A new perspective of load-transfer behavior of rough rock-socketed piles

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ABSTRACT: The response of axially loaded Rock-Socketed Piles (RSPs) has been extensively studied during the past. Most previous works focused on the behavior of smooth RSPs; however, our understanding is that the Load-Transfer Mechanism (LTM) of rough RSPs is still limited. Building on recent experimental and numerical works conducted by the Authors, this paper aims to provide new perspectives of the LTM of axially loaded rough RSPs. To do that, axially loaded rough RSPs are modelled with the Distinct Element Method (DEM) providing results that indicate that socket roughness is one of the crucial factors affecting the LTM of rough RSPs. Finally, the response of the mobilized axial load (with depth) and the corresponding mobilized shaft resistance, are presented and discussed.

Keywords: Rock-Socketed Piles (RSPs), Distinct Element Method (DEM), Load-Transfer Mechanism (LTM), socket roughness.

1 INTRODUCTION

For more than 40 years, several works have studied the behavior of axially loaded Rock-Socketed Piles (RSPs); in particular, for its application as deep foundations in civil engineering (Pells et al. 1980, Seidel & Haberfield 1995, Melentijević & Olalla 2014, Gutiérrez-Ch 2020, and Gutiérrez-Ch et al. 2021b). This is because rock sockets can carry heavy concentrated loads from superstructures reducing pile settlements.

The results of previous studies (see e.g., Horvath et al. 1983, Dai et al. 2017) and the Authors' recent experiences (Gutiérrez-Ch et al. 2019, 2020, 2021a, 2021b) have shown that socket roughness is one key factor affecting the load capacity of RSPs. However, a better understanding about the influence of socket roughness on the Load-Transfer Mechanism (LTM) of RSPs is still necessary. This work contributes in that direction, investigating the LTM of RSPs through Distinct Element Method (DEM) numerical modelling of rock-socketed pile testing considering socket roughness.

2 NUMERICAL MODELLING OF ROCK-SOCKETED PILE TESTING CONSIDERING SOCKET ROUGHNESS

In this work, the behavior of axially loaded RSPs is analyzed by three dimensional (3D) DEM models developed with the Particle Flow Code (PFC) (Itasca Consulting Group Inc. 2014). Figure 1 shows an idealized scheme of a RSP and the corresponding 3D DEM model developed to simulate its behavior under axial loads considering socket roughness. The main aspects of the 3D DEM model can be summarized as follows:

a) The RSP had a void base, since only shaft resistance is analyzed herein.
b) R and L are 0.4 m and 0.8 m, respectively. Also, to reduce the computational time, a 45-degree angle portion of the pile (instead of the whole pile) is employed.
c) Pressure loads are applied on the wall head pile ($Q_1 = 0.125$ MPa) and on the wall head rock ($Q_2 = 0.1$ MPa) replicating, respectively, the self-weight of the pile embedded in the soil stratum and an overlying soil stratum (see Figure 1a).
d) The socket roughness at the pile-rock interface is simulated through sinusoidal profiles with different amplitudes (h) characterized with the Roughness Factor ($RF = h_m L_t / RL$) defined by Horvath et al. (1983), where h_m is the mean amplitudes of asperities, R is the nominal socket radius, L_t is the total travel distance along the socketed wall, and L is the nominal socket length (see Figure 1b). This type of surface is employed to replicate the typical socket roughness resulting in rock drilled with an auger tool (O'Neill et al. 1996) or with a core barrel tool (Skejić et al. 2022).

