Proceedings of ISFOG 2025
5TH INTERNATIONAL SYMPOSIUM ON
FRONTIERS IN OFFSHORE GEOTECHNICS
Nantes, France | June 9-13 2025

ISBN 978-2-85782-758-0

Pile-boulder resistance relationship for pile tip buckling during impact driving

D. Cathie*
CATHIE Group, Brussels, Belgium

O. Zarzouras
CATHIE Group, Brussels, Belgium

**David.Cathie@cathiegroup.com*

ABSTRACT: The presence of buried boulders can be a critical aspect during installation of impact driven open-ended tubular piles. A pile-boulder contact implies that for each hammer blow the boulder will be pushed down and away from the pile, or the pile tip may buckle, or both, which can lead to installation problems and even refusal.
To model the reaction force of the boulder on the pile, a one-dimensional visco-elastic plastic model approach is proposed, which is based on the dynamic response of the pile end bearing proposed by Simons and Randolph (1985), including the lumped boulder mass in the pile-boulder response. The reaction force is presented in terms of the boulder displacement, i.e. as a non-linear spring which accounts for the impact point, the boulder size and mass, the properties of the embedded soil, and the characteristics of the travelling force wave in the pile.
A 2D axisymmetric finite element model was developed in Abaqus to confirm the proposed model for the boulder response during a single blow, when the boulder is impacted vertically by the pile along its vertical axis, performing non-linear transient dynamic analyses. Assuming homogeneous, isotropic soil behaviour and considering the boulder sufficiently deep, its response will be the same in any direction and therefore 3D modelling is not needed. To calibrate the associated correction factors for the 1D formulation, sensitivity studies were performed varying the boulder size and the soil strength and stiffness.

Keywords: Pile impact driving, pile-boulder response model, tip buckling, finite element analyses

1 INTRODUCTION

For offshore structures, open-ended tubular piles are considered one of the main foundation solutions, in a group or single large monopiles. During installation they are usually impact driven to the required depth, with buried boulders being a serious hazard.

When a pile encounters a boulder, the impact wave from the hammer is transmitted through the pile-boulder contact, generating a contact force which in turn causes the boulder to displace. As the pile continues to advance, any lateral boulder movement results in a change in position of the contact point between the pile and boulder. The boulder progressively moves downwards and laterally outwards (or inwards) from the pile until the pile tip has passed the boulder. During this process the pile tip may be damaged, potentially resulting in refusal. There are cases with driven piles distorted at or close to the pile tip leading to refusal before target penetration is reached.

To model the reaction force of the boulder on the pile and to define the reaction force due to the boulder there are two key issues: the evaluation of a realistic boulder trajectory as the boulder is pushed to one side by the pile, and the realistic boulder reaction which would include dynamic response effects (Fig.1).

