs BOWW-G190 and BAPP-G670 are all located in zone 2111 but their mean B-to-G ratios are different (one exhibiting the high-frequency difference and the other being on average 1, See Figure 3-2 of the report). As another example, BUHZ-G040 are located in the same zone and show the difference in the high-frequency amplitudes, whereas BZN2-G140 that are located in different zones provide average ratios around 1.

As a further example, Figure 2 reports the amplification functions from the GMM V5 for zone 1032 and 1202 corresponding to the zones where BLOP and G180 are located, respectively. As can be seen the difference between the two amplification functions is minor (less than 10 % at high-frequencies).

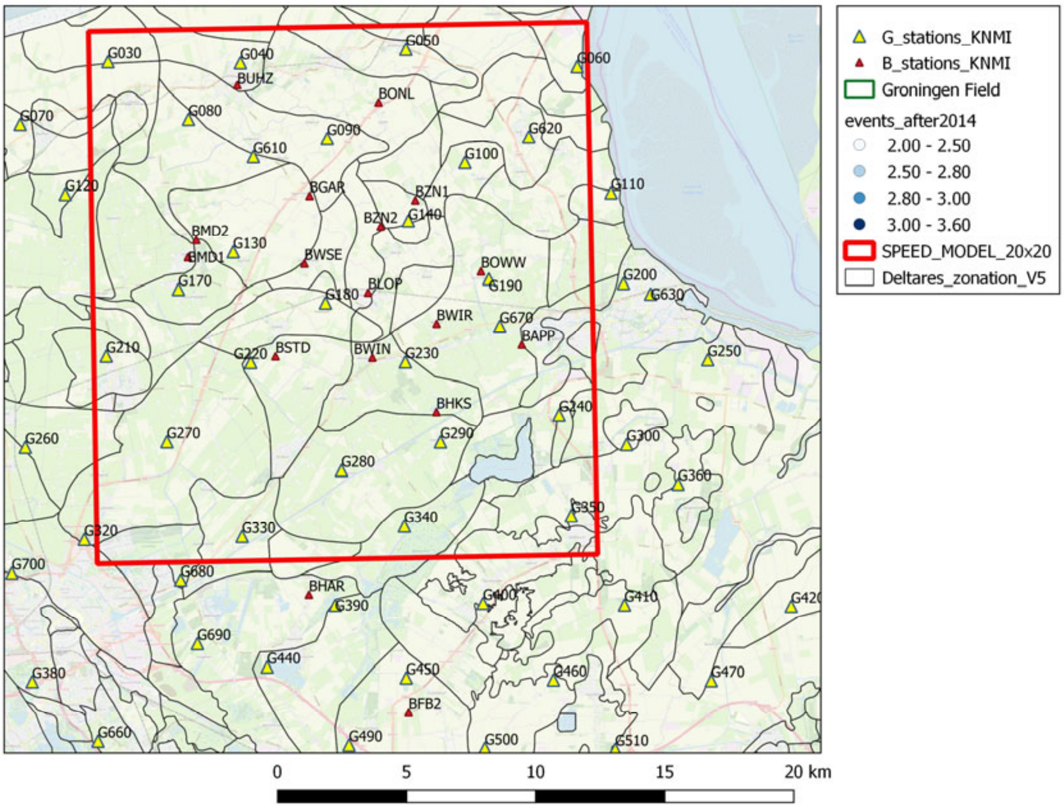

Figure 1: map of B and G stations in the Groningen field showing the GMM V5 zonation.

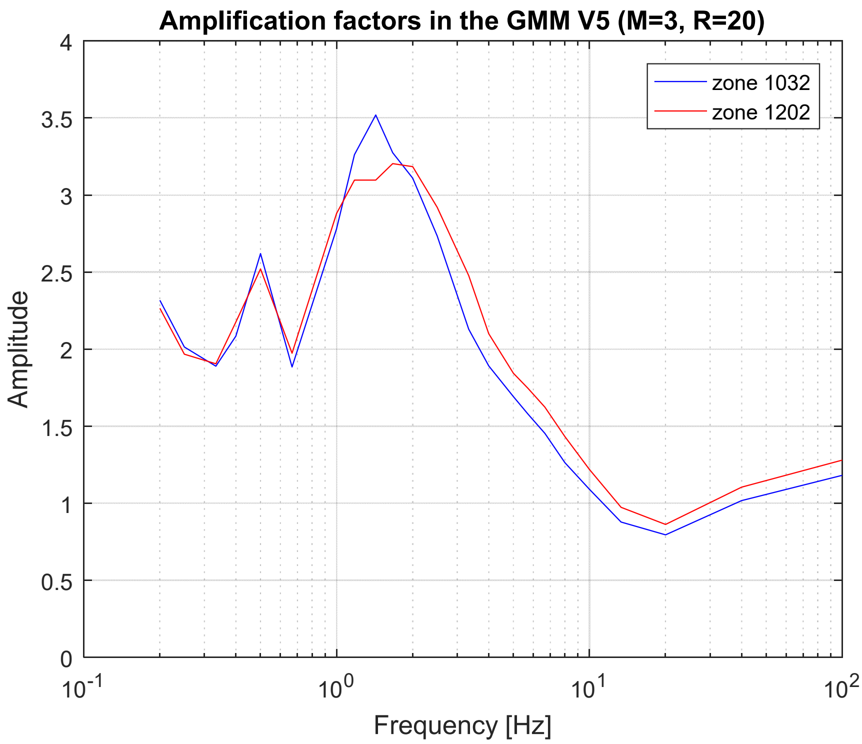

Figure 2: Amplification functions from the GMM V5 for zones where stations BLOP (1032) and G180 (1202) are located.

2] The results in Figures 3.4, 3.5, 4.2 and 4.3 show a large variability in spectral ratios as a function of frequency. There is unfortunately no discussion in the document on the significance of the results in view of the large variability in the ratio's.

These figures lump together the ratios from all the considered station pairs and, as a consequence, it is expected to see larger variability with respect to the variability of ratios for single pairs (e.g., figure 3-2). In order to show the significance of the median ratios we added in each figure the standard deviation of the distribution. We note that the standard deviation around the median for PSA ratios is of the same order of the aleatory variability of the GMM V5 and of recent GMPEs in general. For example, the σ_{ln} of the B-to-G ratios is about 0.45 for PGA which is smaller than the value of about 0.6 given by the GMM V5 (and by e.g., NGA-west 2 GMPEs). The standard deviation is slightly larger for G-to-G stations ratios (σ_{ln} =0.7) but again consistent with the GMM V5.

3] Buildings could somewhat influence the amplitudes at high frequencies, both on the horizontal and vertical components. In the report it is shown that there are no systematic differences between B and G accelerometer amplitudes on the vertical component FAS and PSA. This makes it likely that especially site conditions play a role. Obviously, people have chosen the best sites to build their villages. Moreover, sites have been improved before building, by e.g., replacement of clay by sand. Hence, on average, B-stations are likely on better sites, with less (high-frequency) amplification than in the 'free field' G-network. These shallow site conditions largely affect S-waves on the horizontal component, but do not much affect P-waves which have up till 5 times longer wavelengths in the shallow subsurface (for the same frequency) and are less affected by the reduction in shear modulus.

Our report pointed out differences between the high-frequency ground motions recorded at several adjacent B and G stations. There is no doubt that there are variations between the natural soil properties (particularly Vs) at G and B stations. The question is whether such natural variations can explain the relatively large differences observed in the amplitudes. We believe that relatively small differences in the shallow-most soil layers, as are expected between B and G stations locations, cannot explain such ground-motion differences (as also shown for example by the similar amplification functions in Figure 2 above). Of course, if much larger differences in Vs are found locally due to artificially-improved ground conditions at B stations before the building construction (as the KNMI scientists seem to suggest) this could explain the difference in the high-frequency ground motion.

Furthermore, we would like to stress that resonance effects of the building are generally well recognizable by a fundamental frequency (of the structure) that is in most cases amplified. However, it does not seem to be the case at B stations. We offer two possible alternative explanations in the report: 1. Soil-foundations kinematic interactions and 2. Decrease of the amplitude of the horizontal components due to velocity inversion caused by artificial soil on which the sensor is located. Finally assessing the origin(s) of differences in the high-frequency amplitudes of the recordings at B and G stations is beyond our scope.

Details:

P4: "KNMI communicated that an error was found in the parameterization of the G0 sensors that caused recordings of such sensors being about a factor of 2 smaller than what they should be. The G0 data have now been corrected by KNMI and they are available from their portal." → "KNMI communicated that an error was found in the parameterization of the G0 sensors that caused recordings of such sensors being a factor of 2 smaller than what they should be. The G0 data were corrected by KNMI *on December 17, 2018* and they are available from their portal."

Agreed.

P5: Td_{rup} = 2s (based on theoretical considerations, see Kishida et al., 2014): if Td_{rup} was indeed based on theoretical considerations it should be a value between a few milliseconds and about 100 ms for the considered earthquakes.

We agree. Kishida et al. (2014) suggested increasing the theoretical source duration to some extent based on empirical data. Based on Greek data with magnitude above 3.5 they proposed a source duration of 10s which appears large for the Groningen events (mostly M =2-3). Based on preliminary tests and visual inspection of identified windows we set Td_{rup}=2s. A different Td_{rup} can be envisaged but the impact on the final results will be negligible and it will not change the conclusions of the report.

