Numerical Modelling of a Rock Socketed Pile under Compression Loading

Minu Ann George[1] and V. B Maji[2]

[1] Research Scholar, Department of Civil Engineering, Indian Institute of Technology Madras, Chennai-600036
[2] Associate Professor, Department of Civil Engineering, Indian Institute of Technology Madras, Chennai-600036
minuann@gmail.com

Abstract. With the number of high-rise structures increasing day by day in metropolitan cities of most developing countries like India, the optimal choice of foundation is getting more attention. If the rock is available at reasonable depths and where the option of the open foundation is ruled out, the choice of engineers and consultants is to install piles in the rock so that the full structural capacity is utilized by mobilizing shaft and end bearing resistance. Rock socketed piles are bored cast in situ piles that are drilled and socketed into rock strata of adequate strength for a specific length (socket length) to achieve the design capacity. Several methods are available for evaluating the load-carrying capacity of these piles. As rock is a complex material, in addition to strength, several other rock mass properties like the influence of discontinuities also need due consideration in the design stages. In the present study, the influence of joints on pile performance is investigated using the finite element software, Plaxis 3D. Three-dimensional modelling is performed by simulating discrete joints as well as a jointed rock as a continuum. The performance of the rock socketed piles is discussed, and the results are systematically presented in this paper.

Keywords: Rock Socketed piles, Joints, Plaxis 3D, Socket length.

1 Introduction

Piles are elements that form part of the foundation system of a structure capable of transferring the load coming to it to the strata in which it is installed by means of friction along the shaft, end bearing or a combination of both. Rock socketed piles (see Fig. 1), as the name suggests are socketed in rock for a length as per the design to meet its structural capacity. A lot of empirical and semi-empirical procedures are available for evaluating the load carrying capacity of these piles for which mostly strength, either shear strength or uniaxial compressive strength of rock core is considered. Some of these procedures are detailed in IS [1,2] and IRC [3] codes. However, when piles are installed in rock strata, care shall be taken to study the strength characteristics of rock along with the presence of any inherent weaknesses like discontinuities, cavities, degree of weathering etc. The rock strata encountered at a site is often discontinuous, non-homogenous and anisotropic in nature and hence the effect of these heterogeneities need to be accounted in design, as this pose difficulty in predicting the response of structures constructed on them.

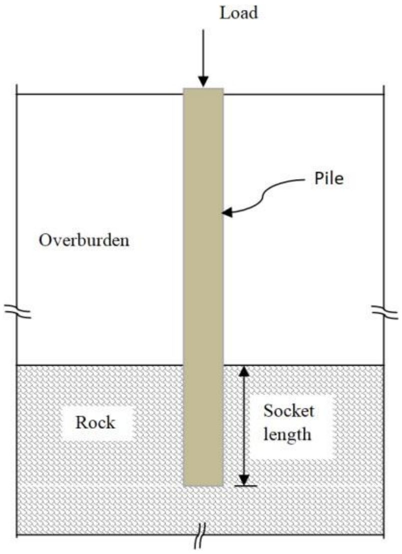

Fig. 1. Typical sketch of Rock socketed pile (Not to scale).

Experimental studies in laboratory or field have a lot of limitations in terms of the iterations that can be carried out even though they are best suitable for validation purpose. Numerical studies provide flexibility and ease in solving Geotechnical problems. By numerical modelling, the mechanisms can be better analyzed by varying the assumptions at different stages of study. There are different methods of numerical modelling techniques like finite element method, distinct element method, finite difference method and hybrid methods available. In this paper, a numerical study is presented to analyze the axial load response of a single pile in jointed rock with the help of Plaxis 3D software that employs finite element technique.

2 Numerical Study

2.1 Brief Methodology

The methodology of work includes modelling a pile in jointed rock and studying its response when acted upon by an axial load. The pile geometry considered for the analysis includes a 1m diameter pile with an overall length of 13m, including an embedment of 11m in the overburden layer and 2m in rock strata. This profile is taken from the study reported by Lee et al. (2013) that in turn has referred to the field case study reported by Jeong et al (2010). The rock stratum is reported to be high to moderately weathered gneiss. The side and bottom boundaries are considered the same as that of Lee et al. (2013) with the bottom-most boundary at a distance of 1.5L below the pile toe and the side boundaries at a distance of 20D from the pile (see Fig. 2 and Fig. 5). In this study the pile is modelled as a volume element with elastic behaviour [4]. The jointed rock is modelled both as (1) Continuum and as (2) Intact rock with discrete joints as discussed below.

