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Research Article

A Comparative Analytical Investigation on the Effects of Different P-Y Curves for a Laterally Loaded Single Pile Design in Saturated Sandy Soil

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Abstract

The correct definition of p-y curves is important for the accuracy of the behavior of horizontally loaded piles, especially in liquefiable water-saturated loose sandy soils with high liquefaction potential. Within the scope of this study, p-y curves of a single pile placed in a saturated loose sandy soil were prepared with the approaches generally accepted in the literature, and the effects of the soil response depending on these curves on the pile design parameters were examined comparatively. In this study, these curves drawn according to API sand, Reese sand and Liquefied sand at different depths of the pile. This behavior difference in the p-y curves significantly affected the displacements, bending moments, shear forces and ultimate lateral resistance values that occur in the lateral loaded pile. Lateral deflections, bending moments, shear force and lateral load carrying capacity of the pile, which are important outputs used in the design of the piles, should be designed with considering the differences in the p-y curves.

Keywords: P-y curves, Lateral loaded pile, Saturated sand, liquefied sand model, ultimate lateral resistance

Doymuş Kumlu Zeminde Yanal Yüklü Tek Kazık Tasarımı İçin Farklı P-Y Eğrilerinin Etkilerinin Karşılaştırmalı Analitik Olarak İncelenmesi

Öz

P-y eğrilerinin doğru tanımlanması, özellikle sıvılaşma potansiyeli yüksek, sıvılaşabilir suya doygun gevşek kumlu zeminlerde, yatay yüklü kazıkların davranışının doğruluğu için önemlidir. Bu çalışma kapsamında, literatürde genel kabul görmüş yaklaşımlarla, doymuş gevşek kumlu zemine yerleştirilmiş tekil bir kazık için p-y eğrileri hazırlanmış ve bu eğrilere bağlı zemin tepkisinin kazık tasarım parametreleri üzerine etkileri karşılaştırmalı olarak incelenmiştir. Bu çalışmada, bu eğriler kazıkların farklı derinliklerinde API kumu, Reese kumu ve Sıvılaştırılmış kuma göre çizilen eğrilerle temsil edilmiştir. P-y eğrilerindeki bu davranış farkı, yanal yüklü kazıkta oluşan yer değiştirmeleri, eğilme momentlerini, kesme kuvvetlerini ve nihai yanal direnç değerlerini önemli ölçüde etkilemiştir. Kazıkların tasarımında kullanılan önemli çıktılar olan yanal sehimler, eğilme momentleri, kesme kuvveti ve yanal yük taşıma kapasitesi p-y eğrilerindeki farklılıklar dikkate alınarak tasarlanmalıdır.

Anahtar Kelimeler: P-y eğrileri, Yanal yüklenmiş kazık, Doygun kum, Sıvılaşmış kum modeli, Yanal yük taşıma kapasitesi

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1. Introduction

The pile-soil interaction is generally defined by a Winkler model where the pile is modelled as a beam supported by springs. P-y curves are used as a common method for the analysis of laterally loaded piles. The response of the soil is usually represented by the springs and the spring stiffnesses are defined by p-y curves which reflect the non-linear behavior between soil response and lateral displacement of the pile. With p-y curves, the pile is modeled as Euler-Bernoulli beam, and the soil resistance to lateral translation of the piles is modeled with the aid of independent springs along the depth.

As commonly known, p-y curves are accepted as the most used technic to determine the resistance of any soil to the pile under lateral loading [1-6]. Many p-y curves have been developed by the researchers for clayey soils [3, 5, 7] and for sandy soils [3, 4, 8]. Therefore, different researchers and agencies (such as API) proposed different methods for p-y analysis of piles in sands.

P-y curves usually account for different soil conditions with non-linear springs in which the soil response is based on the pile lateral displacement by means of non-linear p-y curves. Yet the p-y curves are accepted as essentially reflect the real site conditions and usually in close agreement with the lateral load tests [9-10].