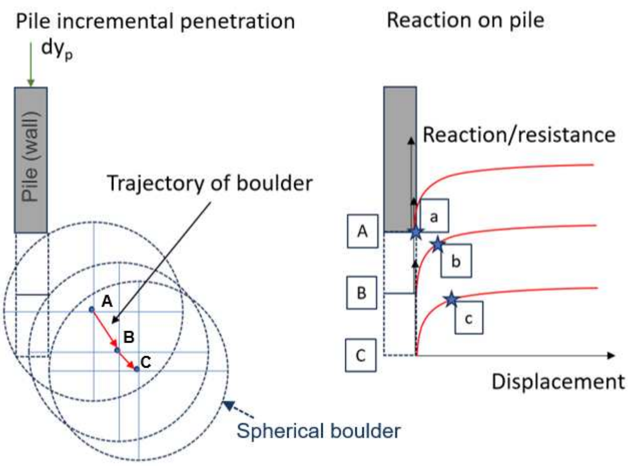

Figure 1. Concept of proposed pile-boulder model

2 PILE-BOULDER RESPONSE MODEL

To solve the complex interaction between pile and boulder, the following simplifying assumptions have been made: (1) the boulder is spherical considering only translation, i.e. no rotation; (2) there is a single contact point between pile and boulder, with frictionless boulder-pile contact, i.e. only normal resistance to the boulder is considered; (3) the pile is rigid and not deforming during impact, hence the full effect of pile displacement, velocity and acceleration is transmitted to the boulder. This provides a high estimate of the actual boulder reaction as in reality the pile will not be rigid; (4) the soil resistance to the boulder movement is the same in all directions, i.e. no dependency on direction and depth; (5) the reaction at pile-boulder contact point consists only of the boulder inertia and the soil resistance which is assumed visco-elastic plastic; (6) the soil resistance component is limited to the static collapse load of the surrounding soil, considering an equivalent bearing capacity mechanism.

The above assumptions imply that the boulder response is independent of whether the pile is open- or close-ended and its size; the boulder trajectory can be defined geometrically as it only depends on the position (around the boulder circumference) of the initial pile-boulder contact point. Hence the boulder reaction transferred on the pile can be calculated from the boulder trajectory and its position relative to the pile, at each increment of pile penetration.

2.1 Boulder reaction model

The proposed contact force model is depicted in Fig. 2. It is based on the Simons and Randolph (1985) model for assessing pile tip resistance.

The dynamic reaction of the visco-elastic components of the system (Fig. 2) is based on Lysmer and Richart (1966) as a closed form solution for the motion of a circular rigid footing on the surface of an elastic half-space. However, since the boulder mass is a significant contributor to the pile-boulder response, the lumped mass is also considered in the model.

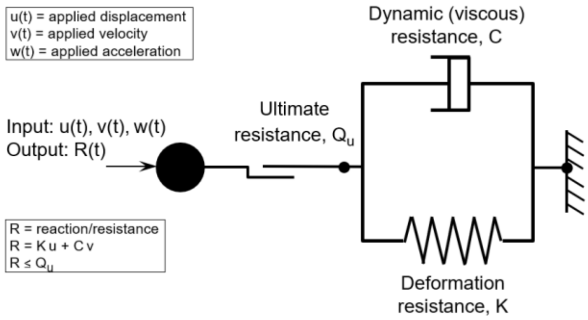

Figure 2. Conceptual visco-elastic plastic model for boulder response

In mathematical terms, the reaction force (R) [kN] generated by the pile's displacement (u) [m], velocity(v) [m/s], acceleration (w) [m/s^2] transmitted to the boulder by the pile can be calculated as:

$$R = min\,(\beta_k\, K\, u + \beta_c\, C\, v,\; Q_u) + \beta_m\, M\, w \qquad (1)$$

where K is the stiffness (static component); C refers to dynamic component (damping); M is the boulder mass (inertia component); Q_u is the ultimate resistance of a deeply embeded boulder. Model coefficients β_k, β_c, β_m have been introduced to account for the embedment effect (as is for instance discussed in FHWA 2008).

Fig. 3 presents an example of the boulder reaction components included in the analytical formulation (Eq. 1) using a realistic velocity-time history input, for a typical pile and hammer used in the offshore industry.

3 FINITE ELEMENT MODEL

To confirm the proposed model for the boulder response during a single-blow and calibrate the associated coefficients for the 1D formulation, non-linear transient dynamic analyses were performed using the finite element software Abaqus.

