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Load-deformation response of laterally-loaded large diameter piles in rock considering shaft vertical interfacial friction

Réponse charge-déformation des pieux de grand diamètre chargés latéralement dans la roche en tenant compte du frottement vertical de la peau de l'arbre

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ABSTRACT: The design of pile foundations against lateral forces and overturning moments caused by the superstructures needs to ensure an adequate margin of safety and tolerable response of displacement. Some closed-form solutions predicting the lateral response of rock-socketed piles are available; however, most of them are simplified and developed based on problems studied in soil. The major drawback in traditional approach (e.g., via p-y curves) is the implicit assumption that the piles is allowed bend freely as a beam. However, the shaft interfacial friction would prevent free bending and this effect becomes significant as the pile diameter increases when founded in rock. In this study, the influence of vertical shaft interfacial friction on the response of laterally-loaded large diameter rock-socketed piles is investigated using a numerical model.FLAC3D is utilised to carry out the numerical study including non-linearity in rock-pile interface. The pile and the surrounding rock mass are modelled using elastic solid elements. Interface is assigned between the pile and surrounding rock mass to capture the effect of shaft vertical interfacial friction. The results of numerical analysis are presented in dimensionless format so that direct comparison against the results of available closed-form solutions can be performed; it is observed that the vertical shaft interfacial friction has a significant influence on the lateral response of large diameter piles in rock. Based on the numerical results, modified closed-form solutions to accommodate the contribution of vertical shaft interfacial friction are proposed.

RÉSUMÉ: La conception des fondations sur pieux contre les forces latérales et les moments de renversement causés par les superstructures doit garantir une marge de sécurité adéquate et une réponse tolérable au déplacement. Certaines solutions de forme fermée prédisant la réponse latérale des pieux à alvéoles rocheuses sont disponibles; cependant, la plupart d'entre eux sont simplifiés et développés en fonction des problèmes étudiés dans le sol. L'inconvénient majeur de l'approche traditionnelle (par exemple, via les courbes p-y) est l'hypothèse implicite que les pieux peuvent se plier librement comme une poutre. Cependant, le frottement de l'arbre de la peau empêcherait la flexion libre et cet effet devient significatif lorsque le diamètre du pieu augmente lorsqu'il est fondé dans la roche. Dans cette étude, l'influence du frottement vertical de la peau de l'arbre sur la réponse des pieux à alvéoles rocheux de grand diamètre chargés latéralement est étudiée. FLAC3D est utilisé pour mener à bien l'étude numérique incluant la non-linéarité dans l'interface roche-pile. Le pieu et la masse rocheuse environnante sont modélisés à l'aide d'éléments solides élastiques. L'interface est assignée entre le pieu et la masse rocheuse environnante pour capturer l'effet du frottement vertical de la peau de l'arbre. Les résultats de l'analyse numérique sont présentés dans un format sans dimension afin de pouvoir effectuer une comparaison directe avec les résultats des solutions de forme fermée disponibles; on observe que le frottement vertical de la peau du puits a une influence significative sur la réponse latérale des pieux de grand diamètre dans la roche. Sur la base des résultats numériques, des solutions de forme fermée modifiées pour tenir compte de la contribution du frottement vertical de la peau sont proposées.

KEYWORDS: lateral load, large diameter pile, rock-socketed pile, FLAC3D, closed-form solution.

1 INTRODUCTION

The design of pile foundations against lateral forces and overturning moments caused by the superstructures needs to ensure an adequate margin of safety and tolerable response of displacement. Some closed-form solutions predicting the lateral response of rock-socketed piles are available (e.g., Carter and Kulhawy 1992); however, most of them are simplified and developed based on problems studied in linear soil medium (e.g., Reese 1956, Matlock and Reese 1960, Randolph 1981) and following by the development of nonlinear p-y curves (Matlock 1970, Reese et al. 1975), which has been recommended in some design codes (API 2010, DNV 2014). The major drawback in traditional approach (e.g., via p-y curves) is the implicit assumption that the pile is allowed bend freely as a beam. However, as shown in Figure 1a, the shaft interfacial friction would prevent free bending and this effect becomes significant as the pile diameter increases when founded in rock. The anomaly in the traditional approach is that against axial loads (see Figure 1b), the reliance is placed on interfacial friction but such is completely neglected when considering the performance of piles under bending, which may potentially underestimate the response of piles under combined load case as shown in Figure 1c.

