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ORIGINAL PAPER

A Novel Approach to Simulate Cone Penetration Test Using Conventional FEM

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Abstract Large deformation problems (LDPs) in geotechnical engineering are solved using advanced large deformation finite element (LDFE) formulations like coupled Eulerian–Lagrangian, arbitrary Lagrangian–Eulerian, material point method, remeshing and interpolation technique by small strain, etc. The LDFE formulation solutions are time-consuming compared to the conventional finite element method (FEM). In the study, the inefficiency of the conventional FEM to solve LDPs is highlighted and a new methodology is proposed and used to address a typical LDP, i.e., cone penetration (CP) test. The CP test in sand and clay is simulated using PLAXIS 2D program. The proposed methodology can represent the numerical simulations of continuous penetration of the cone using conventional FEM. In the proposed methodology, a reduction factor is introduced to represent the variation of ultimate resistance of the cone when continuously penetrated in the soil. The present study results are compared with those results available in the literature to assess the suitability of the proposed methodology for solving a typical LDP in geotechnical engineering i.e., CP test.

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Keywords Finite element methods · Sands · Clays · Numerical modelling · Deformation

List of symbols

A	Cross-section area of embedded cone
c	Cohesion of soil
d_c	Diameter of cone
E	Modulus of elasticity
F	Resistance force
h_c	Height of cone
r_c	Radius of cone
R_{int}	Interface strength between cone shaft and soil
S_u	Undrained shear strength of clay
w	Cone displacement
α	Apex angle of cone
γ	Unit weight
ν	Poisson's ratio
ϕ	Friction angle of soil
ψ	Dilation angle of soil

1 Introduction

The large deformation is an elusive term in civil engineering (Konkol 2014). According to Krabbenhoft and Zhang (2013), if the strains, i.e., deformations of soil or displacement of structural elements (like footing or pile) in a system are more than 10%, then it is considered as a large deformation problem (LDP). The large deformations (LDs) are encountered in many geotechnical engineering problems such as successive landslides (Cuomo et al. 2021), penetration of pile (Dijkstra et al. 2011), testing of geosynthetics (Mishra et al. 2016, 2017), sinking of open caisson (Chavda et al. 2020; Zhang 2021), formation of soil plug while installation of open-ended pipe pile (Fan et al. 2021a, b), penetration of strip footing (Qiu et al. 2011), uplift plate anchor (Al Hakeem and Aubeny 2021), penetration tests like cone penetration (Pucker et al. 2013), etc. In geotechnical engineering, LDPs are addressed by experimental and numerical simulations. The experimental simulations are expensive and time-consuming (Souli and Benson 2013) and therefore, numerical simulations are widely used to address LDPs. The conventional finite element method (FEM), also referred to as standard FEM, is based on the assumption that small deformations occur within the finite element (FE). Moreover, the conventional FEM uses Lagrangian description to describe the deformations within the FE under the application of load. It is noted that due to LDs, the geometry of the elements changes and it distorts, due to which analysis may stop or explicate the faulty results. The distortion of FE mesh and the faulty results are the limitations of the conventional FEM for solving LDPs. This may affect the outcome of a study and misled the practician engineers (Wang et al. 2015; Yuan et al. 2017; Zhang et al. 2018). Therefore, the conventional FEM cannot handle large deformations, and it is not able to solve LDPs in geotechnical engineering (Konkol 2014; Wang et al. 2015). The distortion of the mesh due to extensive displacement of elements in the simulation of continuous penetration of cone is depicted in Fig. 1. Recently, Chouhan and Chavda (2021) have also reported the limitations of the conventional FEM to simulate LDPs in computational geomechanics.

Over the time, researchers have developed large deformation finite element (LDFE) formulations to overcome the limitations of the conventional FEM to solve LDPs. The LDFE formulations are developed to overcome the issues related to mesh distortion. In computational geomechanics, the LDFE formulations such as updated Lagrangian (UL), arbitrary Lagrangian–Eulerian (ALE), coupled Eulerian–Lagrangian (CEL), remeshing and interpolation technique by small strains (RITSS), particle finite element method (PFEM), material point method (MPM), etc. have been used by many researchers to solve LDPs (Nazem et al. 2008; Tian et al. 2014; Kardani et al. 2015; Wang et al. 2015 2020; Gupta et al. 2015; Aubram 2015; Grabe and Wu 2016; Liu et al. 2016; Khoa and Jostad 2016; Chen et al. 2019a b; Kim et al. 2019; Martinelli and Galavi 2021; Fan et al. 2021a). The ALE and CEL are extensively used LDFE formulations in the field of geotechnical engineering (Nazem et al. 2008; Aubram 2015; Gupta et al. 2015; Kardani et al. 2015; Wang et al. 2015; Grabe and Wu 2016; Khoa and Jostad 2016; Chen et al. 2019a,b). Recently, Augarde et al. (2021) have presented a review on numerical modelling techniques used to address LDPs in geotechnics and it can be referred to get more insight about LDFE formulations used in geotechnics. The advanced LDFE formulations are computationally costly and they need advanced computing systems i.e., highly configured computer or workstation to simulate complex LDPs. Moreover, it is noted here that it may not be possible for the practician engineers to have this computational facility to