P6: what is the black vertical line in Figure 2.2 and 2.3 (last panels), please explain

The black line represents the frequency corresponding to the largest SNR.

P6: line 2: in order assess -> in order *to* assess

Corrected.

P7: Figure 2-4: the last S-wave onset pick largely affects the fitted Ts line. This pick does not make sense. It would imply that S-waves propagate relatively fast up till 30 km and afterwards slow down considerably.

The last S-wave onset pick correspond to station N030 for which windows identification seems appropriate (see figure 3), although we recognized that the S-wave onset is probably slightly later in time. As long as the main S-wave energy is included in the window, small differences in the arrival times will have a negligible impact on the selected cut-off frequencies of the filter.

We agree that the fitted polynomial Ts model is probably not appropriate for distances larger than 30-35 km and should not be extrapolated. However, it provides adequate fit to the data, especially below 30 km.

P17: "spectral rations"-> spectral ratio's

Corrected

P18-20 Figure headers "B to G stat…"-> "G to G stat.."

Corrected

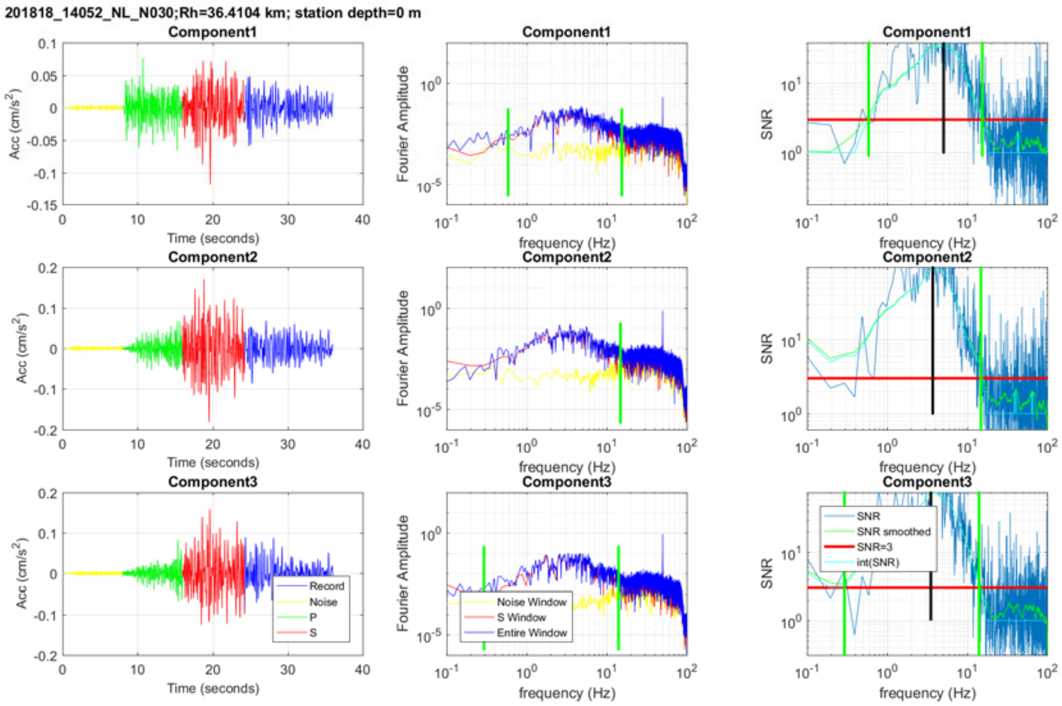

Figure 3 - Event 20180108_140052, station N030. Example of identification of P-waves, S-waves and noise windows, calculation of signal to noise (SNR) ratios and identification of high-cut and low-cut frequencies of the filter. The black line (right graphs) represents the frequency corresponding to the largest SNR.

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MEMORANDUM

To:

From:

CC:

Date: 30-04-2019

Ref.: 1018-0338-000

Re: KEM04: Data driven study on seismic structural features of Groningen ground motions”

In a review of the report (SEISTER, 19-04-2019) from KNMI (KNMI, 2019) it is suggested that differences in local site conditions could potentially explain differences in measured response between the B- and G-stations from the KNMI network. In this document a comparison of site conditions of closely spaced B- and G-stations as mentioned in (SEISTER, 19-04-2019) based on available information is presented. In Figure 1 the pairs of stations are shown. For each pair of station the measured CPT value (cone resistance and friction ratio) are shown and the distance of the CPT to the B- or G-station is shown.

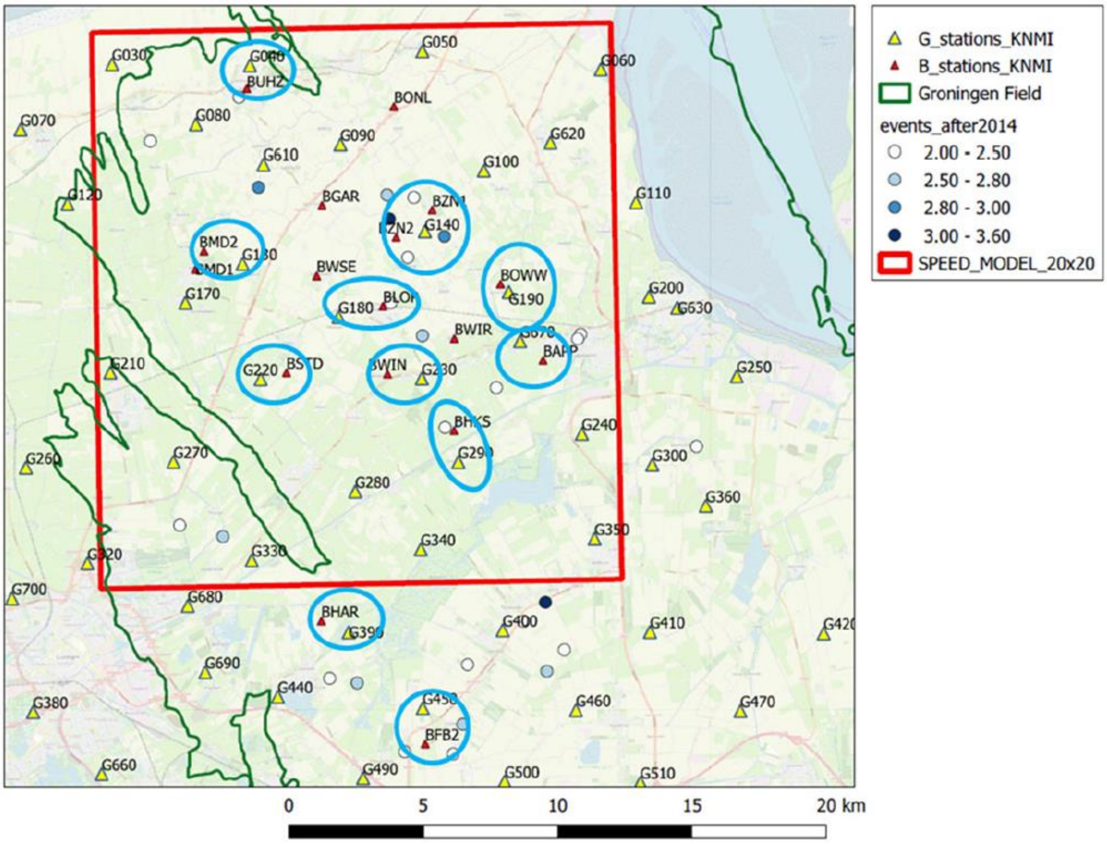


Figure 3-1 : Selected pairs of B and G0 stations in the Groningen field.

