NON-LINEAR VERSUS LINEAR FOUNDATION MODELLING IN DYNAMIC RESPONSE OF AN AJ70 JACK-UP

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ABSTRACT

In dynamic analyses of jack-up platforms according to ISO 19905-1 [2] the foundation is generally modelled as a linear spring. The damping action of the foundation is included as viscous damping at a fixed percentage of the critical damping of the platform instead of modelling the more complex non-linear, hysteretic (rate independent), behavior of the foundation. While such an approach is generally conservative it can underestimate the actual damping provided by the foundation. In this paper the effect of non-linear versus linear foundation modelling on the dynamic response of a harsh-environment deep water accommodation jack-up has been evaluated by means of time domain simulations. The foundation stiffness curve is derived based on analyses as described in the accompanying paper [1] and uses a non-linear foundation model based on kinematic hardening. Foundation damping is computed by FEA based on soil damping defined on a material level. The results suggest a significant effect of the non-linear foundation on the dynamic response. The resulting dynamic amplification factors are compared to that determined based on linear foundations as is general practice. A significant increase in damping and consequentially a reduction in inertial response is identified.

KEY WORDS: Non-linear foundation, Kinematic hardening, Dynamic Amplification, Hysteretic damping

INTRODUCTION

Jack-up structures have developed over the last decades towards operations in deeper water with harsh environments such as the North Sea. The increasing water depth poses several challenges. Larger jack-ups, which are required to operate in these conditions, attract larger loads from wind, current and waves. These larger platforms generally have a longer natural period, which is closer to the excitation period of the waves as they have a larger elevated weight and reduced system stiffness due to the increase in leg length. The effect of damping becomes more significant as the natural period of the jack-up approaches the peak period of the wave spectrum. The large-diameter skirted footings of large jack-up platforms such as the GustoMSC design AJ70 can generate a significant amount of rotational fixity and damping which improves the global response. This is particularly important when the foundation is taking advantage of competent soils, such as those frequently encountered in the North Sea and other locations around the world. This increases the importance of modelling the non-linear behavior of the foundation accurately.

A detailed model of the foundation behavior of the skirted footings of a harsh-environment jack-up is described in the accompanying paper [1]. This approach has been developed by the Norwegian Geotechnical Institute (NGI) over the last decades and has been implemented in recent site assessment studies by GustoMSC. In this paper an example analysis is shown for the new GustoMSC design AJ70-X150-500 accommodation jack-up suited for operation in up to 150m of water depth in the North Sea.

Generally, in the dynamic response simulations of the structure the foundation is represented by a linearized foundation rotational stiffness and a fixed contribution to global damping. The footing behavior may also be modeled by use of a non-linear hysteretic foundation model. In this paper the results are presented from a model that includes kinematic hardening behavior at the foundation. Results from both approaches, both in line with ISO 19905-1 [2], are compared. Also, the outlines of a best-fit method, which can be used to take advantage of complex foundation behavior using a simplified model, are proposed.

DESCRIPTION OF AJ70 AND DESIGN CONDITIONS

The AJ70-X150-500 is designed to provide space and support equipment for 500 persons and is based on GustoMSC's CJ-series of cantilever drilling jack-ups. The unit has been designed to operate year-round in water depths up to 150 meter in harsh environments.

The jack-up is equipped with a large deckhouse arrangement that provides permanent accommodation and facilities for 500 persons in accordance with relevant NORSOK standards. The jack-up has three X-braced truss legs which are elevated and lowered by means of an opposed pinion, electrically driven, rack and pinion jacking system. The unit is locked in place by means of a fixation system once elevated to target air gap. The foundation is provided by relatively flat skirted footings. These are fitted with piping systems for filling of cavities remaining after installation. Principal dimensions are given in Table 1 and an artist impression is shown in Figure 1.

Table 1 - Principal dimensions of AJ70

Item	Value	Unit
depth of hull	12.0	m
leg length	206.7	m
longitudinal leg spacing	60.6	m
transverse leg spacing	70.0	m
leg chord spacing	18.0	m
footing area	380	m^2
skirt height	2.0	m

Figure 1 - Artist impression of AJ70

The conditions for the present analyses are taken as in [1]. General conditions are 135 m water depth and 30 m air gap. The unit's elevated weight is taken here as 220 MN. The skirted footings are placed on a stiff clay soil.

FOUNDATION MODEL

Deriving Foundation behavior

Geotechnical engineers can provide the foundation's rotational stiffness and damping typically expressed as a function of the moment load applied to the foundation. The foundation stiffness and damping curves will typically be based on finite element analyses and should consider effects of cyclic loading, preload and the vertical and horizontal load relevant for the situation. The effect from cyclic loading may be accounted for by the accumulation methods described by Andersen [3].

The case presented [1] considers a 22m diameter footing resting on the seabed with 2m deep skirts penetrated into the seabed. An idealized 2 layer soil profile was considered, consisting of a 7m thick highly over-consolidated clay (OCR = 40) underlying an over-consolidated clay (OCR = 4). The vertical foundation ultimate bearing capacity exceeds the pre-load of the jack-up.

The secant rotational stiffness for various load levels is computed by FEA based on soil stress-strain relations described on element level. The computation of the secant rotational stiffness is well documented in [1] with special attention to the effect of cyclic loading. Likewise, the foundation damping for various load levels can be computed by FEA based on the damping-strain relation described on element level. The computation of foundation damping is not standard in jack-up site assessment and not considered in [1]. However, foundation damping represents a potential for reducing loads and can be considered in projects where relevant soil damping data exist.