On the other hand, design charts developed based on numerical modelling (e.g., boundary elements, or finite elements) are available (e.g., Poulos 1971, Banerjee and Davies 1978, Kuhlemeyer 1979). From design point of view, reading design charts is a cumbersome solution and less attractive than closed-form solution and their use is seriously limited by broad assumptions made in developing them.

In this study, the influence of shaft vertical interfacial friction on the response of laterally-loaded large diameter rock-socketed piles is investigated and closed-form solutions are modified based on the solution proposed by Carter and Kulhawy (1992) to accommodate the contribution of vertical interfacial friction.

It should be noted that, in this study, the effect of groundwater is not included. The rock surface and pile head are on the same level and no surface slope is considered. The pile is assumed to be made of concrete and the pile head is 'free' against rotation, the latter is valid for large diameter piles as the piles are much stiffer than the capping beam or the raft.

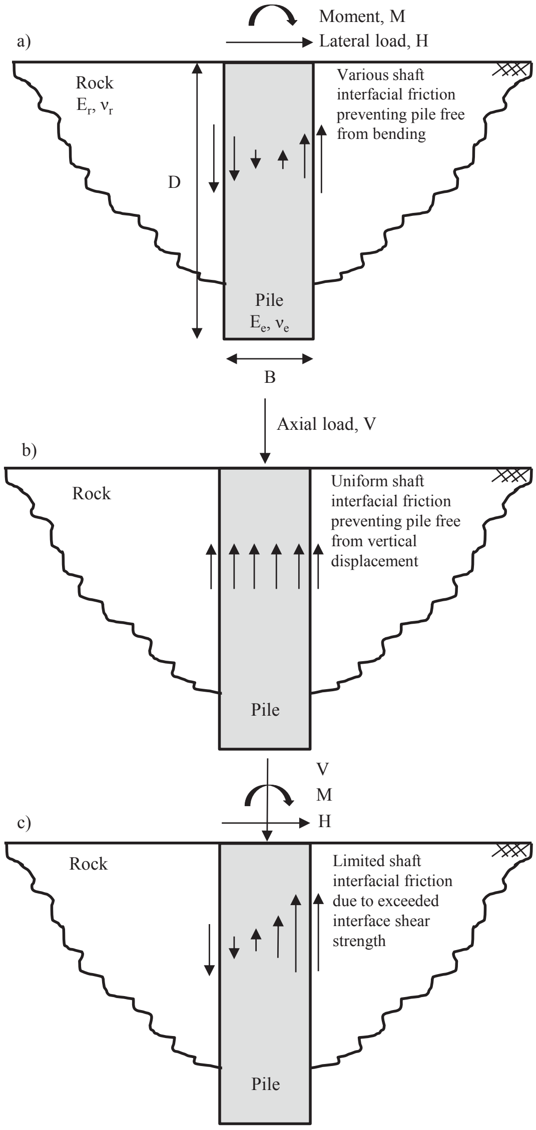

Figure 1 a) Laterally loaded rock-socketed pile considering shaft interfacial friction, b) vertically loaded rock-socketed pile considering shaft interfacial friction and c) combined load case may cause limited shaft interfacial friction

2 NUMERICAL MODELLING AND ANALYSIS

The problem of laterally loaded-rock-socketed pile can be idealised as shown in Figure 1a assuming a cylindrical pile socketed in rock subjected to a lateral force (H) and an overturning moment (M). According to Carter and Kulhawy (1992), the pile can be described using an equivalent Young's modulus (E_e) and Poisson's ratio (ν_e), pile depth (D) and diameter (B). The equivalent Young's modulus can be determined based on concrete Young's modulus (E_c) and area moment of inertia of pile (I_c) adopting Eq. 1 and the equivalent Poisson's ratio is assumed as concrete Poisson's ratio (ν_c) as 0.25.

$$E_e = \frac{E_c I_c}{\pi B^4/64} \tag{1}$$

As concrete members do crack under even Serviceability Limit State, modifications can be made iteratively or incorporate in a non-linear numerical model to take account of the reduced pile rigidity (Vithanara, 1999).

The surrounding rock is assumed to be homogenous and isotropic elastic rock-mass, which can be described using Young's modulus of rock mass (E_r) and Poisson's ratio of rock mass (ν_r).