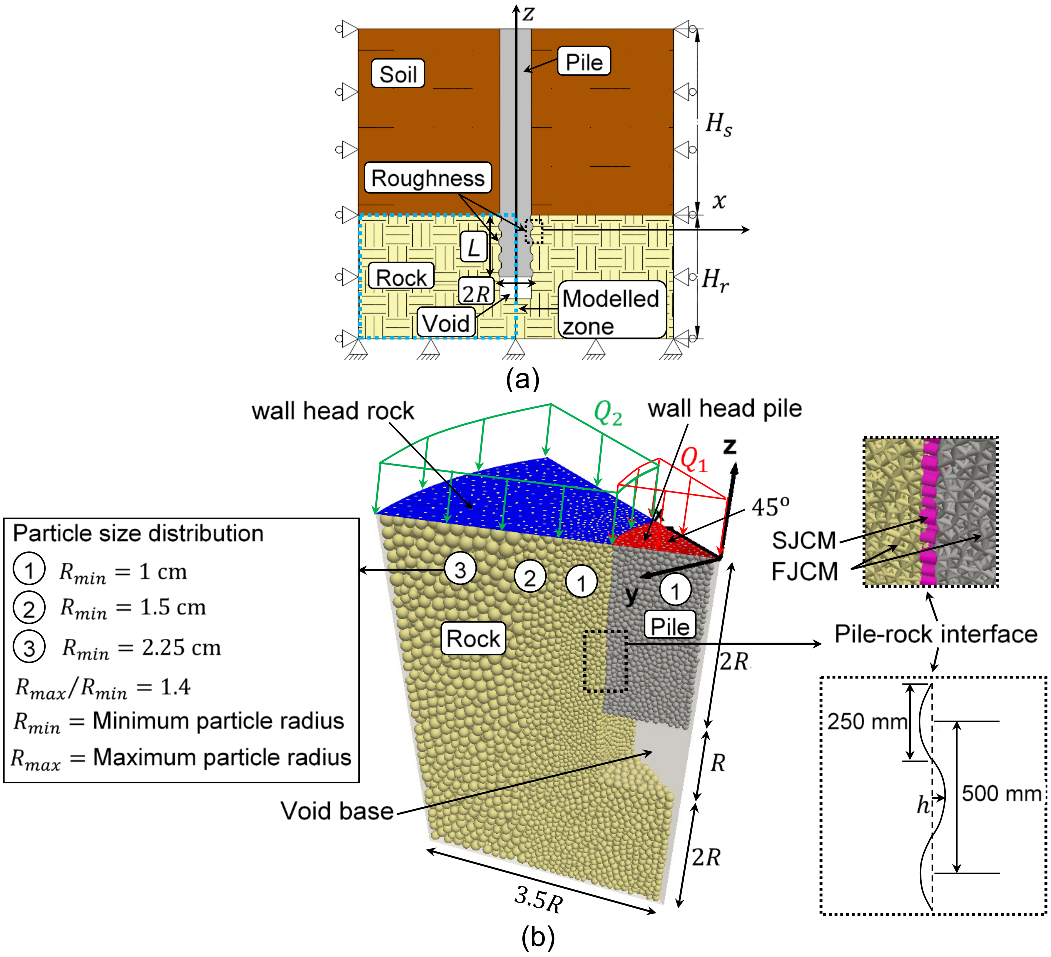


Figure 1. (a) idealized scheme of a RSP modelled, (b) 3D DEM RSP model, with information about contact models employed, about particle size distribution and the asperities geometry at the pile-rock interface (modified from Gutiérrez-Ch et al. 2021a).

e) The Flat-Joint Contact Model (FJCM) is used to simulate the macroscopic response of the concrete pile and rock materials, whereas the Smooth-Joint Contact Model (SJCM) is employed to model the behavior of the pile-rock interface. The calibration of the micro-mechanical FJCM (see Table 1) and SJCM (see Table 2) parameters and the methodology developed to build the 3D DEM model of the RSP are discussed in previous works (see Gutiérrez-Ch et al. 2018, 2020 for details).

Table 1. Micro-mechanical properties of FJCM (Data from Gutiérrez-Ch et al. 2018).

	Sandstone-S3	Concrete-C1
Particle micromechanical properties		
Effective modulus, E^*(GPa)	1.90	27.00
Normal-to-shear stiffness ratio, $k^* = k_n/k_s$	1.45	2.75
Friction angle $\emptyset$ (º)	35	30
Ball density, $\rho(kg/m^3)$	2550	2500
Minimum radius, R_{min} (mm)	1.00	0.80
R_{max}/R_{min}	1.40	1.50
Flat-joint micromechanical properties		
Effective modulus, $\overline{E^*}$(GPa)	1.90	27.00
Normal-to-shear stiffness ratio, $\overline{k^*}$	1.45	2.75
Cohesion, c (MPa)	7.90	13.55
Tensile strength, σ_t (MPa)	3.50	6.00

Table 2. Micro-mechanical properties of SJCM (Data from Gutiérrez-Ch et al. 2018).

	Sandstone(S3)-Concrete(C1)
Joint normal stiffness, $k_{n\,SJ}$ (MPa/mm)	10
Joint shear stiffness, $k_{s\,SJ}$ (MPa/mm)	5
Joint coefficient of friction, μ_{SJ} (tan $\emptyset$ (º))	0.70