Computation of foundation damping

The foundation damping was calculated by the NGI in-house FE program INFIDEL [4], [5]. INFIDEL is a pseudo-static non-linear, 3-D Finite Element program primarily intended for soil-structure interaction analysis to aid design of offshore structures. The soil was modelled as undrained with a hyperbolic stress-strain relation starting from G_{max}. The hyperbolic stress-strain curves were fitted to the stress-strain curve used in the analyses documented in [1]. In addition, a separate damping versus shear strain relation for the soil is input to the program. The damping expresses the energy loss during a cycle with the given strain amplitude. The damping curves suggested by [6] were used to establish one damping curve used for both layers in the analysis. The curve represented equivalent number of cycles N_{eq} = 10, Plasticity Index PI = 25 and the average of OCR=4 and 40.

It is noted that since the damping-strain relations used in the analyses are general curves and not interpreted from the same soil and laboratory tests as the stress-strain, some inconsistency may occur. The analysis is done only for a typical 'neutral' (i.e. not a true leeward nor windward) leg and the load combination increasing to H = 7.5 MN and M = 600 MNm. The foundation stiffness and damping as computed from the INFIDEL analyses are shown as function of load in Figure 2. The figure shows separately the calculated soil damping and rotational stiffness as a function of applied moment. The stiffness is also shown in the form of the backbone curve as Moment versus rotation.

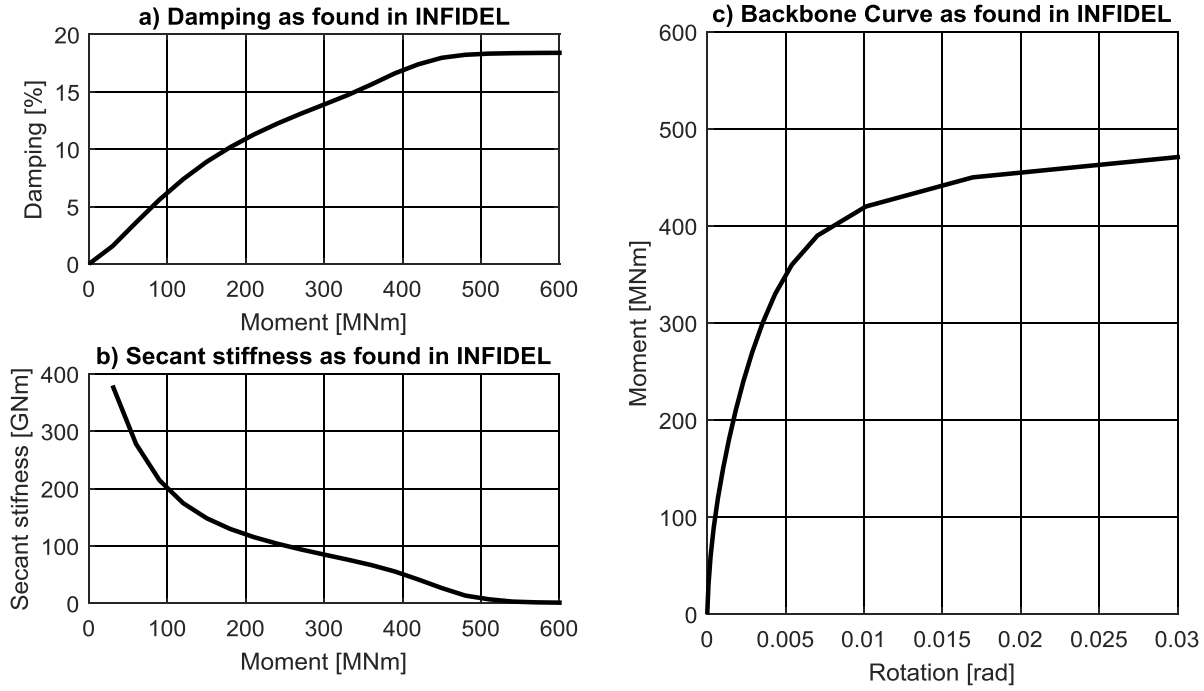

Figure 2 - Backbone and damping as calculated with INFIDEL

Kinematic hardening model

The non-linear foundation model used in this study is a kinematic hardening (KH) type model. The applied foundation model considers rotational degrees of freedom only. In the following the general terms force and displacement are used instead of moment and rotation.

The kinematic hardening behavior is exemplified in Figure 3a. In the graph, the force is increased from zero to F_{max} and then cycled. The initial loading path follows the backbone curve as specified. The backbone curve is the only input to the kinematic hardening model. The subsequent cycle of the force with amplitude F_{max} follows the kinematic hardening behavior based on Masing's rule, as indicated in [7] and [8].

The potential energy E_p in the cycle is visualized in Figure 3b and is defined as

$$E_p = \frac{1}{2} F_{max} u_{max}$$

The damping ζ can now be expressed as a ratio of dissipated energy and potential energy so that

$$\zeta = \frac{E_d}{2\pi F_{max} u_{max}} = \frac{E_d}{4\pi E_p}$$

Both E_d and E_p depend solely on the backbone curve and the force amplitude. Hence for any cycle amplitude of a system that adheres to pure kinematic hardening, ζ_{foot} is a function of F_{max}.