The main triggering mechanism of lateral movement is liquefaction, which is the major reason of softening of the soil. Many researchers [11] suggested that the true nonlinear response of liquefiable soils undergoing lateral movement is so confusing and difficult to model correctly. In lateral movement, the lateral force applied to the pile by soil response is defined as a function of relative displacement between the soil and pile. For this reason, the correct definition of p-y curves is important for the accuracy of the behavior of horizontally loaded piles, especially in liquefiable water-saturated loose sandy soils with high liquefaction potential. Therefore, within the scope of this study, p-y curves of a single pile placed in a saturated loose sandy soil were prepared with the approaches generally accepted in the literature, and the effects of the soil response depending on these curves on the pile design parameters were examined comparatively.

2. Material and Method

2.1. The Soil Profile and Modelling of the Pile

Soil profile and pile type were kept constant in all analyses to compare the effects of different p-y curves on the design parameters on a horizontally loaded single pile for this study. In this context, a loose sandy ground completely saturated with water with liquefaction potential was evaluated. The average internal friction angle of the soil along the entire layer was determined as 30o and the average saturated unit weight was determined as 16 kN/m3. The screen view of the soil profile is shown in Fig. 1.

All mechanical parameters of the single pile examined in all analyses are shown in Table 1. In addition, the static axial force, shear force and clockwise moment values applied to the single pile at the pile cap, being constant in all analyses, are 1000 kN, 250 kN and 100 kN.m, respectively as shown in Fig. 1.

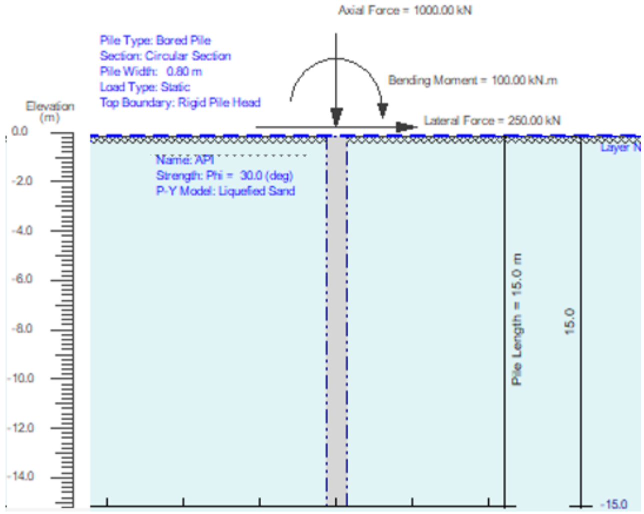

Fig. 1 Soil profile and designed pile for this study

Table 1. Design of pile parameters

Pile Parameters	Values
Pile Type	Bored Pile / Drilled Shaft
Section Type	Circular Section
Pile Diameter (m)	0.800
Pile Segment Length (m)	15.000
Gross Section Area (m^2)	0.503
Section Perimeter (m)	2.513
Moment of Inertia (m^4)	0.02010619
Pile Material Stiffness, E (kPa)	35000000
Pile Batter (Degree)	0.00
Ground Surface Angle (Degree)	0.00
Pile Top Boundary	Free Pile Head
Bending Stiffness Option	User-defined Elastic Bending
Bending Stiffness ($kN.m^2$)	3562566.64

