Closure to “Centrifuge Tests on Rock-Socketed Piles: Effect of Socket Roughness on Shaft Resistance” by Gutierrez-Ch J.G.[1*], Song G.[2+], Heron C.M.[3°], Marshall, A.[4°] and Jimenez R.[5*]

The Authors thank the Discussers for their interest in our work, and for the interesting points raised. Some additional information and discussion about these points is presented next.

Johnston’s Discussion

The Authors acknowledge the relevance of his recent contributions to this field (Johnston 2020, 2021), which were not available to us at the time of submission. The Discusser raises three main points, related to (i) the relevance of load tests to improve our understanding of the shear resistance of rock-socketed piles; (ii) the pseudorock used in the tests, the way in which it was produced, and possible subsequent implications in terms of expected behavior; and (iii) the availability of triaxial (or similar) tests to characterize the contractant or dilatant behavior of the pseudorock.

On the relevance of centrifuge tests

The Authors believe that, although the effect of roughness on socket shaft behavior has been, of course, previously investigated, the novel centrifuge testing

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methodology with FBG sensors proposed in the paper is useful to explore new aspects of rock socket behavior, or to confirm others. For instance, note that, to our knowledge, the influence of socket roughness on the axial load distribution of rock sockets was measured herein for the first time. In any case, the Authors agree with the Discusser's comments that quantifying socket roughness in real sockets should be a crucial next step in this line of research.

Pseudorock production, and its associated behavior

Here, the Discusser indicates that "rock, including soft rock, is a brittle and dilatant material … [that] does not become ductile and contractant until confining pressures are much higher and probably greater than experienced in socketed piles". In essence, and as indicated by the Discusser, this point is very similar to the main idea he presented in Johnston (1991) discussing a paper by Indraratna (1990). Similarly, the Discusser points to one previous publication (Johnston and Choi, 1986) in which methods for "the development and manufacture of a synthetic soft rock for use in experimental laboratory investigations" are proposed, showing also that the resulting rock –referred to as "*Johnstone*", and manufactured from a mixture of mudstone powder, cement, water and set accelerator which is compressed under high stress so that particles are consolidated into a dense structure– is similar to the Melbourne mudstone. According to the Discusser, this produces "a structure which leads to the dilatancy observed in natural soft rocks […] with brittle, dilatant behavior occurring with low confining pressures and ductile, contractant behavior occurring with higher confining pressures".

The Authors would like to point out, however, that while this method to manufacture "*Johnstone*" might be optimal "as a highly accelerated repetition of the geological processes" leading to the formation of Melbourne mudstone (Johnston and Choi, 1986) and to obtain similar (brittle and dilatant) behavior than that observed in heavily overconsolidated mudstones, there are other geological processes leading to the formation of soft rocks that may involve lower stresses (think, for instance, of shallow water calcareous or biogenic weak rock formations), hence providing them with a different behavior. For instance, Indraratna (1991) provides ample evidence for more ductile behavior –citing, e.g., the work by Hoek & Brown (1980)– and indicating that "ductility can be pronounced in weathered rocks, heavily jointed rock masses and some weak rocks, including evaporites, under normal engineering conditions"; Indraratna (1991) also provides additional examples in which "greater ductility and elasto-plastic yielding are expected" in the field. It is argued by these Authors that a wide range of intermediate behaviors should be probably expected in real weak rocks, corresponding to different geological conditions worldwide.

In any case, however, readers should note that the Authors were not trying to reproduce one specific type of weak rock response (contractive or dilatant), according to the soft rocks associated to the geology of a particular site. Rather, the aim was to obtain a rather soft pseudorock –with an intact uniaxial compressive strength between 1–12 MPa– so that, according to Seidel and Collingwood (2001), the relevance of roughness on shaft behavior would be maximized. We certainly agree with the Reviewer that the response of rock-socketed piles in brittle, dilatant material merits investigation and should be considered for further detailed investigations.

Laboratory tests

Regarding the last point, some preliminary consolidated undrained (CU) triaxial tests were conducted by the Geotechnical Laboratory of CEDEX –a Spanish Government Agency for Studies and Research in Public Works– with pseudorock formulations similar (but not exactly equal) to the pseudorock employed in the centrifuge tests. (CU triaxial test results correspond to a mixture with an intact uniaxial compressive strength, UCS, of $\sigma_c = 1.5$ MPa, or slightly larger than the UCS from the pseudorock finally used in our work, of $\sigma_c = 1.14$ MPa; such pseudorock was prepared using a mixture of sand, cement, bentonite and water, with proportions by percent mass of 59.5 %, 15 %, 8 % and 17.5 %, respectively). Results are presented in **Fig. 1**, so that they can at least serve as a basis for qualitative analysis or discussion.

