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SEISMIC RESPONSE OF WIND TURBINES ON CAISSON-TYPE FOUNDATIONS IN SOFT CLAY

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Abstract: *Increasing interest in offshore wind turbines internationally has led to an increasing demand for seismically robust designs. Where subsoils are predominantly soft clay, an effective foundation option for resisting the design loads is a suction caisson but there is limited experience of such foundations in earthquake loading. Previous research has suggested that shallower foundations attracted less seismic load and were therefore preferable from an earthquake design perspective, but the wider applicability of this was unclear. In the present study, the finite element code PLAXIS is used to create a 3D representation of a caisson type foundation in a soft clay, modelled using the HSSmall model to capture nonlinearity and hysteretic soil behaviour. The results are validated against the original physical model. The study is then widened to four foundation geometries and four strong motions. Response spectra recorded on the foundation at ground level differ greatly from surface response spectra but are very well matched with response spectra generated at the depth of the caisson base. This is seen to be because the caisson behaves as a rigid object controlled by accelerations at its deepest level. It is consequently recommended that the spectra used for tower designs on such foundation can be estimated based on response of free field soil at the depth to which the foundation will reach.*

Background

Suction caissons have been a popular, efficient and low-vibration foundation solution for a number of years, particularly but not exclusively in offshore applications. Recent years have seen a resurgence in interest, as suction caissons have become a candidate foundation for fixed-base offshore wind turbines, first tested by Byrne et al. (2002), more recently reviewed by Houlsby (2016) and installed, for example, at the European Offshore Wind Deployment Centre (EOWDC) off the coast of Aberdeen in the UK by Vattenfall. Offshore wind arrays often contain many individual structures (e.g. 175 turbines in the London Array) and are often subject to strict regulations limiting environmental impact, including vibration during installation (Marmo et al., 2013). Suction caissons therefore have a number of advantages as they may be quicker to install and provide lower installation vibration than conventional driven piles and can be employed in greater water depths than gravity base structures and with the possibility of lower material costs. However, there remain some questions over aspects of their performance, particularly in sandy or layered soils (Houlsby, 2016).

The motivation for the present study came whilst investigating the potential for development of an offshore wind array at a site of moderate water depths and ground conditions comprising soft clay soils. This indicated that suction caissons could be a good option for the site. However, the region was also subject to a moderate seismic hazard. The dynamic behaviour of a suction caisson in soft clay has been investigated in some studies previously. Brennan et al. (2006, 2010) used centrifuge model tests of caissons in clays during earthquakes to show that strong motions were more likely to transfer into deeper caissons than shallower ones, indicating a possible benefit to seismic response. Bertalot et al. (2017) observed a reduction in response spectra when comparing free field motion to the top of a caisson, based on results of 3D finite element (FE) modelling, which suggests they had captured a similar process to the previous centrifuge model tests. Gaudio and Rampello (2019) also the importance of incorporating soil plasticity in the design, in this case applied to seismic response of caisson-supported bridge piers. Their modelling was 3D PLAXIS, utilising the "HS Small" constitutive model described by Benz at al. (2009). These FE studies were not validated against other testing, but when investigating static loading then Lorenti and Lehane (2017) used a centrifuge model to show that 2D PLAXIS models were able to reproduce caisson settlements measured provided a suitable constitutive model was

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used to capture soil nonlinearity, in this case HS. A direct vibration study was carried out, also in 3D FE, by Latini et al. (2016) who observed reducing dynamic impedance at lower soil stiffnesses.

The literature therefore provides some guidance but earthquake loading tests are limited, the structures tested in earthquake loading were different from tall wind turbine structures, and offshore wind turbines are subject to limits on verticality to ensure continued operation (e.g. Cox and Bhattacharya, 2017) that may prove a more stringent criteria than dynamic stresses. This work therefore aims to investigate the dynamic behaviour of tall towers representative of wind turbines, on suction caissons in soft clay. This will be achieved by validating that the response from the Brennan et al. (2006) centrifuge tests can be adequately reproduced, then creating a defined geometry problem, then subjecting the benchmark caisson to multiple seismic events and collating response spectra. The effect of adjusting caisson diameter and penetration depth shall then be examined.

Validation case study

Before creating the model for parametric study, the validation case must be created based on previously carried out centrifuge tests. The original tests described by Brennan et al. (2006, 2010) were carried out at 50g (i.e. length and gravity were both scaled by a factor of 50) and comprised caissons of 5 m diameter prototype scale in a layer of normally consolidated kaolin clay of thickness 17 m as shown in Figure 1a. The initial caisson tested (and used as the validation case here) extended to a depth of 10 m, and supported a short structure representative of a pipeline manifold. This structure is seen above the white clay in Figure 1b. The clay was prepared in an equivalent shear beam container designer to match the dynamic vibrations of soil, however the design soil was a dry sand of medium density (Brennan and Madabhushi 2002) which may be stiffer than NC clay. This may have influenced measured data and must be considered in setting up the validation case within the FE.