This study used a 3-Dimensional explicit finite difference based program FLAC3D, version 6.0 (Itasca 2017) to numerically investigate the effects of shaft vertical interfacial friction and derive design aids. A $25\,m \times 25\,m \times 40\,m$ was modelled utilising solid finite difference elements. Figure 2 shows that solid polyhedral elements of brick type were used to model the foundation, and each solid element consisted of tetrahedral sub-elements to define the strain rates and corresponding space intervals.

For numerical modelling, Hawksbury Sandstone Class II was employed to simulate surrounding rock mass with typical stiffness and strength parameters as listed in Table 1 according to Bertuzzi (2014), Oliveira (2014), and Pells et al. (2019). It should be noted that, to investigate the effects of shaft vertical interfacial friction, the surrounding rock has been modelled elastically. It has also been assumed that no vertical or horizontal tectonic locked-in stress fields exists.

Table 1 Typical Hawksbury sandstone Class II rock mass properties (after Bertuzzi 2014, Oliveira 2014, Pells et al. 2019)

Rock mass property	Value
Density ρ_{soil} (kg/m^3)	2500
Young's modulus E_r (MPa)	2000
Friction angle $\emptyset_r$ (°)	58
Cohesion c_r (kPa)	500
Tensile strength T_r (kPa)	125
Poisson's ratio ν_r	0.2

Randolph (1981) and Carter and Kulhawy (1992) mentioned that to approximately capture the effects of variations in Poisson's ratio of rock mass, an equivalent shear modulus of rock mass (G*) defined by Eq. 2 is suggested.

$$G^* = \frac{E_r\left(1+\frac{3\nu_r}{4}\right)}{2(1+\nu_r)} \tag{2}$$

According to Randolph (1981) and Carter and Kulhawy (1992), the pile head lateral displacement (u) and rotation (θ) of the pile in homogeneous rock mass depends on the relative moduli of the pile and rock mass, modulus ratio (E_e/G^*), and the geometry of the pile, slenderness ratio (D/B). Table 2 lists the parametric study performed in this paper. Note that for each pile slenderness ratio, all the modulus ratios have been analysed.

Table 2 Performed parametric study

Parameter	Considered cases			
E_e/G^*	2.11	21.1	211	2110
D/B	1	2.5	5	10

To incorporate the material difference between the concrete pile and the rock and to capture any possible separation and sliding between them, the interface elements available in

FLAC3D were assigned between the pile and the surrounding rock as shown in Figure 2. Each interface element is a three-nodded triangular element that could be represented by two spring-sliders to simulate normal and shear behaviour across the contacting surfaces. The shear and normal stiffness values of the interface elements are set at ten times the equivalent stiffness of the neighbouring elements using Eq. 3.

$$k_s = k_n = 10\left[\frac{\left(K+\frac{4}{3}G\right)}{\Delta z_{min}}\right] \tag{3}$$

where K and G are the bulk and shear modulus of the neighbouring element, respectively, and Δz_{min} is the smallest width of the adjacent element in the normal direction. This assumption was used to avoid any intrusion from adjacent elements while preventing excessive computational time and eventually optimising the simulation. The shear strength (S_s) was defined by Eq. 4 to capture possible pile sliding along the interface during the analysis.

$$S_s = c_s A + tan\,\emptyset_s F_n \tag{4}$$

where c_s and $\emptyset_s$ were the cohesion and friction angle assigned to the rock-pile interface simulating shaft vertical interfacial friction, A was the contact area and F_n was the resultant normal force acting on this area. Note that the dilation angle (d) was assumed to be zero. According to Itasca (2017), the normal and shear forces generated on the interfaces at time ($t+\Delta t$) are determined using the following equations:

$$F^{(t+\Delta t)}{}_n = (K_n u_n + \sigma_n)A_i \tag{5}$$

$$F^{(t+\Delta t)}{}_{si} = F^{(t)}{}_{si} + (K_s \Delta u_{si}{}^{(t+0.5\Delta t)} + \sigma_{si})A_i \tag{6}$$

where $F^{(t+\Delta t)}{}_n$ and $F^{(t+\Delta t)}{}_{si}$ are the normal and shear force vectors at time ($t+\Delta t$), respectively, u_n is the absolute normal penetration of the interface node into the target face, Δu_{si} is the incremental relative shear displacement vector, σ_n and σ_{si} are the additional normal and shear stress vectors added due to interface stress initialisation, respectively, and A_i is the representative area associated with the interface element.

