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Behaviour of Rock Socketed Pile in Jointed and Weathered Rockmass Under Earthquake Loading

Mudavath Naveen[1]* and Ankesh Kumar [2]
[1] Indian Institute of Technology Roorkee,
Roorkee, India, 247667
[2]Sardar Vallabhbhai National Institute of Technology,
Surat, India, 395007
chintunp225@gmail.com

ABSTRACT: Rock socketed piles efficiently transfer the heavy loads from high-rise buildings, long-span bridges, and offshore structures to bearing strata. In the present study, A 3D finite element analysis of a rock socketed pile subjected to earthquake loading is carried out by PLAXIS 3D and the rock socketed pile is embedded in a jointed rockmass and weathered rockmass. The pile material is modeled as linear elastic, whereas Mohr's Coulomb and Hoek- Brown material models are used for the simulation of soil and rock. The acceleration-time history of the 1991 Uttarkashi earthquake is considered for the seismic analysis. The observations are recorded to understand the effect of dynamic loading on the displacement of socketed piles for different socket lengths. The effect of soil cover depth and socket length are also studied in the present work. The socket length considered is 3, 5, and 10 times the diameter of the pile. It is observed that the settlement of the rock socketed pile increases with an increase in weathering grade from W0 to W4. The settlement of the rock socketed pile is also dependent upon the GSI parameter of rockmass.
Keywords: *Rock socketed pile; Earthquake loading; Weathered rockmass; Jointed rockmass*

1. Introduction

Rock socketed piles efficiently transfer the heavy loads from high-rise buildings, long-span bridges, and offshore structures to bearing strata of the rock. In engineering practice, designers and engineers should embed the pile tip into a harder rock layer to improve the bearing capacity of the pile foundation, which is generally known as the rock-socketed pile. The strength of the rock socket is depended upon the strength of surrounded rockmass (weathered and jointed rockmass) [1]. Weathering is a disintegration process that results in decreasing the engineering properties of rockmass. The weathered rockmass is classified into different weathered grades [2] and based on engineering properties of weathered rockmass of basalt, granite, and quartzite [3-5]. The experimental studies on the pile subjected to lateral loads in weathered rock slopes, and the results indicate that the higher slope angle causes more pile deformation [6].

The jointed rockmass consists of angular blocks of a hard, brittle material that are interlocked together [7]. The discontinuity space is sometimes filled with weak materials. The strength of such rock mass is determined by the strength of the intact rock, the number of joints, dip direction, spacing of joints, and shear strength parameters of the discontinuities. Further, the jointed rockmass can be classified on the bases of the geological strength index (GSI) and the GSI is a characterized system based on visual inspection of geological conditions and used both hard and weak rockmass [8]. Hoek-

Brown is a nonlinear material model criteria for the simulation of jointed rockmass [9]. The existing correlation between GSI and engineering properties of intact rocks can be used for predicting the engineering parameters of rockmass.

The structural response of rock socketed pile under seismic conditions was evaluated by various researchers using physical and numerical modeling techniques [10-12]. The behavior of socketed piles under seismic conditions and it is observed that an increase in the socket length under the same seismic loading conditions decreases the peak acceleration at the head of the socketed pile [13]. The behavior of rock socketed pile subjected to combined loading is carried out by varying socket length & soil cover [14]. The length of socket length required for the socketing is 1D to 3D (D is the diameter) of the pile [15]. The response of the short and flexible pile under seismic conditions (EI Centro earthquake records) in different soils by using the finite element (FE) numerical tool ABAQUS [16]. The earthquake loading parameter is an important parameter that can be considered for the safe design of rock socketed piles towards settlement. There is still a lack of research on the response of rock socketed piles under earthquake loading in weathered and jointed rockmass.

Hence, in the present study, an attempt is made to understand the behavior of pile socketed in weathered and jointed rockmass under seismic loading conditions. A parametric analysis is also carried out to determine the effect of rock socketed pile in the jointed and weathered rockmass. The time history of the 1991 Uttarkashi earthquake i.e., Peak ground acceleration (PGA) vs time history is used to observe the pile behavior under seismic loading [17]. The performance of rock socket length under given earthquake loading is evaluated in detail. The disturbance factor is considered as zero (Undisturbed) for the entire analysis of jointed rockmass. The results obtained from the analysis are being used for the economical design of rock socketed piles.

