Influence of API p-y Procedures on Design of Offshore Piles in Clay

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Abstract. In case of long piles used to support fixed offshore platforms, load in lateral direction is often a major component of design loads significantly influencing their design. Generally, API (American Petroleum Institute) recommendations are followed for design of piles for platforms in Indian offshore. In case of soft clay, API RP 2GEO (2011) recommendation for generating lateral soil resistance-displacement (p-y) data is based on the procedure given by Matlock (1970). However, for clays where undrained shear strength (s_u) is more than 100 kPa and p-y procedure for stiff clay is recommended to be followed, relevant API codes have generally referred to the p-y procedure given by Reese et al. (1975). Problems are sometimes encountered in analysis when stiff clay occurs near the seafloor and the procedure for p-y data given by Reese et al. (1975) is applied. Therefore, a comparative study was carried out by applying both these p-y procedures in stiff clays to examine the influence of the procedures on design of piles. Cyclic p-y data were generated in line with offshore loading environment. Comparative results show that the influence of the p-y procedures is significant especially, when the pile's lateral displacement normalized with pile diameter crosses certain limits.

Keywords: Offshore, Pile, Lateral

1 Introduction

Open-ended steel tubular piles are the permanent foundation for offshore jacket platforms. In general, the diameter of piles for these fixed jacket platforms in Indian offshore is within the range of 1.2 to 2.4 m. Vertical penetration below the seafloor may be typically, 60 to 150 m. As such, these piles are long or flexible piles. For design purpose, the piles should be safe in capacity against design loads, their displacement should be within allowable limit governed by the purpose for which the platforms are built and the structural stress should be within allowable limit. Design of offshore jackets and piles are carried out using interactive analysis of soil, pile and structure applying numerical technique. For the soil-pile interactive analysis, the lateral resistance versus displacement of soil at various depths below the seafloor is represented by 'p-y data'. These data represent the non-linear lateral stress-strain behaviour of soil. For generating the p-y data, API [1] recommends, in the absence of other procedures, to follow the method based on Matlock (1970) in case of soft clay. As per the referred code, undrained shear strength (s_u) limit for using the soft clay procedure is 100 kPa, beyond which the p-y procedure for stiff clay is recommended to be considered. Relevant API codes do not recommend any particular procedure for stiff clay, but, have generally referred to the procedure given by Reese et al. (1975) for many years, although in recent version [1], the procedure is referred for "structured" stiff clay only. The procedures already mentioned, are hereafter referred as 'soft clay' and 'stiff clay' p-y procedures respectively in the paper.

2 Background of the Study

There are locations in western Indian offshore where the design value of s_u in some layers near the seafloor is 100 kPa or more. It was observed in certain cases that due to change of procedure for generating p-y data when s_u exceeded 100 kPa, there was significant impact on analysis. For clays with value of s_u 100 kPa or slightly more, nearly the same result is ideally expected from analysis, irrespective of applying any of the two procedures for p-y data. It was of interest to verify this aspect. Further, practical difficulties sometime arise in carrying out analysis of existing piled structures when soil near seafloor at the site is predominantly stiff clay and the 'stiff clay' p-y procedure is applied for pile-soil-structure interactive analysis. In some of such cases, the analysis suddenly collapses while applying increasing lateral load on the structure. Therefore, a comparative study was carried out on the effect of the two p-y procedures on analysis of offshore piles where soil near seafloor was mainly stiff clay. Pile-soil interactive analysis was carried out on single, fixed-headed, vertical pile with purely lateral loads using cyclic p-y data as per the referred procedures.

