16th World Conference on Earthquake, 16WCEE 2017

Santiago Chile, January 9th to 13th 2017

Paper N° 2260

Registration Code: S- L1461935500

THE USE OF NON-LINEAR SITE RESPONSE ANALYSIS TO INCORPORATE VERY SOFT SOIL RESPONSE IN ASSESSING MAN-INDUCED SHAKING HAZARD

Z. Lubkowski(1), J.E. Go(2), M. Vasileiadis(3)

(1) *Associate Director, Arup, Infrastructure, London, Ziggy.Lubkowski@arup.com*
(2) *Associate, Arup, Infrastructure, London, James.Go@arup.com*
(3) *Engineer, Arup, Infrastructure, London, Michael.Vasileiadis@arup.com*

Abstract

This paper presents a region-wide site response study conducted to assess ground shaking due to man-induced earthquakes. The region is in an area of historically low seismicity where gas extraction over the past decades have led to man-induced earthquakes. A region-wide site response analysis study was performed to assess the severity of shaking.

The formations encountered at or near the surface typically consists of normally consolidated to moderately overconsolidated Holocene and Pleistocene age deposits. These comprise of marine clay and sand with inclusions of peat. The soft deposits in the top 6 to 10m typically have undrained shear strengths ranging from 20 to 40kPa. It is anticipated that the overlying soft soil deposits will significantly modify the bedrock motions as these are transmitted up through the soil column and to the ground surface. The soft soils behave non-linearly, as they have a limited capacity to transmit seismic waves to the surface due to their low strength, and the high hysteretic damping associated with large strain cycles. Hence, the motion at the surface of the soil deposit can be changed significantly as has been seen in earthquakes in Mexico City in 1985 and Loma Prieta in 1989.

A region-wide site response study was conducted to assess the ground shaking. The amplification of seismic ground motions due to the overburden soil deposits was evaluated assuming a one-dimensional (1D) soil column excited by vertically propagating horizontal shear waves. A total of 46 representative 1D soil columns were developed using the available geotechnical and geophysical data. Site response analysis was performed using the 1D non-linear site-response analysis software Oasys SIREN. The program models the soil as a series of lumped masses connected by non-linear springs.

Non-linear ground response was developed based on the results of more than 4,500 site response analyses. Using the region-specific non-linear ground response a surface PGA map was generated. The region-wide study has shown that accounting for the non-linear behaviour of soft overburden soils reduces the surface PGA values by as much as 40%. Insights gleaned from the regional study were used to develop the code to include the effect of soil non-linearity on the spectral parameters (PGA and spectral accelerations at short and long periods) and spectral shape for use in structural design in line with the NEHRP methodology.

Keywords: Non-linear soil response; man-induced earthquakes; very soft soils; design spectrum development

1. Introduction

Soft overburden soils, such as those found in the Groningen area, greatly influence the ground response during seismic excitation. During ground shaking, soils modifies the ground motion and can amplify certain frequencies whilst deamplifying other frequencies. The authors have performed a regional study for Groningen studying the effect of soft overburden soils on ground response. Results of the study indicate that the Peak Ground Acceleration (PGA) is significantly reduced due to the limited capacity of the soils to transmit seismic waves to the surface. This is due to its low stiffness and high damping with large strain cycles. Insights gleaned from the regional study were used to develop the NEN NPR 9998 [1] ('NEN NPR') design response spectrum.

This paper shows how very soft soils influence ground shaking and uses the Groningen regional study as an example. We briefly describe the near surface geology of the region, the effect of non-linear soil behaviour, the method used to assess soil response, and key results of the regional ground response analysis and how they were used to update the local design code.

2. Near-surface Geology

The formations encountered at or near the surface in the Groningen area typically consist of normally consolidated to moderately overconsolidated Holocene and Pleistocene age deposits. These deposits were formed due to glacio-fluvial, aeolian, and marine sedimentation. The Holocene formations, which outcrop the majority of the Groningen region, comprise of marine clay and sand with inclusions of peat.

3. Local Code

The NEN NPR 9998 [1] defines the seismic hazard for the Groningen region. The first edition of the code defined a PGA and spectral shape for a single soil class. Fig.1 shows the location-dependent 475-yr ground level PGA. The highest PGA is about 0.36g at Loppersum. The PGA attenuates with distance with the lowest PGA values given near Veendam, approximately 25km southeast of Loppersum.

The NEN NPR PGAs were developed for relatively stiff sites, with the time-averaged shear wave velocity at the top 30m (V_{S30}) of 200m/s (corresponding to EN-1998-1 Ground Type C [2] or ASCE-7 Site Class D [3]). V_{S30} is calculated using the shear wave velocity values in the upper 30m of the soil profile using the formula:

$$V_{S30} = \frac{30}{\sum_{i=1,N}\left(\frac{h_i}{V_i}\right)} \tag{1}$$

Where h_i and V_i correspond to the thickness (m) and the shear wave velocity (m/s) of the i^{th} layer, in a total of N layers, existing at the top 30m.

Review of available geotechnical and geophysical data consisting of 248 Cone Penetrometer Tests (CPTs), and 66 Seismic CPTs (SCPTs), indicate that the majority of the Groningen area is underlain by very soft deposits (clays, organics, and peats). The soft deposits in the top 6 to 10m typically have estimated undrained shear strengths ranging from 20 to 40kPa and indicated that the V_{S30} is significantly lower than 200m/s (Fig. 2). Since the majority of the study area has V_{S30} less than 200m/s and is underlain by soft overburden soils, a region-specific site response study was performed to quantify a representative soil response for the study area.

4. Effect of Soft Soils on Soil Response

Fig. 3 shows a graphical representation of the site (or ground) response analysis (SRA) process. The motion at the surface of the soil deposit (or 'free surface motion') can be very different to those observed at a location where bedrock is exposed (or 'rock outcropping motion') as has been seen in earthquakes in Mexico City in 1985 and Loma Prieta in 1989. The overlying soil deposits modify the bedrock motions as these are transmitted up through the soil column and to the ground surface.