The kaolin clay had been poured from slurry and consolidated by applying a suction of -100 kPa to the model base. Only limited characterization is available to describe the soil in the centrifuge test. Brennan et al. (2006) reported properties of G_s = 2.6, plastic limit w_P of 30%, liquid limit w_L of 51%. Previously unreleased data shows moisture content varying between 53% and 59% through the soil depth, indicating the soil to be at approximately liquid limit with a mean unit weight of 16.7 kN/m^3.

A number of measurements were available, however for brevity the dynamic measurements considered are accelerations recorded at the base of the soil corresponding to input motion (A.2 in Figure 1a), in the soil 5 m below the surface (A.6) and on the structure (A.9). Two of the six increasingly strong earthquakes applied are considered, earthquakes 1 and 6. The measured accelerations for these two events are shown in Figure 2. Note in Figure 2 the larger amplitude of earthquake 6 at input is greatly attenuated such that soil and structure accelerations are of similar amplitude to those in the milder earthquake 1, due to soil being of such low shear strength that it was unable to transmit the high accelerations. One further piece of data available was a lateral load-displacement of the caisson when a monotonic load was applied above mudline (Brennan et al., 2006), and this data is able to assist in monitoring system stiffness.

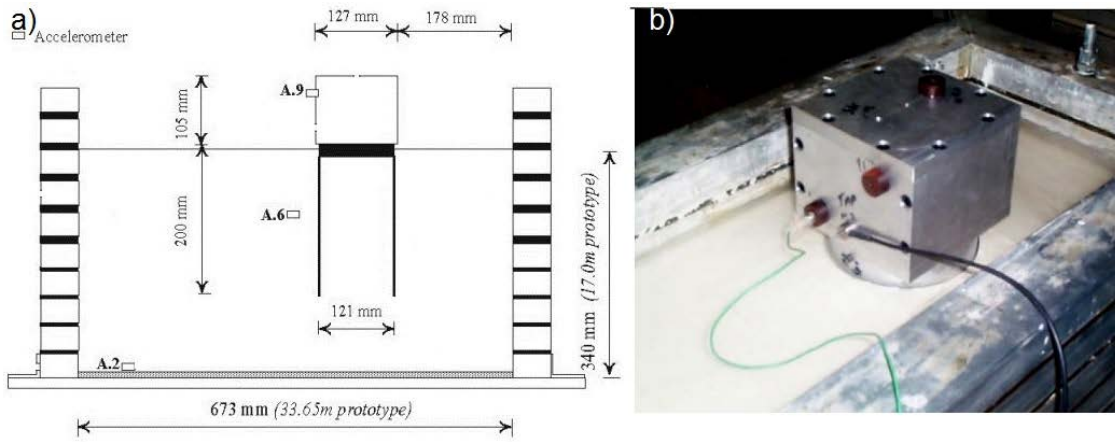

Figure 1. Original centrifuge test a) layout and selected instrumentation b) photograph