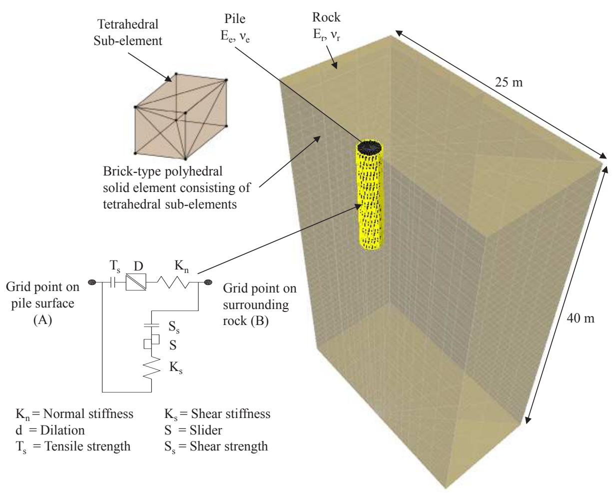

Figure 2 Developed numerical model of idealised laterally-loaded rock-socketed pile considering the effect of shaft interfacial friction

To investigate the effects of shaft vertical interfacial friction, the interface strength conditions listed in Table 3 were tested. The 'appropriate' interface strength was determined based on surrounding rock mass strength (Table 1) with a strength reduction factor of 0.67.

Table 3 Interface strength condition

Interface strength condition	Slippery	Appropriate	Fully bonded
Cohesion c_s (kPa)	0	300	1e6
Friction angle $\emptyset_s$ (°)	0	44	89
Tensile strength T_s (kPa)	0	75	1e6

3 RESULTS AND DISCUSSION

The numerical results considering the appropriate interface strength have been presented in Figures 3 to 6 showing the pile head responses in terms of the relationships of load-displacement, moment-rotation, load-rotation and moment-displacement, respectively using dimensionless displacement against the modulus ratio and slenderness ratio.

Based on the results of numerical model when Eq. 7 is valid, the pile response is more 'flexible' (i.e., as if the pile were infinitely long) and only depends on modulus ratio as shown in Figures 3b to 6b. Eq. 8 and Eq. 9 provide closed-form expressions estimating the pile head deformation of 'flexible' piles. The curves of proposed equations (i.e., 'Appropriate Interface') have been plotted in Figure 3a to Figure 6a to show the adequacy of the prediction of the 'flexible' pile response in elastic rock-mass.

$$\frac{D}{B} \geq 2.5\left(\frac{E_e}{G^*}\right)^{1/7} \tag{7}$$

$$u = \frac{H}{G^*B}\left(\frac{E_e}{G^*}\right)^{-1/4} + 1.2\frac{M}{G^*B^2}\left(\frac{E_e}{G^*}\right)^{-3/7} \tag{8}$$

$$\theta = 1.2\frac{H}{G^*B^2}\left(\frac{E_e}{G^*}\right)^{-3/7} + 9\frac{M}{G^*B^3}\left(\frac{E_e}{G^*}\right)^{-3/4} \tag{9}$$

On the other hand, when Eq. 10 is valid, the shaft response is more 'rigid' (i.e., as if the pile were short and stubby) and only depends on pile slenderness ratio as shown in Figures 3a to 6a. Eq. 11 and Eq. 12 provides closed-form expressions estimating the pile head deformation of 'rigid' piles. The predicted curves (i.e., 'Appropriate Interface') plotted in Figures 3b to 6b demonstrates the accuracy of the prediction of the 'rigid' pile response.

$$\frac{D}{B} \leq 0.1\left(\frac{E_e}{G^*}\right)^{1/2.3} \tag{10}$$

$$u = 0.7\frac{H}{G^*B}\left(\frac{D}{B}\right)^{-2/3} + 0.6\frac{M}{G^*B^2}\left(\frac{D}{B}\right)^{-4/3} \tag{11}$$

$$\theta = 0.6\frac{H}{G^*B^2}\left(\frac{D}{B}\right)^{-4/3} + 0.6\frac{M}{G^*B^3}\left(\frac{D}{B}\right)^{-5/3} \tag{12}$$

For 'intermediate' piles, of which the slenderness ratio is bounded by Eq. 13, Carter and Kulhawy (1992) suggested that the deformations at the pile head can be taken as 1.25 times the greater of the following:

i) the deformations of a 'flexible' pile with the same modulus ratio, or

ii) the deformation of a 'rigid' pile with the same slenderness ratio.

$$2.5\left(\frac{E_e}{G^*}\right)^{1/7} \leq \frac{D}{B} \leq 0.1\left(\frac{E_e}{G^*}\right)^{1/2.3} \tag{13}$$

The aforementioned equations can be applied to the range of modulus ratio as $1 \leq E_e/G^* \leq 1e5$ and the range of slenderness ratio as $1 \leq D/B \leq 10$, particularly, for piles with diameter greater than 2 m. Closed-form solutions Eq. 7 to Eq. 13 are modified based on the solutions developed by Carter and Kulhawy (1992).