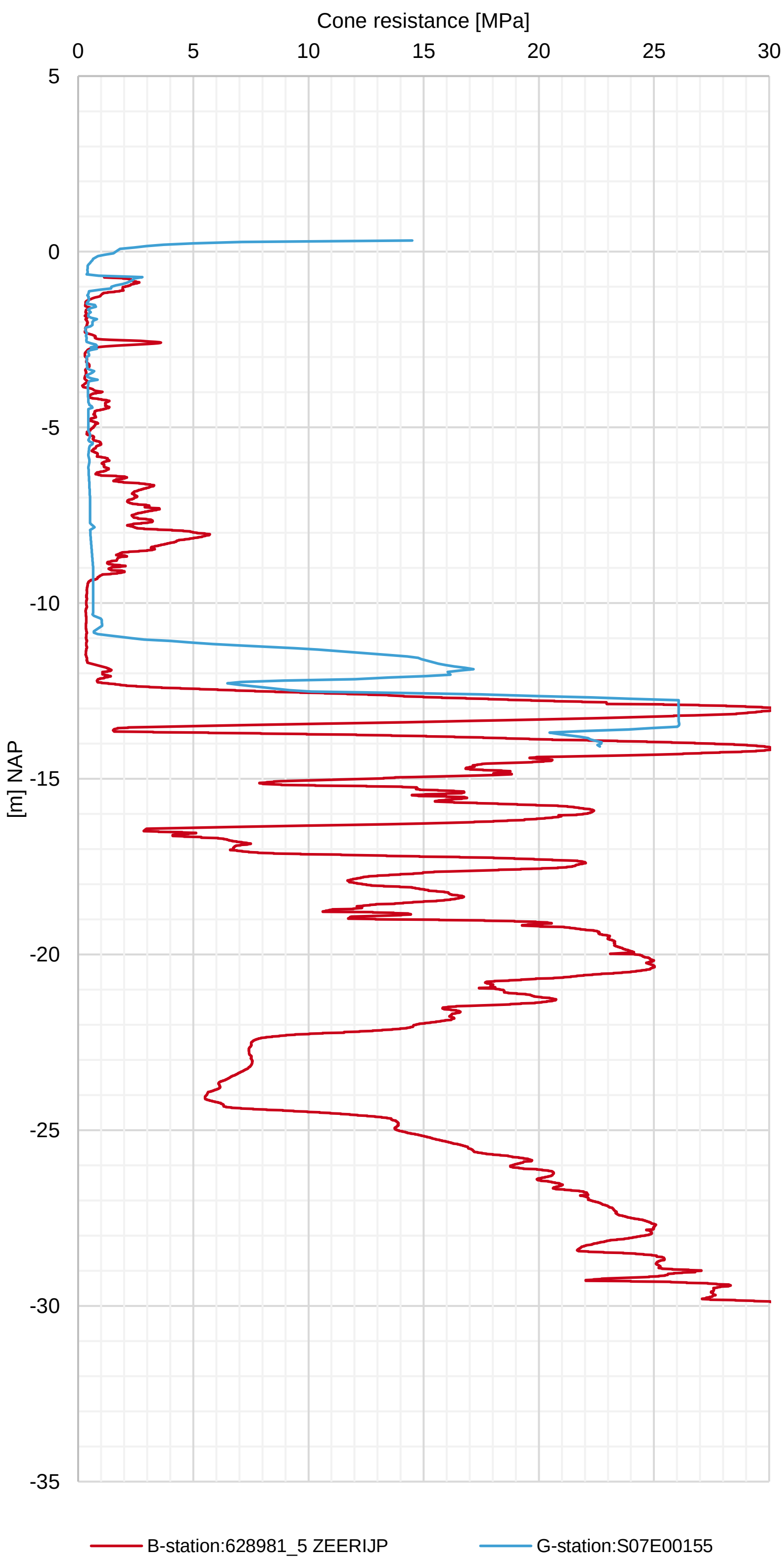
Figure 1; Figure 3-1 adapted from (SEISTER, 19-04-2019)

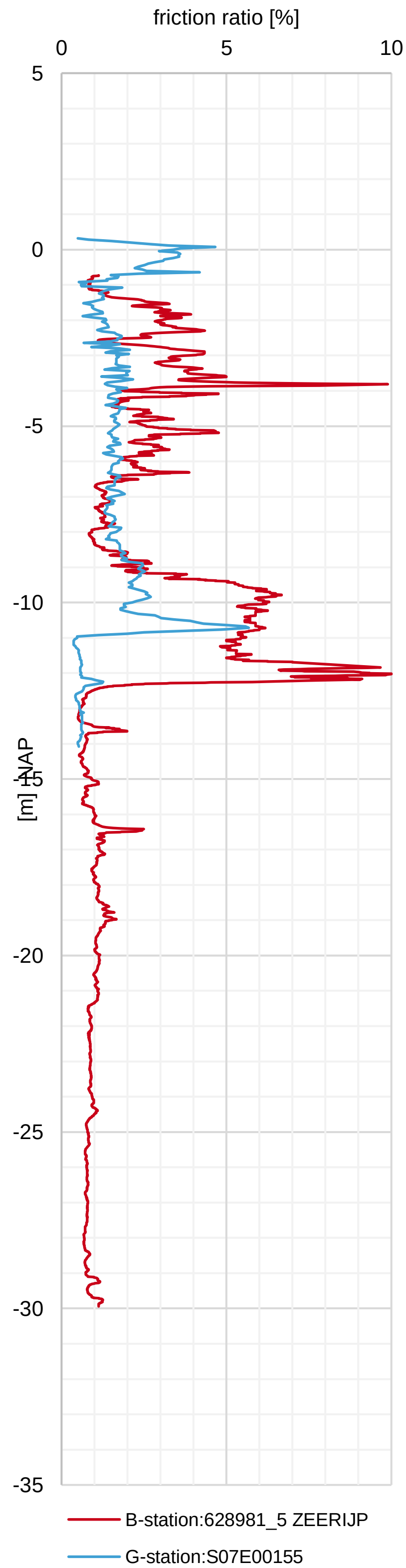
KNMI. 2019. *Comments_seister_Draft report_2019.* sl : KNMI, 2019.
SEISTER. 19-04-2019. *Analysis of consistency between B- and G-stations records for induced events in the Groningen gas field. Draft Report, Document no: STR_FUG_18P17_01.* 19-04-2019.

1018-0338-000

Comparison closest available CPT at B- and G-stations

B-station	BZN2	Distance to CPT	97.2 [m]	Geological zonation	1003
G-station	G14	Distance to CPT	21.6 [m]	Geological zonation	1004





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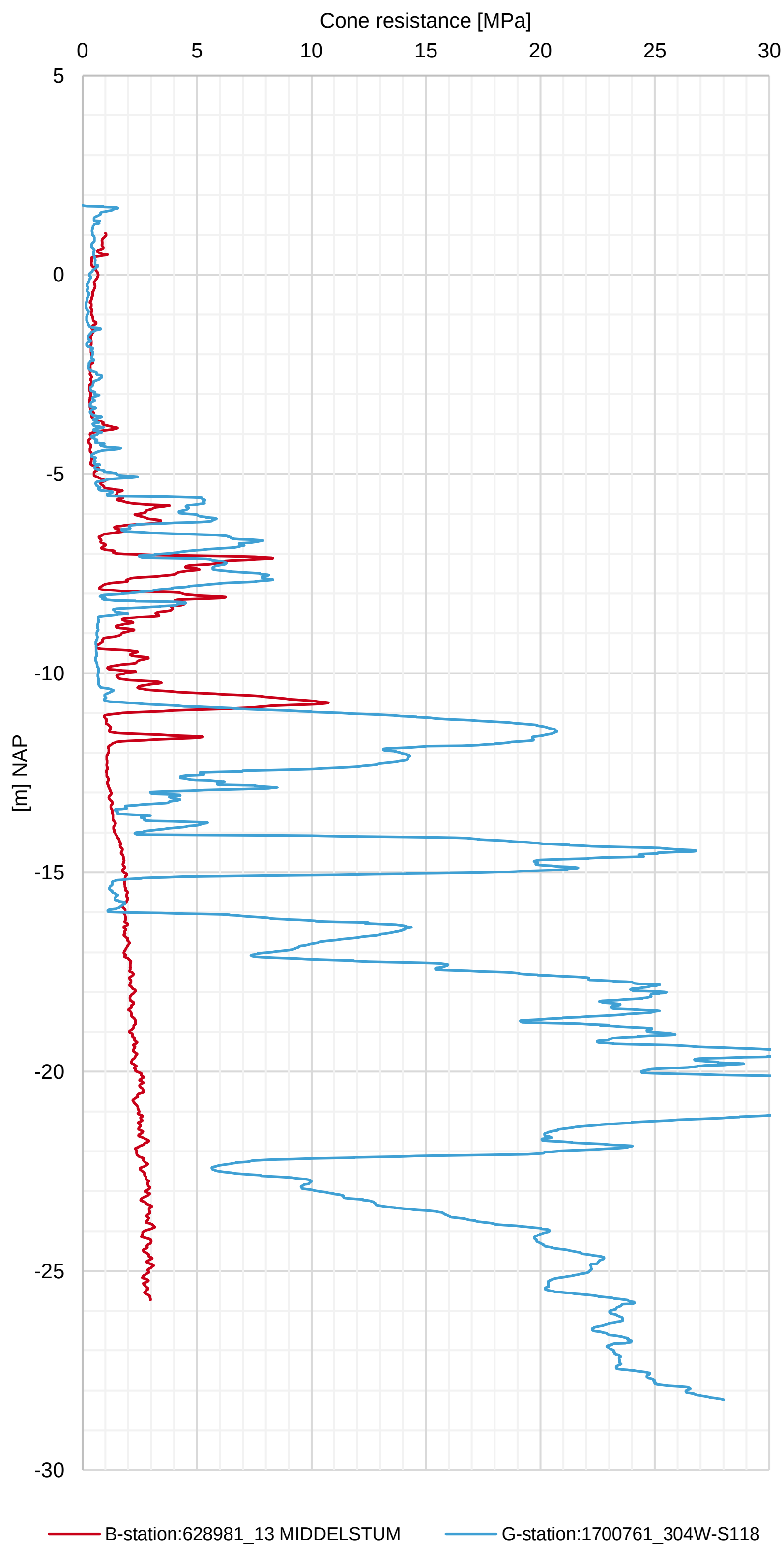
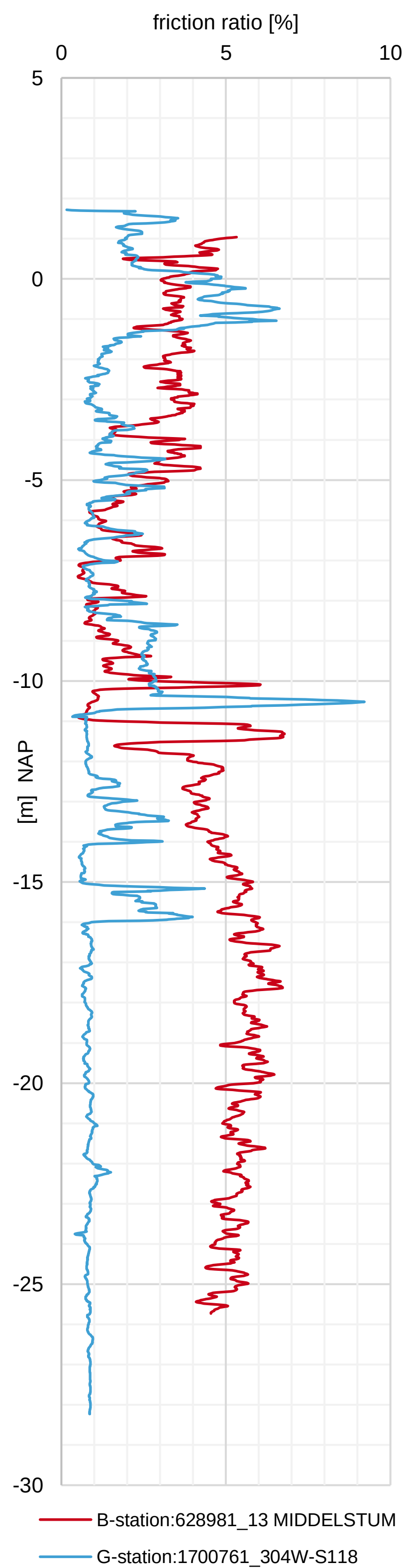
Comparison closest available CPT at B- and G-stations