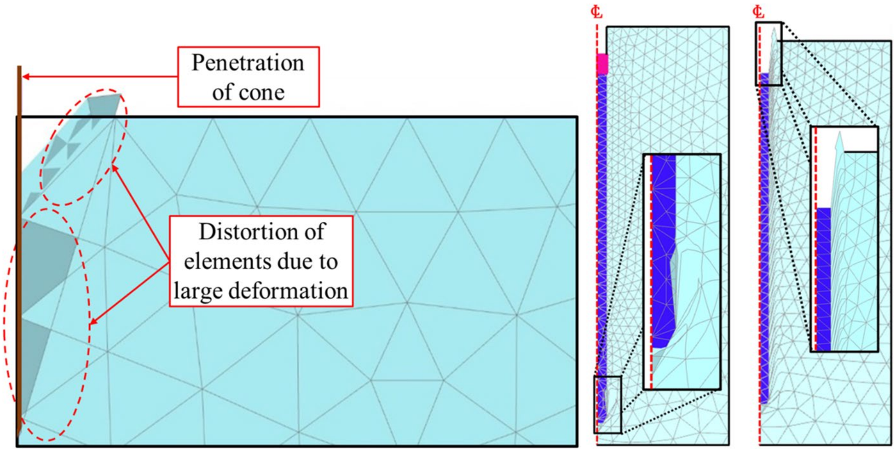


Fig. 1 Distortion of finite elements due to large deformation in conventional FEM

run advanced LDFE formulations. Therefore, there is a need to explore and provide a suitable methodology that can accurately solve LDPs using the conventional FEM.

The objective of the paper is to highlight the inefficiency of the conventional FEM to solve LDPs and then provide a methodology that can be used to address LDPs using conventional FEM, which can be helpful to practician engineers. Chouhan and Chavda (2021) presented a review of LDPs in geotechnical engineering and discussed the possible use of conventional FEM to simulate the LDPs. It is noted that the cone penetration (CP) test problem has been attempted by many researchers using almost all LDFE formulations in both sand and clay, and corresponding results are available for comparison. Therefore, in the study, the simulation of a typical LDP i.e., CP test in sand and clay is attempted using the conventional FEM. Firstly, the continuous penetration of the cone starting with its tip on soil is simulated in order to highlight the inefficiency of conventional FEM to solve CP test. Then, a new methodology is proposed to represent the continuous penetration of the cone in CP test. The interface elements are assigned between the shaft of the cone and soil to obtain only the cone resistance. Then, the cone resistance corresponding to each embedment depth is superimposed to represent the continuous penetration of the cone in the soil. The present study results are compared with the results available in the literature that used LDFE formulations to solve the CP test. In the study, a reduction factor is determined and used in order to have an accurate evaluation of cone resistance corresponding to the continuous penetration of cone in the CP test. The need for further study to attempt other LDPs in geotechnical engineering is also discussed in the paper.

2 Simulation of CP Test Using Conventional FEM

Numerical simulation of cone penetration (CP) test is a complex problem as it involves large deformations with reference to the relative displacement between the cone and soil (Lim et al. 2018). Many researchers have used advanced formulations like coupled Eulerian–Lagrangian (Gupta et al. 2015; Wang et al. 2015; Fallah et al. 2016), discrete element method (Arroyo et al. 2011), arbitrary Lagrangian–Eulerian (van den Berg 1994; Walker and Yu 2006; Liyanapathirana 2009; Tolooiyan and Gavin 2011; Fan et al. 2018), remeshing and interpolation technique by small strain (Wang et al. 2015), material point method (Beuth and Vermeer 2013; Ceccato et al. 2016; Martinelli and Galavi 2021), smoothed particle hydrodynamics method (Kulak and Bojanowski 2011), and particle finite element method (Monforte et al. 2017; Gens 2019) to simulate the CP test. In the study, the CP test in sand and clay is simulated using conventional FEM, i.e., PLAXIS 2D program. PLAXIS 2D is a user-friendly program widely used in computational geomechanics. The finite element (FE) model, mesh convergence study, and methodology to simulate the CP test are presented in proceeding sub-sections.

2.1 FE Model and Material Properties

The CP test is simulated numerically by penetrating a cone of diameter, $d_c = 35.8$ mm and apex angle, $\alpha = 60^\circ$ in the FE soil domain. An axisymmetric model with 15-noded triangular elements having 12-Gaussian Quadrature stress points is used. Based on the formation of the plastic zone, a FE domain of 1 m × 1 m is finalized for the analysis. The details of the FE model, type of element, and soil domain are depicted in Fig. 2. The fixed fixities are assigned to

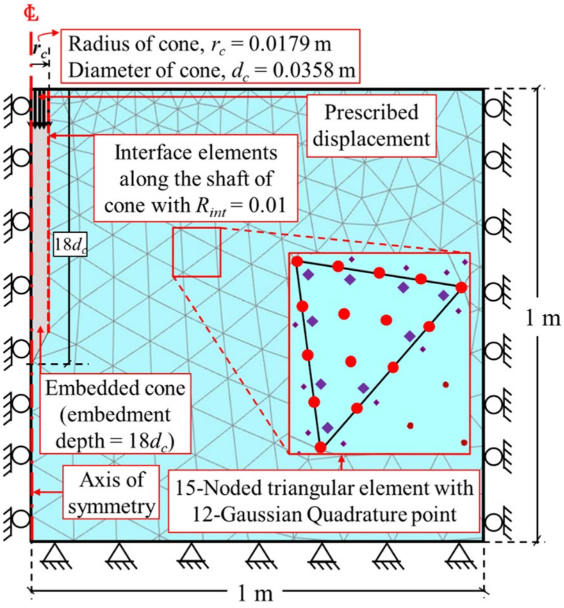


Fig. 2 FE model for simulation of cone penetration

Table 1 Material and geometrical parameters of cone

Parameters	Symbol	Cone	Unit
Material model	–	Linear Elastic	–
Conditions	–	Non-porous	–
Unit weight	γ	20	kN/m^3
Modulus of elasticity	E	210	GPa
Poisson's ratio	ν	0.30	–
Diameter of cone	d_c	0.0358	m
Height of cone	h_c	0.031	m
Apex angle	α	60	degree