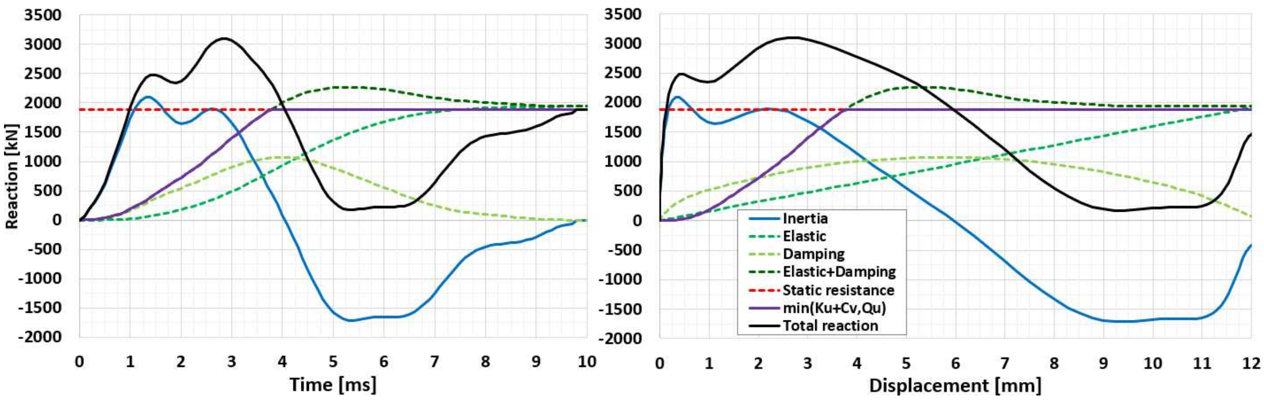

Figure 3 – Example for boulder reaction model [D:1.0m, Su=100kPa, G/Su=200]

3.1 FEM geometry and boundary conditions

The model assumptions permit the generic boulder response to be modelled adequately using a 2D axisymmetric finite element (FE) model for the case when the boulder is impacted vertically by the pile on its vertical axis, without modelling the pile (Fig. 4). The reaction is normal to the boulder and the boulder experiences purely vertical displacement. This case is therefore a special case of impact at any point on the boulder perimeter which results in movement normal to the contact point. The generic response is then used for all other contact points (with appropriate account of the direction of the movement), justified by the uniform resistance which would apply in all directions.

The boulder was considered at depth equal to approximately 10 times the boulder diameter (10xD). The total soil domain in the model was extended equally above and below the boulder. Laterally the boundaries were selected sufficiently far to avoid any effects on the analysis results, i.e. approximately 10xD (Fig. 4), and to limit boundary reflection effects within the simulation time (total analysis duration 0.1 seconds). In addition, infinite elements were applied to the boundaries of the soil domain to model the far field region, which have linear behaviour, providing stiffness in static solid continuum analysis and provide "quiet boundaries" for the finite element model in the dynamic analysis (Fig. 4).

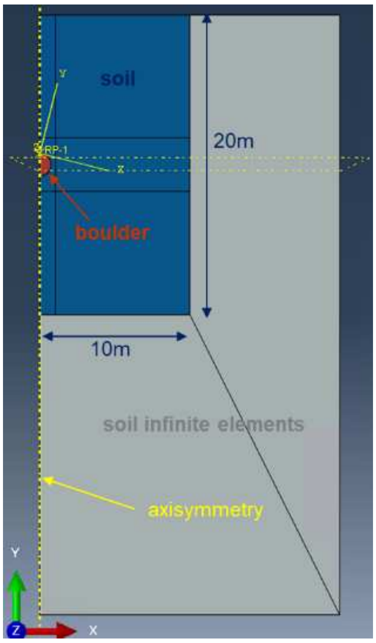

Figure 4. FE boulder response model overview (D:1.0m)

3.1.1 Material properties

The boulder was defined as an elastic material with intact rock properties. The soil constitutive behaviour is elastic-perfectly plastic (Mohr-Coulomb), considering undrained conditions and cohesive material properties, defining the density (ρ), the Shear modulus (G) and the soil undrained shear strength (S_u). Table 1 summarises the material properties used in the models.

Table 1. Material properties for FE analyses

Material	ρ [kg/m^3]	G [kPa]	S_u [kPa]
Soil (elastic perfectly plastic)	2000	200-500 S_u[1]	75-200[1]
Boulder (rock)	2600	15000	-

Notes: (1) Varying values as part of the parametric investigation

To avoid meshing, numerical convergence issues and improve results accuracy, the mesh was refined around the boulder with a minimum element size of 0.04m (Fig. 5).