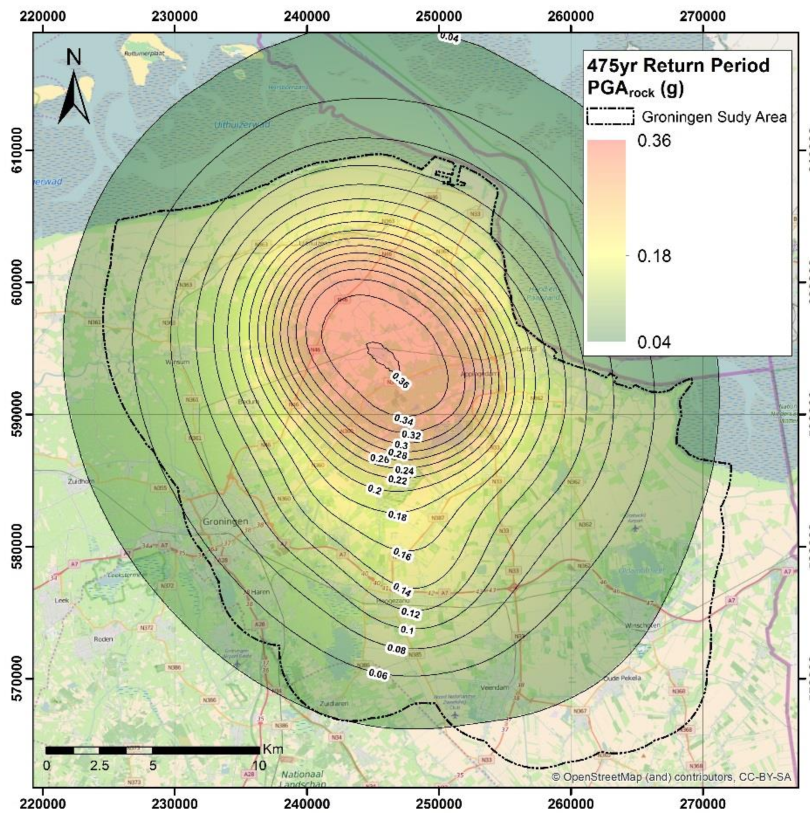

Fig. 1 – NEN NPR ground-level PGA map (based on the NPR:9998, Dec 2015)

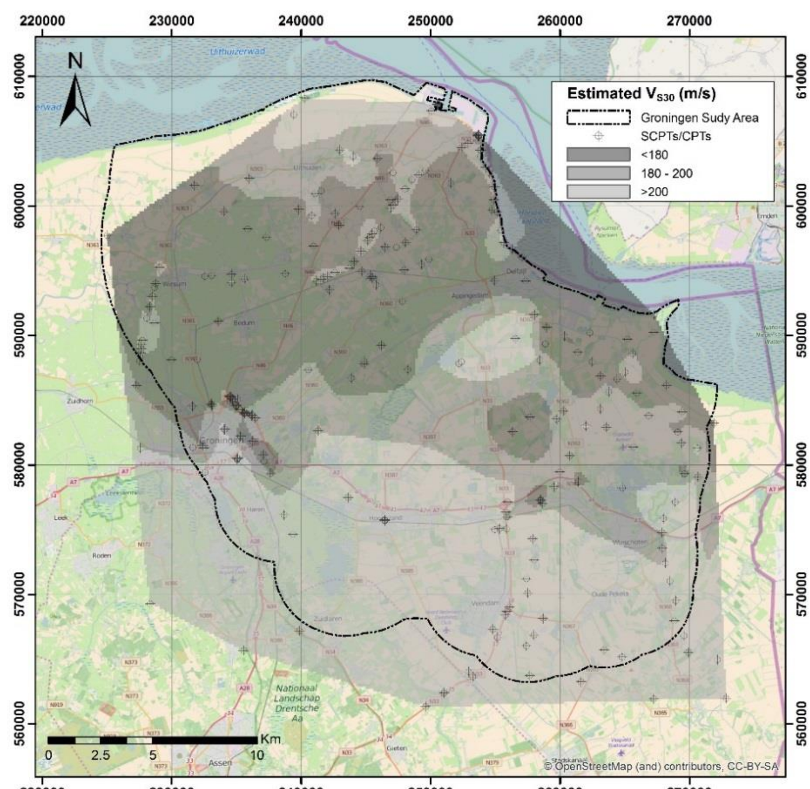

Fig. 2 – V_{S30} map for the Groningen region based on geotechnical data

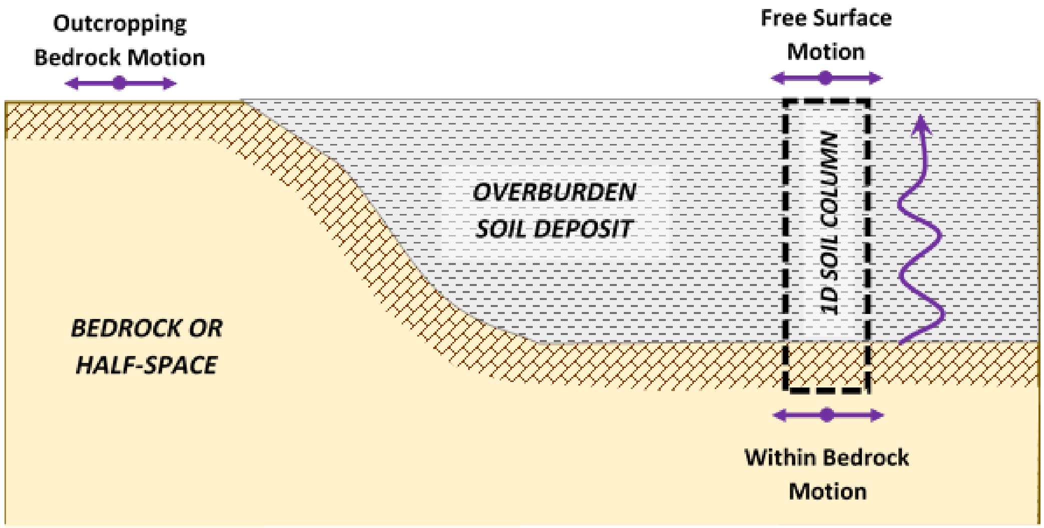

Fig. 3 – Idealization of a 1D site response analysis

Amplification of seismic ground motion due to the overburden soil deposits is typically evaluated assuming a one-dimensional (1D) soil column excited by vertically propagating horizontal shear waves. For this regional study, SRA was performed using the 1D non-linear site-response analysis software Oasys SIREN. The program models the soil as a series of lumped masses connected by non-linear springs [4]. SIREN uses the finite difference method and propagates shear waves vertically through the soil column from the underlying bedrock or half-space (Fig. 4). The program operates in the time domain enabling it to model non-linear soil properties with hysteretic damping. SIREN has been compared to DEEPSOIL and shown to generate similar results [11].