3 Lateral Loading on Long Offshore Piles

In case of long offshore piles, the soil near the seafloor influences the result of lateral loading. Beyond a certain depth below seafloor, the soil reaction in response to applied lateral load at pilehead is negligible. The bending moment, lateral displacement, shear and rotation in pile with respect to a specific lateral load depend on the soil characteristics (represented by characteristics of p-y springs), properties of pile material, pile geometry and pilehead restraint. The focus of the present study is primarily on the impact of application of the two API-referred 'soft clay' and 'stiff clay' procedures for generating cyclic p-y data for stiff clay layers. As mentioned already, application of the two procedures on stiff clays is to find how the p-y procedures make difference in the analysis with the same soil, pile and lateral loads.

Figure 1 shows typical patterns of bending moment and displacement in response to lateral load for a long pile with free and fixed-headed conditions. However, the comparative analysis presented in the paper was carried out considering piles as "fixed-headed" in view of very high restraint on pilehead against rotation generally applicable for offshore jacket structures.

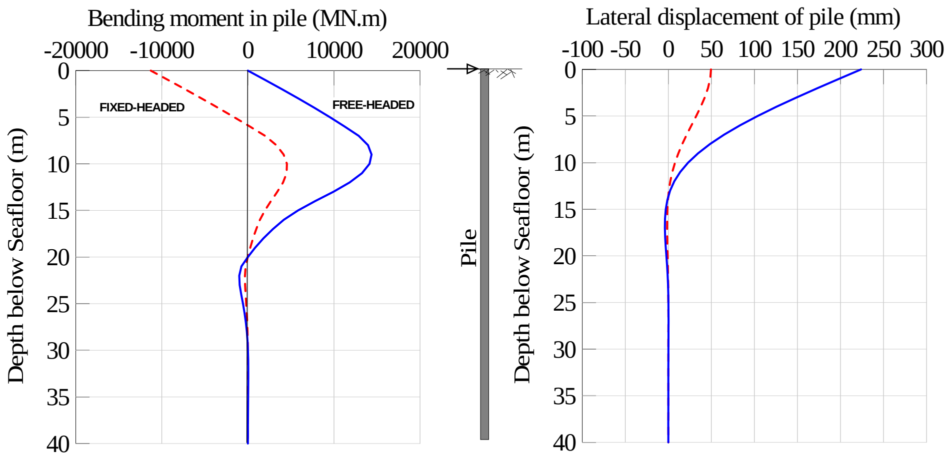

Fig. 1. Typical pattern of bending moment and displacement for a long pile in response to applied lateral load at pilehead.

4 Pile and Soil Data

For the comparative study presented in this paper, first an ideal soil profile with 100 kPa as constant s_u has been considered since this is the transition s_u value where the procedure of p-y is to be changed as recommended by API [1]. This profile is subsequently referred to as 'soil-1' in the paper. Open-ended steel tubular pile with outer diameters ranging from 1.219 m to 2.134 m with pile wall thickness of 50 mm and vertical penetration of 90 m were considered for the study with this profile. The purpose of selecting the range of pile diameters was to examine the variation of results of analysis with respect to the practical range of diameter for long piles generally used for fixed platforms in Indian offshore.

Subsequently, an actual soil profile from a platform location in western Indian offshore, where both soft clay and stiff clay exist near seafloor was also analysed. The pile outer diameter for the platform was 1.829 m with wall thickness of 44 mm for 80 m below seafloor and 50 mm for 2 m of the pile length above its bottom. Relevant part of soil (subsequently referred as 'soil-2') data for the platform location has been presented in Table 1.

Table 1.'soil-2' design parameters.

Soil layer	Depth (m)	s_u (kPa)	ϕ' (deg.)	γ' (kN/m^3)	k (MN/m^3)	ε_{50} (%)
1	00.0-05.8	19	-	6	-	1.5
2	05.8-16.0	100	-	9	-	1
3	16.0-18.3	55	-	9	-	1
4	18.3-21.3	55	-	7	-	1

5	21.3-26.5	280	-	10	-	0.5
6	26.5-31.0	140	-	10	-	0.5
7	31.0-40.2	140-160	-	7.5	-	0.5
8	40.2-43.5	-	30	10	16.5	-
9	43.5-54.0	160-250	-	8.5	-	0.5

Note: ¤'=effective angle of internal friction;¥'= effective unit weight;£$_{50}$ = strain at 50% failure stress; k=rate of increase with depth of initial modulus of subgrade reaction for lateral soil resistance Limit unit end bearing pressure for layer-8 is 3 MPa.