the lower boundary to restrict the movement of the nodes in the vertical and horizontal directions, and roller fixities are assigned to the vertical boundaries to allow the movement of nodes only in the vertical direction. It is noted that the water table is not considered in the study. The fine mesh is used for the FE analysis based on the mesh convergence study. A prescribed displacement is assigned to the line representing the top width of the cone in order to evaluate the ultimate load i.e., the ultimate resistance (see Fig. 2). The rigid cone is modelled as Linear Elastic with non-porous conditions to represent the real case. The geometrical and material parameters of the cone are taken from Gupta et al. (2016) and are given in Table 1. The nonlinear material model, i.e., Mohr–Coulomb model, is used to represent the soil. The material properties of sand and clay (taken from Gupta et al. 2016; Wang et al. 2015 respectively) are provided in Table 2.

2.2 Mesh Convergence Study

The mesh convergence study is carried out to ascertain that the FE results are converged to a solution that is independent of the FE mesh size (i.e., size and type of element). In the present study, both *h*- and *p*-refinement techniques are used. Figure 3 depicts the basics of *h*- and *p*-refinement techniques. In *h*-refinement, the element size is reduced from very coarse to very fine (as options available in PLAXIS) without changing the type of element, whereas in *p*-refinement, the element type is varied, i.e., the capacity of the element is enhanced without changing the size of element. For the *p*-refinement study, the two available options in PLAXIS i.e., 6-noded and 15-noded triangular elements are used. The mesh details, ultimate load, and normalised computational time for the mesh convergence study are given in Table 3. The FE analysis depends on the computational resources,

Table 2 Material properties of sand and clay

Parameters	Symbol	Sand (Gupta et al. 2016)	Clay (Wang et al. 2015)	Unit
Material model	–	Mohr–Coulomb	Mohr–Coulomb	–
Conditions	–	Drained	Undrained	–
Unit weight	γ	20.0	0.10	kN/m^3
Modulus of elasticity	E	100	2.98	MPa
Poisson's ratio	ν	0.25	0.49	–
Cohesion	c	0.10	10.0	kN/m^2
Angle of friction	ϕ	37.5	0.10	degree
Dilation angle	ψ	7.50	0.00	degree

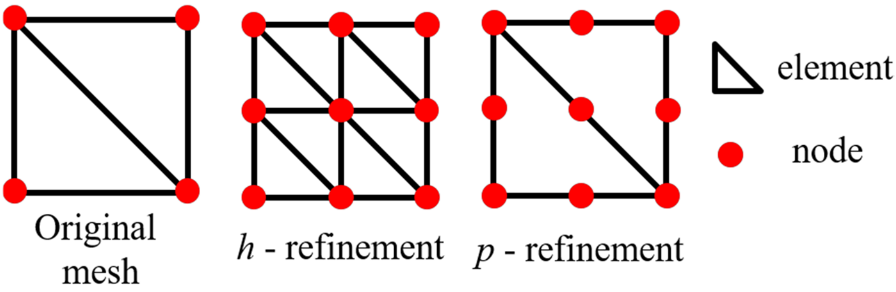


Fig. 3 *h*- and *p*-refinement techniques

Table 3 Mesh convergence study for fully embedded cone

Mesh details		15-noded triangular element		6-noded triangular element	
Mesh type	n	Q_u (N)	T	Q_u (N)	T
Very coarse	97	90.631	1	345.342	1
Coarse	205	80.782	1	181.949	2
Medium	358	73.045	4.50	108.800	3
Fine	805	61.107	13.25	80.764	3
Very fine	1471	56.906	46.75	69.117	18

n – no. of elements, Q_u – ultimate load, T – normalised computational time

which significantly affect the computational time i.e., a numerical problem takes different computational times depending on the configuration of the computer used for the analysis. For the present study, the normalised computational (NC) time is used to generalise the results of the mesh convergence study. The NC time is obtained by dividing the computational time corresponding to different types of mesh with minimum computational time (i.e., computational time corresponding to very coarse mesh). For the present FE analysis, a workstation with configuration as Intel Core i9-9900 K CPU @ 3.60 GHz, 64 GB RAM, 500 GB SSD is used.

The mesh convergence study is performed for the specific case of a fully embedded cone in the sand i.e., only the cone is fully embedded (see Fig. 4). A prescribed displacement is assigned to the top of the cone for all the cases, and the ultimate load is evaluated. The results of the mesh convergence study are presented in Fig. 4. Based on the *p*-refinement study, a 15-noded triangular element is chosen for further analysis as there is a significant difference in the results for 6-noded and 15-noded triangular elements. From the *h*-refinement study, the fine mesh is selected as the FE results are converging at the fine mesh. It is noted that there is a significant difference in normalised computation time between fine mesh (NC = 13.25) and very fine mesh (NC = 46.75) corresponding to the case of 15-noded triangular elements. Therefore, based on the mesh convergence study, the 15-noded triangular elements and fine mesh is selected for all the FE analyses of the CP test.