2. Finite Element Model

A two-layer soil-rock model is considered for the analysis as shown in figure 1. The pile is modeled as a linear elastic material whereas the soil and rock are modeled by using Mohr-Coulomb and Hoek-Brown material models in jointed rockmass conditions [18-19] and for the weathered rockmass Mohr-Coulomb material model is considered for both rock and soil. A medium ten-node triangular element is used in the analysis. The model boundaries are 20 times the diameter of the pile in both the x and y directions and 2 times the length of the pile in the z-direction [14].

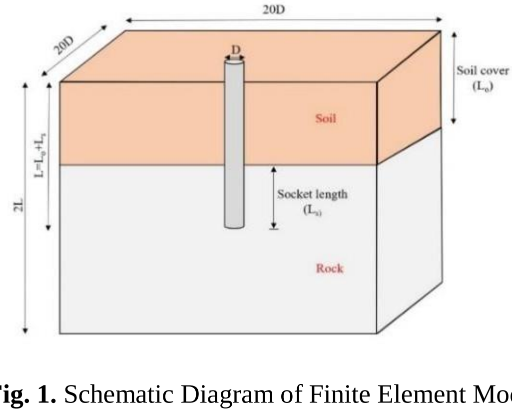


Fig. 1. Schematic Diagram of Finite Element Model

3. Validation

3.1 Pile subjected to Earthquake Loading

The numerical model employed for the present analysis is validated by the literature. The response of the pile subjected to the 1940 El Centro earthquake (Mw = 6.9) reported is selected for the validation of the present model [16]. The Mohr's Coulomb model and linear elastic material models are considered to model the soil domain and the pile respectively. The pile has a diameter of 0.5 m and a length of 4.5 m. The Young's modulus and Poisson's ratio of the pile are taken as 29580 MPa and 0.2 respectively. The material properties are listed in Table 1 for Mohr's coulomb material model. Figure 2 represents the displacements of the pile along the length of the pile under given earthquake loading. It is observed that the present analysis has good agreement with the results [16].

Table 1. Material Properties of c-soil [16]

Soil parameters	c -Soil
Shear Modulus, *G* (kPa)	$6*10^4$
Bulk Modulus, *K* (kN/m^2)	$3*10^5$
Cohesion, c (kN/m^2)	37
Coeff. of Permeability, k(m/s)	$1*10^{-9}$
Mass density, (Mg/m^3)	1.5
Friction Angle, φ (°)	0

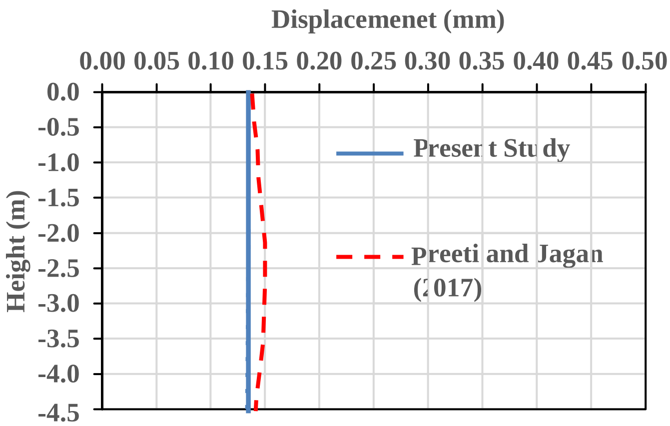


Fig. 2. Displacement vs Height of the pile

4. Numerical simulation

4.1 Material properties of jointed rockmass

The material properties of yield material constant (m_i), GSI value, and, uniaxial compressive strength of limestone and shale rockmass (σ_{ci}) are taken from the literature [20]. The material parameters namely the deformation modulus of rockmass (E_{cm}) are computed from empirical correlation provided by researchers using the GSI parameter, as shown in Tables 2 and 3 [21-22]. For undisturbed rockmass, the empirical equation 1, and 2 can be used to obtain the deformation modulus of rockmass [23-25].

$$E_m = \sqrt{\frac{\sigma_c}{100}} x10^{\frac{GSI-10}{40}} \qquad \sigma_{ci} < 100 \text{ MPa} \tag{1}$$

$$E_m = 10^{\frac{GSI-10}{40}} \qquad \sigma_{ci} > 100 \text{ MPa} \tag{2}$$

Table 2. Material properties of limestone

GSI	**m_i**	**υ_{cm}**	**σ_{ci} (MPa)**	**E_{cm} (GPa)**	**γ_{sat} (kN/m^3)**
10	10	0.2	54	0.73484	22
25	10	0.2	54	1.7425	22
50	10	0.2	54	7.348	22
75	10	0.2	54	30.988	22
100	10	0.2	54	130.676	22