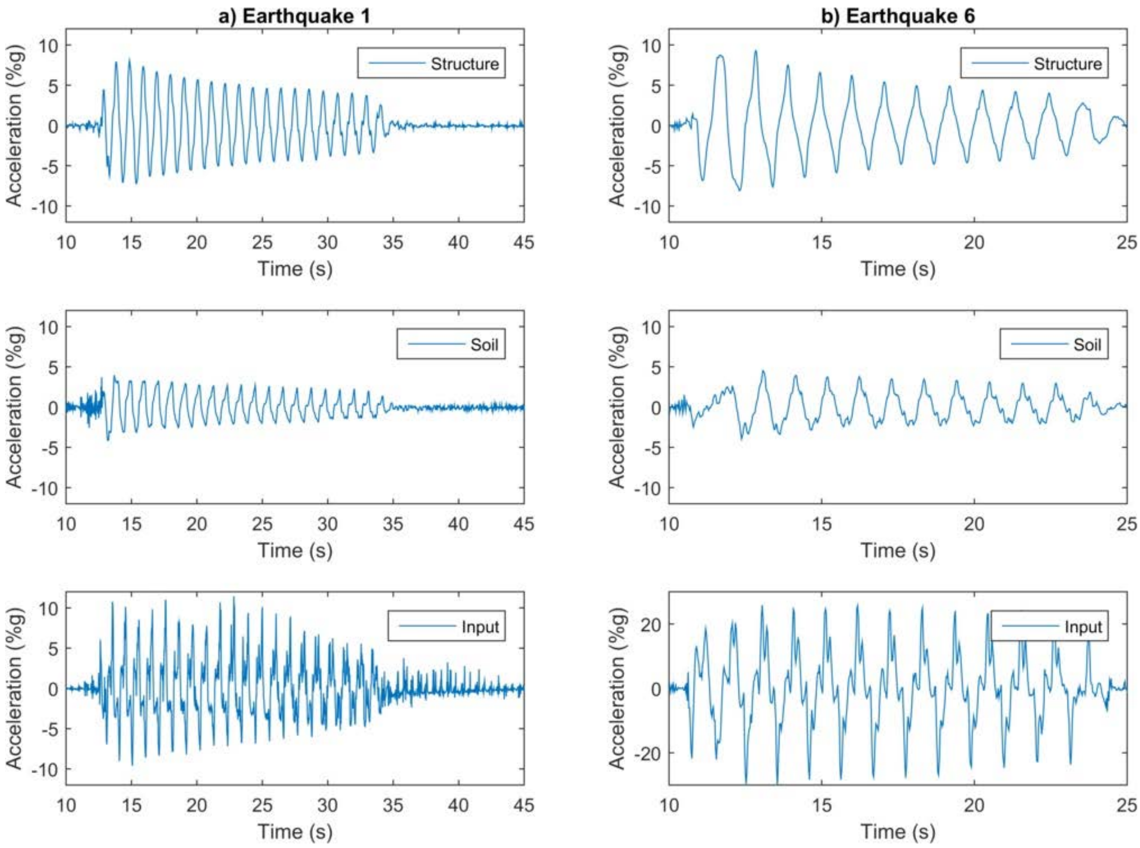

Figure 2. Measured accelerations in the centrifuge tests a) earthquake 1 b) earthquake 6

Modelling and validation

PLAXIS modelling

In common with the literature study of Gaudio and Rampello (2019), this study uses the commercially available code PLAXIS 3D. For the validation case, a domain is set up to mimic the dimensions of the centrifuge test as shown in Figure 3a. Caisson and superstructure are defined as plate elements with thickness 0.625 m and elastic parameters E = 200 GPa, G = 100 GPa and Poisson's ratio v = 0.1. Each component was assigned a weight in line with the physical model. Interface elements are created between structure and soil, in which the material parameters mirror the soil material parameters with the exception of residual strength R_{intr} which is set as 1 rather than 0.65 within the soil.

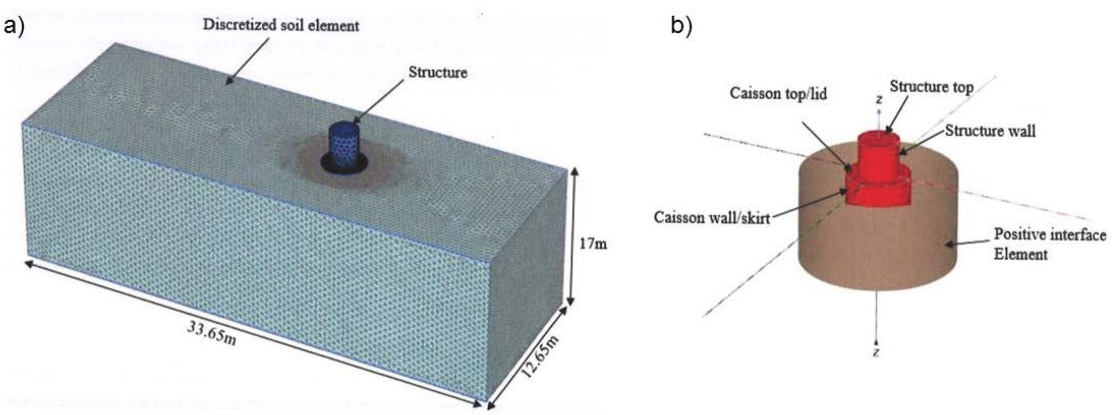

Figure 3. 3D finite element model of a) system and b) structure

Material modelling

In line with the observations from the literature and the large attenuations seen in the centrifuge test (Figure 2), it was seen as essential to have a soil model capable of modelling soil nonlinearity. The HSSmall model was chosen, in common with Gaudio and Rampello (2019), as it pays special attention to the low stress cycles such as are frequently present amongst the strong shaking of an earthquake. As such limited soil data was available from the original tests, many of the HSSmall parameters required estimating and refining based on results. Three sets of model parameters were trialled, the first set based on data for pure kaolin clay from Benz (2006) with subsequent alternative model sets identified as “change 1” and “change 2”.

Parameter	**Value based on Benz (2006)**	**First modification (“Change 1”)**	**Second modification (“Change 2”)**	**Unit**
Saturated unit weight γ_{sat}	17	17	17	kN/m^3
Triaxial compression stiffness E_{50}^{ref}	1500	750	375	kN/m^2
Primary oedometer stiffness E_{oed}^{ref}	750	375	187.5	kN/m^2
Unload/reload stiffness E_{ur}^{ref}	8000	4000	2000	kN/m^2
Reate of stress dependence m	1	1	0.8	
Cohesion c	0	0	0	
Friction angle φ	21	21	21	°
Dilatancy angle ψ	0	0	0	°
Reference pressure p^{ref}	100	100	100	kN/m^2
Small strain stiffness G_0^{ref}	33300	16650	8330	kN/m^2
Shear strain at 0.7 G_0, $\gamma_{0.7}$	0.0002	0.0002	0.0002	
Poisson’s ratio ν	0.2	0.2	0.2	
Failure ratio R_f	0.9	0.9	0.9	
Stress ratio in primary compression K_0^{nc}	0.64	0.64	0.64	
Residual strength R_{intr}	0.65	0.65	0.65	

Table 1. Material model parameters used, HS Small model for normally consolidated kaolin clay

Validation results

Initially, the original values from Table 1 were used in the material model and tested in order to measure how closely this was able to predict the moderate (earthquake 1) and strong (earthquake 6) centrifuge motions shown in Figure 2. The dynamic accelerations measured were as shown in Figure 4. Notable in these results is that whilst the FE provides a passable representation of structure accelerations during the moderate earthquake (Figure 4b), it overpredicts the amplitude for the soil motions in either earthquake (Figures 4a and 4c) and the structure in the stronger earthquake (Figure 4d). Therefore, it was seen that these parameters did not adequately represent the behavior of the physical system.

