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Understanding the behaviour of a new robotic device for next-generation site investigation: A 3D DEM Exploration

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Accelerating advancements in robotic engineering provide an opportunity for developing economical and efficient site characterisation devices, particularly for critical offshore applications. A new intelligent robotic device, ROBOCONE (Figure 1), is being developed for site characterisation and design of offshore structures, which would be capable of mimicking the load histories of the soil inside the ground at a desired depth [1]. The obtained soil constitutive properties would support an efficient design of offshore structures, considering "whole life" stress-strain histories. ROBOCONE could apply lateral, shear, and torsional modes (Figure 1(a)) of loading on the surrounding soil, operated remotely from the ground. In the pursuit of developing such a device, a prior understanding of its behaviour is essential. The lateral loading static and cyclic responses of offshore foundations are critical aspects of their design. The present work highlights the lateral module (P-Y Module) behaviour of the ROBOCONE device (Figure 1(a)) under various stresses, using 3D Discrete Element Modelling (DEM). The P-Y module moves horizontally at a desired depth in the ground and this lateral motion is numerically simulated using commercial DEM software, Particle Flow Code (PFC3D) [2].

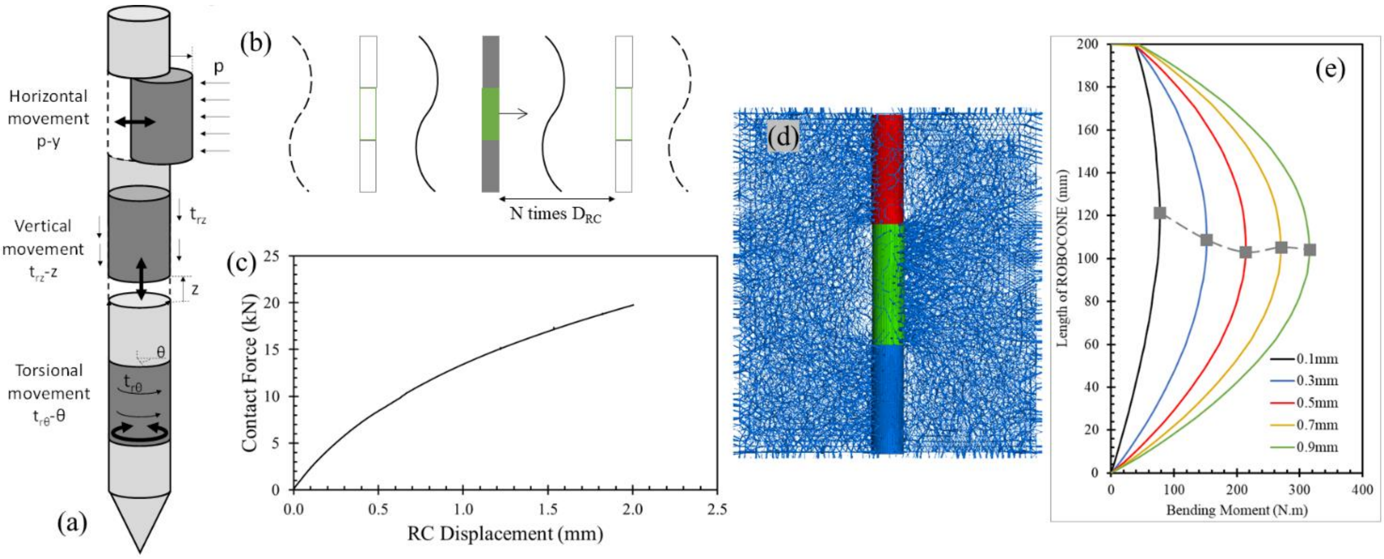

Figure 1: (a) Schematic of ROBOCONE device (b) Periodic boundary schematic for boundary effects (c) Reaction forces from P-Y module movement (d) Force chains on device (e) Bending moment along ROBOCONE length.

The proposed dimensions of the P-Y module are 200mm long and 54mm diameter (D_{RC}). Present DEM model uses rigid walls as P-Y module placed in a rigid monodisperse 3D granular assembly with grain diameter of around 1/3rd D_{RC} [3]. The Hertz contact model micro-parameters for grain-grain (E_{50} value of 27.4±2.2MPa) and grain-wall contacts are shown in Table 1. A 10 times higher shear modulus of grain-wall contact than the grain-grain contacts is sufficient to have stiffer response. The servo mechanism in PFC enables the model to reach desired average stresses. The primary objective of this work is to understand the ROBOCONE P-Y module behaviour and thus the lateral soil reaction curves without the influence of boundary. For the current testing mode, where the module moves laterally in the soil, the ratio of the moving object to soil bed dimensions for no boundary effects is unprecedented.

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A simple and innovative method of using periodic boundaries is proposed in the present study. Conventionally, periodic boundaries replicate the representative volume element infinitely at the boundaries. Due to the presence of ROBOCONE in the centre of the model, the required extent reduces to half in X and Y directions, as schematically shown in Figure 1b. This paper discusses the model side to ROBOCONE diameter, L/D_{RC}, (e.g., 9, 18, 30) influence on the P-Y curves (at a given stress level). The effects of random particle generations for different models in PFC software can be minimized using same central core zone of contacts with ROBOCONE for each simulation, while the extent of model side is increased. ROBOCONE wished-in-place rather than driving/jacking in the model reduces the DEM computation costs. Limited amount of lateral displacement of the ROBOCONE (around 2.5mm) is sufficient to establish the effectiveness of the proposed modelling. Optimum loading rate (the lateral velocity of P-Y module) of around 0.8mm/s, which can maintain the inertial number lower than the threshold value of 7.9×10^{-5}[4] further helps the computational efficiency.

Table 1: Micro parameters of the DEM model.

Parameter	Value	Parameter	Value
Grain radius	8.5mm	Grain-Grain shear modulus	2GPa
ROBOCONE radius	27mm	Grain-Wall shear modulus	20GPa
Grain friction	0.25	Poisson ratio	0.3
Wall friction	0.10	Timestep	$\sim 10^{-6}$

Once the optimum L/D_{RC} value is obtained, the quantitative outcomes from these simulations are the lateral soil reaction curves at different stress levels and also the bending moments on the ROBOCONE P-Y Module. Though the ROBOCONE model in these simulations is a rigid wall and doesn't mobilize in bending, the moments calculated from the magnitude and locations of each contact force on the P-Y module provide an estimate of bending stresses generated on the module. These results provide a basis for developing an understanding of the physical capacity of the robotic device in sustaining the lateral forces. Figure 1(c) shows preliminary results of soil reaction curve from the P-Y module at 500kPa stress level for L/D_{RC} value of 9. The changes in the contact forces during the P-Y module motion can be qualitatively assessed through the changes in the force chain network (Figure 1(d)). Figure 1(e) shows a representative plot of bending moments calculated at different lateral movement stages of the P-Y module, and the maximum value at a desired displacement of the P-Y module suggests the physical design requirements of the ROBOCONE. The results from these DEM simulations would directly inform the design of the robotic device for ground investigation and hence improve the economical offshore foundation designs.

Contributor statement

SSK performed the numerical simulations and drafted the abstract. DI supervised the data analysis and contributed to the drafting of the abstract. BC contributed to the numerical simulations part and drafting of the abstract. AD and DI provided technical support from the design perspective for accurate modelling and contributed to the drafting of the abstract.

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