Cyclic p-y data were generated with both 'soft clay' and 'stiff clay' procedures for clays with s_u of 100 kPa or more for the comparative analyses. Details of the procedures for generating the p-y data for clay layers are referred to the API code [1] and corresponding papers [2 and 3] for the procedures. Data of p-y for the sand (layer no. 8 in 'soil-2') were generated following API [1] procedure, although the influence of the layer on the analysis result is not significant.

For the analysis with data of 'soil-1', cyclic p-y curves generated by using both the referred procedures are shown in Fig. 2 for depths at seafloor and at 10 and 20 m below seafloor. However, for the interactive analysis, p-y curves have been used at every meter depth along the pile depth below seafloor.

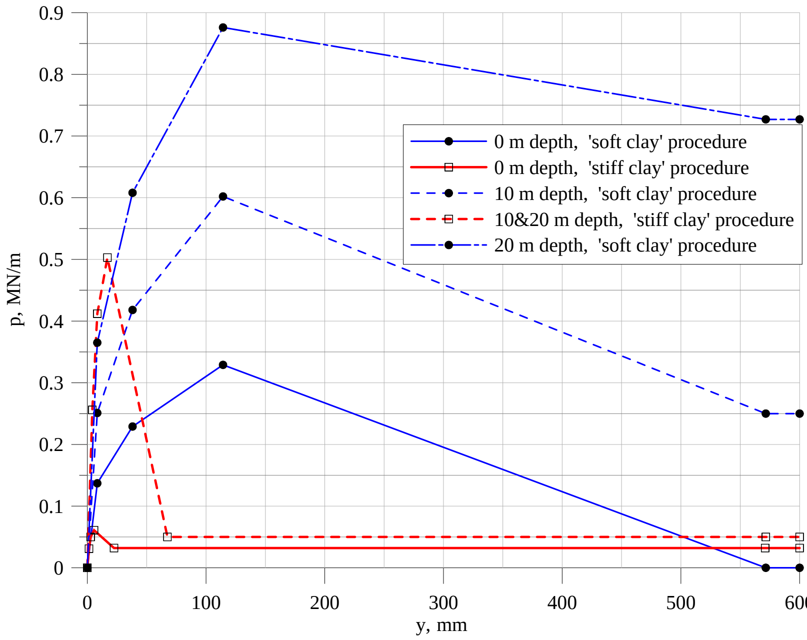

Fig. 2.p-y data as per the 'soft clay' and 'stiff clay' procedures at 0 m, 10m and 20.0 m depths for pile diameter 1.524 m in soil with constant s_u of 100 kPa.

It may be observed that the initial parts in the graphs with both the procedures are similar in pattern. But, as the soil displacement increases, the soil stiffness with respect to individual procedure may vary significantly. It may also be observed that, except for the p-y curve at seafloor, post-peak degradation of stiffness of the p-y springs is more as per the 'stiff clay' procedure when compared with the 'soft clay' procedure. It may be due to presence of secondary structures such as fissures and joints in the stiff clay where the tests were conducted for deriving the 'stiff clay' procedure. Further, the peak lateral resistance of soils is also different with the two procedures.

It may be mentioned that degradation of soil resistance is more with increasing displacement of soil in case of cyclic p-y data compared to static. However, analysis considering static p-y data is out of scope of this paper. Only cyclic p-y data have been used in the present study in view of the standard practice of the offshore industry for analysis of piles for fixed platforms.