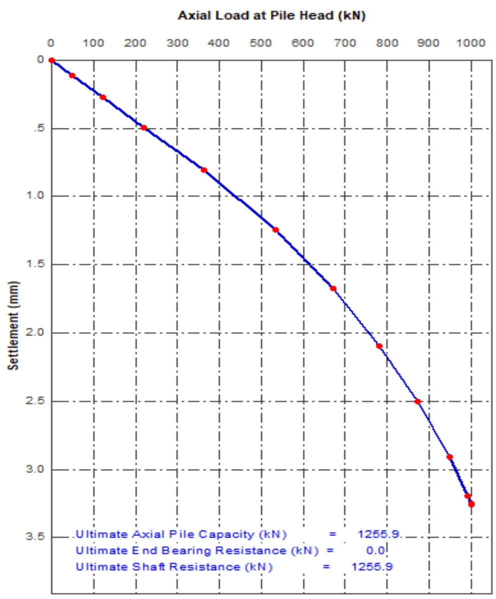

Fig. 2 Pile axial load vs settlement curve and axial load capacity of the pile

Pile axial load versus settlement curve drawn by using PileLAT software program is shown in Fig. 2. The pile axial load capacity was estimated as 1255,9 kN according to this curve and it has been seen that the carrying capacity is sufficient according to the applied forces.

2.2. P-y Curve Models Used in The Study

Soil Three different p-y curve models were used in this analytical study. These curve models are API for sand [12], Reese for sand [4] and Liquefied model for sand [13-14].

2.3. PileLAT software program

PileLAT program was used in all analyses conducted within the scope of this study. PileLAT is a finite-element based program that analyses the behaviour of single piles mainly under lateral loading based on p-y curves for various soils and rocks. It is a useful tool for pile design and analysis by both structural and geotechnical engineers [15].

3. Results and Discussion

P-y P-y curves drawn according to API sand [12], Reese sand [4] and Liquefied sand [13-14] at different depths of the pile are shown in Figs. 3-5. As can be clearly seen from these figures, the use of different models in the drawing of p-y curves causes the curves to be obtained differently. Of course, these differences will also lead to significant differences in the design of lateral loaded individual piles. Bending moments, shear diagrams and lateral load carrying capacity of the pile, which are important outputs used in the design of the piles, will be seriously affected by the differences in the p-y curves. It is important to define the p-y curves correctly in saturated loose sand soils with high liquefaction potential. Therefore, in this study, the effects of different p-y curves, which are widely used in the literature, on the design of lateral loaded single piles were investigated. Especially on sandy soils with high liquefaction potential, this effect was investigated and presented in the findings. liquefaction potential. Therefore, in this study, the effects of different p-y curves, which are widely used in the literature, on the design of lateral loaded single piles were investigated. Especially on sandy soils with high liquefaction potential, this effect was investigated and presented in the findings.

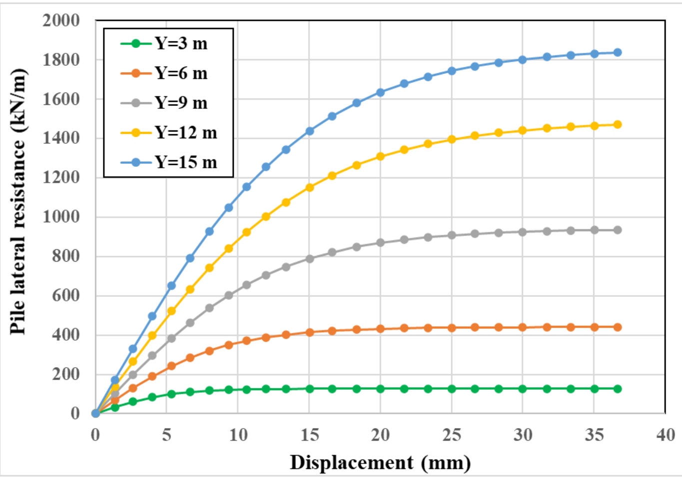

Fig. 3 P-y curves for API sand [12] at different depths of the pile

When these three different p-y curves are compared, it is seen that especially the Liquefied sand model [13-14] is very different from the curves proposed by API sand [12] and Reese sand [4]. When the Liquefied sand model is compared to these other two models, the reactions of the ground against the pile are different. While the resistance of the ground is much lower than the other two models, the lateral displacements are seen to be very high.