B-station	BMD2	Distance to CPT	69.0	[m]	Geological zonation	1001
G-station	G13	Distance to CPT	526.9	[m]	Geological zonation	1001





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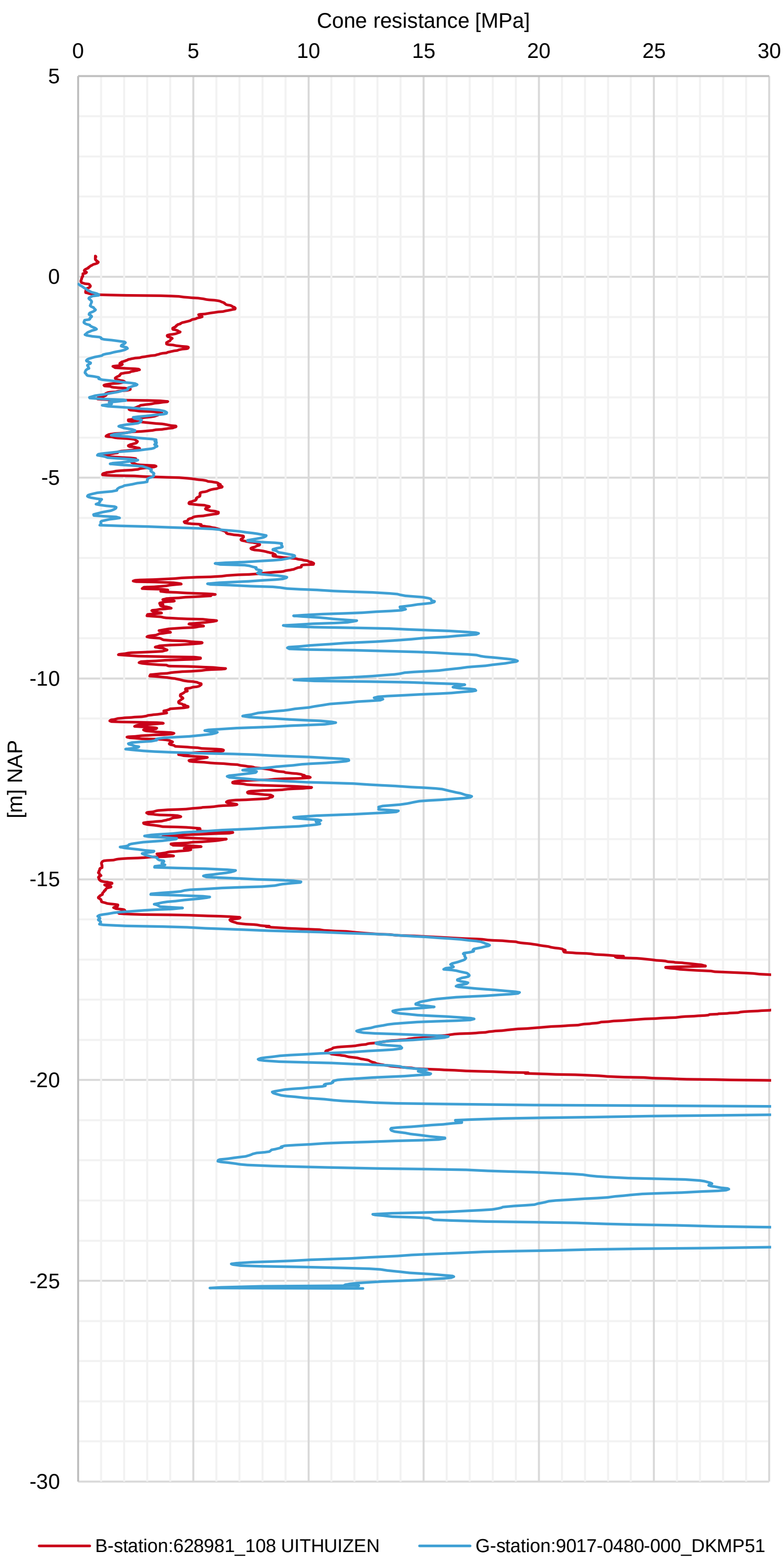
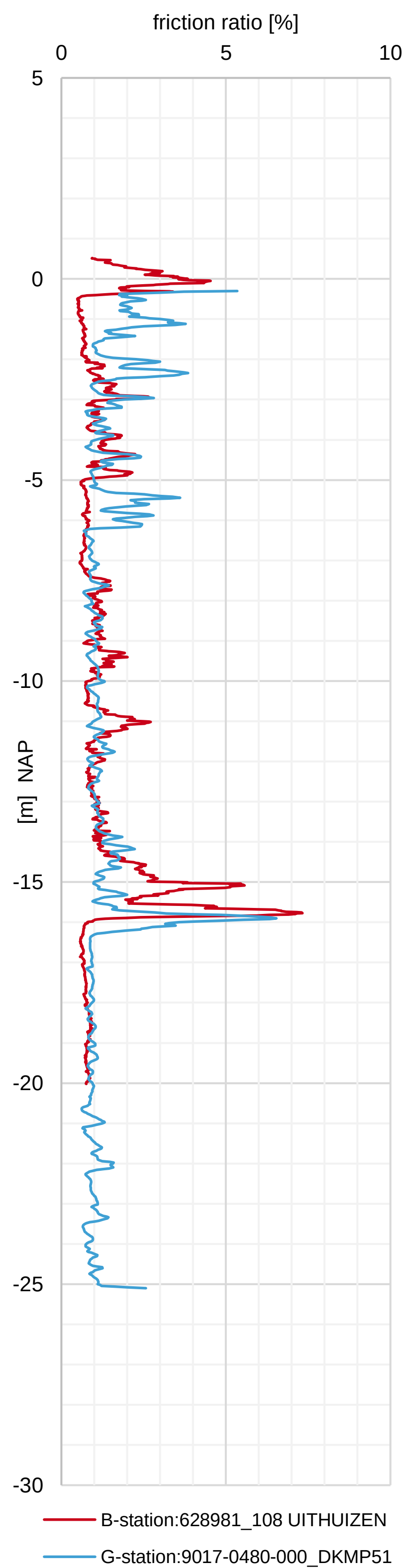
Comparison closest available CPT at B- and G-stations

B-station	BUHZ	Distance to CPT	61.3 [m]	Geological zonation	801
G-station	G04	Distance to CPT	106.5 [m]	Geological zonation	801