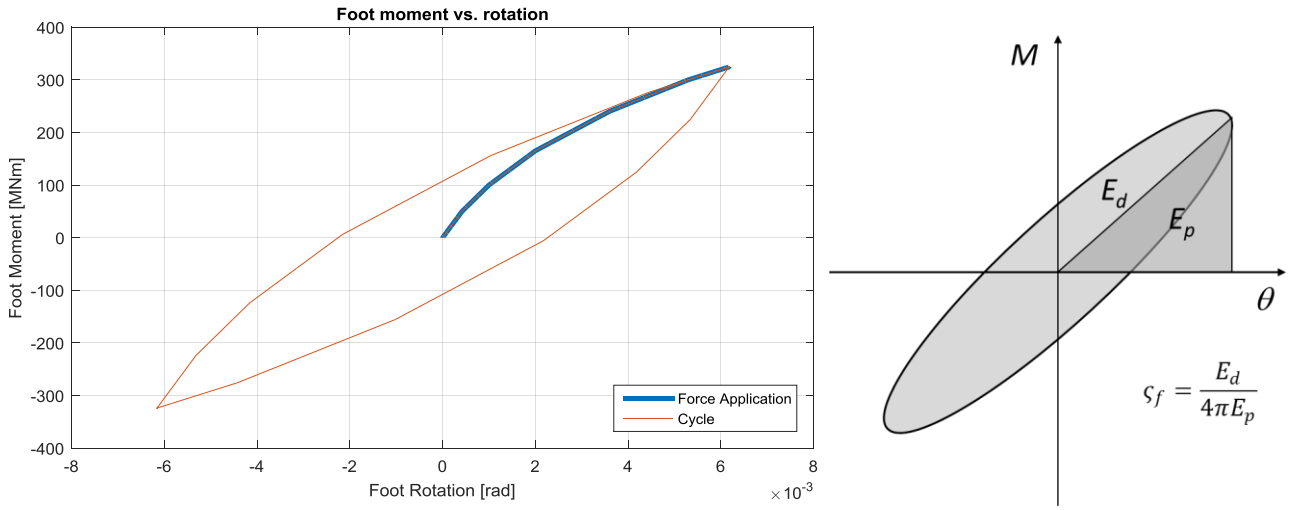

Figure 3 - a) Kinematic hardening behavior of footing moment versus rotation b) Visualization of Ed and Ep surface

Practical application in time domain analyses

The foundation stiffness and damping in Figure 2 are the basis for defining a nonlinear foundation response. During a load-unload-loop, the backbone curve will also describe an energy loss or damping due to the hysteretic nature of the response. The stiffness and the damping of the Kinematic Hardening Model should ideally be consistent with the curves in figure 2. However, the available soil data may show some disagreement as will be demonstrated further on. The implementation of the foundation behavior in the structural analyses should then be approached conservatively by not overestimating the damping.

In the present example case there is some disagreement between the stiffness and the damping results from INFIDEL if pure kinematic hardening behavior is assumed. It was therefore chosen to model the foundation response by two different approaches:

1) By matching the damping curve from INFIDEL, reffered to as the *damping-matched backbone curve*,

2) by matching the stiffness curve from INFIDEL, reffered to as the *stiffness-matched backbone curve*.

If the *stiffness-matched backbone curve* is used in a pure kinematic hardening foundation model, the resulting damping would be according to the yellow line in the damping graph in Figure 4. The yellow line has been calculated in accordance to the formulae presented in the previous section. The damping would be over-estimated compared to the results from INFIDEL. The resulting damping from the stiffness-matched model approaches 50% damping for large displacements, while soil material damping rarely approaches 30% (e,g, [6], [9] and [10]. In the present example it was found that soil damping approaches 20% at large strains.

The *damping-matched backbone curve* has a different secant stiffness (i.e. modified backbone curve) and only crosses the original backbone curve in the origin and one more point. This point of intersection was chosen here to correspond to the expected maximum footing moment as found in the simulations. This approach is in line with [11], where a general procedure for establishing such a backbone curve is presented. This approach is modified here such that the resulting damping curve from the backbone curve is exactly matched to that of INFIDEL over its full domain. Since the maximum footing moment is initially unknown, the process of finding the correct backbone curve and using it in simulations is iterative. The backbone curve thus obtained is represented by the red line in Figure 4. As we are interested in studying the effect of non-linear foundation models on damping ratios en inertial loads the damping-matched backbone curve has been used in the time domain analysis presented in this paper incorporating the non-linear kinematic hardening (KH) foundation model.