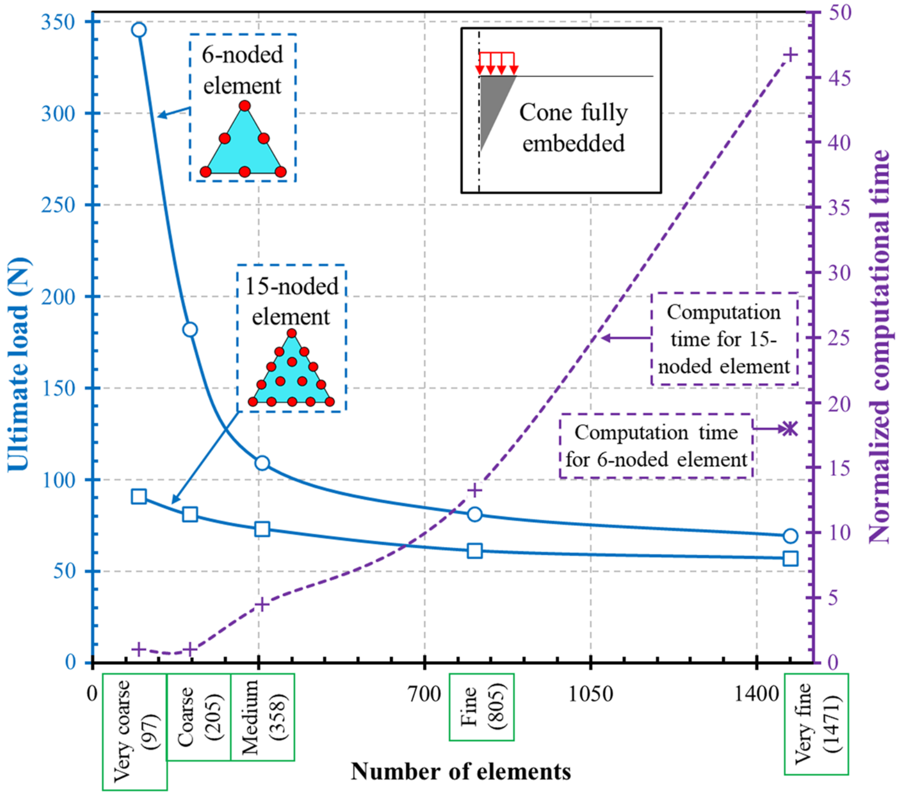


Fig. 4 Mesh convergence study for fully embedded cone

2.3 Proposed Methodology to Simulate CP Test Using Conventional FEM

The CP test is a LDP as there is an extensive relative displacement between the cone and soil particles during continuous penetration of the cone. The conventional FEM is not able to solve LDPs due to the distortion of finite elements of the soil domain as it is based on the small deformation theory and uses Lagrangian formulation in the analysis. It is noted here that there are two issues in the simulation of the CP test using the conventional FEM. Firstly, the simulation of continuous penetration of the cone is not possible as the elements of the FE soil domain will distort and the analysis may stop even after the distortion is observed in a few elements when a prescribed displacement of a large value is assigned. The second issue is the extraction of the cone resistance from the total resistance of the cone and shaft. For the former issue, the penetration of the cone is simulated considering the position of the cone at different embedment depths instead of continuous penetration. It is simulated in stages with different embedment depths varying from $0d_c$ (i.e., the apex of cone is at ground level) to the desired embedment depth (i.e., depending on the required depth of investigation, in this study up to $18d_c$). For the latter issue, i.e., to have only the cone resistance, the interface elements ($R_{int}=0.01$) are assigned at the periphery of the shaft of cone. With this, the shaft resistance is eliminated from the total resistance. Figure 5 depicts the schematic representation of the proposed methodology used in the analysis in which the CP test is performed considering different embedment depths of the cone and the interface elements are assigned to the shaft of cone.

The series of cone penetration is simulated systematically from the initial stage, $0d_c$ (i.e., cone tip is at the ground surface) to the final stage, $18d_c$ in the sand. Firstly, the cone is modelled having zero embedment depth and prescribed displacement is assigned to the top width of the cone to determine the ultimate load (see Case 1 in Fig. 5). Then, the cone is modelled for the embedment depth $=0.2d_c$, and the corresponding ultimate load is determined. Similarly, the embedment depths are gradually increased up to $18d_c$, and the ultimate loads are evaluated corresponding to each increment of the embedment depths of the cone. It is noted that the applied prescribed displacement is large enough such that the ultimate load is mobilised for each case (see Fig. 7). For all