In order to improve the modelling of soil behaviour, it was decided to reduce the soil stiffness by a factor of 2 and 4 in order to produce the two alternative parameter sets shown in Table 1. In order to observe how this changed the response of the system the lateral load-displacement of the caisson was compared to a lateral displacement of the FE model, modelled using a point load. The results of this exercise are shown in Figure 5. Figure 5 shows that, like the dynamic tests had suggested, the original parameter set produced a soil that was too stiff. The reduced stiffness of “change 1” provided a closer match, but to best represent the prototype soil behaviour the “change 2” parameter set, in which stiffnesses are four times less than the Benz values, must be used. The dynamic tests were then re-run with the new parameter sets and shown (Figure 6) to provide a better match in this domain as well, with the best match again coming from the “change 2” parameter set.

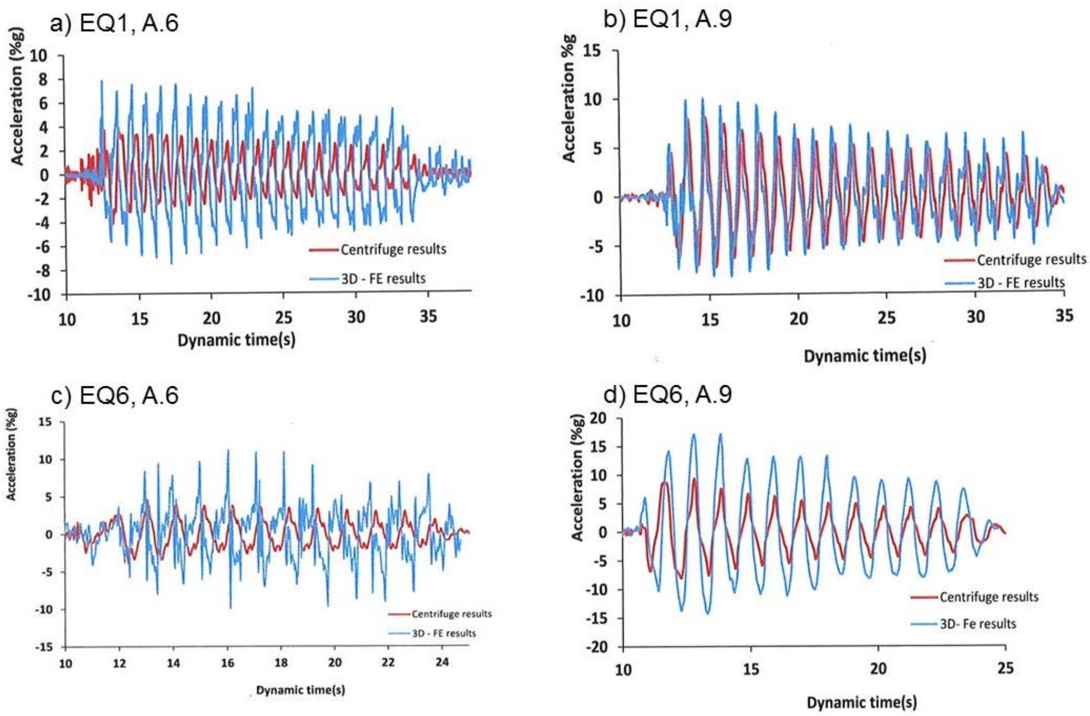

Figure 4. Comparison of measured centrifuge and initial FE predictions for a) earthquake 1, soil; b) earthquake 1, structure; c) earthquake 6, soil; d) earthquake 6, structure.