To demonstrate the effects of shaft vertical interfacial friction, the predicted deformation curves considering interface condition of ‘Slippery’ and ‘Fully Bonded’ were plotted based on numerical results adopting the same method utilised in the pile response prediction of ‘Appropriate Interface’. It should be noted that the prediction curves of ‘Fully Bonded Interface’ are similar to what have been reported in Carter and Kulhawy (1992).

In Figures. 3 to 6, it is obvious that the response curve of pile head considering appropriate shaft vertical interfacial friction (appropriate interface) is between the response curves of shaft considering ‘slippery’ interface and ‘fully bonded’ interface. In particular while the slenderness ratio become smaller (e.g., pile diameter increases while depth remains the same), pile head experiences less lateral deformation and rotation comparing to pile with ‘slippery’ interface due to the mobilisation of shaft vertical interfacial friction. On the other hand, comparing to pile with ‘fully bonded’ interface, the pile head experiences more lateral deformation due to possible yielding of the interface strength (e.g., gapping or separation).

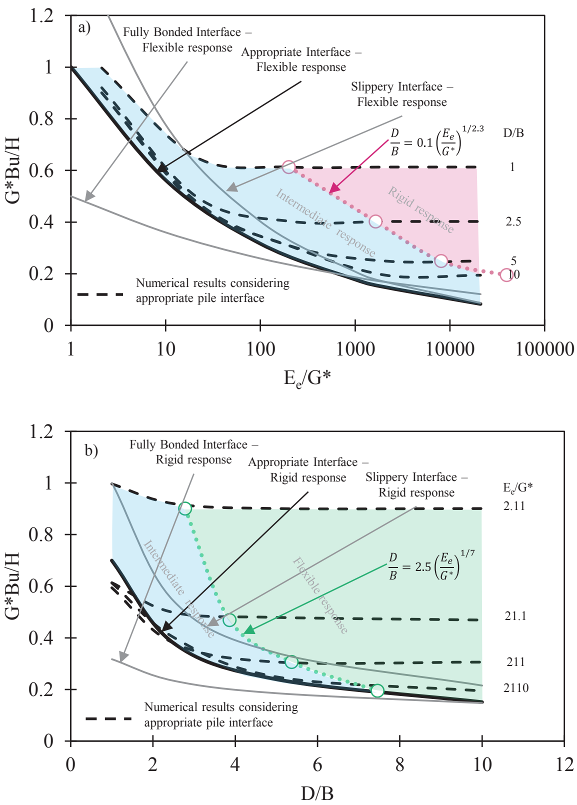

Figure 3 Lateral load-displacement relationships: a) ‘flexible’ pile response and b) ‘rigid’ pile response

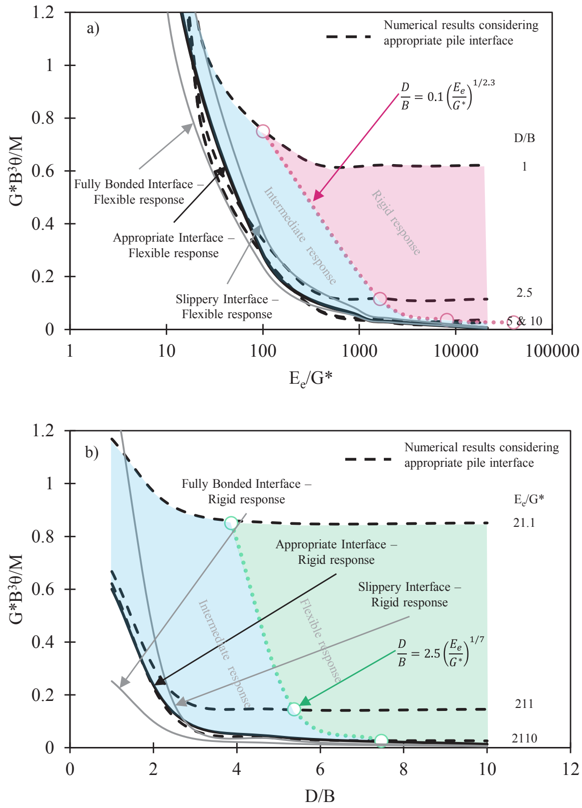

Figure 4 Moment-rotation relationships: a) ‘flexible’ pile response and b) ‘rigid’ pile response