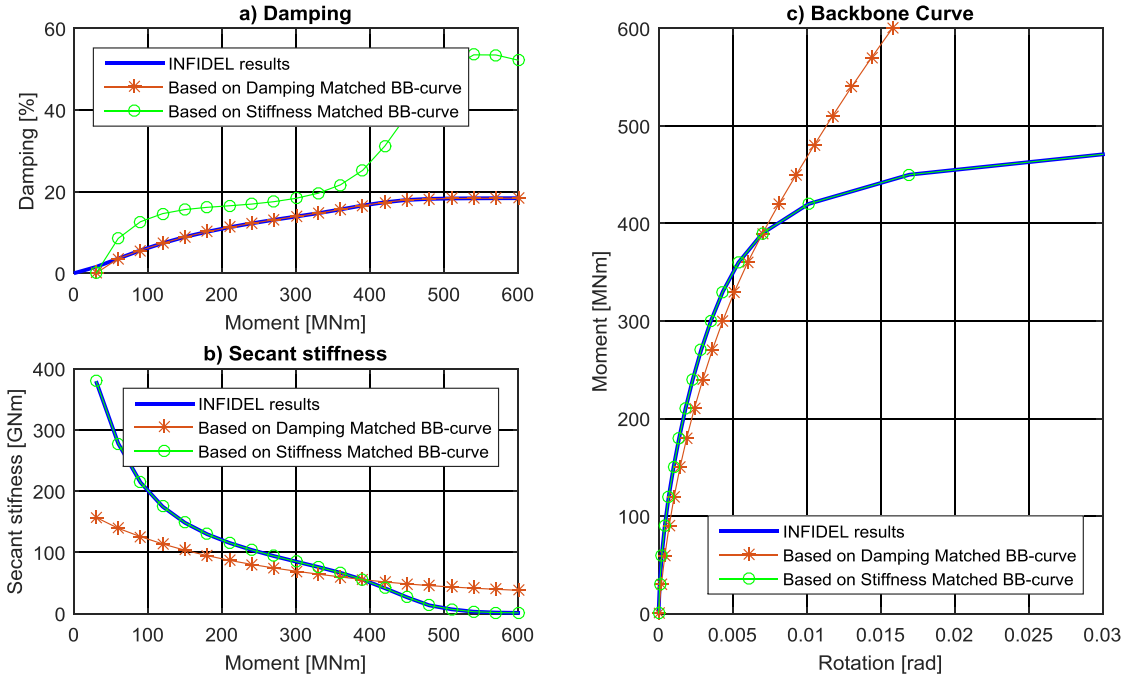

Figure 4 - Damping, secant stiffness and backbone curve for INFIDEL data and applied KH model

TIME DOMAIN ANALYSES INCORPORATING KINEMATIC HARDENING BEHAVIOR

General

Sixty time domain simulations of 3 hour duration are performed for environmental loads acting in the longitudinal and transverse direction of the jack-up. The simulations are performed in a proprietary GustoMSC time domain analysis program SIMSEP. For each of the 60 simulations a the quasi-static (no inertia accounted for) and the dynamic (inertia included) behavior of the platform is calculated. The structural model used in the analysis matches the geometry and weights of the jack-up. Each of the three legs of jack-up is modelled by 20 equivalent leg beam elements. The interface between the leg and the hull is modeled by springs and the hull is modeled by beams. Representative nodal masses are included on all nodes. Hydrodynamic loads on he model

are generated from simulated irregular long crested Stokes' 2nd order wave theory and the Morison equation assuming H_s = 14.7 m and T_p = 16.7 s. A 1.25 m/s current is considered. The contribution of structural and hydrodynamic damping is included by an assumed constant value of 2.5% of critical damping on the first dynamic mode. Relative hydrodynamics are therefore not included.

The Dynamic Amplification Factor (DAF) is the main indicator of inertial response. It is found by dividing the maximum overtruning moment (OTM) of the model in quasi-static calculation by that of the dynamic calculation. A representative DAF for the OTM is found by collecting the maximum OTM encountered in each of the 60 quasi-styatic and dynamic calculations and fitting a Gumbel distribution through them. The representative DAF on OTM is then found by taking the ratio of the dynamic (Dyn) OTM and the quasi-static (QS) for a probabillity of non-exceedance of 63%, which is in line with ISO [2] guidance.

Simulation results

The simulation results for the longitudinal heading are shown in Figure 5.

A *damping matched backbone curve* is specified for the kinematic hardening macro-elements. The secant rotational stiffness is matched at the assumed maximum footing moment $M_{foot;a}$ = 390 MNm, as vissible as an intersection of the INFIDEL and damping matched backbone curve in Figure 4c. The resulting maximum footing moment from the dynamic simulations at 63% probability is equal to $M_{foot;r}$ = 425 MNm. For this maximum footing moment the DAF on OTM in the longitudonal direction is 1.34. This is a slight oversetimation of the DAF as the maximum footing moment is the simulations exceeds that assumed in the derivation of the backbone curve. A second simulation was performed therefore where the backbone curve was fitted to a maximum footing moment of 420 MNm. this resulted in a footing moment in the simulations of 391 MNm and a DAF of 1.30. The true DAF on OTM will thus be somewhere between 1.30 and 1.34 In the remainder of this paer a DAF of 1.34 is used however.

The DAF on OTM in the transsverse direction was obtained in the same manner. Concluding, the DAF was found to be 1.34 for longitudinal heading and and 1.51 for transverse heading.