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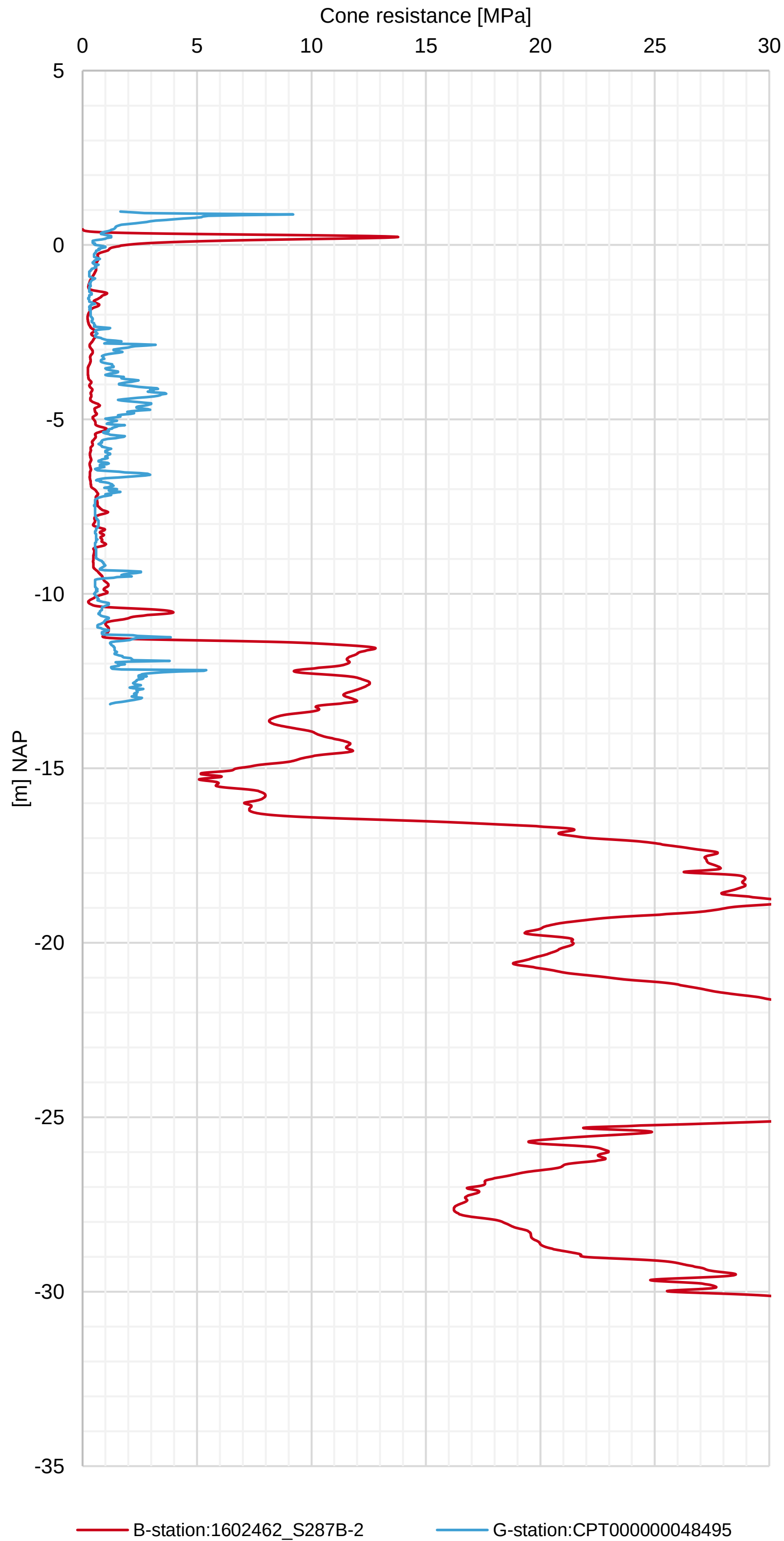
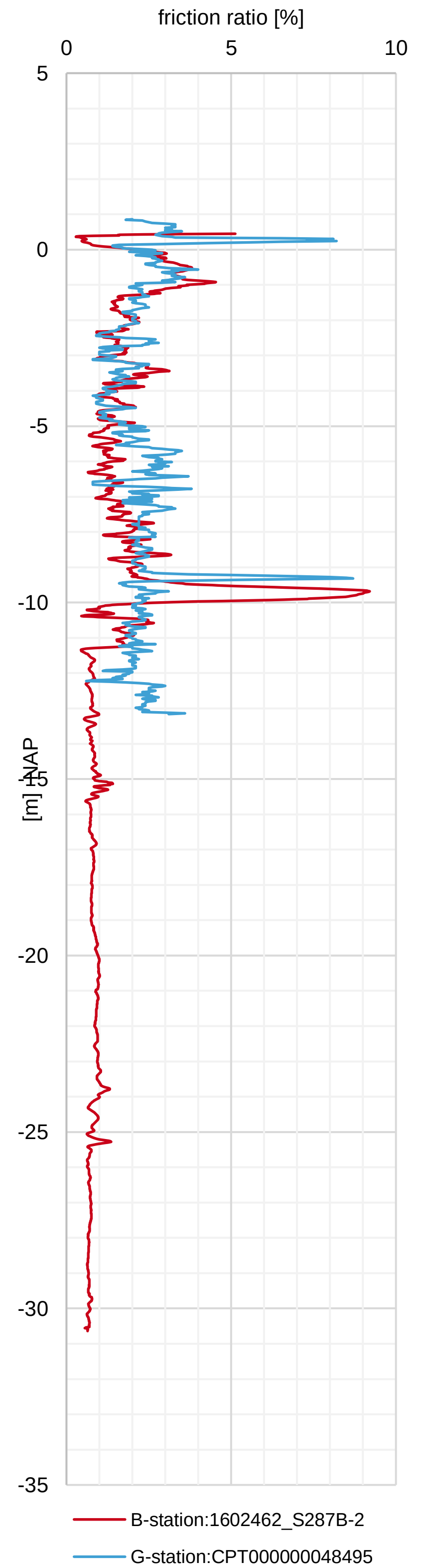
Comparison closest available CPT at B- and G-stations

B-station	BLOP	Distance to CPT	17.9 [m]	Geological zonation	1104
G-station	G18	Distance to CPT	7.6 [m]	Geological zonation	1202





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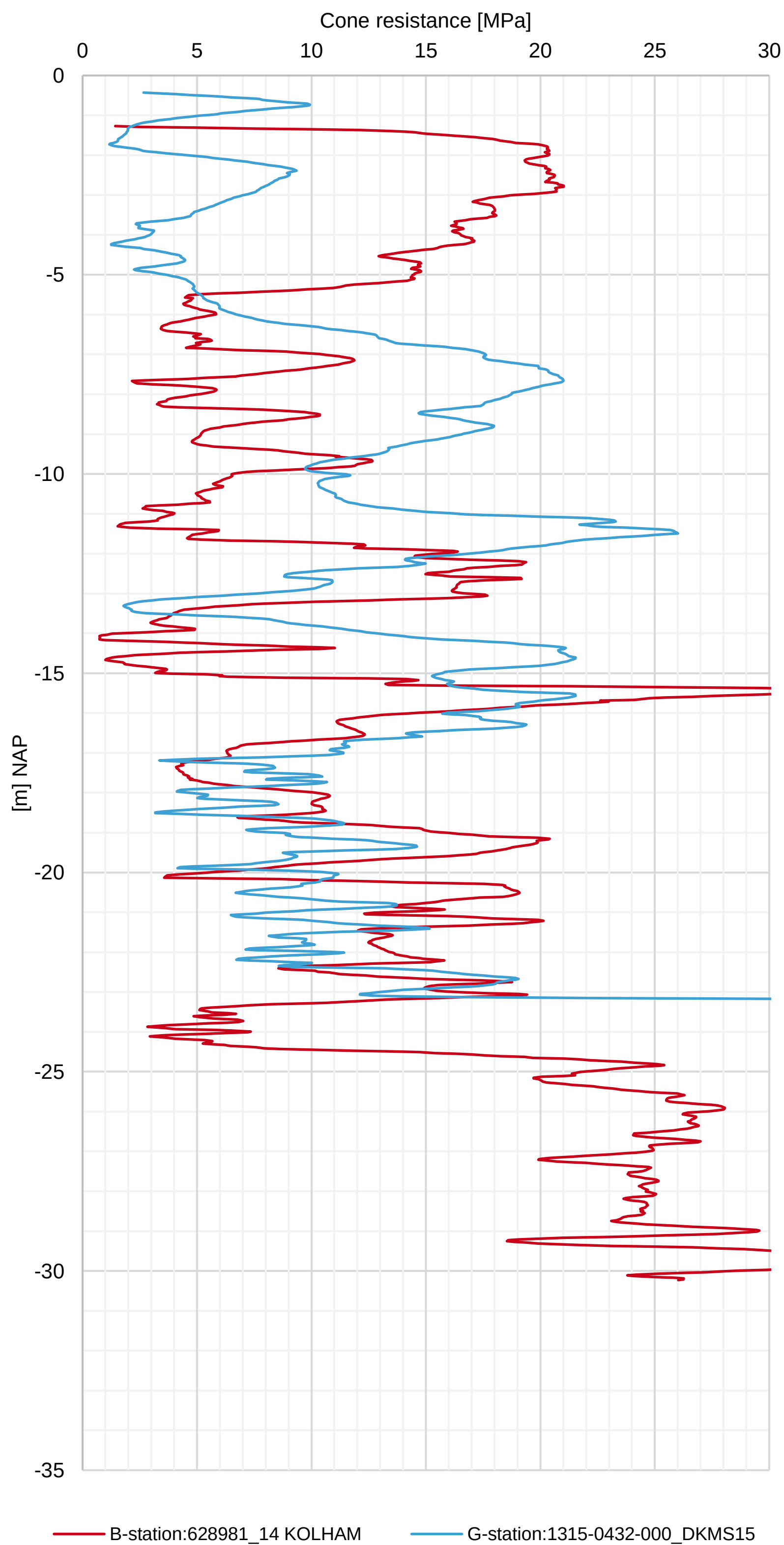
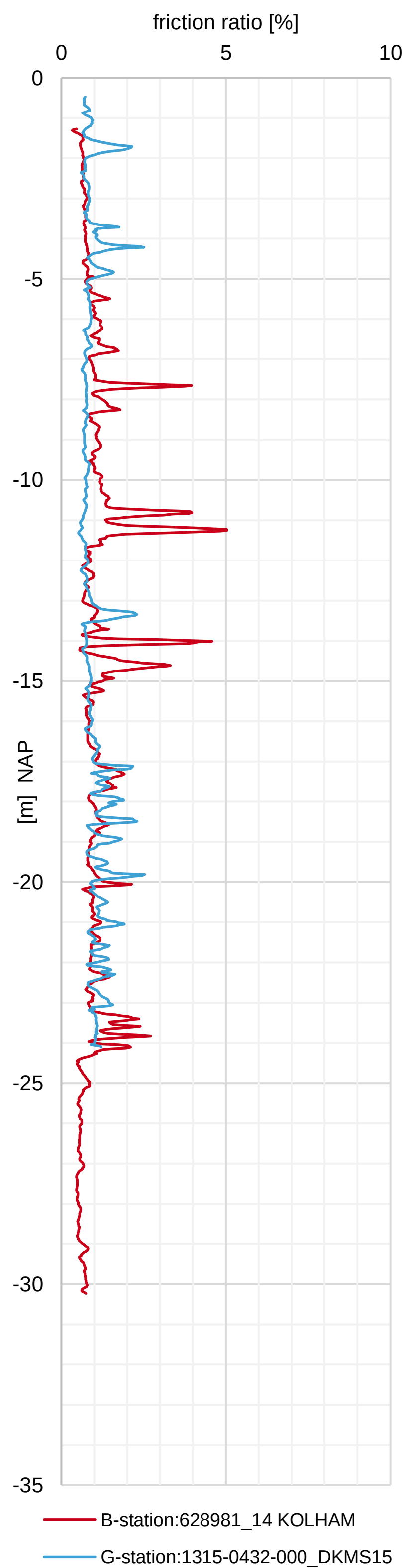
Comparison closest available CPT at B- and G-stations