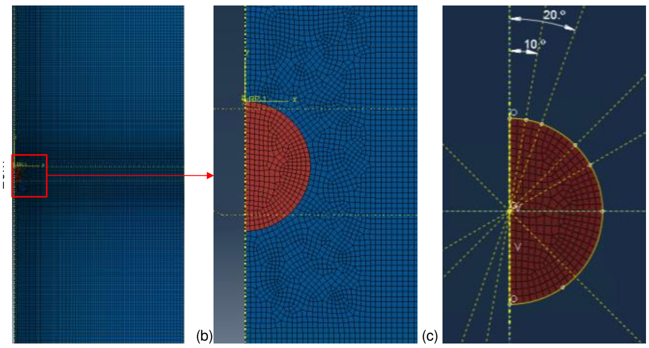

Figure 5. Mesh refinement and predefined surface for velocity input (example of D: 1.0m)

Table 2 presents the different element types used in the Abaqus model, the corresponding mesh size and approximate number of elements (total number of elements approximately 28k). For the model validation a sensitivity analysis on the different mesh size was considered.

Table 2. Material properties for FE analyses

Material	Element type	Element size[1] [m]	No. elements (appr.)
Boulder	CAX4R	0.04	315
Soil	CAX4R	0.04	28k
	CINAX4		350

Notes: (1) Min. element size (local refinement applied)

For the transient dynamic analyses, the dynamic soil behaviour was accounted for. Generally, it is dependent on the shear strain (which can be expressed in terms of the G/Gmax ratio) and the hysteretic damping. For this study, soil properties were not modelled as strain dependent (constant shear modulus value considered), while the target hysteretic damping, ξ (constant value), in Abaqus was introduced via equivalent Rayleigh damping values (Chopra, 1995).

3.1.2 Boulder-soil interface

Regarding the boulder-soil interface, a classical surface-to-surface contact for the boulder-soil interaction was introduced. For the normal behaviour the pressure-overclosure is defined as “hard contact”. This means that the surfaces transmit no contact pressure unless the nodes of the secondary surface contact the main surface, and no penetration is allowed at the constraint location. The tangential behaviour was defined with a friction coefficient set to 1.0 (rough boulder) and no shear strength limit. The soil-boulder interface allows permanent displacement, and separation of elements normal to the interface.

3.2 FE analysis steps and output

To establish the initial conditions and to obtain equilibrium for the defined load and stress conditions, gravity was introduced in the first “static” step.

To specify the boulder bearing factor (in analogy to the bearing capacity factor for shallow foundations), and hence the ultimate resistance of the boulder (Q_u), static analyses were performed, vertically displacing the boulder to mobilise the ultimate static soil resistance (Table 3).

To simulate the blow and the pile tip impact on the boulder, transient dynamic analyses were performed by applying a velocity signal (time-history) over a predefined surface area (arc) around the boulder (Fig. 5), utilising a realistic input time history based on impact driving of a large diameter monopile (Fig. 6). Note that the single blow considered corresponds to a “typical” pile set value for a single blow (and hence boulder displacement in the direction of the loading) of about 12mm (Fig. 6).

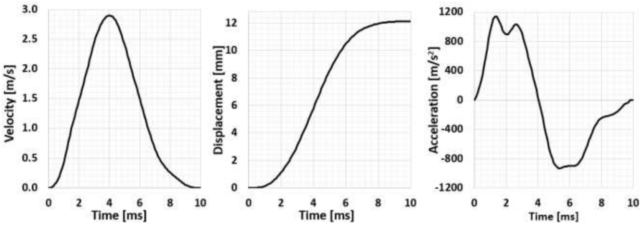

Figure 6. Realistic input time history for impact driving a large diameter monopile

To evaluate the model response the following output parameters were evaluated: reaction force on the boulder considering the different components as described in Eq. 1; and the time histories of the boulder displacement, velocity and acceleration.

To validate the model, mesh- and time-step-sensitivity studies were performed. Specifically, different values for the element size and different time steps were evaluated, checking consistency of the results before concluding on the selected model configuration.