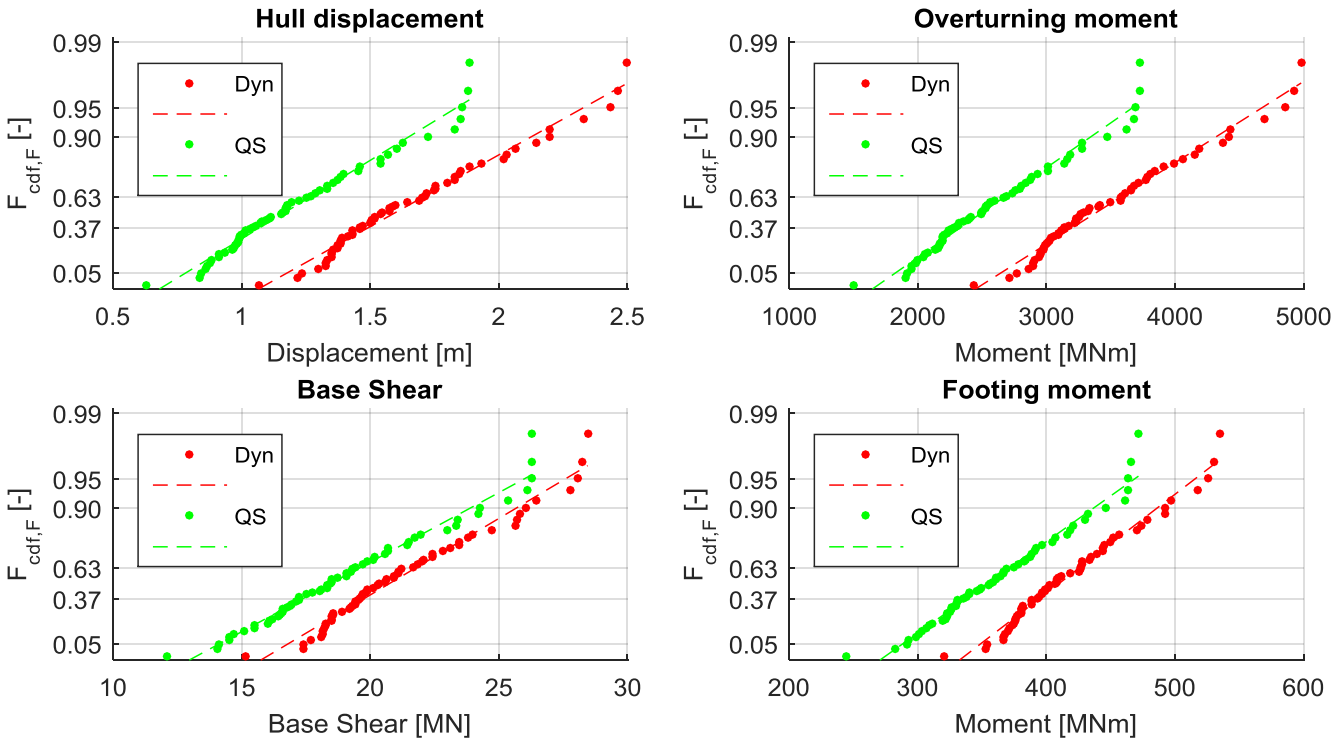

Figure 5 - Maxima from 60 simulations at longitudinal heading with non-linear KH foundation model

COMPARISON BASED ON LINEARIZED STIFFNESS AND DAMPING METHODS

Simulations according to ISO 19905-1 [2] linear stiffness approach

In general practice, the foundation model in time domain simulations is simplified to a linear elastic spring and constant damping. An established guidance as suggested in ISO 19905-1 is to take 80% of the linear elastic initial rotational stiffness as value for the dynamic rotational spring stiffness. Soil damping can be added to the structural and hydrodynamic damping for which guidance suggests that 2 to 3% damping may be considered for an extreme storm situation.

In the (linearized) time domain analyses performed for the present example, the dynamic rotational stiffness is defined as K = 130 GNm/rad, which is 80% of the estimated initial stiffness in line with ISO guidance as described in [1]. The natural period of the platform associated with this stiffness is 8.2 seconds. Simulations have been performed for a low estimate of soil damping (total global damping taken as 5% of critical) and a high estimate value (total global damping taken as 7% of critical).

Simulation results for K = 130 GNm/rad and 5% global damping

The results of the simulations that incorporate 5% global damping are presented in Figure 6. The DAF as found is 1.55 for the longitudinal wave heading and 1.67 for the transverse heading.

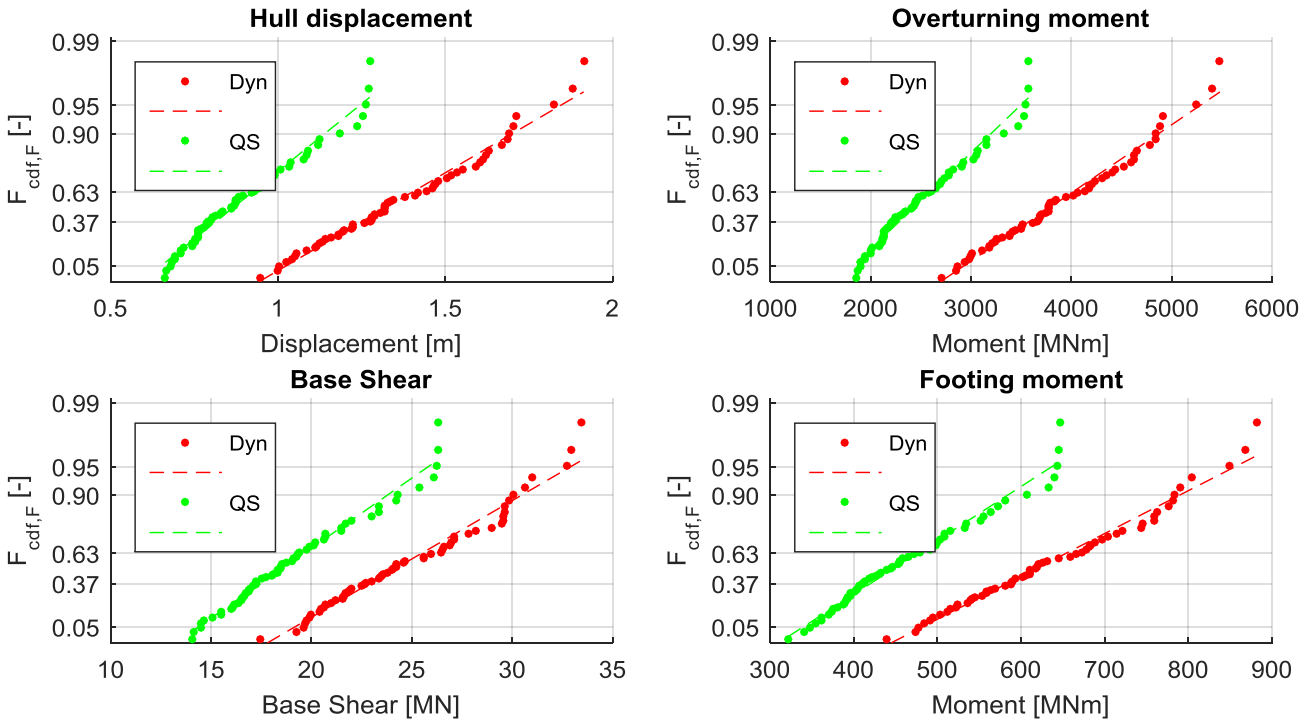

Figure 6 - Maxima from 60 simulations at longitudinal heading in accordance with ISO at 5% total damping