B-station	BFB2	Distance to CPT	86.8	[m]	Geological zonation	403
G-station	G45	Distance to CPT	1281.2	[m]	Geological zonation	403





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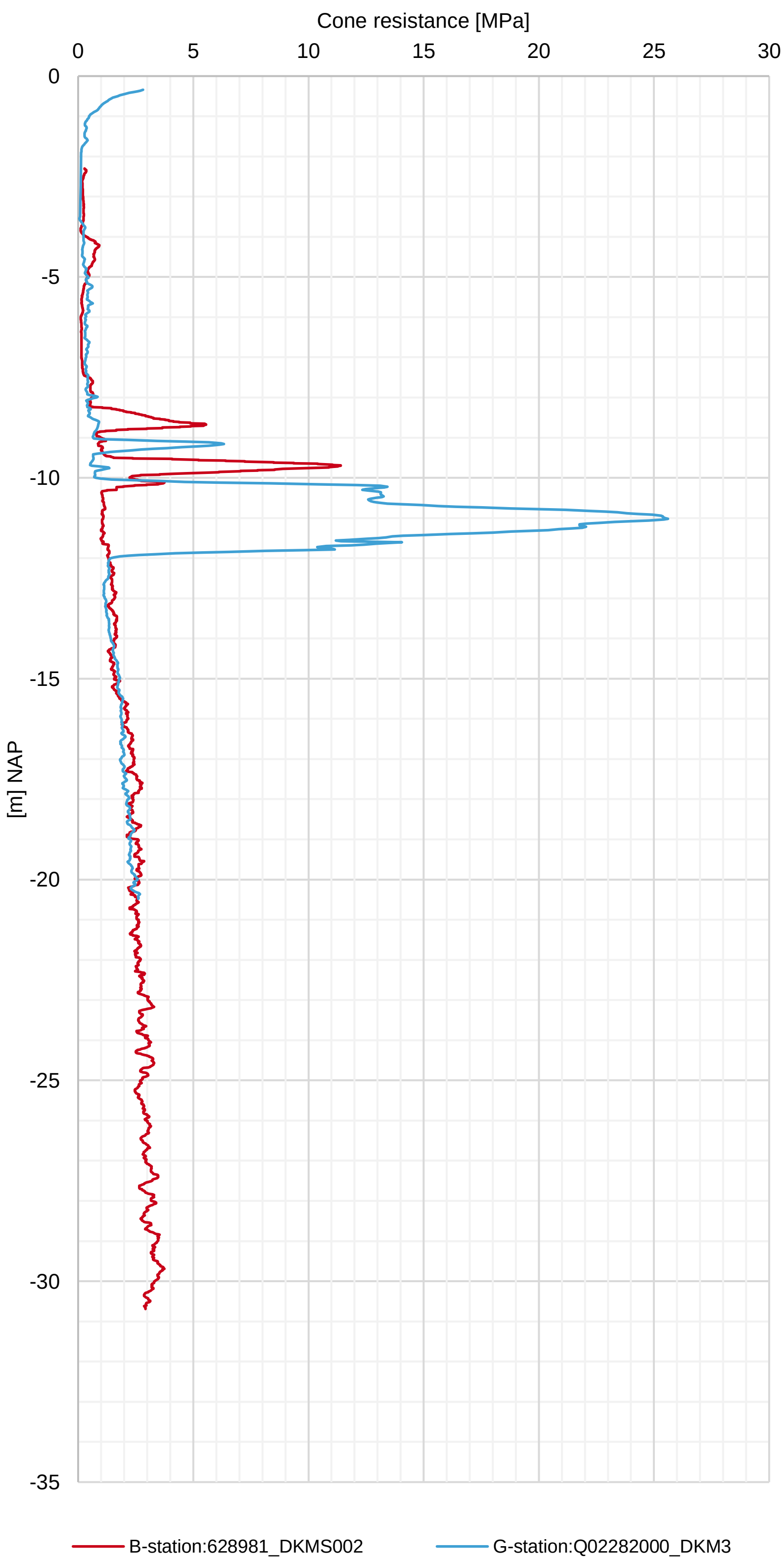
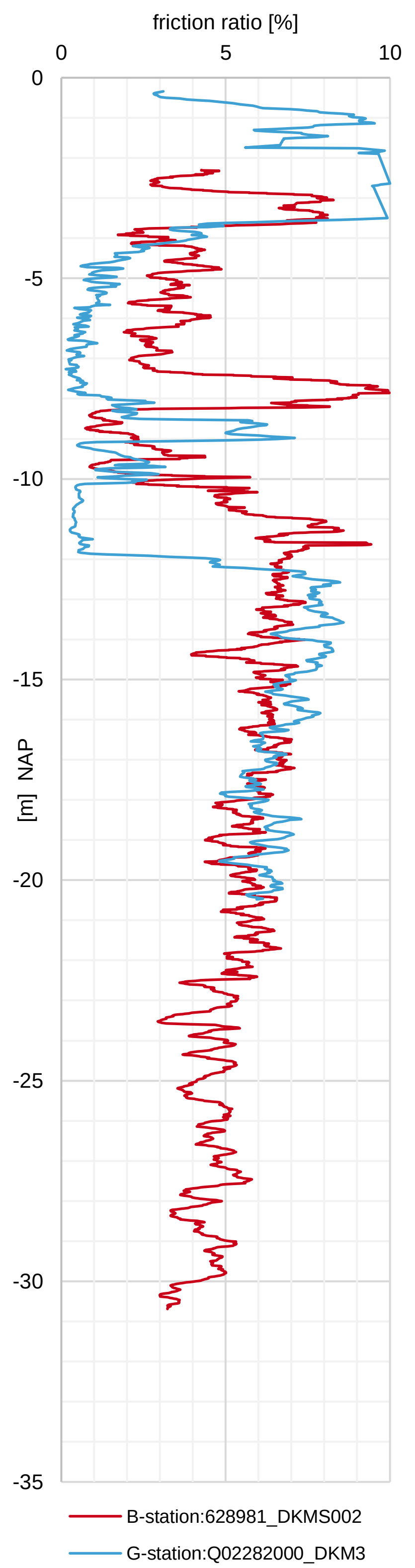
Comparison closest available CPT at B- and G-stations

B-station	BAPP	Distance to CPT	142.6	[m]	Geological zonation	2104
G-station	G67	Distance to CPT	505.2	[m]	Geological zonation	2104