3.3 FE analyses performed

For the selected model configuration, parametric investigations were performed by varying the following:

- Load rate (static or dynamic) to define the equivalent bearing capacity factor for the ultimate resistance of the boulder (Q_u);
- Boulder size, ranging between 0.5m and 1.5m, considering for the low end of the range the ability of available site characterisation methods to identify boulders; and for the high end of the range that for larger boulder sizes that they would be avoided in case identified at a specific location;
- Soil strength and stiffness, which are obviously significant parameters of the model (ranges specified in Table 1);
- Contact area between pile annulus and boulder (for FE model): to account for this effect, the arc over which the input velocity pulse was varied between 10° and 45°. Note that for a typical value of pile (open ended monopile) tip wall thickness of 100mm the contact between a 1m-wide boulder and the pile tip would roughly correspond to an arc of 10°.

Table 3. Sensitivity on parameters to calibrate the boulder response model

Load rate	Boulder diameter [m]	Arc applied velocity [°]	Purpose
Static	0.5 - 1.5	45	Backbone static deflection curve
Dynamic	1.0	45	Soil strength effect
Dynamic	1.0	45	Soil stiffness effect
Dynamic	0.5-1.5	45	Boulder size effect
Dynamic	1.0	10 - 45	Area over which the velocity is applied

Notes: (1) Local refinement applied

3.3.1 FE analyses results

Comparison plots between the FEM and the analytical calibrated model are presented in Fig.7 for the case with: D: 1.0, Su=100kPa, G/Su=200, arc: 45° considering the input time history (shown in Fig. 6).

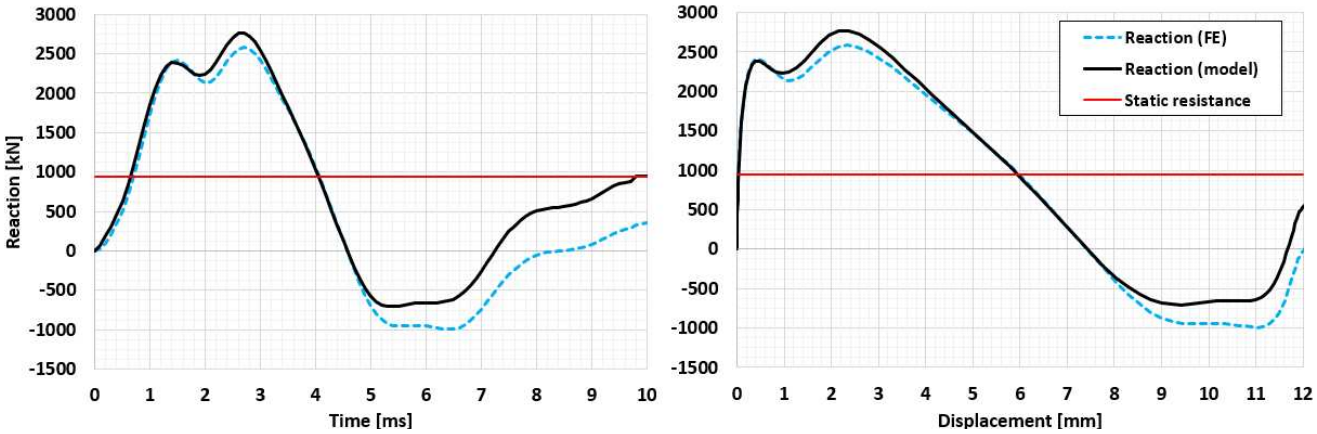

Figure 7 - Boulder reaction: analytical formulation versus finite element results - D:1.0m, Su=100kPa, G/Su=200

Initially, the boulder generates a very stiff response with the reaction force developing rapidly, for less than 1mm displacement during the first 1-2ms. The maximum reaction force is achieved at a displacement 2-4mm (around 3ms). Overall, the reaction force between the FE and proposed model with calibrated beta values is quite satisfactory, both in terms of the shape and the peak reaction force value. Consequently, it is confirmed that the boulder peak response is dominated by the inertia.