(1) The behaviour of Jointed rock, when modelled as a continuum (see Fig. 2), is represented using Jointed Rock Model as well as a user-defined Iso-JRMC model. Only one sliding plane is considered for the study with the joint configuration represented by dip angles of 0 and 45°. The dip and strike angle definition in Plaxis 3D is shown in Fig. 3.

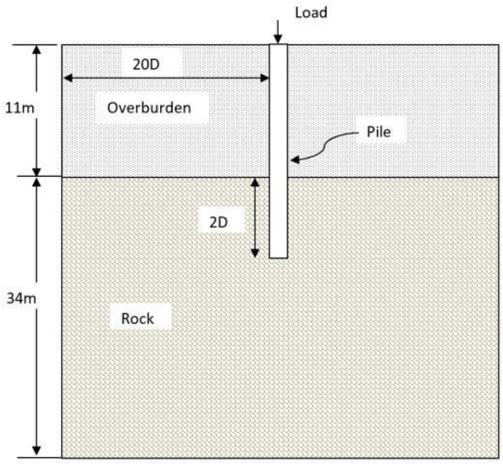

Fig. 2. A 2D representation of Pile in Jointed Rock modelled as a continuum (Not to scale)

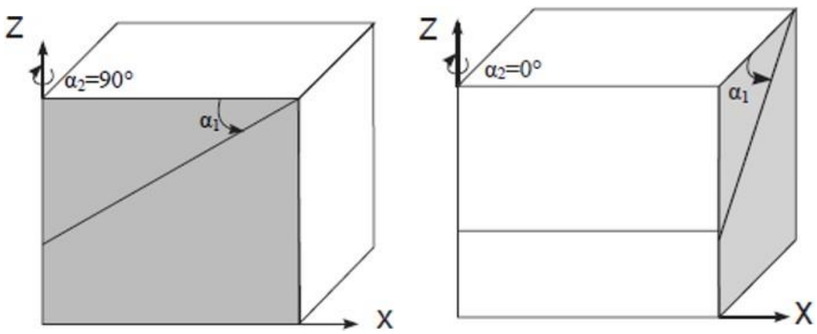

Fig. 3. Failure directions defined by Dip angle, α1 and Strike angle, α2 [5]

The Jointed Rock Model (JRM) is an anisotropic elastic perfectly plastic model for studying the behaviour of stratified and jointed rock layers. This model is suitable for joint sets that are parallel and the spacing between joints is small when compared to the overall dimension of the structure. This model (see Fig. 4) assumes the jointed rock as an intact rock (a transversely anisotropic elastic material) with optional stratification direction and major joint directions. It is possible to define a maximum of 3 sliding planes in JRM of which the first plane coincides with the direction of elastic anisotropy.

Along the sliding planes, the shear stresses are limited according to Coulomb’s criterion. This means that on reaching the maximum shear stress, plastic sliding will occur. In addition to plastic shearing, a tension cutoff criterion is used to limit the tensile stress on each plane.

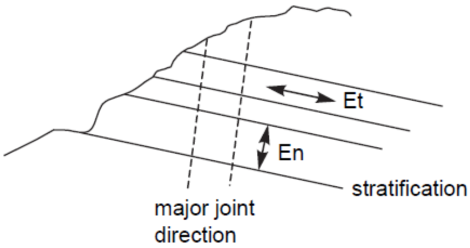

Fig. 4. Jointed Rock Model concept [5]

One limitation of JRM is that plastic deformations can occur only along the failure directions. This may lead to locking if a potential failure mechanism requires other than the predefined failure directions. To overcome this limitation, a user-defined model which is Isotropic Jointed Rock with Mohr-Coulomb (Iso-JRMC) failure criterion is introduced in Plaxis software.