[Fig. 1 approx. here]

Results in **Fig. 1**(a) show that positive pore pressures are generated, hence suggesting an overall contractive behavior, although the generated pore pressures start to decrease at around strain levels associated with the peak deviatoric stress. Note also that behavior is rather ductile (**Fig. 1**), especially for higher confinement levels, hence agreeing with the strain-stress response suggested by Hoek and Brown (1980, 1997) for “average” to “very poor” rock masses.

Also, note that, although radial deformations/displacements were not measured at the shafts or piles during the tests, the roughness profiles employed for the piles can be used as an indicator of (maximum) expected dilation normal to the shafts, that would range from a basically null value for the “smooth” pile, to about

2-4 cm (at prototype scale) for the rougher piles. Then, considering an estimated normal stiffness (K_n) for the rock-concrete socket interface (see **Fig. 2**), it results that, except for “smooth” piles, normal stresses –and hence the associated minor principal (σ_3) stresses– associated with large displacements at the socket interface would be in the range of 2.6-9.8 MPa, hence being in the range of, or even significantly higher for rougher piles, than the 3 MPa maximum confinement considered in the triaxial tests, so that a rather ductile behavior would be expected for the pseudorock used in our centrifuge tests. Therefore, the validity of the Discusser´s statement that “[behavior] does not become ductile and contractant until confining pressures are much higher and probably greater than experienced in socketed piles” is, again, dependent on other aspects such as rock strength and socket roughness and, in the Authors’ opinion, cannot be taken as a generally valid observation.

[Fig. 2 approx. here]

Diyaljee’s Discussion

The discussion by Diyaljee focuses on the following two main aspects: (i) the global stiffness of rock-socketed piles, and (ii) the influence of corrosion on the axial load of the aluminum piles tested.

Global stiffness evaluation

First, the Discusser mentions that “the stiffness reported in Fig.6b is derived as the ratio of applied load to a deflection corresponding to 1% of the diameter of the pile”. This may be a misunderstanding since the global stiffness presented in Fig. 6b is obtained as the pile load divided by the corresponding pile settlement.

On the other hand, the global stiffness shown in Fig. 6b represents the global pile response under axial load, and it could be affected by several aspects (e.g., pile diameter, socket roughness, rock type, normal and shear stiffnesses at the pile-rock interface, etc.). However, considering that only the socket roughness is varied in this case, while the other aspects are kept constant, results presented in Fig. 6b mainly illustrate the effect of socket roughness on the global pile stiffness response.

Influence of corrosion on axial load

With respect to the discusser's second point, corrosion was observed on all model piles, however the Authors only have a post-test calibration factor for the pile with $RF = 0.025$. Post-calibration tests could not be conducted on the other two piles (i.e., piles with $RF = 0.050$ and 0.106) because of damage that occurred when the Authors extracted them from the pseudorock. The Authors appreciate the interest of the Discusser on the pile's corrosion magnitude and the pH of the pseudorock mixture; however, such aspects were unfortunately not measured at the time (in part due to the above-mentioned extraction damage) and neither can be measured at this stage. Finally, the Authors agree with the Discusser's comment that for future research on this topic, it would be interesting to analyze the benefits of adding corrosion inhibitors to the pseudorock mixture used.