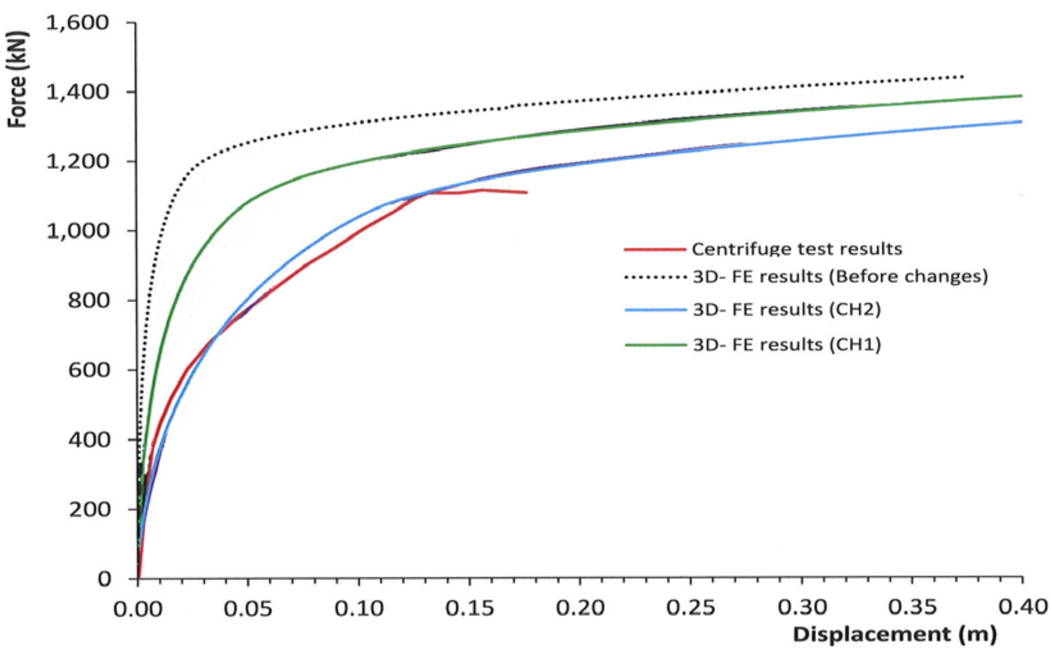

Figure 5. Comparison of monotonic lateral stiffness of caisson in each set of soil, compared to centrifuge results.

Based on these validation studies, it was concluded that the 3D PLAXIS model using HSSmall constitutive model was capable of modelling suction caissons in soft clay in terms of system stiffnesses (Figure 5) and dynamic behaviour in moderate (Figures 6a and b) and strong (Figures 6c and d) earthquake events. A good match of centrifuge data was obtained using the parameter set identified as “change 2” in Table 1.

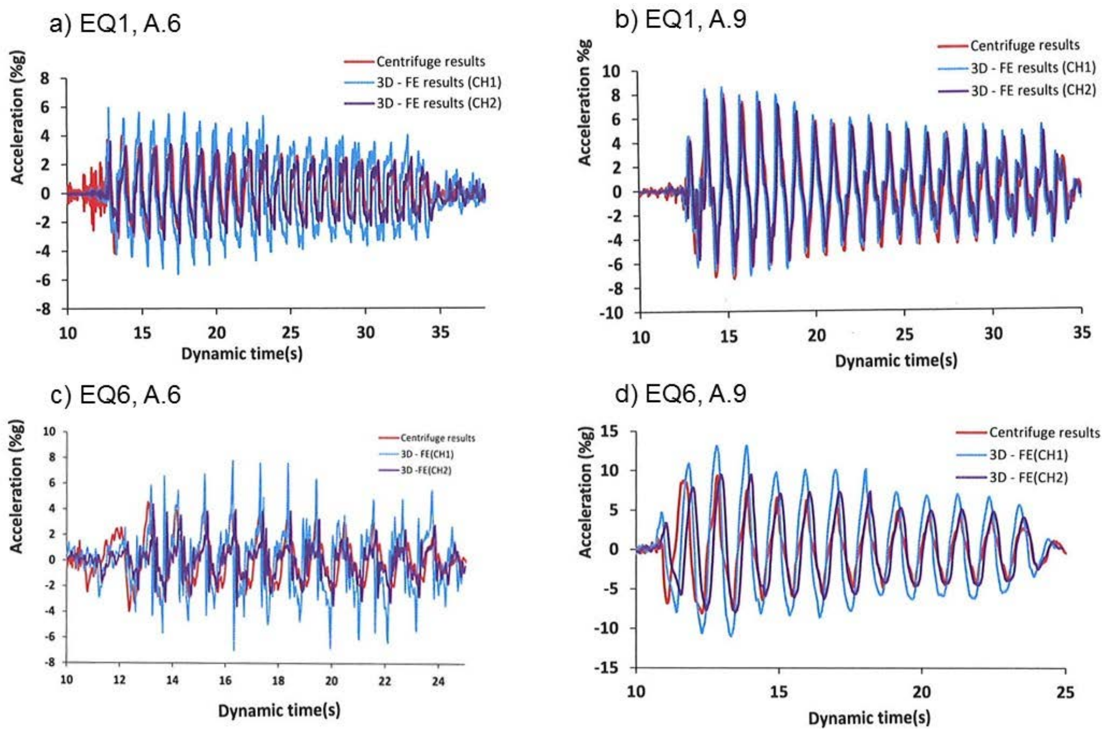

Figure 6. Comparison of measured centrifuge and FE predictions with reduced-stiffness material model parameters, for a) earthquake 1, soil; b) earthquake 1, structure; c) earthquake 6, soil; d) earthquake 6, structure.