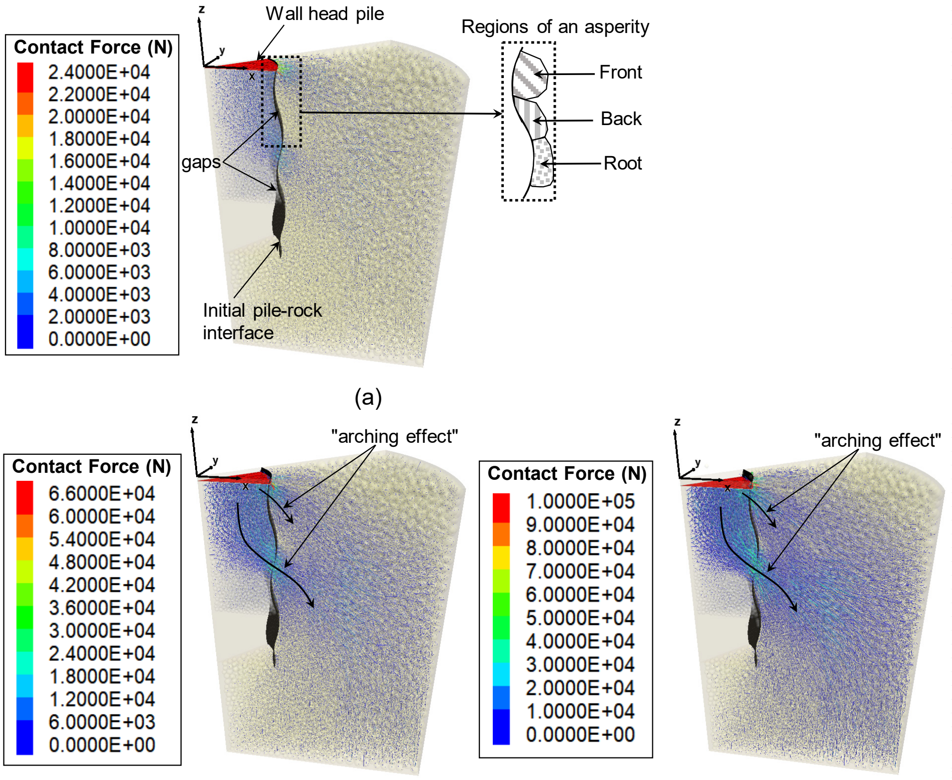
3 RESULTS

In this section, results corresponding to a DEM pile testing conducted on a rough RSP (with an asperity amplitude of $h = 20$ mm that corresponds to a $RF = 0.050$ see Figure 1b) are presented.

3.1 Inter-particle force distribution

Figure 2 shows the 3D views of the inter-particle force distribution recorded at different pile settlements (δ) expressed as a function of the pile diameter (D). Note that, at the beginning of loading (i.e., for $\delta = 1\%D$), (i) the transmission of forces from the pile to the rock mainly occurs at the front of the upper asperity, (ii) an “unloaded” area is formed at the back of such asperity due to a gap that occurs at the pile-rock interface during pile loading, and (iii) most of the forces in the pile body are located in its upper portion, hence showing that axial loads are not transmitted down to the lower portion of the pile (see Figure 2a).

Upon further loading (i.e., for $\delta > 1\%D$), the force-chain loads continue to increase due to the pile downward displacements, with pile forces being transferred to the rock along a wider region at the front of the asperities, so that an “arching effect” in the load transfer from the pile to the surrounding rock is observed (see Figure 2b-c), which suggests that the LTM of rough piles is not fully vertical as in typical interpretation of smooth piles, and that most of their axial stress is mobilized in the upper half of the pile.



(a)

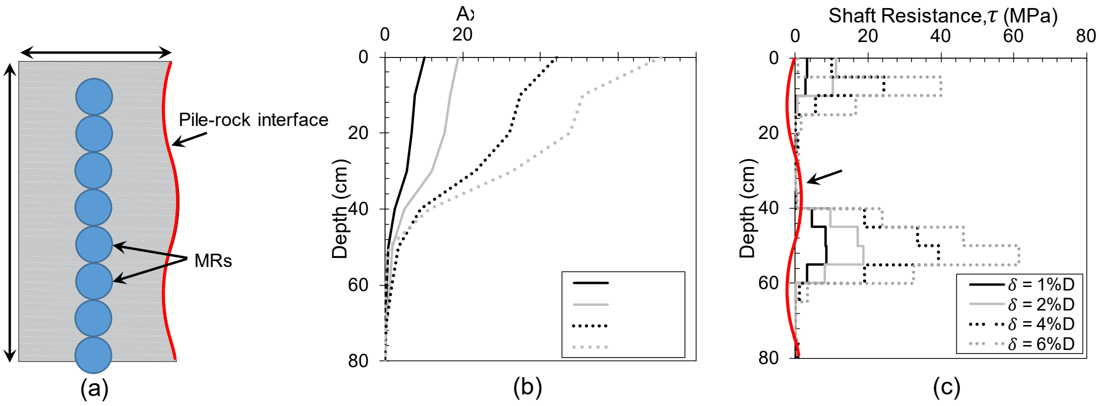
(b)

(c)

Figure 2. Inter-particle force distribution for a RSP with $RF = 0.050$: (a) $\delta = 1\%D$, (b) $\delta = 3\%D$, (c) $\delta = 5\%D$.