The Iso-JRMC model is a combination of the jointed rock model (with isotropic elastic part) and the Mohr-Coulomb (MC) model. In this model, plasticity is expected to occur in the three stratification and joint directions, while an overall MC criterion is considered in all directions. Hence, a continuous failure mechanism will be obtained in this model. A limitation of the Iso-JRMC model is that it considers only isotropic rock mass. In JRM and Iso-JRMC models, the joint properties and inclination with respect to strike and dip are assigned in the material properties tab sheet. The rock is considered to be isotropic in nature for the present study.

(2) Jointed rock is represented as Intact rock with discrete joints as shown in Fig. 5 (MC criterion) at a spacing of 1m and with joint configurations represented by dip angles of 0 and 45^{o}.

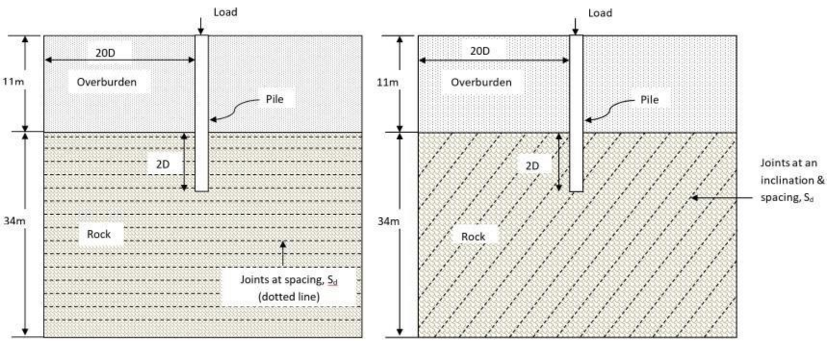

Fig. 5. A 2D representation of Pile in Jointed Rock with Discrete Joints (Not to scale)

The intact rock is created first and later the Discrete Discontinuity element available in Plaxis 3D is used to create discrete joints at a spacing of 1m (see Fig. 5). Joint elements (see Fig. 6) are formed by node pairs. That is, two nodes with identical coordinates at each node position separating the rock mass on either side of discontinuity. The joint elements have zero thickness but they act as separate feature with their own material.

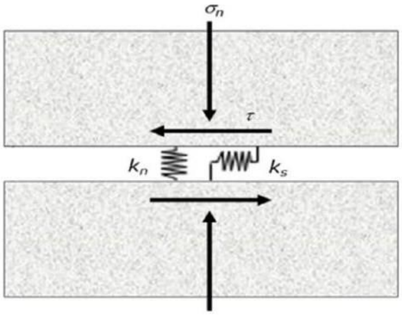

Fig. 6. Discontinuity element [5]

2.2 Subsurface Profile

Table 1 and Table 2 give the subsurface profile and material properties considered for the Numerical study taken from the work reported by Lee et al. (2013).

Table 1. Subsurface Profile and Parameters considered for the Study [6].

Type	Depth (m)	Modulus, E (MPa)	Poisson's ratio, ν	Friction angle, ϕ (degrees)	Cohesion, c (kPa)	Unit weight, γ (kN/m^3)
Soil	0-11	50	0.3	30	10	18
Rock	11-45	2400	0.3	35	300	22.6
Pile	0-13	28000	0.15	-	-	24

Table 2. Joint properties [6].

Type	Normal Stiffness, k_n (MPa/m)	Shear Stiffness, k_s (MPa/m)	Friction angle, ϕ (degrees)	Cohesion, c (kPa)
Pile-Soil interface	30	15	50% of soil	50% of soil
Pile-Rock interface	2000	1000	50% of rock	50% of rock
Joints	400	400	Same as rock	10% of rock

2.3 Model

The subsurface profile is created in Plaxis 3D using the data given in Table 1, and the joint properties are taken from the details given in Table 2. Pile is modelled as a volume, and the interfaces are assigned along the pile shaft as well as the pile tip. The interfaces have properties assigned from the adjacent soil/ rock strata. The effect of pile installation is not considered in the model. A medium mesh is considered globally in Plaxis

3D with local refinements at selected areas of the model [8]. The mesh comprises of 10 node tetrahedral elements (see Fig. 7).