Parametric study

In order to evaluate the dynamic performance of suction caissons supporting tall towers, the validated case is modified to better represent a prototype offshore wind turbine. To fit a prototype turbine equivalent to the Vestas V164 8MW design, chosen as these are currently installed along with suction caissons at the Vattenfall EOWDC site off Aberdeen. Towers of height 95 m and 130 m were created giving natural frequencies of 0.25 Hz and 0.14 Hz respectively. Operationally, rotation is designed to be 0.175 Hz giving blade-pass frequency of 0.53 Hz, meaning these designs are “soft-stiff” and “soft-soft” respectively, using the classifications of Adhikari and Bhattacharya (2012). This work however does not consider operational aspects further. Figure 7 shows the model created for Plaxis 3D; further details are presented in Mrema (2018).

Seismic analysis was carried out on a number of structures. Presented here are structures of breadth B = 20 and 25 m respectively and depth D = 15 m. These are subjected to four input motions chosen to cover a range of shaking frequencies. Figure 8 shows the motions as time series and in terms of the 5% damping elastic spectrum, recording stations shown in the caption.

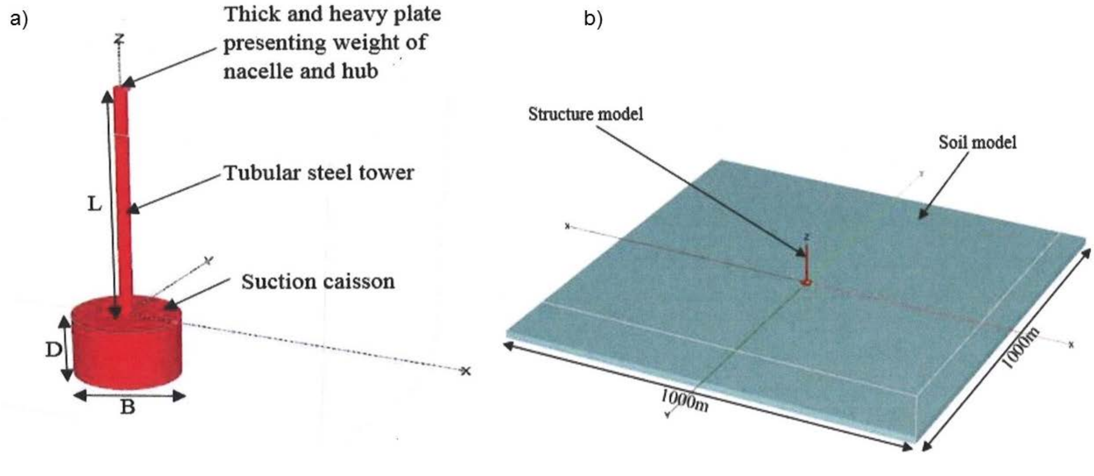

Figure 7. 3D FE model of a) structure and b) system for parametric study. Soil depth = 40 m