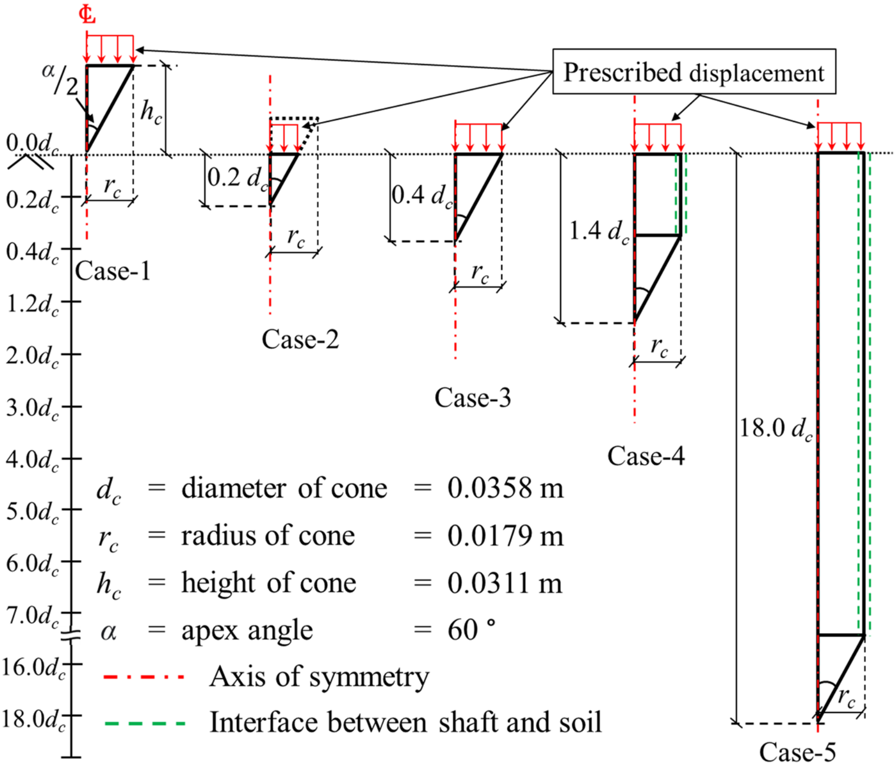


Fig. 5 Schematic view of proposed methodology to simulate the cone penetration test

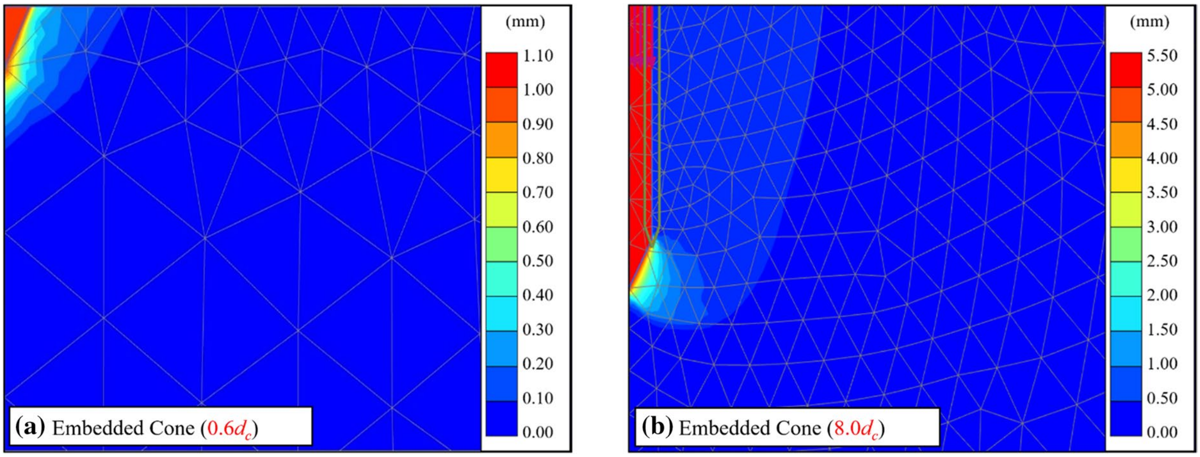


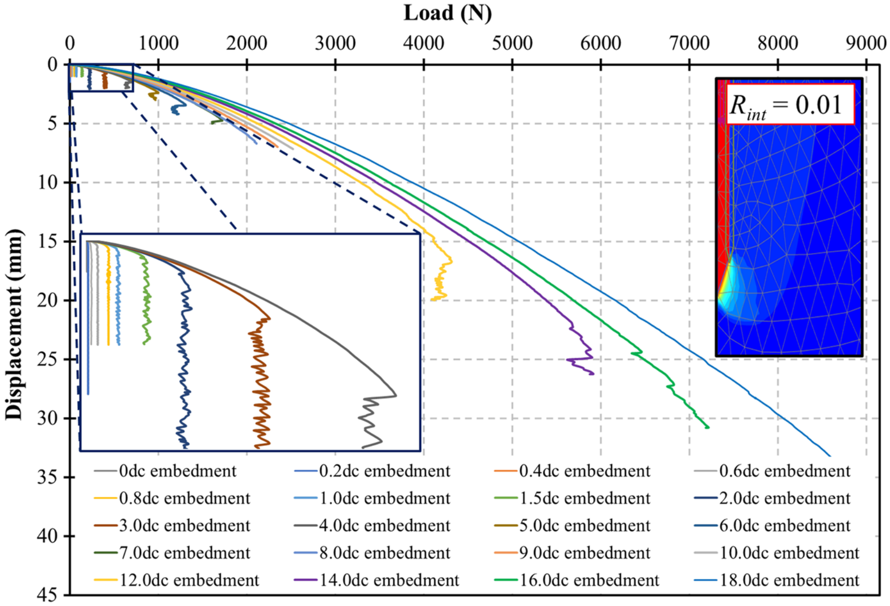
Fig. 6 Total incremental displacement contours for embedment depth of 0.6d_c and 8.0d_c

the cases, the interface elements are assigned at the periphery of the shaft of cone with $R_{int} = 0.01$ and the interface between the cone and soil is kept as rough with $R_{int} = 1.0$. Now, the cone resistance is evaluated for each embedment depth by dividing the obtained ultimate load with the corresponding cross-section area of the embedded cone. The evaluated cone resistance corresponding to each embedment depth is superimposed to obtain a cone resistance that represents the resistance of the cone during continuous penetration. Similarly, the same methodology is used to evaluate the cone resistance in clay.