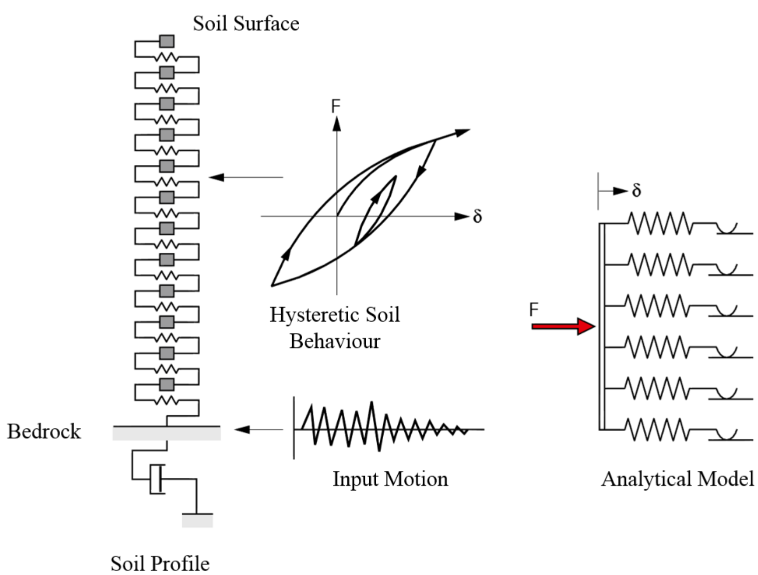

Fig. 4 – Diagrammatic illustration of 1D non-linear SRA

5. Site Response Analysis Methodology

A total of 46 representative 1D soil columns were developed using the available geotechnical data. A typical soil profile is shown in Fig. 5. A region-specific CPT-V_S correlation was developed to provide quick and reliable estimates of shear wave velocity (V_S) using readily available CPT data, following the PEER [7] guidelines. The degradation of the soil stiffness under cyclic loading is modelled using shear modulus degradation (G/G_0) curves

(Fig. 6). The Darendeli's [8] model was chosen to simulate the degradation of the soil stiffness with strain and is a function of mean confining stress (σ'_m), plasticity index (PI), and overconsolidation ratio (OCR). The G/G_0 curves were modified to be asymptotic to the undrained shear strength at larger strains. Soil degradation properties were derived from published sources due to a lack of site-specific degradation properties. However, the impact of varying the shear wave velocity by ±20% was investigated, which is a more significant varying than the degradation properties, and the methodology developed was shown to be robust. The effect of bedrock depth was also investigated and results were shown not to be very sensitive. The use of relatively short (i.e. 30m deep) 1D columns was shown to successfully capture the fundamental site period and to provide conservative results for the structural periods of the building types encountered in the area.

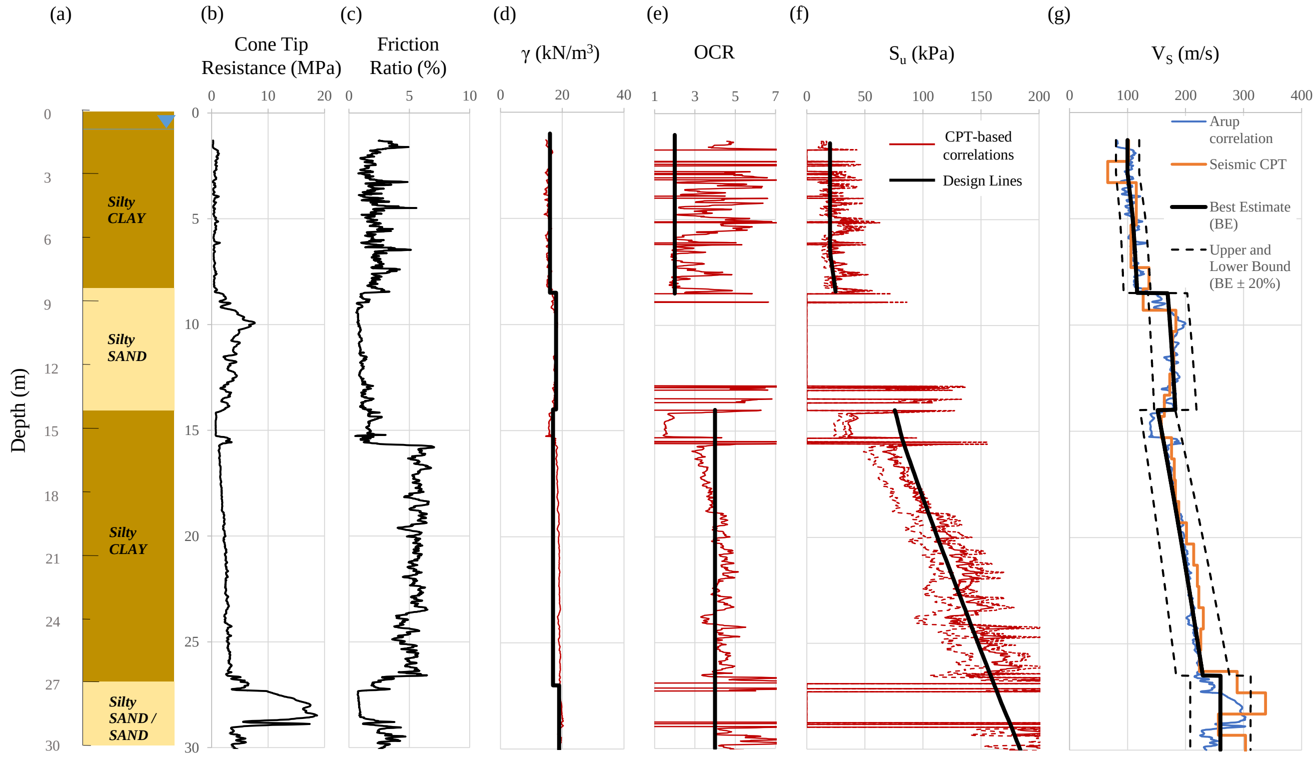

Fig. 5 – Typical Groningen soil profile: a) stratigraphy; b) CPT tip resistance; c) CPT friction ratio; d) unit weight; f) overconsolidation ratio; e) undrained shear strength; and g) shear wave velocity