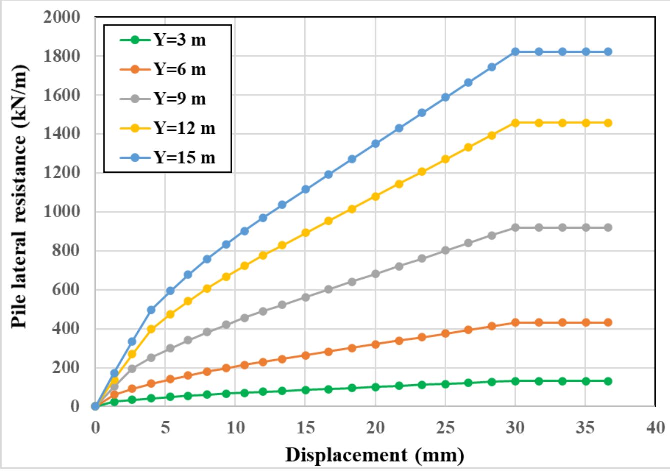

Fig. 4 P-y curves for Reese sand [4] at different depths of the pile

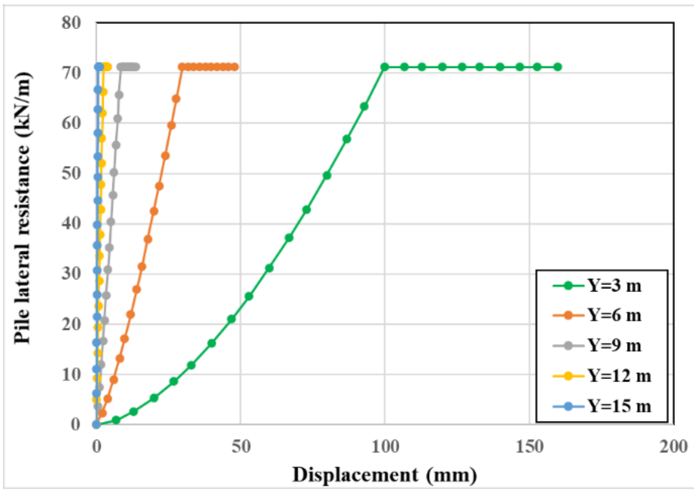

Fig. 5 P-y curves for Liquefied sand [13-14] at different depths of the pile

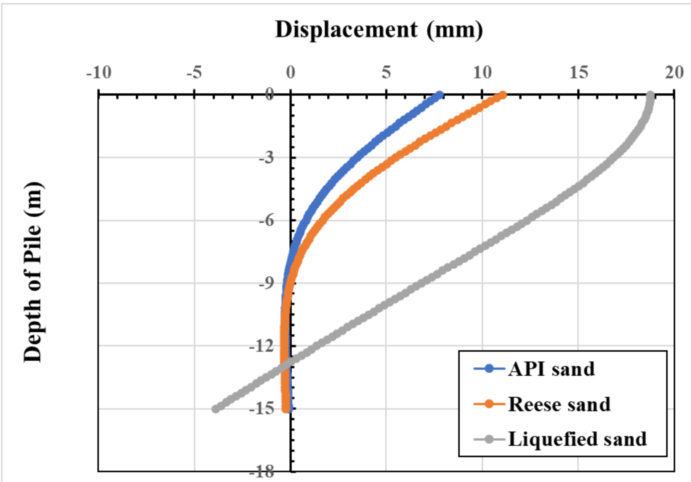

Fig. 6 Lateral deflection with respect to depth of the pile for all p-y curves

Lateral deflection with respect to depth of the pile for all p-y curves are presented in Fig. 6. According to this figure, as expected, maximum deflections were obtained in the pile cap. The maximum lateral deflections at the pile cap for API sand, Reese sand and Liquefied sand models are 8 mm, 11 mm and 19 mm, respectively. On the other hand, for API sand and Reese sand models, lateral deflections at the pile base level did not occur, while for liquefied sand model this value was calculated as -4 mm. As it is clearly seen from Fig. 6, the lowest deflections are calculated for the API sand model, while the highest deflections are calculated for the Liquefied sand model.