5 Analysis, Results and Discussion

5.1 Soil with Constant s_u(for profile 'soil-1')

Analysis was performed by increasing the lateral load on pile and corresponding results of displacement, bending moment etc. were noted. Lateral displacement and bending moment for pile diameter 1.524 m corresponding to an applied lateral load of 2000 kN has been shown in Fig.3.

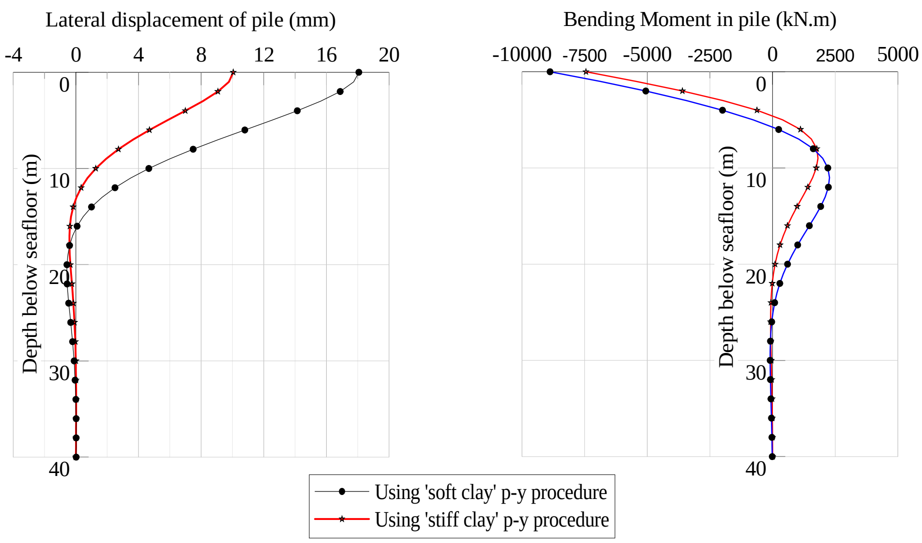

Fig. 3. Pile displacement and bending moment for pile diameter 1.524 m corresponding to lateral load of 2000 kN applied at pilehead.

Lateral displacement and bending moment at pilehead with respect to increasing lateral loads are shown in Figure 4 for the pile (diameter 1.524 m) using both the p-y procedures.

It may be observed that the displacement at pile head is lesser by about 30-40% on applying the ‘stiff clay’ procedure when compared with the ‘soft clay’ procedure up to a limit of lateral load on the pile. Similarly bending moment is also less with the ‘stiff clay’ procedure up to a limit of lateral load; however, the difference in case of bending moment is lesser compared to displacement. Thus, at relatively lower lateral loads, the pile response is found to be stiffer when using the ‘stiff clay’ procedure compared to results from using the ‘soft clay’ procedure. For the pile diameter of 1.524 m, limiting lateral load is found to be about 3500kN up to which the ‘stiff clay’ procedure gives lesser bending moment and lateral displacement. When the load exceeds this limit, the displacement and bending moment increase rapidly and the foundation collapses.