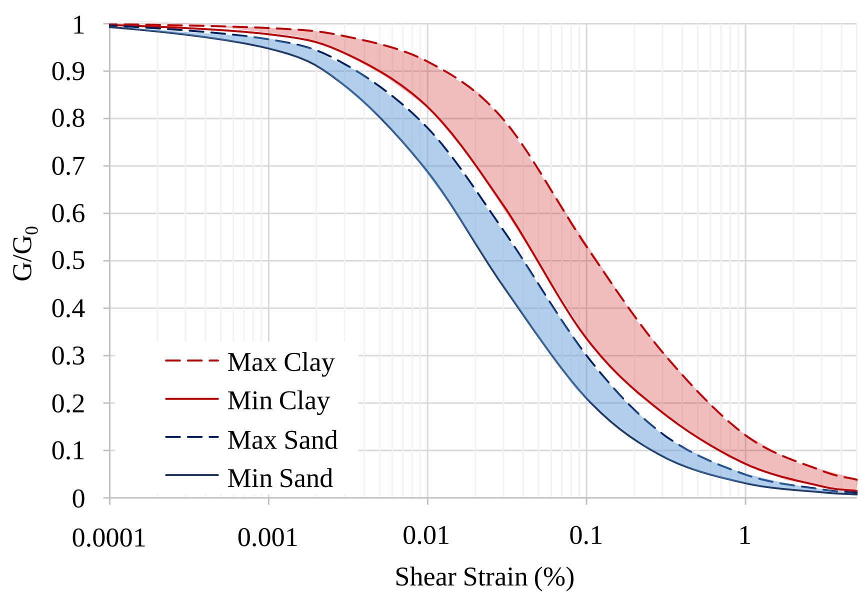

Fig. 6 – Modulus degradation (G/G_0) curves for clays and sands

The 1D soil columns were excited using 14 acceleration time histories. The acceleration time histories were developed using recorded ground motions during actual earthquake events with similar characteristics (magnitude, source-to-site distance, and significant durations) of the design earthquake event. The time histories were spectrally-matched to be consistent with the NEN NPR spectrum (Fig. 7) Note that the available measured local records are of very low magnitude events, hence they could not be used to assess local amplification functions in order to validate the results.

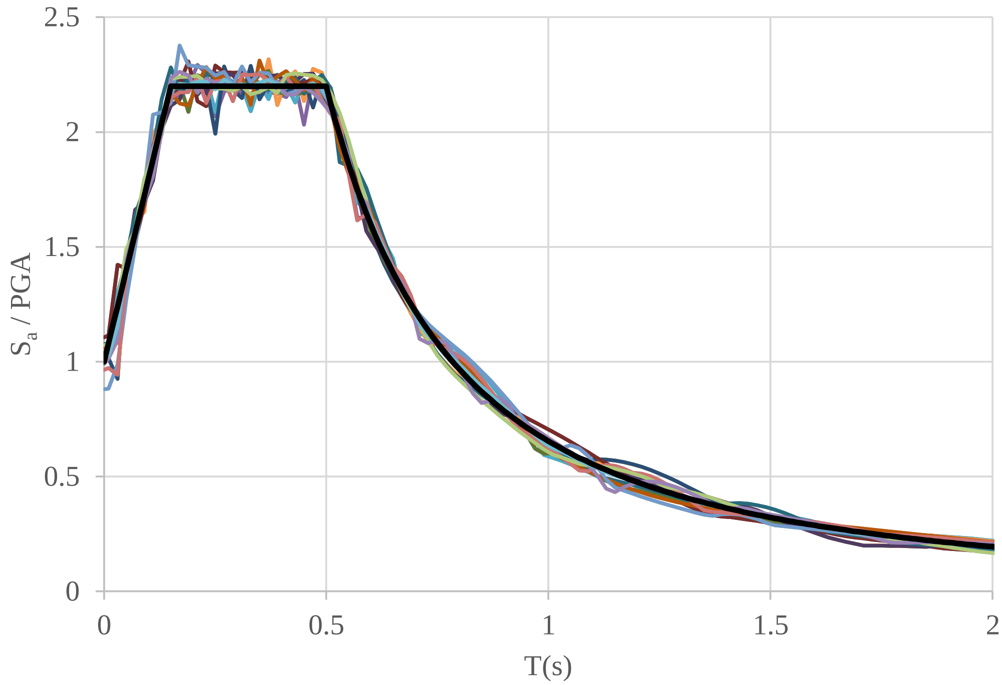

Fig. 7 – Response spectra of the spectrally-matched time histories (coloured lines) compared to the NEN NPR target spectrum (black line) for PGA=1g

6. Site Response Analysis Results

A total of 4,508 SRA runs were performed. To assess the soil amplification (or deamplification), plots comparing the input PGA and the surface PGA were developed (Fig. 8). It can be seen that the soil response is non-linear:

- At low input PGAs (0.05 to 0.15g), the surface PGA is mainly amplified (surface > input); and
- At higher input PGAs (>0.15g), the surface PGA is de-amplified (surface < input).

The non-linear response is due to the limited capacity of the soft surface layers to transmit seismic waves to the surface due to their low strength, and the high hysteretic damping associated with large strain cycles.

A non-linear ground response as a function of input PGA was developed by fitting a lognormal curve through the dataset (‘Mean’ line in Fig. 8). In order to encompass the majority of the data points, the region-specific non-linear ground response was taken as Mean + Standard Deviation (Stdev) of the dataset (solid red line in Fig. 8).