Considering the dynamic cases summarised in Table 3, the beta factors were selected, concluding to a single set of values based on the examined cases:

$$\beta_m = 1.3, \qquad \beta_k = 4.0, \qquad \beta_c = 1.7$$

Based on the FE model results, the effect of the different investigated parameters is presented in Fig. 8 in terms of reaction force versus displacement:

- Generally, as expected, stronger and stiffer soils result in larger boulder reaction forces. However, this is not proportional to the relative increase in strength or stiffness. As shown in Fig. 8a and Fig. 8b, the reaction force only increased about 20% for more than twice the strength or stiffness increase;
- The dominating effect of the boulder mass on the reaction force is highlighted in Fig. 8c. For instance, a boulder with 1.5m diameter experiences a peak reaction force approximately 3 times larger compared to a 1.0m wide boulder, while for D: 0.5m the peak value is approximately 6 times smaller. These results imply that the reaction is roughly proportional to the mass ratio;
- Finally, Fig. 8d indicates that there is a small influence of the area where the input velocity is applied on the FE results. For the 10° arc case, the peak value of the reaction is approximately 15% larger than for the case with an arc of 45°, with somewhat different shape.
- Finally, note that although the results presented in Fig. 7 and Fig. 8 are directly associated with the input velocity-signal used (Fig. 6), i.e. representing the signature of a specific hammer, they clearly highlight the boulder response.

4 CONCLUSIONS

The force experienced by a driven pile as it encounters a boulder must account for both the dynamic response of the boulder to the impact and the evolving trajectory of the boulder. For a glancing impact, both vertical and horizontal components of the reaction must be determined (Fig. 1). Both components may be assessed with the same proposed model by introducing the relative proportion of vertical and horizontal input function according to the evolving pile/boulder contact point.

The model allows the peak reaction force acting on the pile to be calculated for a given boulder position along its trajectory (i.e. to check structural integrity, tip buckling risk). It also provides the basis for a model to be used in a 1D driveability simulation (e.g. boulder reaction can be added to the end bearing resistance). The peak reaction depends on the boulder size and mass, soil strength and stiffness and the (velocity) input signal. The reaction in the horizontal and vertical direction can be defined based on the geometry and the initial pile-boulder contact position.

Note that since in practice each blow involves pile penetration followed by some rebound, for repeated blows it is reasonable to assume that there are no accumulating residual forces in the spring representing the soil response. Hence, each blow leads to the same peak reaction being experienced by the pile.