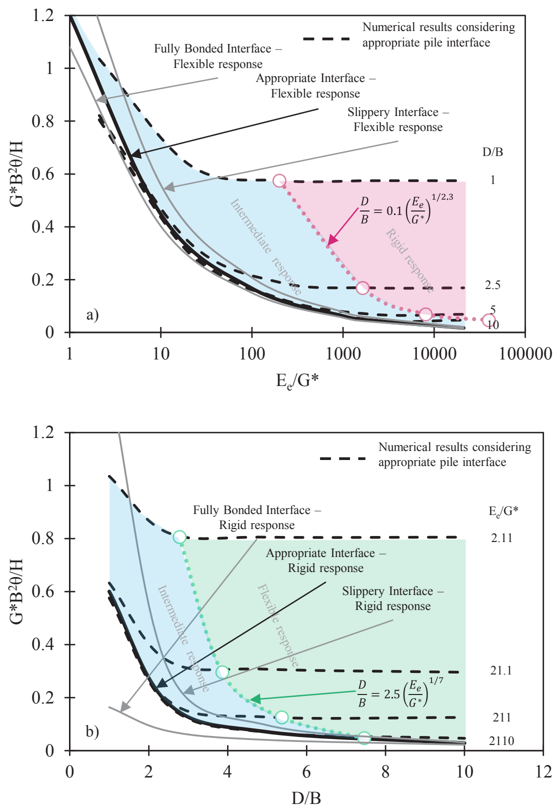

Figure 5 Load-rotation relationships: a) ‘flexible’ pile response and b) ‘rigid’ pile response

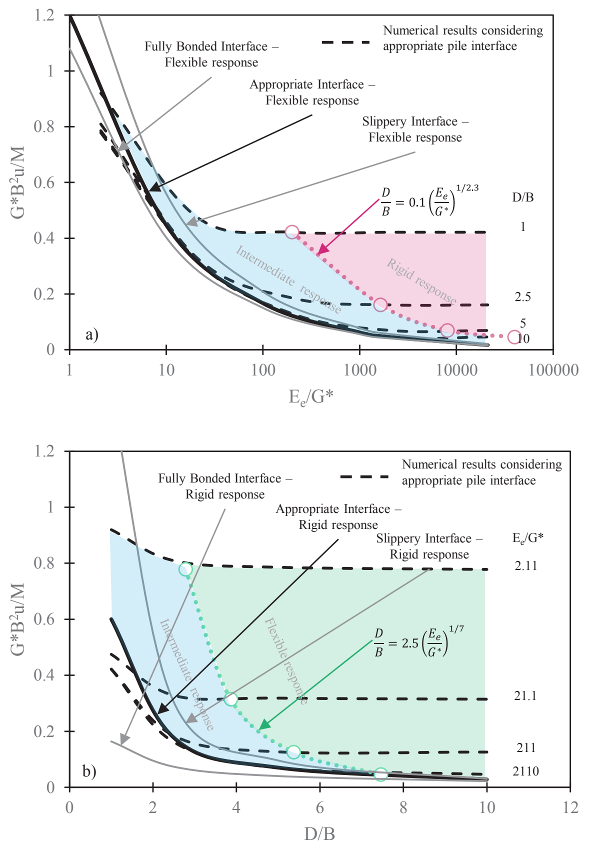

Figure 6 Moment-displacement relationships: a) 'flexible' pile response and b) 'rigid' pile response

4 CONCLUSIONS

A 3D numerical model was developed to conduct the study for large-diameter pile under lateral loads considering shaft interfacial friction. Based on the parametric study, a design aid has been derived to estimate the pile head response at rock surface. Shaft interfacial friction has a significant influence on the response of pile at rock surface level, particularly when the slenderness ratio become smaller (e.g., pile diameter increases while pile depth remains the same).

In this study, it has been assumed that the concrete pile behaves elastically (i.e., neglecting the reduced stiffness due to cracking and yielding of reinforcement). An extended study is underway to develop similar design aids for the full-range response of the pile-rock systems up to Ultimate Limit State which is shown to be required for accurately estimating the seismic behaviour of piles including ductility and damping.

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