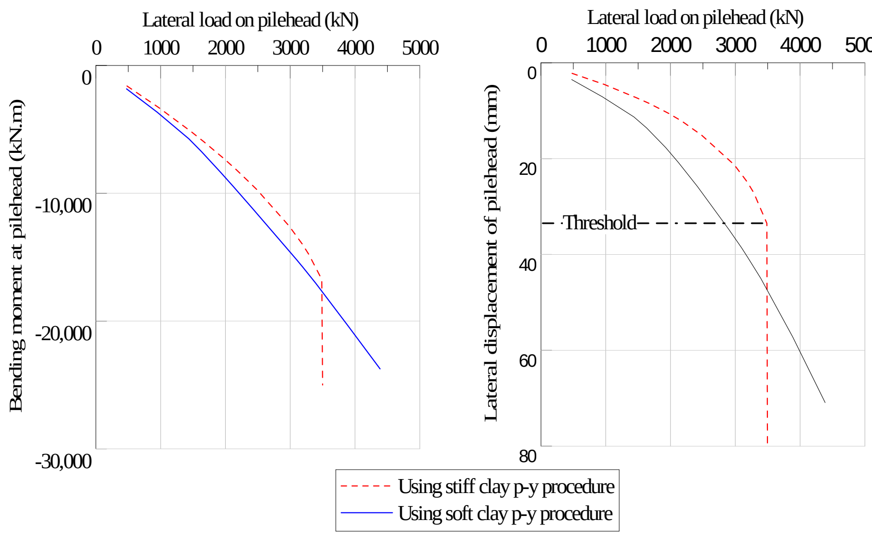

Fig. 4. Pileheaddisplacement and bending moment with variation of lateral load with ‘soil 1’for pile diameter 1.524 m.

Analysis using the ‘stiff clay’ p-y procedure indicates that at relatively higher load, the lateral stiffness of the soil-foundation system drastically reduces after reaching a certain limit of displacement resulting in sudden failure of the foundation. The foundation collapses at relatively smaller lateral displacement when the ‘stiff clay’ p-y procedure is applied. It is thought that this is the reason why problems are sometimes encountered in case of analysis related to modification/requalification of some existing offshore platforms. Generally, for those platforms, lateral load for analysis is higher than that considered in initial design due to change of design wave load over the period since original design and/or increased facilities built in many of them subsequent to their original installation. Generally, problems are faced in analysis of such cases where p-y data are generated using the 'stiff clay' procedure and predominantly stiff clay exist near seafloor. Numerical problem sometimes occur as the foundation suddenly collapses in analysis after reaching the threshold lateral displacement of pile although offshore piles or structures are permitted to undergo much higher displacement from serviceability point of view. As evident from Fig. 4, on using the 'soft clay' p-y model, this problem is not encountered as the lateral displacement and bending moment of pile increases gradually with increasing lateral load till a significantly higher level of displacement.

In order to verify the results for the practically used range of pile diameters, analysis was carried out with different pile diameters to derive the limiting lateral displacement with respect to pile diameter. Results of analysis on the displacement limit (normalised with pile diameter) where the use of the 'stiff clay' procedure may predict sudden collapse of foundation are presented as Table 2. It is observed that the average normalised lateral displacement is 2% at which the foundation is predicted to collapse. This was verified for the 'soil-1' profile i.e. with s_u value of 100 kPa (constant with depth) for the range of pile diameters 1.219 m to 2.134 m.

Table 2. Threshold displacement of pile for 'soil-1' profile with 'stiff clay' procedure.

Pile diameter (m)	Displacement/Diameter (%)	Displacement (mm)	Lateral Load (kN)
1.219	1.9	23.3	2289
1.372	2.0	27.9	2857
1.524	2.2	33.5	3487
1.829	2.0	37.3	4683
1.981	2.1	41.4	5412
2.134	2.0	42.7	6050

5.2 Analysis for Existing Platform with Soil Profile 'soil-2'

Analysis was performed for the 'soil-2' profile of a location from western Indian offshore where a fixed platform exists. The result of displacement and bending moment in pile in response to lateral pilehead load shows a similar trend as in case of 'soil-1'. The result of displacement is shown in Fig. 5. In this case, the soil near seafloor was not completely stiff clay, but stiff clay occurs for a significant depth within the influence zone applicable for lateral resistance of pile. Therefore, the load-displacement response of the pile was expected to be significantly influenced by the stiff clay p-y characteristics in this case also. It is found from the analysis that the foundation is predicted to collapse at a threshold displacement of 3.7% of pile diameter if the 'stiff clay' procedure is used for the stiff clay layers. Therefore, lateral load on the pile cannot be increased beyond a limit in this case also. However, on using the 'soft clay' procedure for the stiff clay layers, the pile continues to displace laterally for a large displacement with increasing lateral load without showing sudden failure of the soil-foundation system.