Simulation results for K = 130 GNm/rad and 7% global damping

The simulations were also performed incorporating 7% global damping to indicate the effect of soil damping. The DAF that was found is 1.46 for the longitudinal wave heading and 1.56 for transverse wave heading.

Comparison

The inertial loads as expressed by their DAF on the overturning moment (OTM) that were calculated from the non-linar foundation model are compared to those using a linear foundation model with either (low-estimate) ζ=5 % damping or (high estimate) ζ=7 % damping. The values are summarized in Table 2. The reduction in

Overturning Moment (OTM) representing the inertial effect is expresed as (DAF_{KH} – DAF_{ISO}) / (DAF_{ISO}-1), which is indicated in the table as relative difference.

Table 2 - DAF results comparison

direction	KH model	linear with ζ=5 %		linear with ζ=7 %	
	DAF	DAF	rel. diff*.	DAF	rel. diff*.
longitudonal	1.34	1.55	-38 %	1.46	-26 %
transverse	1.51	1.67	-24 %	1.56	-9 %

*) relative difference calculated as(DAF_{KH} – DAF_{ISO}) / (DAF_{ISO}-1)

Table 2 indicates a significant reduction in inertial loads of between 24 % and 38 % as compared to the low-estimate linear elasic footing model as achieved by considering the non-linear KH behaviour of the soil. From table 2 it is concluded that inclusion of a kinematic hardening type of foundation model may affect the dynamic behavior of the simulated platform significantly. In the specific case investigated here it resulted in a reduction of the inertia effect.

METHOD TO DETERMINE LINEARIZED STIFFNESS AND DAMPING

Best-fit associated stiffness and damping from INFIDEL curves

In common practice, the application of a kinematic hardening type of foundation model in time domain simulations may not be practically possible, for example due to limitations in the structural analysis software. For these cases it would be helpful if the non-linear stiffness and damping could be linearized into a linear stiffness and damping, similar to the standard ISO guidance, but with values calibrated to the non-linear results based on associated stiffness and damping taken from, for example, INFIDEL data.

This method is referred to here as '*best-fit'* method as suggested in [12]. For a comparable GustoMSC design jack-up (CJ70) in comparable conditions (same footings in stiff clay) similar analyses have been run for typical ALS (10,000-year return period wave) conditions. It was found that the best-fit to the non-linear DAF was found with linear stiffness and constant damping both associated to a peak footing moment found from the non-linear simulations multiplied by a factor γ. This method is not usable in general at present as it requires further development and generalization for different conditions, jack-up designs, foundation types.

Finding best-fit damping and stiffness values

In [12] it is indicated that the damping and stiffness to be used should correlate to the values found at a significant moment $M_s=\gamma*M_p$ where M_p is the peak footing moment *as found from full non-linear simulations* and a suggested value of γ=0.87 for that specific case. It was found for the system considered in the present study that $\gamma \approx 0.8$.

It was found that M_p resulting from the full non-linear model is M_p = 425MNm. This value is based on 60 simulations and found at the 63% probability level. The M_s that yields the best results is M_s = 330MNm. Hence γ = 0.78. The assosiated stiffness, damping and rotation for this foundation moment are K_{FIT} = 76.1GNm/rad, $\zeta_{s;foot}$ = 14.7% and θ_s = 0.00434 rad, based on the results from INFIDEL.

Expressing best-fit soil damping as a global platform damping

The foundation damping can be expressed as global platform damping, which is implemented as viscous damping and defined according to the first mode. To do so, additional knowledge of platform behavior is required. The first mode of the platform is sway of the hull. It is for this mode that damping must be calculated. The applied horizontal force on the hull $F_{x;hull}$ that leads to footing moment M_s must be found. This can be done by a simulation where $F_{x;hull}$ is gradually increased over time on a model that includes K_{FIT} at the foundation. For the platform under consideration it is found that the horizontal hull force $F_{x;hull;s}$ = 12.5MN leads to footing moment M_s = 330MNm. The corresponding hull excursion $u_{x;hull;s}$ = 0.96m.

The dissipated energy at the footings can be related to the platform potential energy to define a general platform damping coefficient due to energy dissipation at the footings.

$$E_{potential;footing} = \tfrac{1}{2} * \theta_s * M_s \qquad \text{and} \qquad E_{dissipated;footing} = 4\pi * \zeta_{s;soil} * E_{p;foot}$$

And as there are three footings $E_{dissipated;platform} = 3 * E_{dissipated;footing}$

$$E_{potential;platform} = \tfrac{1}{2} * U_{x;hull;s} * F_{x;hull;s} \qquad \text{so that} \qquad \zeta_{platform} = E_{dissipated;platform}/(4\pi E_{potential;platform})$$

Substituting the numbers leads to a contribution to the global platform damping of soil damping $\zeta_{soil;platform}$ = 5.3%.