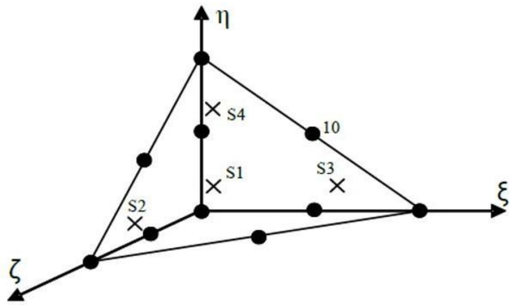

Fig. 7. Ten Noded tetrahedral elements used in the modelling [5]

An initial condition in the form of gravity is assigned to the model. The bottom-most boundary is fixed, the topmost boundary is considered free whereas all the side boundaries are assigned normally fixed. A maximum load intensity of 20 MPa is applied to the pile, and the generated response is studied. The models developed in Plaxis 3D are shown in Fig. 8.

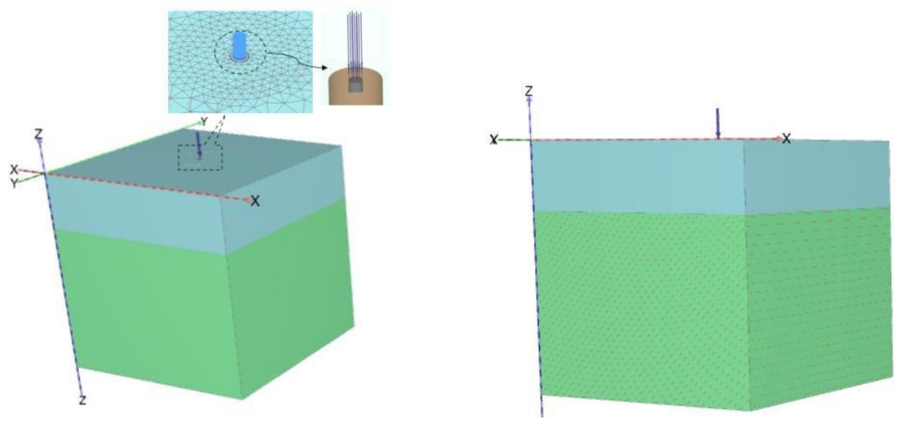

Fig. 8. Typical Models developed in Plaxis 3D (i) Continuum and (ii) Intact Rock with Discrete Joints at 45° inclination.

2.4 Results and Discussion

The response of pile socketed in jointed rock subjected to axial loading of 20 MPa is studied and presented in Fig. 9 and Fig. 10 respectively. The aim of the study is not to quantify the effect of joints but to understand the influence of joints, especially their orientation (indicated by dip angle) on pile performance. The same is visible in the graphs as compared to the field load test data [7]. The models with joints at an inclination of 45° have shown settlement of 24 to 35mm whereas for the model with horizontal joints it is in the range of 25 to 43mm. Moreover, it is seen that the continuum models of JRM and Iso-JRMC produced a result closer to the field load test curve reported by

Jeong et al. (2010) when compared to the case of Rock with discrete joints. It is to be noted that the field test curve includes the effect of joints and other geological aspects of rock mass along with the pile construction technique and quality aspects. As already mentioned, Plaxis 3D does not consider the effect of pile installation and quality. In the models where jointed rock is represented as an intact rock with discrete joints, the intact rock part is assigned a Mohr-Coulomb failure criterion. The joint configuration presented in this paper (dip angle of 0 and 45^o, spacing of 1m in the case of discrete joints) is from a series of trials carried out as part of this study with different joint inclinations and spacings.

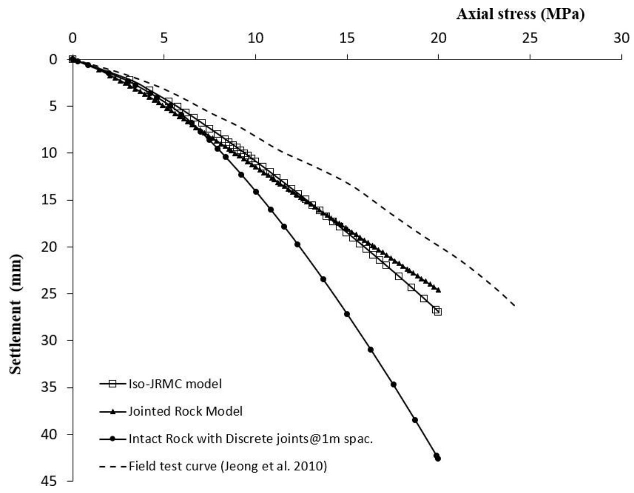

Fig. 9. Axial stress – Displacement response of Pile in Jointed Rock for Joints with Dip angle of 0^o.