Table 3. Material properties of black shale

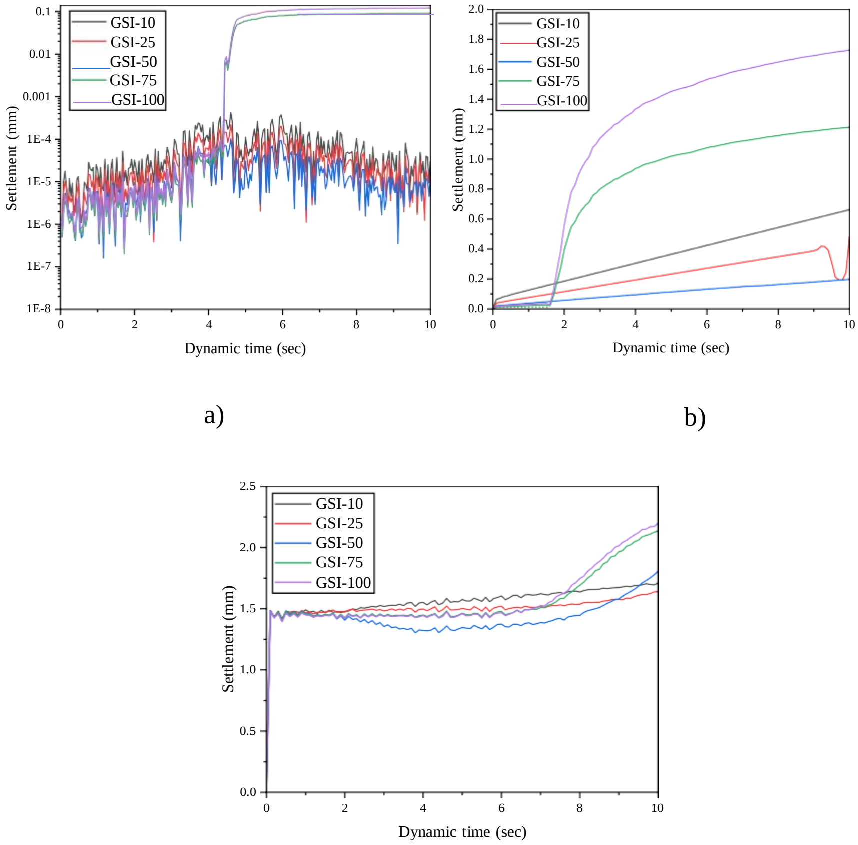
GSI	**m_i**	**υ_{cm}**	**σ_{ci} (MPa)**	**E_{cm} (GPa)**	**γ_{sat} (kN/m^3)**
10	8	0.15	5	0.223	20
25	8	0.15	5	0.530	20
50	8	0.15	5	2.236	20
75	8	0.15	5	9.429	20
100	8	0.15	5	39.763	20

4.2 Rock socketed pile in jointed rockmass subjected to earthquake loading

The analysis is carried out to observe the behavior of rock socketed pile subjected to the Uttarkashi earthquake. A structural load of uniform 10 kN/m^2 is applied to the pile head for this analysis. The settlement at the pile head is observed by varying the GSI (10-100) and socket lengths (3D, 5D, and 10D) for a constant soil cover depth of 5m. The material properties of limestone and black shale are presented in Tables 2 and 3 are used.

4.2.1 Shale jointed rockmass

Shale is a clastic sedimentary rock that contains various minerals, particularly quartz, calcite, and clay mineral flakes. Shale is a soft rock so; the settlements of the rock socketed pile are embedded in jointed shale rock is an important parameter that is considered in the analysis. The settlements of the pile are situated in a disintegrated jointed shale rockmass with GSI-10 and soil cover (5m) by varying socket lengths of 3D, 5D, and 10D, the settlements of the rock socketed pile are 0.0001 mm, 0.5mm, and 1.5 mm respectively, as shown in Fig 3. It is observed that the settlements of the rock socketed pile increase as the socket length increases. The behavior of the rock socketed pile is also investigated by varying GSI values (10, 50, and 100) at constant soil cover (5 m) and socket length (10D) the observed settlement of the rock socketed pile is 1.5 mm, 1.55 mm, 2.1 mm respectively. From this observation, the settlement of the pile increases as GSI increases. The settlement of the rock socketed pile for 3D socket length is minimum as compared to 5D, and 10D socket length.



a) b)