Verification of best-fit associated stiffness and damping

60 quasi-static and dynamic time-domain simulations were used with precisely the same sea states (same random seeds specified) as used in the non-linear foundation simulations presented earlier in this paper. A linearized foundation stiffness, K_{FIT} = 76.1 GNm/rad and a global damping percentage $\zeta_{soil;platform}$ = 5.3 % was specified. It is noted that the stiffness K_{FIT} is 47 % of the assumed initial elastic stiffness, but associated with a higher damping. This is lower than the 80 % assumed generally (but with lower damping), see ISO method discussed above.

The results of the simulations are plotted in Figure 7. The DAF that was found at the 63 % probability level is 1.33 for longitudinal and 1.50 for transverse heading, which is comparable to the DAF as obtained from the KH foundation model indicating the applicatability of the lineralized method ptresented here Sixty simulations with the same random seeds as those previously reported have been re-run incorporating linearized values for foundation stiffness and platform damping, K_{FIT} = 76.1 GNm/rad and $\zeta_{soil;platform}$ = 5.3%. It is noted that the total platform damping is 7.8% adding an assumed contribution of 2.5% due to structural and hydrodynamic damping, in accordance with previously reported simulations. Also noted is that the stiffness associated with this (higher) damping is 47% of the assumed initial elastic stiffness, which is lower than the 80% assumed generally (but with lower damping), see linear ISO method discussed above.

The results of the simulations are plotted in Figure 7. The DAF that was found is 1.33 for longitudinal and 1.50 for transverse heading, indeed similar to the DAF from KH foundation model.

The best-fit value for γ was found by finding the best match in terms of DAF compared to the non-linear simulations. Only a single variable γ is used and both damping and stiffness are determined from it. It is noted that the absolute values as found for the OTM bear a close resemblemce to those from the non-linear simulations presented in Figure 5. The maximum footing moment, however, is significantly overestimated, whilst platform excursion in underestimated compared to the analyses with nonlinear foundation response. This is likely due to overestimation of the stiffness for large rotations compared to the backbone curve as found in INFIDEL.

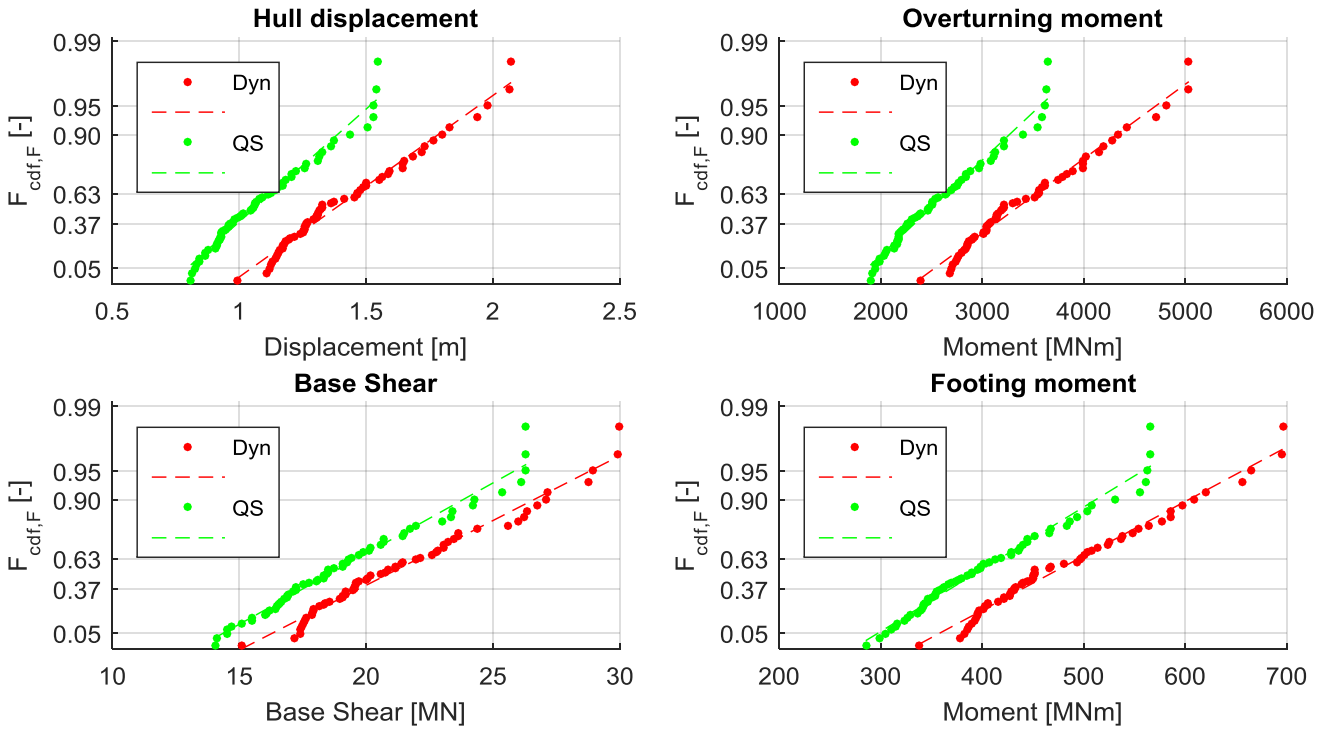

Figure 7 - Maxima from 60 simulations at longitudinal heading with best-fit values used at footing

Validation of equivalent viscous damping and implementation of damping-matched backbone curve

Both dissipated and potential energy in both the foot and in the platform for M_s = 330MNm is measured directly from time domain simulations in order to calculate the equivalent viscous damping coefficient more directly. The results also support and explicit assumption made to find the best-fit equivalent viscous damping. Furthermore, the implementation of the damping-matched backbone curve is further validated.