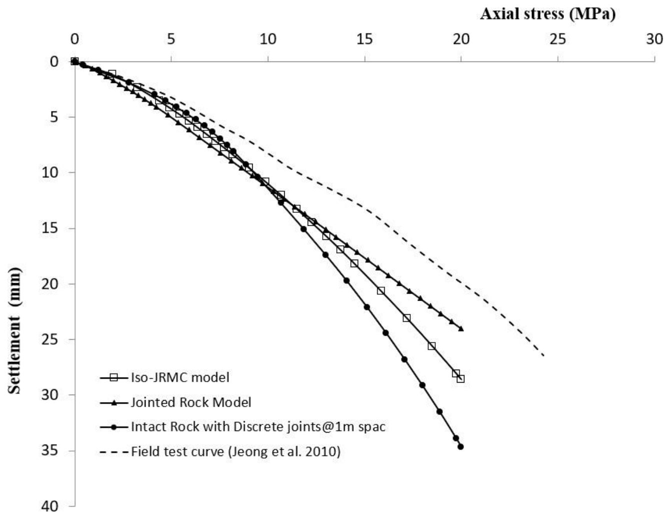

Fig. 10. Axial stress – Displacement response of Pile in Jointed Rock for Joints with Dip angle of 45^o.

3 Summary and Conclusions

A numerical study is carried out in Plaxis 3D for a single pile socketed in jointed rock. The analysis carried out in this study includes analyzing jointed rock as a continuum as well as an intact rock with discrete joints. The behaviour of jointed rock as a continuum is studied using Jointed Rock Model and Isotropic Jointed Rock Mohr-Coulomb Model. A field case study reported by Jeong et al. (2010) is used for comparative study.

It is understood that the consideration of JRM and Iso-JRMC models for the representation of jointed rock strata is a suitable option, giving comparable results with the field case study, with lesser computation efforts. Both JRM and Iso-JRMC models can represent up to a maximum of 3 joint sets including the stratification. This is very much helpful if the geological data pertaining to the site is available and major joint sets are present. Hence the effect of joints on pile can be better studied using this approach. This advantage may not be feasible when modelling jointed rock mass as an intact rock with discrete joints as an interface. The use of discrete joints is suitable in such cases where the effect of joints is to be explicitly studied with site geological data.

References

1. IS 14593: Design and construction of bored cast-in-situ piles founded on rocks - Guidelines, Bureau of Indian Standards, New Delhi (1998).
2. IS 2911 (Part 1/Sec 2): Design and construction of pile foundations – code of practice – Bored cast-in-situ concrete piles, Bureau of Indian Standards, New Delhi (2010).
3. IRC 78 (Sec 7): Standard specifications and code of practice for Road Bridges – foundations and substructure, Indian Road Congress, New Delhi (2014).
4. Haberfield, C.M., Lochaden, A.L.E.: Analysis and design of axially loaded piles in rock. Journal of Rock Mechanics and Geotechnical Engineering 11 (3), 535-548 (2019).
5. Plaxis Connect Edition V22.01, PLAXIS 3D Manual, Bentley Systems (2022).
6. Lee, J., You, K., Jeong, S., Kim, J.: Proposed point bearing load transfer function in jointed rock-socketed drilled shafts, Soils and Foundations 53 (4), 596-606 (2013).
7. Jeong, S., Cho, H., Cho, J., Seol, H., Lee, D.: Point bearing stiffness and strength of socketed drilled shafts in Korean rocks, International Journal of Rock Mechanics and Mining Sciences 47 (6), 983–995 (2010).
8. Naveen, B. P., Sitharam, T. G., Vishruth, S.: Numerical simulation of vertically loaded piles, Proceedings of Indian Geotechnical Conference, December 15-17,2011, Kochi, Paper no. N118 (2011).