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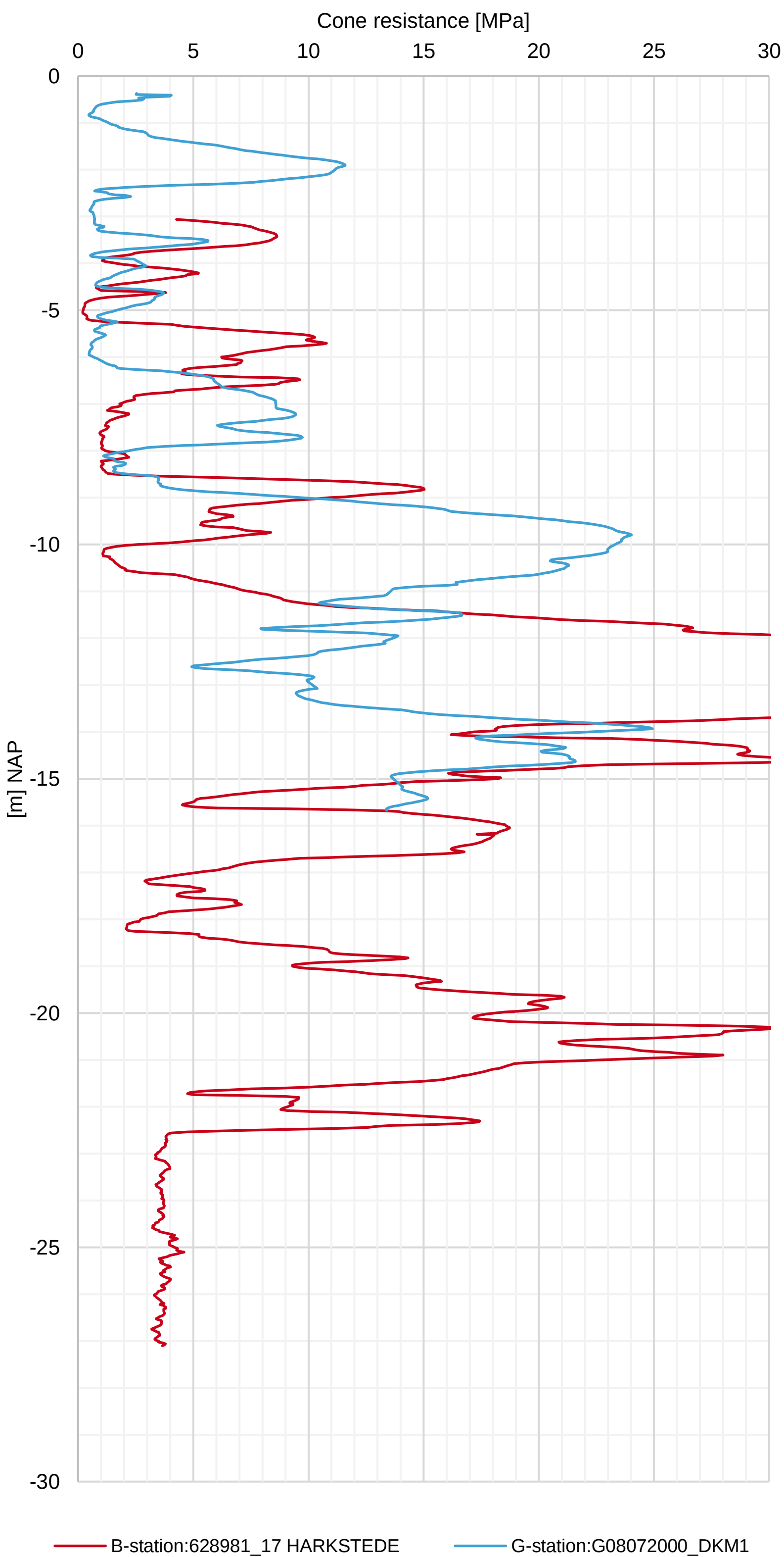
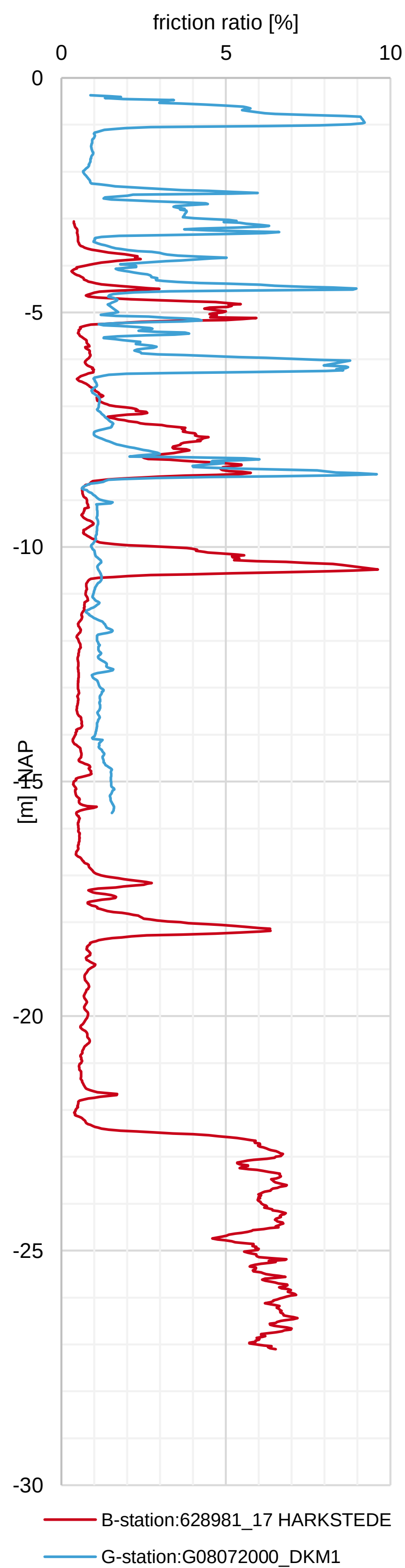
Comparison closest available CPT at B- and G-stations

B-station	BHAR	Distance to CPT	42.3 [m]	Geological zonation	401
G-station	G39	Distance to CPT	918.5 [m]	Geological zonation	3001





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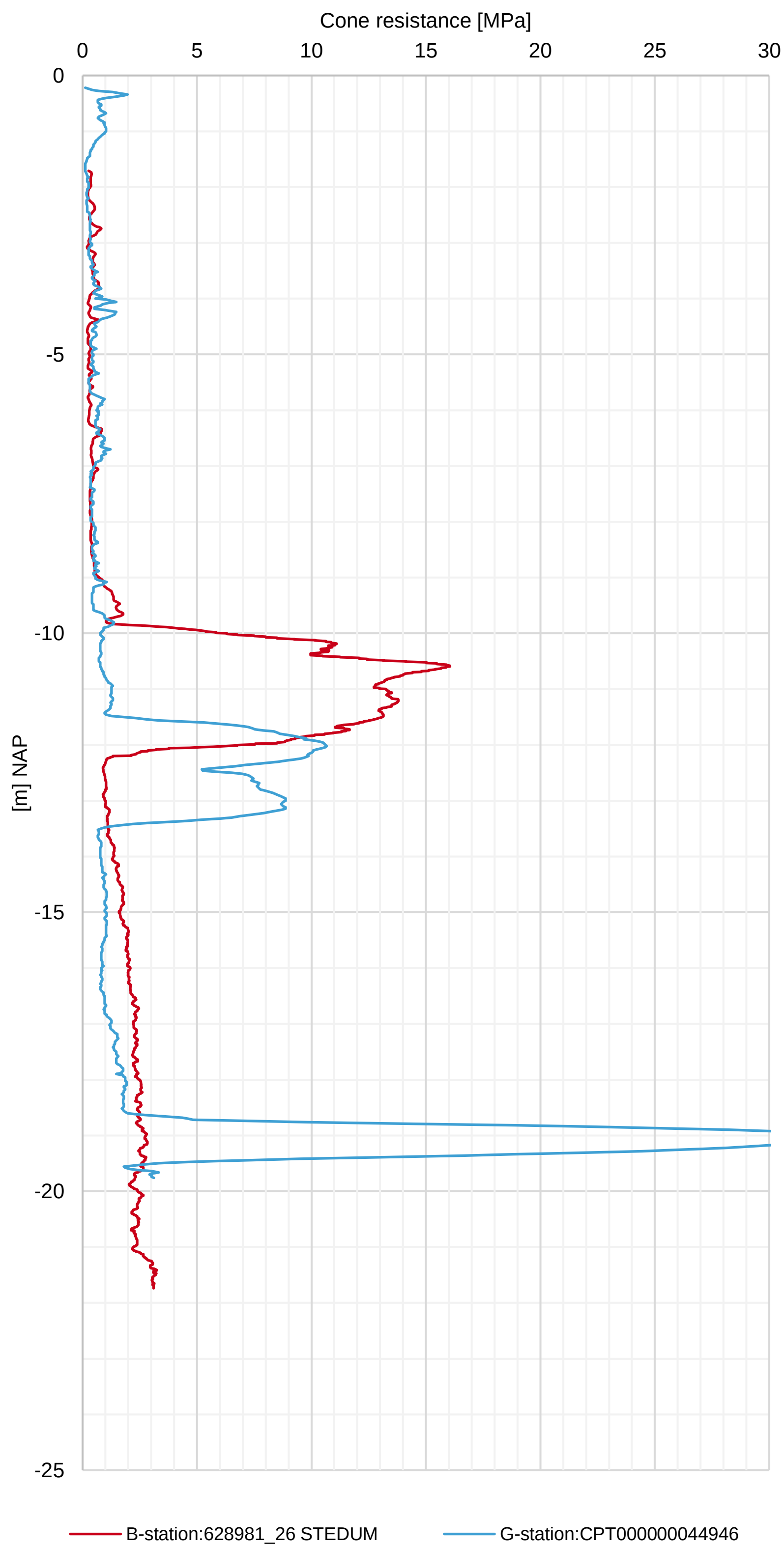
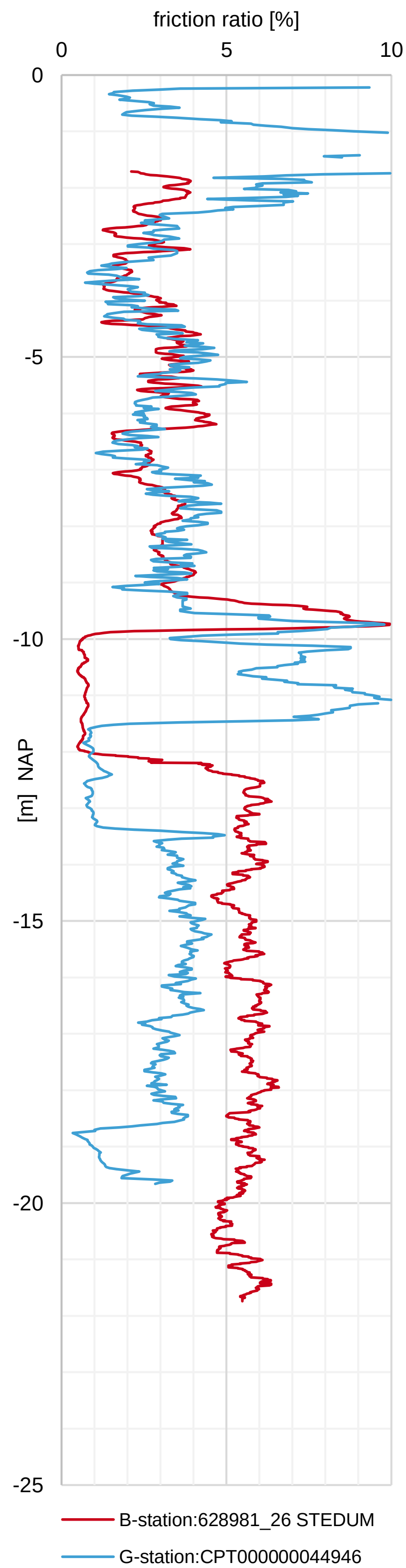
Comparison closest available CPT at B- and G-stations