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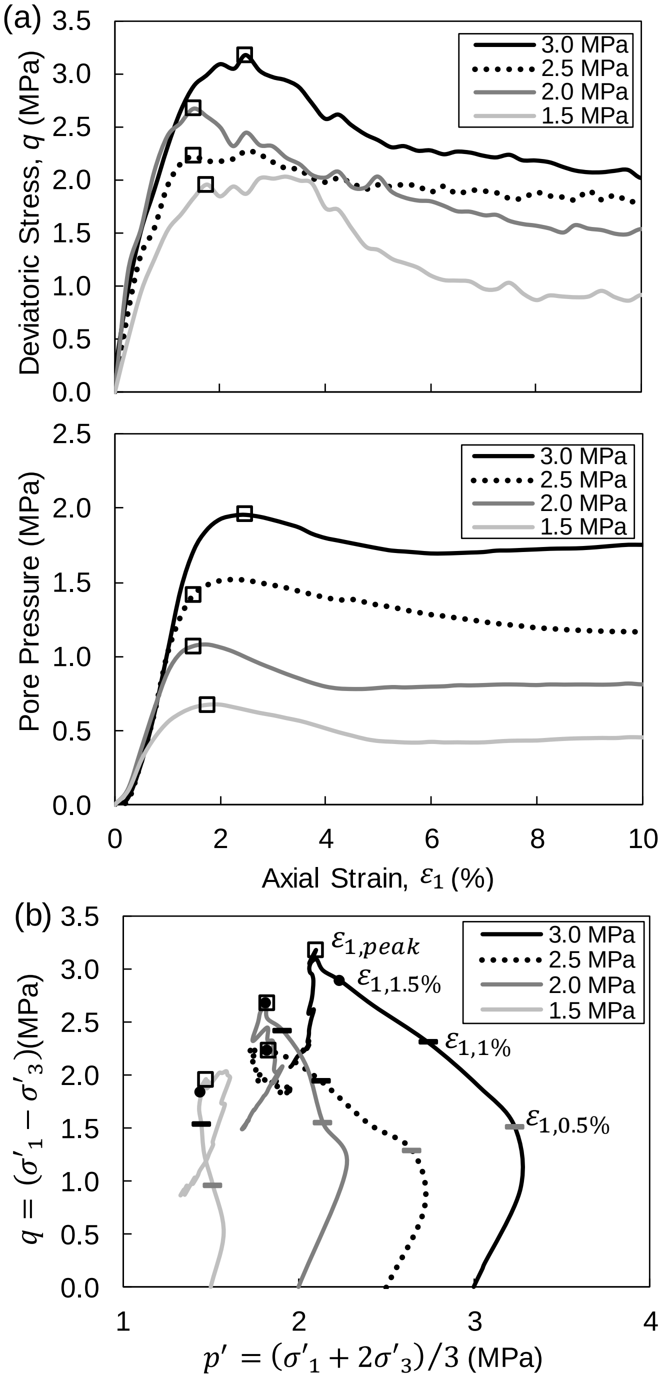

Fig. 1. Consolidated undrained triaxial tests conducted on saturated pseudorock samples, at effective confining pressures between 1.5 to 3.0 MPa: (a) deviatoric stress (and pore pressure) vs axial strain, (b) effective stress paths on Cambridge *p'*-*q* diagram.

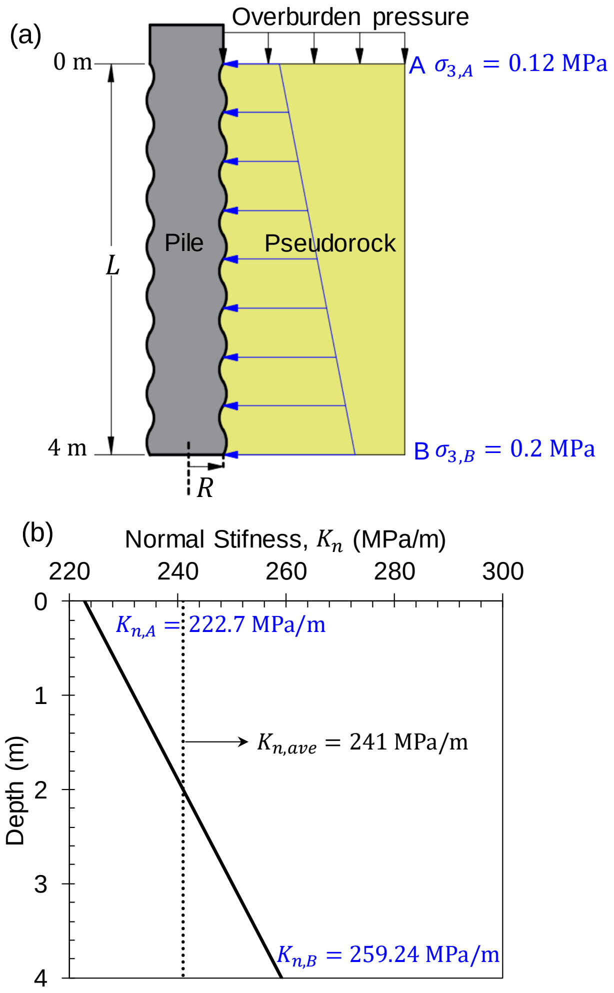

Fig. 2. (a) initial normal stress and (b) normal stiffness with depth at prototype scale.