Using the region-specific non-linear ground response, a surface PGA map was generated taking into account the non-linear response of soft soils (see Fig. 9). Compared to the NEN NPR ground level PGA, the region-specific surface PGA is significantly lower with about 0.21g at Loppersum and 0.11g at Veendam. Fig. 10 shows the ratio of the region-specific surface PGA to the NEN NPR PGA. Blue contours show areas where the region-specific PGA is lower than the NEN NPR, whilst red contours show areas where the region-specific PGA is higher than the NEN-NPR. It can be seen that in the areas of higher seismic intensity (input PGA>0.2g, Fig.1), the region-specific PGA is lower than the NEN NPR PGA by as much as 40% reduction in the Loppersum area (reduction to 0.21g from 0.36g). The difference of the region-specific PGA with the NEN NPR input PGA shows that the non-linear response of the soft overburden soil have a significant effect on ground shaking and needs to be properly taken into account.

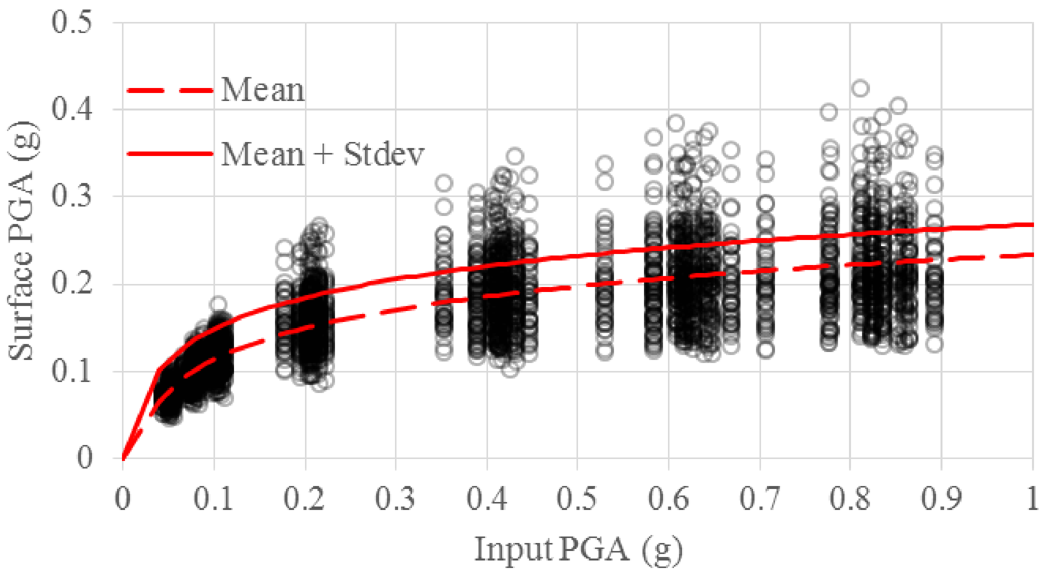

Fig. 8 – Non-linear response curve for PGA

]