3 Results and Discussion

In the present study, a CP test is simulated using conventional FEM. Firstly, the apex of the cone was placed on FE soil domain and the cone was penetrated in the soil to simulate a continuous penetration of

Fig. 7 Load vs displacement plots for various embedment depths of cone with $R_{int} = 0.01$ between soil and shaft of cone



cone. However, the analysis was stopped as Lagrangian description is not able to represent the continuous penetration of the cone (see Fig. 1). The similar observation is reported by Chouhan and Chavda (2021) for the case of continuous penetration of cone in sand. Therefore, a new methodology is proposed which represents the continuous penetration of cone in soil using conventional FEM. The FE CP test is performed in both sand and clay to determine the cone resistance corresponding to the continuous penetration of the cone. Figure 6 depicts the total incremental displacement contours in the soil corresponding to two embedment depths of the cone, i.e., $0.6d_c$ and $8d_c$. From the figure, it is inferred that with the use of interface elements ($R_{int}=0.01$) between the shaft and soil, only the cone resistance is obtained corresponding to rough cone. Figure 7 shows the load–displacement plots of cone penetration corresponding to the cone placed at various embedment depths varying from $0d_c$ to $18d_c$. It is observed from the plots that the load increases as penetration increases and reaches to ultimate load for all CP tests having cone placed at varying embedment depths. Then, the ultimate load is used to determine the cone resistance at various embedment depths. The cone resistance is evaluated by dividing the obtained ultimate load with the corresponding cross-sectional area of the embedded cone. Then, the evaluated cone resistance for each embedment depth is superimposed to obtain a cone resistance plot representing the continuous penetration of the cone from 0 to $18d_c$. Figure 8a–b show the cone resistance variation along the depth representing continuous penetration of the cone in sand and clay respectively. It is noted that the interface between the cone and soil is modelled as rough i.e., interface elements are not assigned for the cone portion. However, the interface $R_{int}=0.01$ is assigned between the shaft and soil to get only the resistance of cone.

It is noted that number of published literature on numerical simulation of CP test are available for comparison (Teh and Houlsby 1991; Walker and Yu 2006, 2010; Liyanapathirana 2009; Wang et al. 2015; Gupta et al. 2016). Figure 9 depicts the comparison of the present study results with the results of CEL from Gupta et al. (2016). It is observed that the cone resistance obtained using the proposed methodology at lower embedment depth (i.e., up to a case when the cone is fully embedded) provides a good match with the CEL. However, the cone resistance from the present study is significantly higher than the results of the CEL as embedment depth is increased to $18d_c$. It is noted that the soil gets continuously disturbed due to the continuous penetration of the cone and thereby providing a lower resistance as compared to the obtained cone resistance using the proposed methodology. This could be the reason for getting the higher value of cone resistance while using the proposed methodology, which infers the limitation of conventional FEM to simulate LDPs in geotechnical engineering. Therefore, a reduction factor is needed to reduce the value of cone resistance obtained from the conventional FEM. A reduction factor of 1.55 is

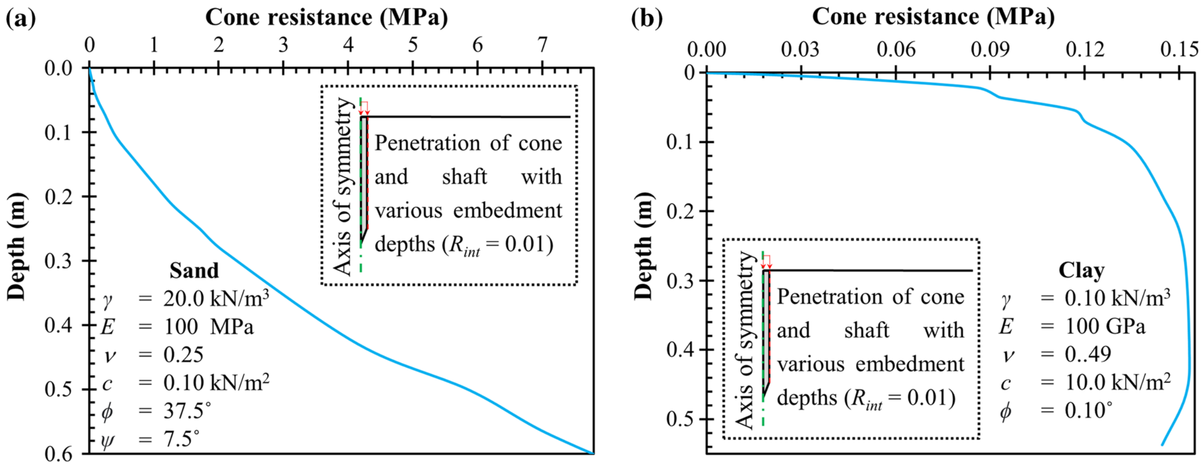
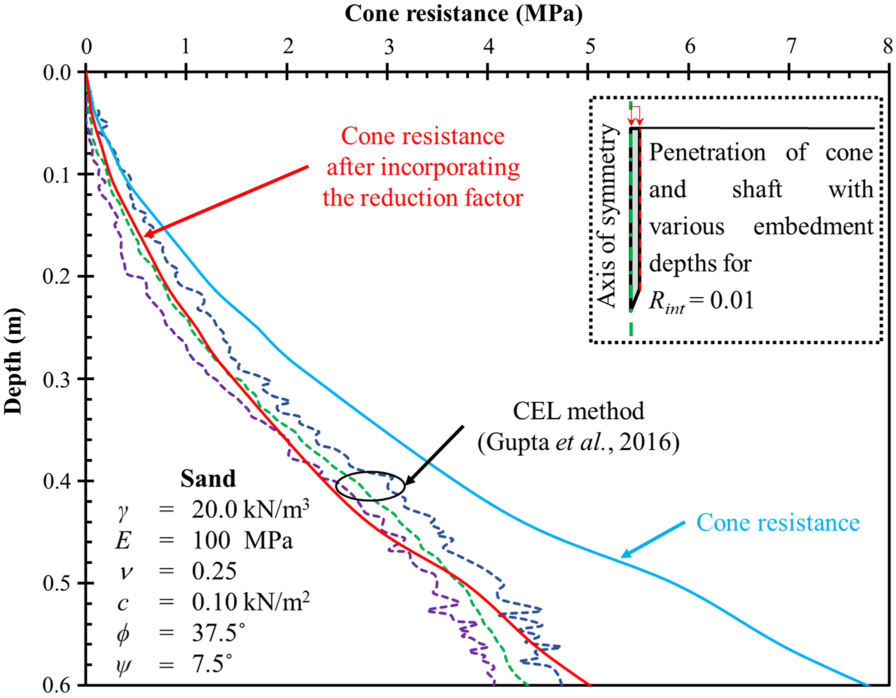