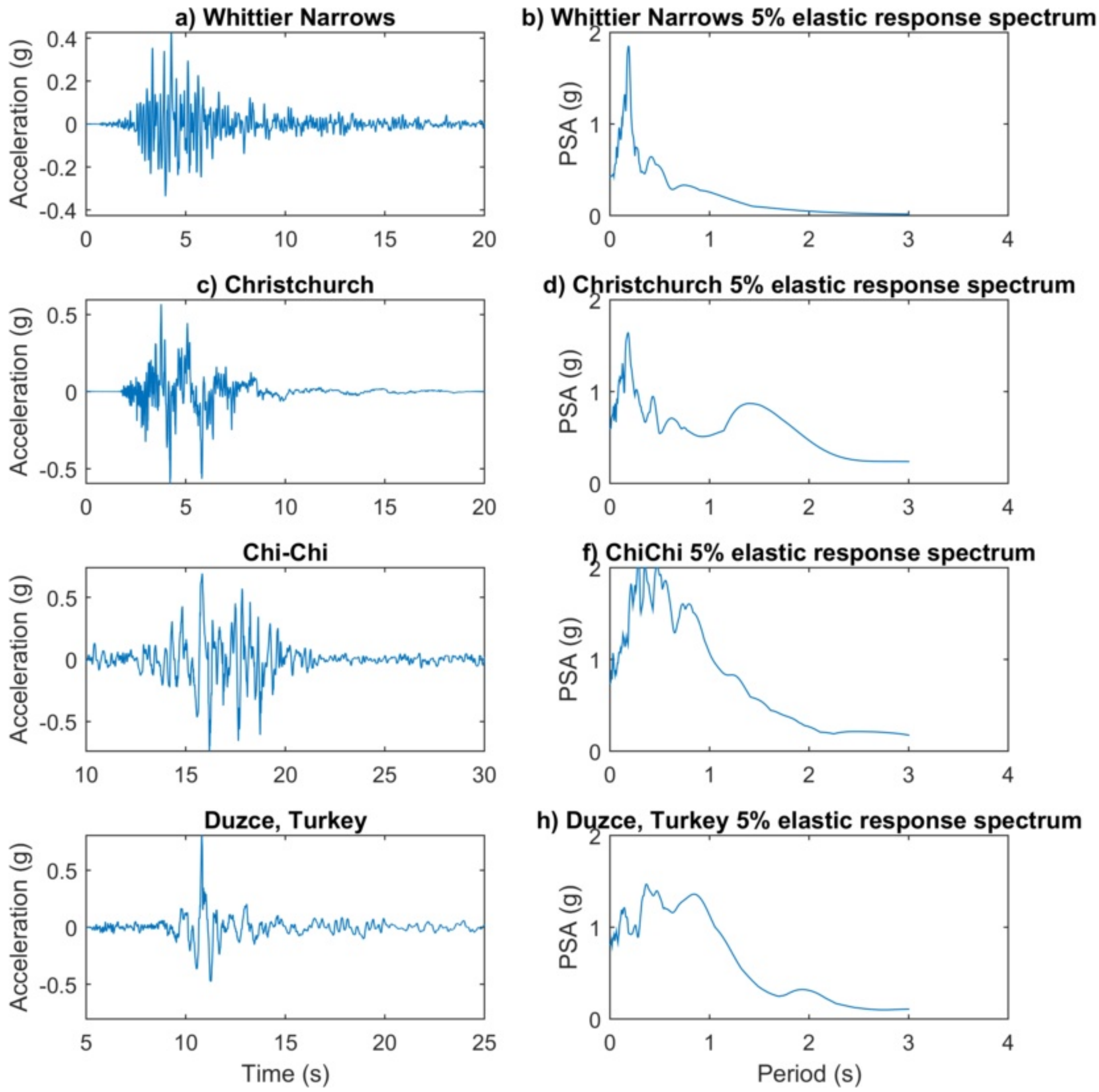

Figure 8. Input motions for parametric study a) Whittier Narrows (LA-Obregon Park) b) Christchurch (Pages Road) c) Chi-Chi (CHY028) d) Duzce, Turkey (Bolu)

Results

For brevity, results presented here are limited to response spectra. The response spectra produced from the motion recorded at the top of the foundation (but not on the tower) as shown in Figure 9 is of interest, because it is this that controls the response of the tower structure. Therefore designers need to know how to determine this parameter in this location. A common activity in seismic design would be a free-field site response, which would generate a response spectrum at the soil surface (Figure 9). To investigate whether this acceleration was representative of the structural behaviour, the response spectrum of each motion for each structure are shown in grey on the left hand side of Figure 10. In all cases it is seen that pseudo-spectral accelerations are significantly less than the equivalents calculated form the input motions, indicating that the soft clay has applied strong attenuation to the motions. This is in line with the literature discussed above, and the validation case. Superimposed on these measured foundation responses is the spectrum experienced in the free field during each event. As can be seen, the two responses bear little resemblance, particularly in the low period range, with significant peaks in response being missed as a result. This is because the very soft normally consolidated soil continues to strongly attenuate the motion as it approaches the surface, whereas the caisson extends deep into the soil and therefore is in contact with soil experiencing stronger shaking. The very low stiffness of the soil compared to the structure means that the near-surface soil imposes little interaction force on the structure, allowing it to move almost independently of the near-surface soil.