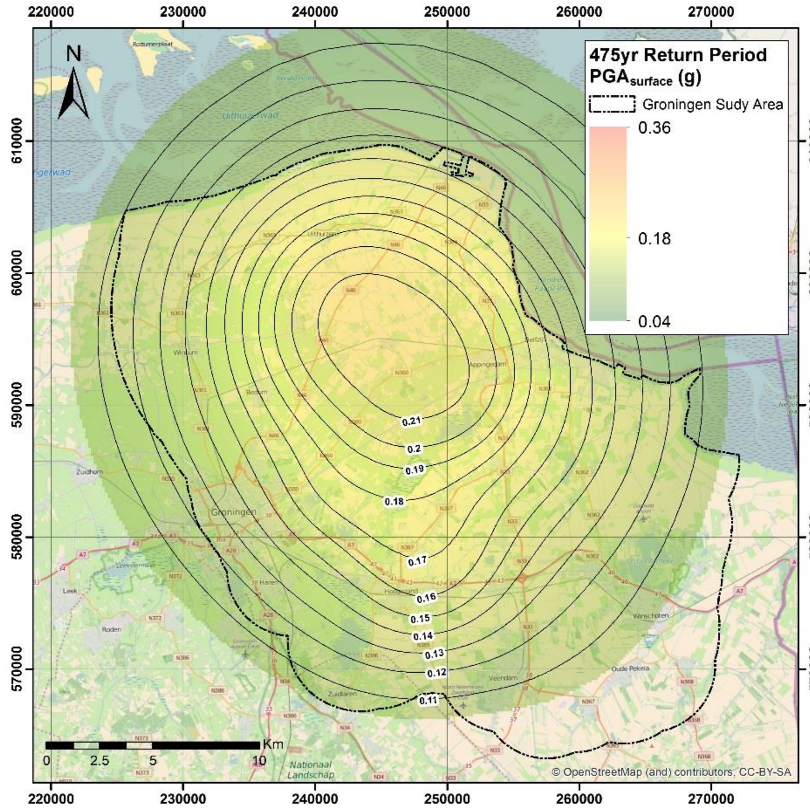

Fig. 9 – Region-specific surface PGA at a recurrence interval of 475 years

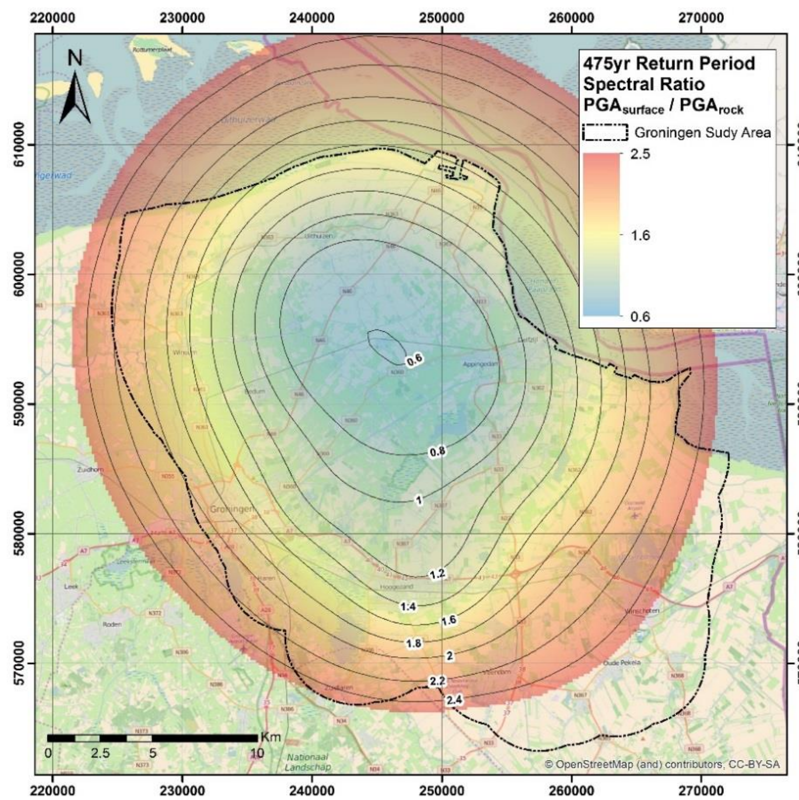

Fig. 10 – Ratio of region-specific PGA to NEN NPR PGA at a recurrence interval of 475 years

7. Non-Linear Amplification Ratios

This study also examined the effect of soil non-linearity on the spectral accelerations at short and long periods, and spectral shape. This section presents the derivation of the short period and long period amplification factors (or site coefficients). Site coefficients indicate whether the input ground motion will be amplified (increased) or deamplified (decreased). Fig. 11 shows how site coefficients are determined for a single site – the ratio of the surface response spectrum and input response spectrum (Fig. 11a) results to the spectral ratios, which practically define the site coefficients (Fig. 11c). In this example, it can be seen that deamplification is evident in the short period band (spectral ratio is less than 1) whilst amplification is evident in the long period band (spectral ratio is greater than 1) (Fig. 11b).

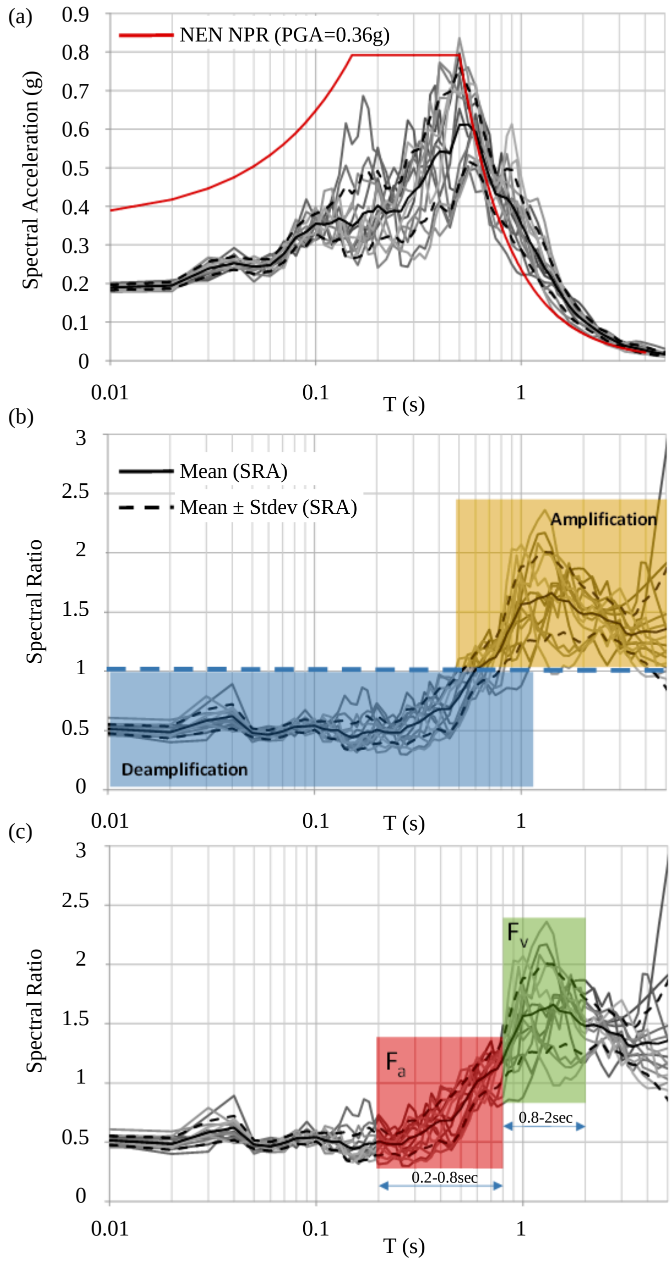

Fig. 11 – Example of a ground model in Loppersum for 0.36 input PGA: (a) response spectra versus input (target) spectrum, (b) spectral ratios amplification/deamplification period ranges, (c) Fa and Fv derivation

Following the NEHRP [9] terminology, the short period site coefficient is termed F_a, whilst the long period site coefficient is termed F_v. The site coefficients were calculated using the ratio of response spectra (RRS):

$$F_a(RRS) = \frac{R_{soil}}{R_{rock}} \times \frac{1}{0.6} \times \int_{0.2}^{0.8} \frac{RS_{soil}(T)}{RS_{rock}(T)} dT \tag{2}$$

$$F_v(RRS) = \frac{R_{soil}}{R_{rock}} \times \frac{1}{0.2} \times \int_{0.8}^{2.0} \frac{RS_{soil}(T)}{RS_{rock}(T)} dT \tag{3}$$

where RS_{soil}, RS_{rock} are the Response Spectra in soil and rock at the same period T and R_{soil}, R_{rock} are the hypocentral distances of the soil and rock stations. The ratio R_{soil}/R_{rock} is equal to unity as both soil and rock locations are the same. The average ratios of the RRS (or spectral ratio) over 0.2 to 0.8s was used for F_a and 0.8 to 2.0s for F_v, as shown in Fig. 11b. The period ranges selected for F_a and F_v generally correspond to those used for obtaining site coefficients in the NEHRP provisions [10]. Fig. 12a presents the input PGA against the short period spectral ratios ranging from 0.2s to 0.8s with spectral ratios selected at 0.2, 0.4, and 0.8sec. A non-linear trend can be observed for F_a. The curve of Mean + 1 Standard deviation was selected as the design F_a curve. It can be seen that for the Mean + 1 Standard deviation curve, amplification is observed for input PGAs less than 0.5g. Amplification can reach values up to 2.2 for very low input PGAs (close to 0.05g), whilst deamplification as low as 0.7 can be observed for input PGA equal to 0.9g.