Fig. 8 Cone resistance vs depth in: **a** sand, **b** clay

Fig. 9 Comparison of cone resistance vs embedment depth of cone



evaluated by dividing the cone resistance from the present study and those of Gupta et al. (2016). Then, the conventional FEM results are revised and re-plotted. The cone resistance plot after incorporating the reduction factor is shown in Fig. 9. With this modification, it is noted from the figure that a good match of present study results with the results of the CEL is observed. Many researchers have reported that the LDFE formulations are computationally costly and require a higher computational facility (Konkol 2014; Wang et al. 2015; Augarde et al. 2021; Chouhan and Chavda 2021). Therefore, it can be inferred that the proposed methodology could significantly reduce the computational cost to solve LDPs in geotechnics.

To check the suitability of the proposed methodology and to get confidence in using the reduction factor, the CP test is also simulated in clay. The same methodology is used for the simulation of CP test in clay i.e., the simulation of cone penetration for different embedment depths to represent continuous penetration of cone in soil and by using the interface elements to evaluate only the resistance of cone. Then, the cone resistance for each embedment depth is superimposed to obtain a cone resistance plot representing continuous penetration of the cone in clay. Figure 8b shows the cone resistance variation corresponding to the continuous penetration of the cone in clay. The CP test simulation results in clay are compared with the numerical results of Wang et al. (2015). Figure 10a depicts the comparison of the present study results with those of different LDFE formulations, i.e., RITSS, EALE, and CEL from Wang et al. (2015). The results are plotted for the normalised parameters i.e., normalised cone resistance (F/S_uA) and normalised depths (w/d_c) as available in Wang et al. (2015); where F is resistance force, S_u is undrained shear strength of clay, A is cross-sectional area of embedded cone, w is cone displacement, d_c is diameter of cone. It is observed from the figure that the proposed methodology results are higher than the results of LDFE formulations which infers the need for a reduction factor. It is noted that the same reduction factor of 1.55 is obtained and used to lower the results of conventional FEM, then re-plotted for the normalised depth, which provides a reasonably good match with the results of LDFE formulations reported by Wang et al. (2015). Therefore, it gives confidence in using the reduction factor of 1.55 for the CP test problem. In Fig. 10b, the comparison of the present study results with the analytical solution of Teh and Houlsby (1991) and ALE results of Walker and Yu (2006), Liyanapathirana (2009), and Walker and Yu