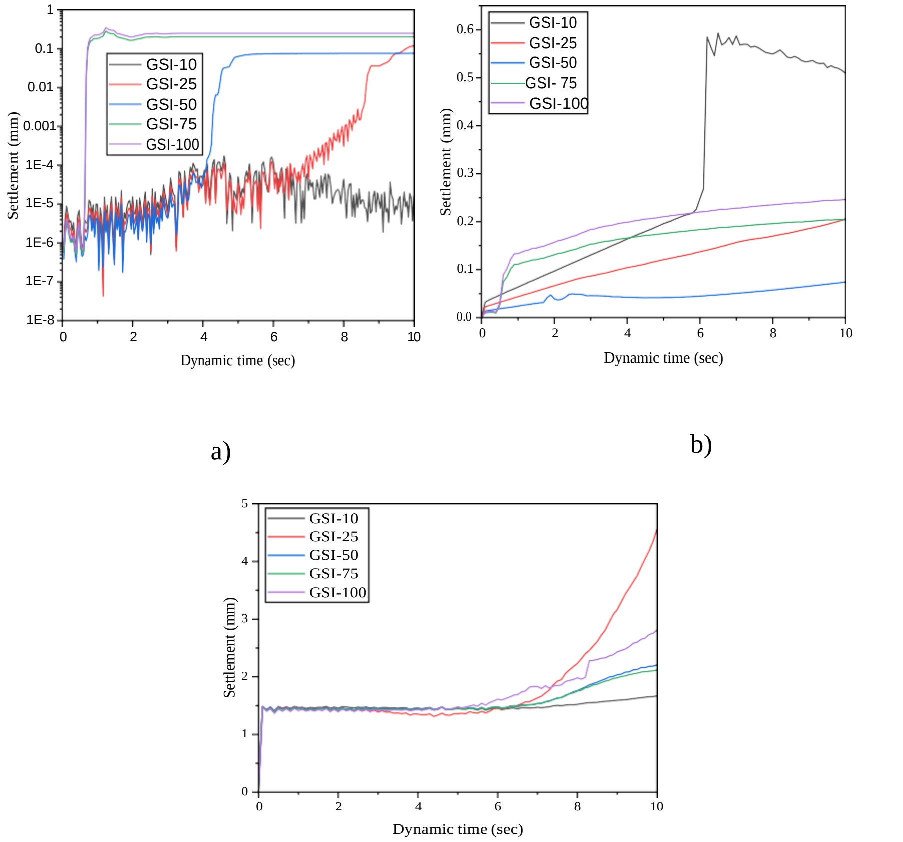
c)

Fig. 3. Variation of settlement with Dynamic time for rock socketed pile in shale

a) 3D Socket length, b) 5D Socket length and c) 10D Socket length

4.2.2 Limestone jointed rockmass

Figure 4 depicts the settlements of the rock socketed pile installed in various grades of jointed limestone under seismic loading with varying GSI and constant soil cover (5m), the observed settlements of the rock socketed pile are 0.1 mm, 0.05 mm, and 2.1 mm for the socketed length of 3D, 5D, and 10D at constant GSI (50) respectively. From this, it is observed that the settlement of the rock socketed pile is affected by varying socket lengths. The settlement of the rock socketed pile for 3D socket length is low because it acts as a short pile and resists lateral earthquake loads acting on the rock socketed pile.



a) b)

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Fig. 4. Dynamic time vs settlement graph of rock socketed pile in limestone

a) 3D Socket length, b) 5D Socket length c) 10D Socket length.

4.3 Rock socketed pile in weathered rockmass subjected to earthquake loading

Weathering is a disintegration process, due to weathering discoloration, straining, altered minerals, and textural changes are visible features in the rockmass. The engineering properties of rockmass also changed which leads to a decrease in the strength of the rockmass. So, weathering is an important parameter to be considered for the safe design of the rock socketed pile.