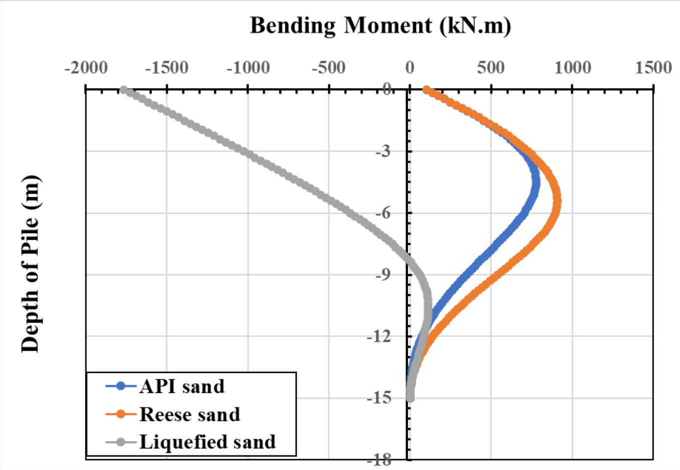

Fig. 7 Bending moment with respect to depth of the pile for all p-y curves

Bending moment with respect to depth of the pile for all p-y curves are presented in Fig. 7. According to this figure, the largest bending moment value (-1800 kN.m) was achieved in the results obtained from the liquefied sand model at the pile cap. The maximum bending moment values for API sand and Reese sand models were achieved as 800 kN.m (at depth of 4 m.) and 900 kN.m (at depth of 5 m.), respectively. No bending moment occurred at the pile base for all p-y curve models. For the Liquefied sand model, negative bending moments were formed up to 8 meters deep, while positive bending moment values were formed after this depth. Moreover, the bending moment values for both API sand and Reese sand models were achieved as 100 kN.m at top of the pile head.

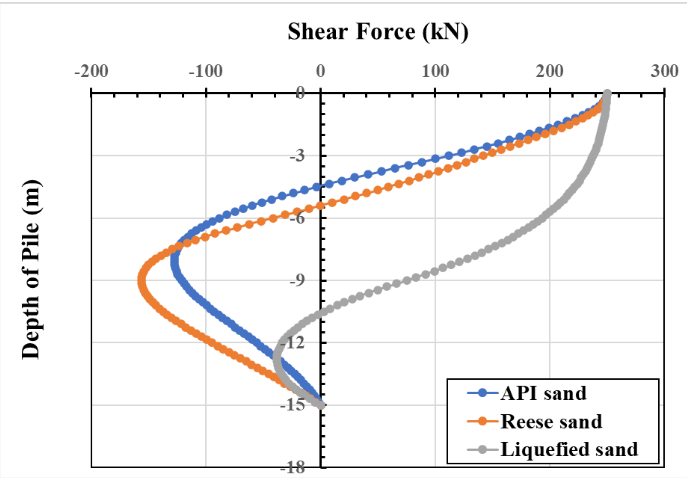

Fig. 8 Shear force with respect to depth of the pile for all p-y curves

Shear force with respect to depth of the pile for all p-y curves are presented in Fig. 8. According to this figure, the largest positive shear force value (250 kN) was achieved in the results obtained from all p-y curve models at the pile cap. On the other hand, the largest negative shear force value (-160 kN) was achieved from Reese sand p-y curve model at the depth of 9 m. Moreover, the shear force for all p-y curve models was achieved as 0 kN at bottom of the pile.

Ultimate lateral resistance with respect to depth of the pile for all p-y curves are presented in Fig. 9. Ultimate lateral resistance value increased with depth depending on the increase in the stiffness of the ground according to this figure. Here, maximum value for ultimate lateral resistance for all p-y curve models reached at the pile base. Ultimate lateral resistance values at the pile base for API sand, Reese sand and Liquefied sand models are 1880 kN/m, 1800 kN/m and 100 kN/m, respectively (see Fig. 9). Ultimate lateral resistance with respect to depth of the pile for API sand and Reese sand models showed similar trend.