3.2 Axial stress and shaft resistance with depth

Figure 3 shows the axial stress (σ_z) and shaft resistance (τ) distribution mobilized along the RSP. Again, to facilitate the discussion, the pile settlements (δ) is expressed as a function of the pile diameter (D). σ_z is computed using Measurements Regions (MRs) located along the pile (see Figure 3a), while τ is calculated using the axial vertical components (i.e., in the z-axis) of contact forces acting on all particles at the pile-rock interface (see the red line in Figure 3a) divided by the nominal shaft area of the interface. Figure 3b-c show that most of the σ_z transfer occurs along the upper half of the pile length, while the mobilized τ is mainly concentrated at the front of the asperities. This behavior is due to the "arching effect" reported in the inter-particle force distributions (see Section 3.1).



(a)

(b)

(c)

Figure 3. (a) 2D locations of MRs to record σ_z along the pile (σ_z), (b) σ_z vs depth, (c) τ vs depth.

3.3 Comparison with experimental and numerical data published in the literature

LTM derived from this work is compared to experimental/numerical results published in the literature. Figure 4 shows the axial stress as a function of normalized depth ─i.e., depth divided by the nominal socket length─ for piles socketed in different types of rocks. The numerical and experimental data are listed in Table 3. (Note that, for centrifuge tests conducted by Gutiérrez-Ch et al. (2021b) and for full-scale tests conducted by Skejić et al. (2022), σ_z is computed from the axial load recorded along the pile divided by the corresponding nominal pile cross section). As shown in Figure 4, the distribution of the mobilized axial load along the pile has a similar trend; in particular, (i) σ_z is mainly concentrated in the upper portion of the pile and it decreases with depth and (ii) σ_z increases as the applied load increases. Also, note that there is more mobilized axial stress in the lower portion of the pile on the DEM test than on the experimental tests; this behavior is expected, since the socket of the experimental tests is longer (Osterberg & Gill 1973).

Table 3. Numerical and experimental data of axially loaded RSPs (base resistance is neglected for all models).

Reference	Type of test	L (m)	D (m)	RF	Type of rock	Uniaxial Compressive Strength (MPa)
This work	DEM test	0.8	0.8	0.050	Sandstone-S3	21.77
Gutiérrez-Ch et al. (2021b)	Centrifuge test	4	0.8	0.050	Pseudo-rock	1.14
Skejić et al. (2022)	Full-scale load test	3	0.9	0.021	Conglomerate	7.5

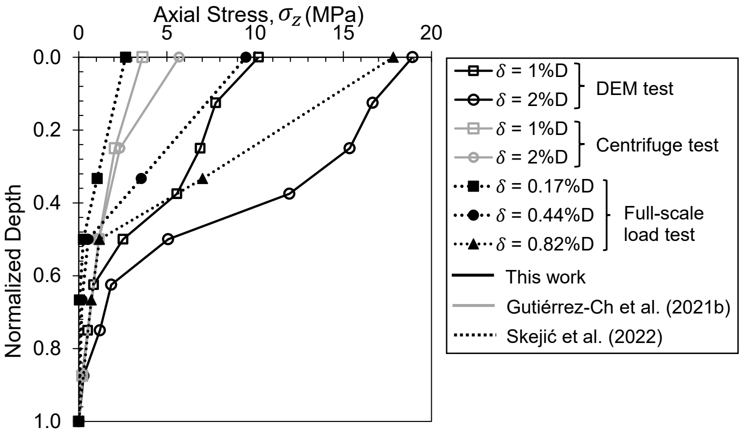


Figure 4. Comparison of σ_z computed from DEM models with experimental data published in the literature.

4 CONCLUDING REMARKS

This work presents numerical simulations of Rock-Socketed Piles (RSPs) to study its Load-Transfer Mechanism (LTM) while considering socket roughness. To that end, a 3D DEM model is built and DEM results have been interpreted in the light of previous works on this topic, and good agreement with experimental and numerical data published in the literature is found. The main conclusions can be summarized as follows:

- Numerical results demonstrated that 3D DEM RSP models are capable to analyze the LTM of RSPs.
- An “arching effect” controls the mechanism of load transfer from the pile to the surrounding rock of the rough RSP; this is a new observation that goes beyond typical interpretation models of axial load mobilization and transfer (with depth). Hence, socket roughness is a crucial factor that affects the LTM of RSPs.

- Finally, additional DEM simulations are necessary to consider different RF values, and to consider rocks with strengths higher than the strength of the concrete piles.

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