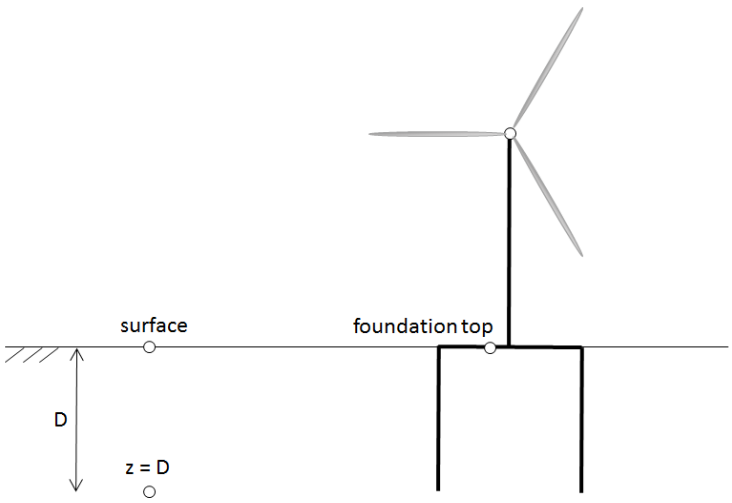

Figure 9. Schematic of places used to generate response spectra for Figure 10

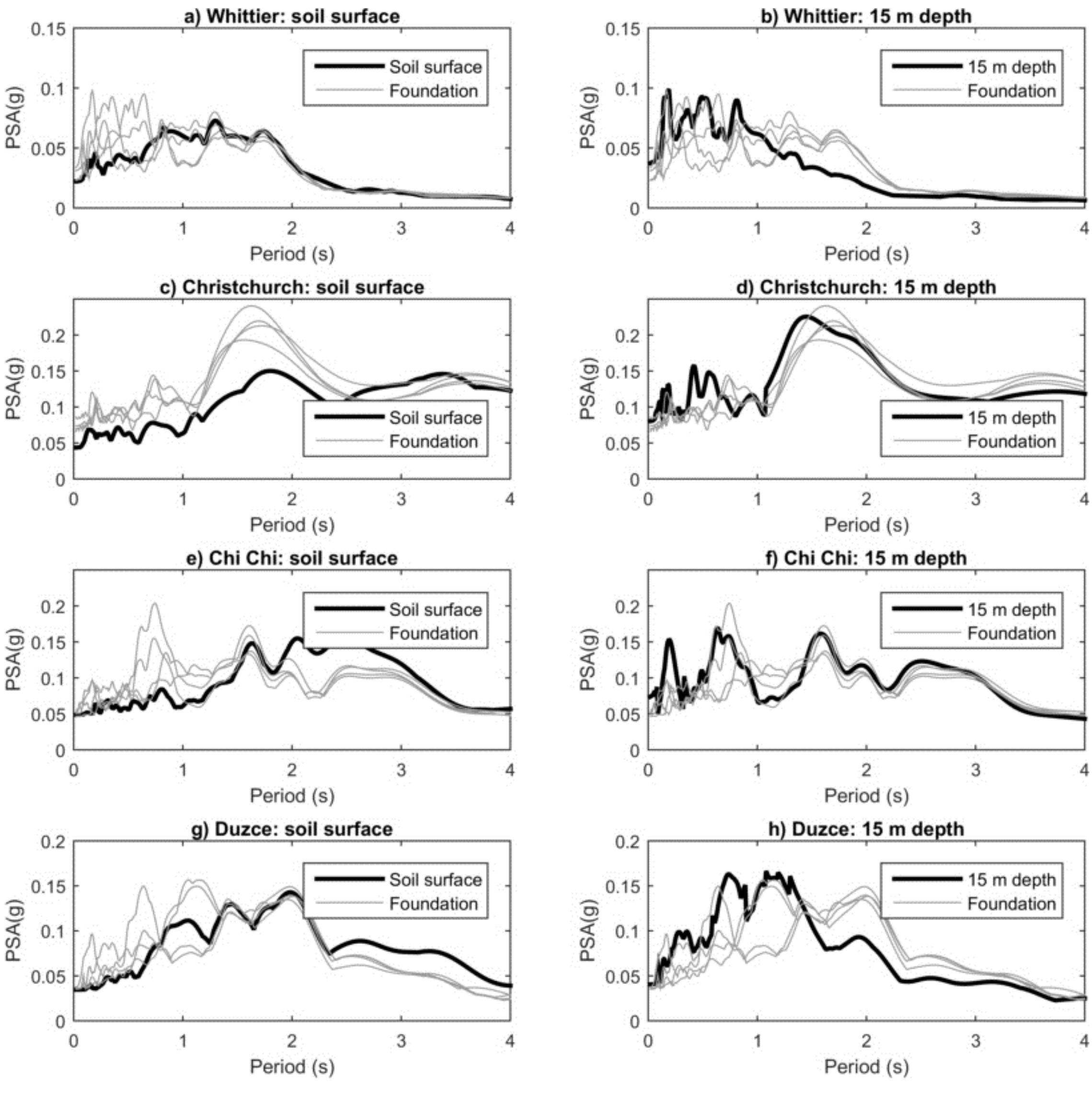

Figure 10. Response spectra measured at top of foundation (all cases) compared to response spectra obtained in free field at ground level (left hand side) and at level of foundation base (i.e. where depth z = D) (right hand side)

As the caisson is stiff it is reasonable to expect that it does not strongly change the accelerations that are entering the structure at its deepest point (i.e. behaviour is close to rigid-body). For this reason, a second comparison is made, between the foundation top motion (as before) and the free field acceleration experienced at a depth equal to the caisson length, i.e. when depth = D (Figure 9). These comparisons are plotted on the right hand side of Figure 10 for each motion. In each case, the soil response at 15 m forms a good upper bound on the foundation response, following the measured foundation response curves well, confirming that the motions entering the caisson (at depth = D) are the ones that govern its dynamics during an earthquake, due to the very low stiffness of the soft clay soil.

This has an important ramification. If site response is required for a new design of suction caisson structure in soft clay, then a site response can be carried out as long as it is understood that the foundation will experience motions equivalent to those at the depth to which the foundation will penetrate. In this study (and for structures of depth 35 m tested in the companion study (Mrema, 2018), those motions were a good match for the response of the overall caisson. However, a wider range of structures now need to be tested to explore the robustness of this finding.

Conclusions

The response of suction caissons in soft clay soils to strong earthquake loads has been presented. The structures were able to be modelled well using the FE code Plaxis 3D. However, it was seen that when compared to a physical model, the initial testing was not perfect and required some modification to correctly match the validation case. Such validation is seen as vital to the veracity of any FE modelling campaign.

Having verified the model was capable of matching the key behavioural aspects of seismic loading of suction caissons in soft clay – strong attenuation of motions in the soil, and less strong attenuation in the structure – a series of strong motions were applied to a number of differently dimensioned structures. Results from caissons of depth 15 m have been presented and it is shown that free field motions bear little resemblance to the caisson motions due to the significant attenuation identified. However, accelerations at a depth equal to the caisson depth produced very similar results to those measured on the caisson itself. It is therefore concluded that accelerations at a depth equal to the caisson depth may be a useful parameter for basing further structural design. Further work is necessary to explore the robustness of this conclusion across a range of foundation geometries.

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