Fig. 12b plots the input PGA against the long period spectral ratios ranging from 0.8s to 2.0s. Due to the large amount of data, spectral ratios were examined for 0.8, 1.0, and 2.0s. A more linear trend can be observed for F_v. The curve of Mean + 2 Stdev was selected as the design F_v curve. It can be seen that for the Mean + 2 Standard deviations curve, amplification is observed for the entire period range, getting values up to almost 2.5 for low input PGAs.

Note that each point in the F_a (see Fig.12a) and F_v (see Fig. 12b) plots represents a single analysis run. The equations of the design F_a and F_v lines are given in Eq. (1) and Eq. (2), respectively:

$$F_a = -0.503 \cdot ln\big(Input\ PGA(g)\big) + 0.6483 \tag{4}$$

$$F_v = -0.8651 \cdot Input\ PGA(g) + 0.2435 \tag{5}$$

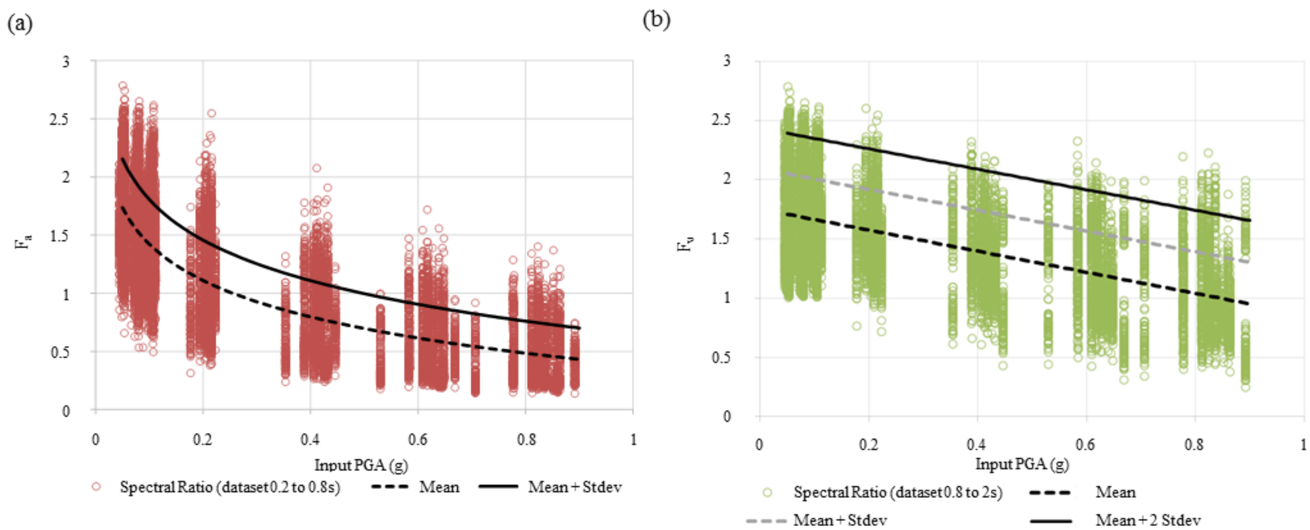

Fig. 12 – Input PGA versus: (a) short period (0.2 to 0.8sec) spectral ratio (F_a), and (b) long period (0.8 to 2sec) spectral ratio (F_v)

8. Derivation of the Design Response Spectrum

A methodology for deriving the design response spectrum curve (Fig. 13) sufficient to characterize the response of the examined locations was developed. The proposed design response spectrum procedure is based on the NEHRP provisions with some modifications for the long period zone and the surface PGA. As shown in Fig. 14 (in green), the decay of the spectral ratio at the long period is inversely proportional to the square of the period (α $1/T^2$) whilst the PGA is equal to a third of the short period spectral response acceleration (S_{MS}), as defined below. The modifications were implemented to better fit the pronounced decay in the long periods observed in the SRA results.

The proposed design spectra are presented for two example sites (Fig. 14), and are compared with actual SRA results from those sites. It can be observed that the proposed design spectrum provides a good fit to SRA results in both the short and long period range and captures the predominant peaks of the SRA results.