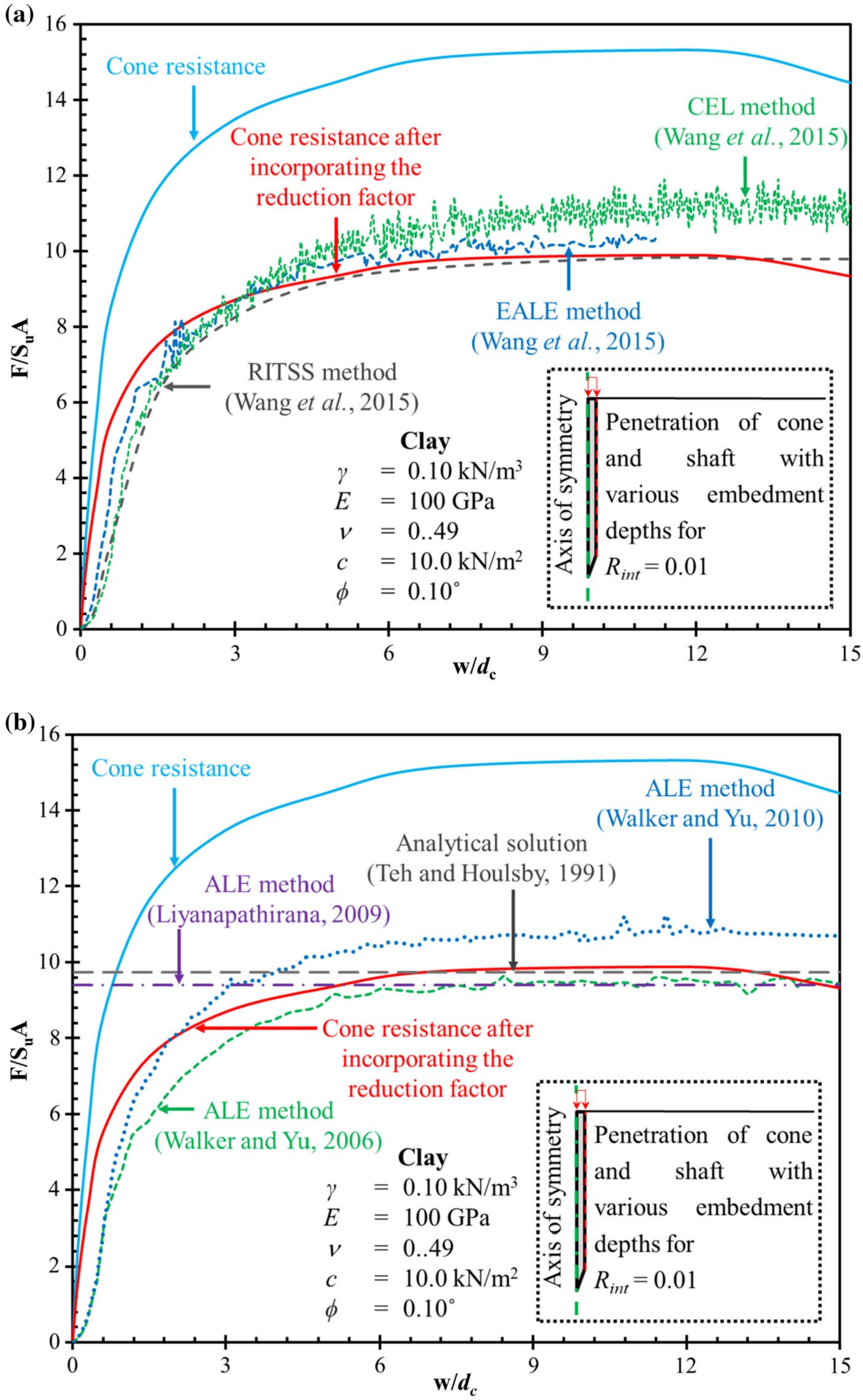


Fig. 10 Comparison of cone resistance in clay: **a** with LDFE formulations, **b** with analytical and ALE

(2010) are shown. The same reduction factor of 1.55 is also used to lower the results and it is found that the results from the proposed methodology match reasonably well for this case too. Therefore, it gives confidence in using the proposed methodology to address the LDPs in computational geomechanics and also the reduction factor of 1.55 for the CP test problem.

In geotechnical engineering, many problems are similar to CP test problem like penetration of pile, installation of open caisson, monopile, offshore foundation like spudcan, etc. Therefore, the proposed methodology can be used to solve such LDPs involving penetration to reduce the computational cost. The reduction factor, in these cases, may vary and hence there is a need to check the applicability of reduction factor of 1.55 for other LDPs in geotechnical engineering. The work in this direction can be followed up in the future.

4 Concluding Remarks

In the present study, a cone penetration test in sand and clay is simulated using PLAXIS 2D program. A new methodology is proposed to simulate the CP test using conventional FEM to represent the continuous penetration of the cone. A reduction factor is proposed and the results of the proposed methodology are assessed by comparing with the results available in the literature. Based on the study, the following conclusions are drawn:

- The cone penetration test is a large deformation problem that involves the simulation of the continuous penetration of the cone and evaluation of cone resistance. It is noted that the conventional FEM is not able to simulate the continuous penetration of the cone.
- A new methodology is proposed to represent the continuous penetration of the cone in the soil using the conventional FEM. The simulation of cone penetration is carried out for different embedment depths of the cone instead of continuous penetration and the interface elements are assigned between the shaft of the cone and soil to evaluate the cone resistance only. Then, the obtained cone resistance corresponding to each embedment depth is superimposed to obtain the cone resistance plot representing the continuous penetration of the cone. It is noted that the results of the proposed methodology match well with the results of the CEL for lower embedment depths in the sand.
- The proposed methodology provides higher results in both sand and clay which infers the inefficacy of the conventional FEM to solve LDPs. Therefore, a reduction factor of 1.55 is introduced to lower down the CP test results of conventional FEM. The factored results are compared with the results of CP test corresponding to AEL, CEL, RITSS, and analytical solutions and are found to match well. This gives confidence in using the reduction factor of 1.55 for the CP test problem using conventional FEM.
- The conventional FEM has limitation of mesh distortion and LDFE formulations require a large computational effort. Moreover, computational time is one of the essential aspects of numerical analysis. The proposed methodology significantly reduces the computational time as it is based on the conventional FEM, which reduces the computational cost of the project. Therefore, the proposed methodology to simulate the CP test using conventional FEM can be used with the reduction factor as the computational time of the analysis significantly reduces.
- It is opined that the proposed methodology can also be adopted to solve other LDPs in geotechnical engineering such as penetration of pile, open caisson, offshore foundation like spudcan, etc. However, the reduction factor has to be evaluated to lower the results obtained using the proposed methodology. It is noted that the reduction factor may be different for other geotechnical engineering problems involving LDs. For such cases, extensive experimental and numerical simulations are required to get more confidence in using the proposed methodology. In the study, the generation of pore water pressure during the penetration of cone in saturated soil is not currently addressed. However, the work in this direction may be taken-up in future.

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Authors' contribution KC acquired methodology and software and contributed to investigation and data curation, writing—original draft. JTC acquired supervision, contributed to conceptualization and methodology and writing—reviewing and editing

Data availability The data and materials in this paper are available on request made directly to the corresponding author.

Declarations

Conflict of Interest On behalf of all authors, the corresponding author states that there is no conflict of interest.

Ethical approval Not applicable.

Consent for publication Not applicable.

Consent to participate Not applicable.

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