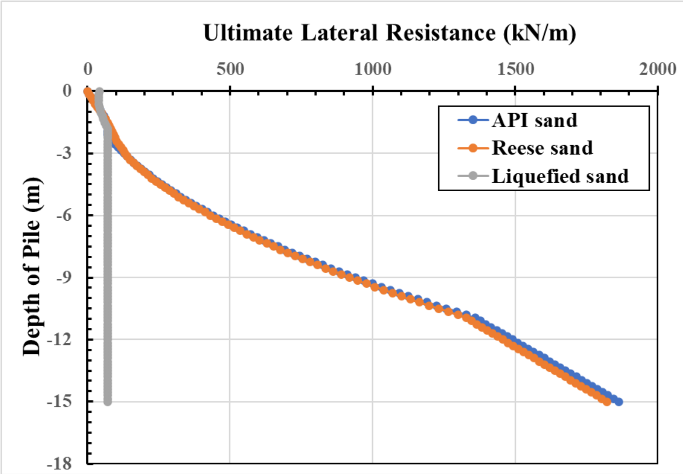

Fig. 9 Ultimate lateral resistance with respect to depth of the pile for all p-y curves

There are several techniques presented by the past research studies and agencies for p-y analysis of piles in sands. These methods differ mostly for drawing p-y curves. In this study, these curves drawn according to API sand [12], Reese sand [4] and Liquefied sand [13-14] at different depths of the pile are shown in Figs. 3-5. As it is clearly seen from these figures, although p-y curves obtained from API sand and Reese sand show similar trend, they have remarkable differences that differ from each other in terms of nonlinearity. However, p-y curves obtained from Liquefied sand model offered a completely different approach from these two approaches throughout the depth. This can be explained by the fact that the response of the liquefied sand model to the pile under the effect of lateral loading in liquefiable soils should be very low. Therefore, it is important to choose the correct approaches in the literature for drawing p-y curves in soils with liquefaction potential.

This behaviour difference in the p-y curves significantly affected the displacements, bending moments, shear forces and ultimate lateral resistance values that occur in the lateral loaded pile as shown in Figs. 6-9. As can be clearly seen in Fig. 6, although the horizontal deflections in API sand and Reese sand models are close to each other, these values in the Liquefied sand model are quite large compared to these two p-y curve models. Moreover, according to Fig. 7, although the bending moment diagrams in API sand and Reese sand models are similar to each other, these values in the Liquefied sand model are quite different compared to these two p-y curve models. Here, we can say that bending moment diagrams are directly related and compatible with deflection curves. The fact that the deflection values of the liquefied model are quite high compared to the other two models causes the bending moment values of this model to be higher than these two models. According to Fig. 8, although the shear force diagrams in API sand and Reese sand models are close to each other, these values in the Liquefied sand model is different from these two p-y curve models. Due to the high horizontal deflection value in this model, the shear forces are also high. The shear force value being higher in the liquefied model has parallels with the behaviour of the p-y curves. Therefore, the effect of p-y curves on the design parameters of horizontally loaded single piles in saturated loose sandy soils is clearly demonstrated in this study. also, this effect is clearly seen on ultimate lateral resistance with respect to depth of the pile for all p-y curves, as can be clearly seen in Fig 9.

4. Conclusions and Recommendations

The conclusions that can be drawn from this study are given as below.

- The use of different models in the drawing of p-y curves causes the curves to be obtained differently. Of course, these differences also lead to significant differences in the design of lateral loaded individual piles in saturated sandy soils.

- Lateral deflections, bending moments, shear diagrams and lateral load carrying capacity of the pile, which are important outputs used in the design of the piles, were seriously affected by the differences in the p-y curves.

- It is important to choose the correct approaches in the literature for drawing p-y curves in soils with liquefaction potential.

- Although lateral deflections, bending moments, shear diagrams and lateral load carrying capacity in API sand and Reese sand models are similar to each other, these values in the Liquefied sand model are quite different compared to these two p-y curve models.

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