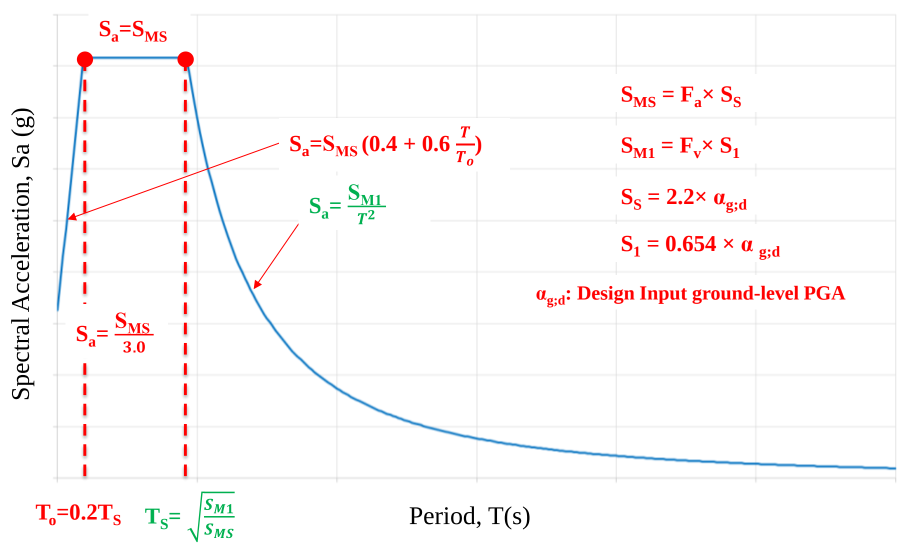

Fig. 13 – Key parameters for deriving the Design Response Spectrum

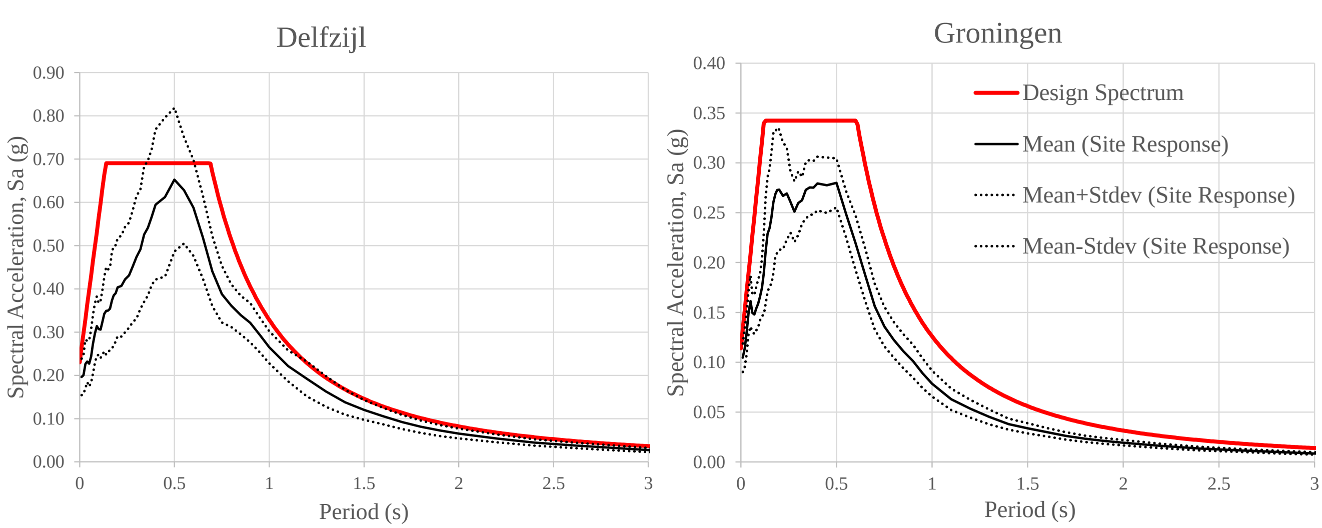

Fig. 14 – Comparison of the Design Spectrum with actual SRA results

7. Conclusions

A region-wide SRA study was conducted for the Groningen area, to assess the effect of soft soils on the site response under man-induced earthquakes. The SRA results indicated that the non-linear response of the soft overburden soils has a significant effect on ground response and should be taken into account. Plots comparing the input PGA and the surface PGA showed that:

- At low input PGAs (0.05 to 0.15g), the surface PGA is mainly amplified (surface > input); and
- At higher input PGAs (>0.15g), the surface PGA is de-amplified (surface < input).

A methodology for deriving the design response spectrum curve sufficient to characterize the response of the examined locations was developed to update the NEN NPR 9998 code. Review of the SRA results indicated that to develop a model for a design response spectrum, it is necessary to understand the non-linear ground response at short and long periods to derive an appropriate spectral shape for the design spectrum. The non-linear ground response was assessed by comparing the input PGA vs the spectral acceleration at both short and long periods. Trends in these plots indicate that the relationship is non-linear for the input PGA vs short period (PGA and 0.2s) spectral accelerations, whilst the trend is more linear at longer periods. Since the non-linear ground response of the short period motion is significantly different from the long period motion, it was judged that the design spectrum should be anchored to both the short period and the long period spectral acceleration similar to the NEHRP (1994) model with separate soil amplification factors (or site coefficients) for the short and long period motions. The proposed surface design response spectrum provides a good fit to the SRA surface response spectra of Groningen sites, in both the short and long period range, and captures the predominant peaks of the SRA results.

8. Acknowledgments

The authors wish to thank the NPR sub-committee for commenting and reviewing this study, as well as, the other members of the seismic team at Arup, London; in particular Francisco Ciruela-Ochoa, Areti Koskosidi, and Ulas Cilingir for their help in checking and plotting the SRA results.

9. References

[1] NPR 9998:2015, *Assessment of buildings in case of erection, reconstruction and disapproval – Basic rules for seismic actions: induced earthquakes*, December 2015, Nederlands Normalisatie-Instituut, Nederlands

[2] Eurocode 8 (2004): *Design of structures for earthquake resistance. Part 1: General rules, seismic actions and rules for buildings*, Brussels

[3] ASCE-7 (2010), American Society of Civil Engineers, *Minimum Design Loads for Buildings and Other Structures*, Virginia, USA

[4] Pappin J (1990): *Design of foundations and soil structures for seismic loading,* Reilly and Brown eds.

[5] Stewart J, Afshari K, Hashash Y (2014): Guidelines for Performing Hazard-consistent One-Dimensional Ground Response Analysis for Ground Motion Prediction. *Technical Report PEER 2014/16*, Pacific Earthquake Engineering Research, Berkeley, USA

[6] Kaklamanos J, Bradley B, Thompson E, Baise L (2013): *Critical Parameters Affecting Bias and Variability in Site-Response Analyses Using Kik-net Downhole Array Data*, Bulletin of the Seismological Society of America, Vol.103

[7] Wair BR, Dejong JT, Shantz T (2012): Guidelines for Estimation of Shear Wave Velocity Profiles. *Technical Report PEER 2012/08,* Pacific Earthquake Engineering Research, Berkeley, USA

[8] Darendeli M (2001): *Development of a new family of normalized modulus reduction and material damping curves*. PhD Thesis, Department of Civil Engineering, University of Texas, Austin, USA

[9] NEHRP (1994), National Earthquake Hazards Reduction Program, *Recommended Provisions for Seismic Regulation for New Buildings*, Part 2 – Commentary

[10] Dobry R, Ramos R, Power MS (1999): Site Factors and Site Categories in Seismic Codes, *Technical Report MCEER-99-0010*, Rensselaer Polytechnic Institute, Troy, NY, USA and Geomatrix Consultants Inc, San Francisco, California

[11] McCully, R., Koulouri, I., Lubkowski, Z., and Pappin, J.W. (2014) Comparison of Eurocode 8 Site Class Amplification Factors with Non-linear Site Response Analysis. 2ECEES, Istanbul.