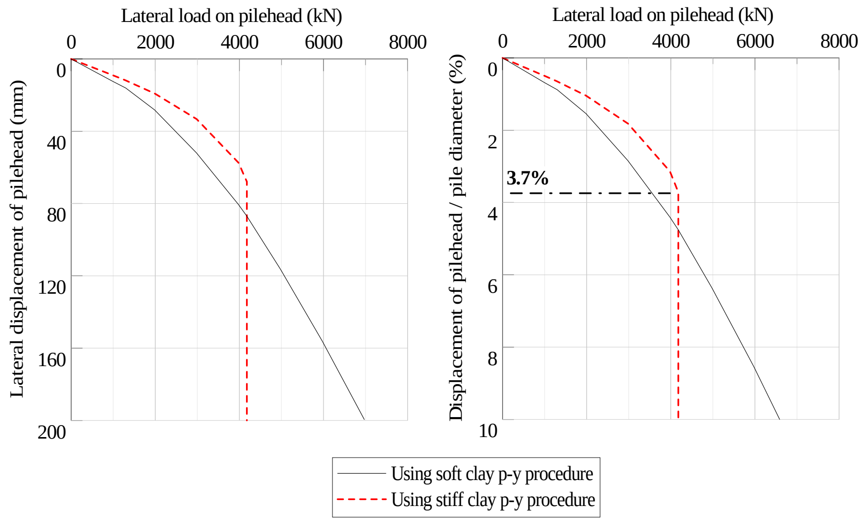

Fig. 5. Pileheaddisplacement and bending moment with variation of lateral load for 'soil-2' and pile diameter 1.829 m.

6 Conclusion

From the study influence of two p-y procedures on flexible and fixed-headed offshore piles, following conclusions are made:

- Application of cyclic p-y data generated by using the procedure given by Reese et al. (1975) on stiff clay results in a stiffer lateral response of the pile till a certain limit of lateral displacement of pile when compared to results from using the procedure of Matlock (1970). In a soil profile with constant undrained shear strength of 100 kPa ('soil-1'), sudden collapse of the soil-foundation system is predicted at displacement of about 2% of pile diameter if the 'stiff clay' p-y procedure is applied. For the case of an actual offshore platform mentioned as 'soil-2'profile, corresponding limit displacement of pile was found to be 3.7% of the pile diameter.
- Numerical problem that is encountered sometimes in the interactive analysis of soil, pile and structure in sites having predominantly stiff clay near seafloor may be due to the brittle nature of failure characterized by the p-y springs as per the 'stiff clay' procedure as indicated by the study. Numerical problem and the lesser limit of displacement before collapse may also be for the reason that, except for the p-y curve at seafloor, post peak degradation of stiffness of the p-y springs is more as per the 'stiff clay' procedure when compared with the 'soft clay' procedure .
- Both the 'soft clay' and 'stiff clay' p-y procedures are ideally expected to produce nearly the same results when the undrained shear strength of the clay is at or very close to the transition s_u value, i.e. 100 kPa. However, differences in results of

analysis are found to be significant. Initial part of the lateral load-displacement response is stiffer when 'stiff clay' p-y procedure is used, but after some limit, the stiffness rapidly degrades leading to prediction of sudden failure.

It is also indicated by researchers [4] that the p-y procedures, referred by API recommended practice may be quite conservative for practical application in case of piles for offshore platforms. It is understood that many consultants use the 'soft clay' procedure much beyond the limit prescribed by API without any known consequent mishaps. In view of the analysis and general opinion of researchers/designers working on offshore geotechnical engineering, there is scope for further research on formulating more realistic p-y procedures for analysis of offshore piles, especially, in stiff clays and layered soil profiles which can improve the results with respect to offshore loading environment and soil behaviour.

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