Firstly, along the lines of the method presented in the previous section, a hull force $F_{x;hull;s}$ that leads to the significant moment on the foot must be found. The damping-matched backbone curve is used, with matched secant stiffness at M_s, so similar values as in the previous section are expected. Hull force of $F_{x;hull;s}$ = 12.6MN leads to footing moment M=331MNm and the corresponding hull excursion $u_{x;hull;s}$ = 0.97m. The force is cycled slowly with amplitude $F_{x;hull;s}$ to find the hysteretic loop.

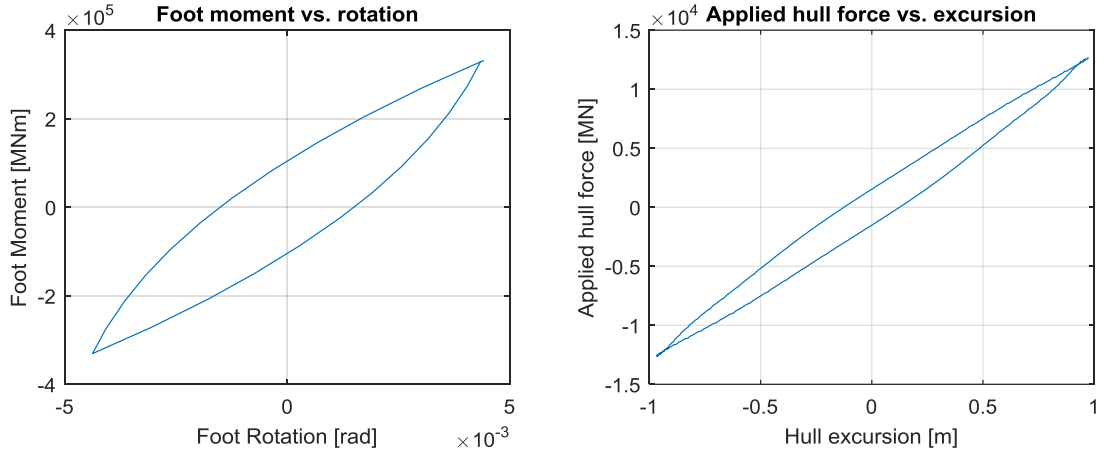

Figure 8 - Hysteresis loops of foot and hull found from a cycling time domain simulation

$E_{d;soil}$ can be found from the surface within the hysteresis loop shown in the left graph in Figure 8. This plot results from an actual time domain simulation where the hull force is slowly cycled. The enclosed surface $E_{d;soil}$ = 1328MJ. The maximum foot rotation θ_s = 0.00438 rad. $E_{p;soil}$ = ½ * M_s * θ_s . $E_{p;soil}$ = 724MJ. Now the foot damping can be calculated: $\zeta_{s;soil}$ = 14.6. All values are in close agreement with the values from INFIDEL and with previously found results.

The energy dissipation at platform level is shown in the right graph in Figure and can be treated in a similar way: $E_{d;hull}$ = 3978MJ. This is 3.00 times $E_{d;soil}$, which supports the three-leg assumption made for the best-fit method. The potential energy of the platform $E_{p;hull}$ = 6109KJ. The platform damping coefficient following from these values $\zeta_{platform}$ = 5.2%, again a close match with results from the best-fit method.

CONCLUSIONS

- A kinematic hardening type model may be used to model a non-linear jack-up footing foundation in time domain simulations.
- The back-bone curve may be defined based on a combination of cyclic stress-strain curves of the stiff clay. Soil damping can be estimated based on damping characteristics of typical stiff clay versus strain level and translated into damping versus footing moment
- Representing the full backbone curve may overestimate soil damping at larger strains in a kinematic hardening model. A *damping-matched backbone curve* is introduced that maintains proper stiffness values around the maximum moment.
- For this specific analysis, the kinematic hardening model for the foundation, which is based on cyclic test data and FE analyses, the DAF of the considered AJ70 was found to be 1.34 and 1.51 for two respective headings, which is lower than the DAF found using standard ISO guidance using linear stiffness at 80% of initial, also with 7% total damping.
- A ‘best-fit’ representation of the non-linear DAF may be achieved by the combination K = 76 GNm/rad and the associated ζ_{foot} = 14.7% (5.3% of critical global damping) from the defined non-linear foundation model (INFIDEL results) which is taken at the load level of 78% of the Peak Footing Moment. This is in reasonable agreement to what was found in [12] considering (for ALS conditions of a CJ70 in comparable stiff clay conditions).

Discussion

- Care is needed as the pure kinematic hardening models, when based directly on stiffness results, tend to overestimate damping in large load cycles as compared to what is found from literature/soil damping tests. A more complex modelling is needed to be able to describe both backbone curve and soil damping properly. Damping-strain and shear-strain formula may not be fully consistent as they were not interpreted directly from the same soil tests, but include some theoretical assumptions. The presently applied damping matched model does not represent the true rotational stiffness as found from INFIDEL
- The present study is limited to rotational foundation stiffness of only a typical neutral leg.
- The present resulting DAFs are specific to this study only, the specific jack-up design and stiff clay conditions. The methodology may be of a more general nature but this requires further development under different conditions, designs etc.

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