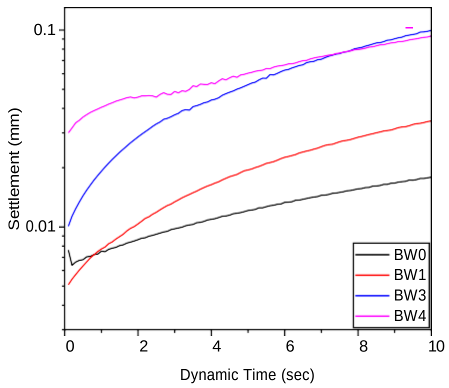
4.3.1 Basalt weathered rockmass

The rock socketed pile embedded in weathered basalt rockmass at fixed soil cover depth (5m) with varying weathering grades and socket length (3D, 5D, and 10D) is considered for the analysis. The rockmass weathering grade properties are taken from the literature The weathering grade properties of rockmass can be taken from the literature [3-4]. The experimental research on different grades of weathered Granite, basalt, and quartzite rocks. Basalt rock sample collected from the Deccan trap exposed in the western part of Lava and Kondali village in Nagpur. the study concludes that the unconfined compressive strength, shear strength, and the deformation modulus (E) weathered rockmass decreased with an increase in weathering grade from W0 to W4. The material properties of basalt rocks [3-4] are listed in Table 4.

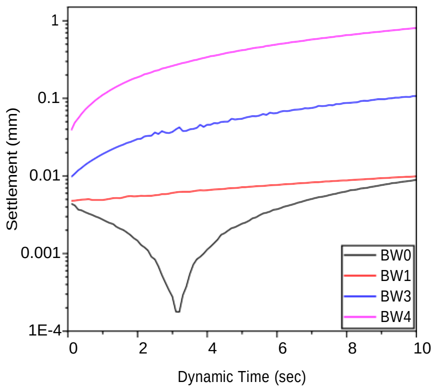
Table 4. Properties of basalt rockmass [3-4]

Material	**E (MPa)**	**R_{inter}**	**c (MPa)**	**ϕ (°)**	**ν**	**γ_{dry} (kN/m^3)**	**γ_{sat} (kN/m^3)**
Soil	15	0.67	0.001	30	0.3	16	18
QW4	1.86	1	4.8	44.06	0.39	21.58	22.66
BW0	46.51	1	26.25	63.38	0.19	29.03	29.04
BW1	20.63	1	18.5	53.71	0.26	26.87	27.36
BW3	2.77	1	8.08	33.33	0.27	24.23	25.11
BW4	0.63	1	1.04	43.87	0.27	17.85	20.79
Pile	29580	1	-	-	0.2	24	-

The settlement of the pile is very less because there is no structural load applied on the rock socketed pile and only the pile subjected to earthquake loading is carried out. The settlement at the pile head is observed for the rock socketed pile. Figure 5 depicts that the settlements of the rock socketed pile increase with the increase in the weathering grade of rockmass, this is due to with the increase in the weathered grade of rockmass, there will be a decrease in strength and deformation parameters of rockmass due to mineralogical changes weathering process. The pile socket length and rock weathering grade have a substantial effect on the settlements of the pile under earthquake loading.



a)



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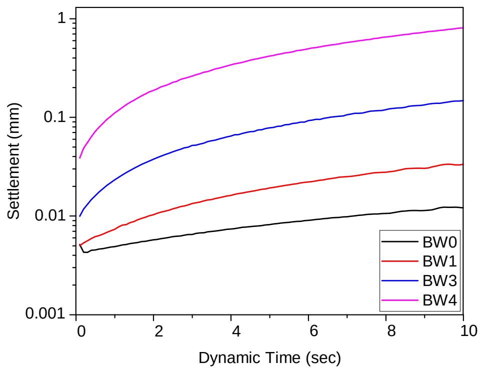

c)

Fig. 5. Dynamic time vs settlement graph of rock socketed pile in basalt weathered rockmass a) 3D Socket length, b) 5D Socket length c) 10D Socket length.

5. Conclusions

The numerical analysis was carried out using the finite element (FE) tool PLAXIS 3D. The numerical model is validated by the results available in the literature. A parametric study is carried out to understand the effect of socket lengths (3*D*, 5*D*, and 10*D*) on the displacement of the pile. Further to encounter the behavior of the pile embedded in weathered and jointed rockmass, different weathering grades (W0, W1, W3, W4) and GSI (10, 25, 50, 75, 100) values are considered for the analysis. Based upon the observed results the following conclusions are drawn

- The settlement of the rock socketed pile increases with the increasing socket length, this is due to a socket length increase the length of the pile also increased which may lead to pile failure in bending/buckling.
- The settlement of rock socketed pile increases with an increased weathering grade of rockmass, this is due to, as weathering grade of rockmass increases, the weathering process changes the mineralogical, mechanical, and physical properties of basalt rockmass.
- The settlement of the rock socketed pile is affected by the GSI parameter of rockmass, this is due to lower GSI having poor quality of rockmass with laminated shear joints, and higher GSI having a smaller number of discontinuities with the good angular interlocking of grains.

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