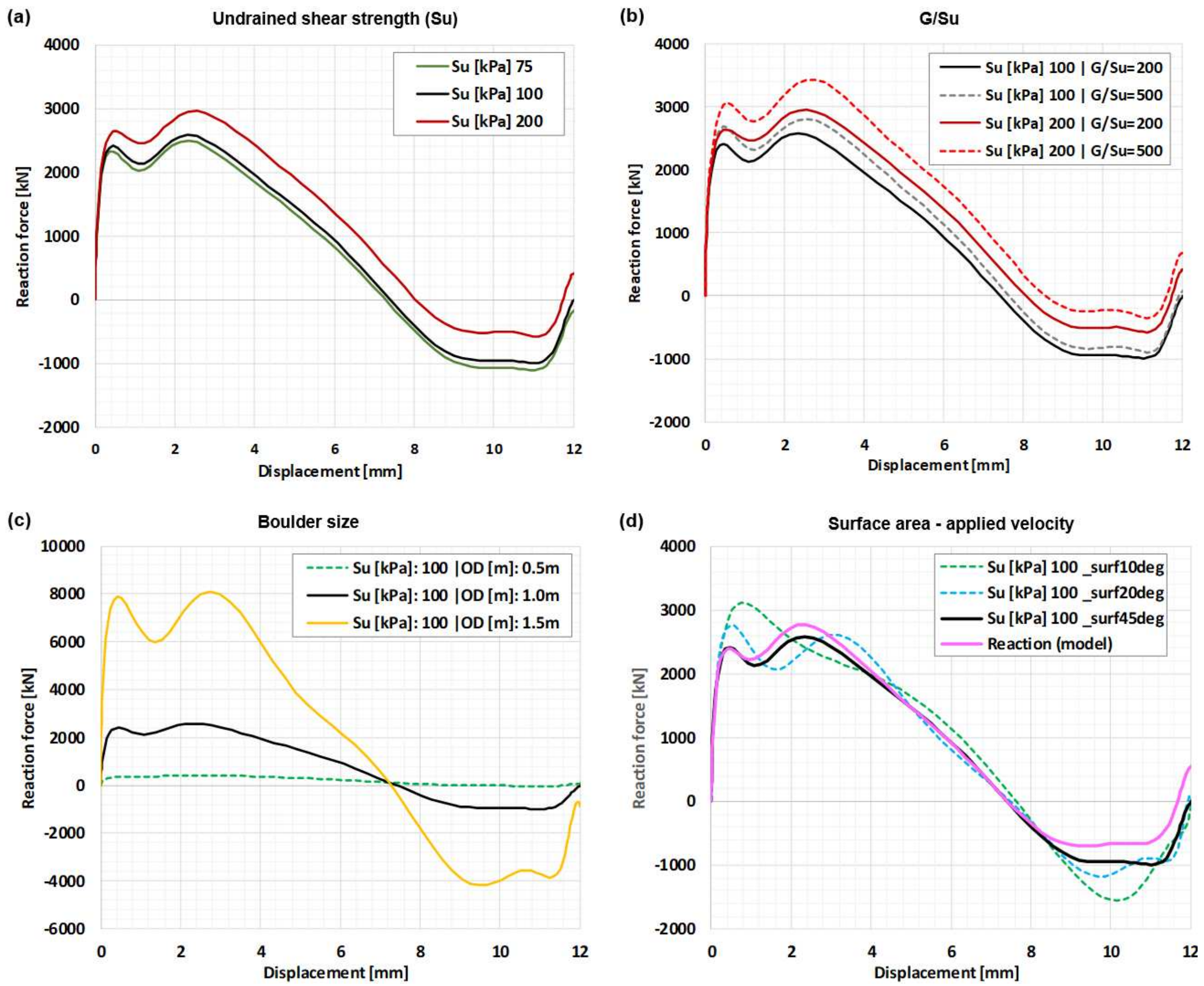

Figure 8 – Finite element model results – Sensitivity on: (a) soil undrained shear strength; (b) soil stiffness; (c) boulder size; (d) surface area (arc) for applied velocity

AUTHOR CONTRIBUTION STATEMENT

D. Cathie: Conceptualisation, original model drafting, methodology, implementation, supervision.
O. Zarzouras: Conceptualisation, finite element assessment, data analysis, writing, reviewing, editing.

ACKNOWLEDGEMENTS

The current study was part of the Carbon Trust VERBATIM project (Verification of Buckling Assessment and Behaviour in Large Monopiles). The authors are grateful for the support and funding by BAM. (Bundesanstalt für Materialprüfung und -prüfung).

REFERENCES

Chopra, A.K. (1995). *Dynamics of structures - Theory and applications to earthquake engineering* - 3rd Edition., Prentice-Hall, Inc. New Jersey, USA

Loukidis, D., Salgado, R., Abou-Jaoude, G. (2008). *Assessment of Axially-Loaded Pile Dynamic Design Methods and Review of INDOT Axially-Loaded Pile Design Procedure*. FHWA/IN/JTRP-2008/06. Department of Transportation and Purdue University, West Lafayette, Indiana

Lysmer, J. and Richart F.E. (1966). Dynamic response of footing to vertical loading, *Journal of the Soil Mechanics and Foundations Division*, ASCE, Vol. 92, pp 65-91.

Simons, H.A and Randolph, M.F. (1985). A new approach to one dimensional pile driving analysis, In: *5th Inter. Conference in Numerical Methods in Geomechanics*, Nagoya, Japan, pp1457-1464.