B-station	BSTD	Distance to CPT	301.7 [m]	Geological zonation	1102
G-station	G22	Distance to CPT	209.0 [m]	Geological zonation	1005





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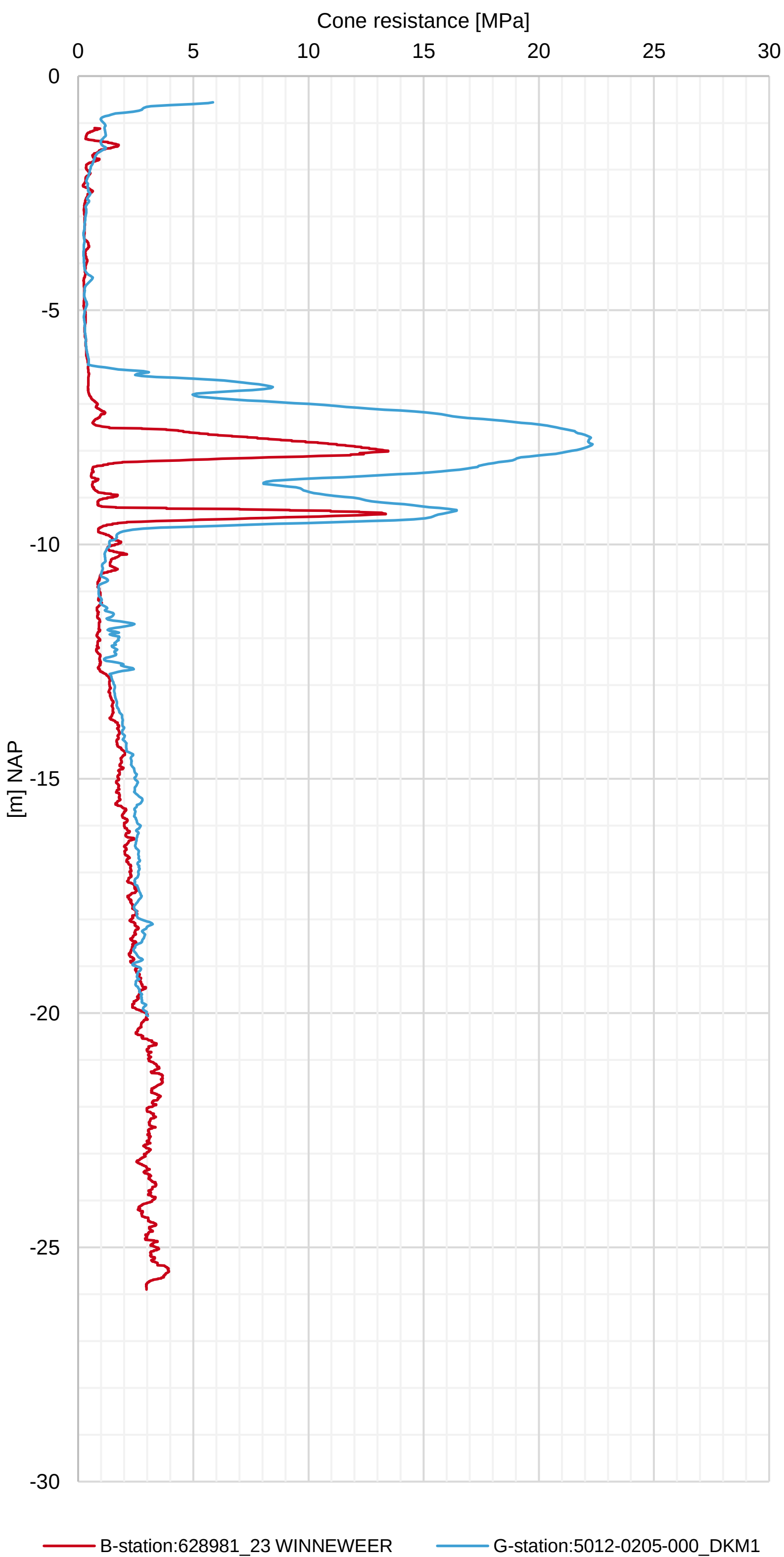
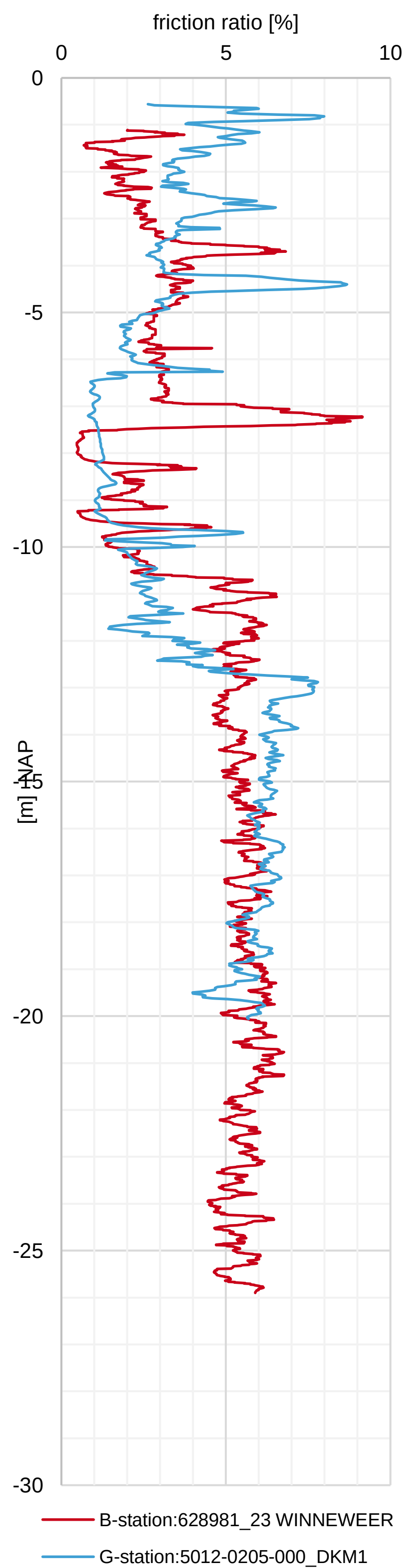
Comparison closest available CPT at B- and G-stations

B-station	BWIN	Distance to CPT	56.4 [m]	Geological zonation	2102
G-station	G23	Distance to CPT	171.5 [m]	Geological zonation	2102





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Comparison closest available CPT at B- and G-stations

B-station	BOWW	Distance to CPT	36.0	[m]	Geological zonation	2104
G-station	G19	Distance to CPT	118.6	[m]	Geological zonation	2104