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Review on Laterally Loaded Piles in Horizontal and Sloping ground

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Abstract - *This paper includes a brief review of analytical, experimental and numerical studies carried out on the topic laterally loaded pile on level and sloping ground. Pile foundations are extensively used to support various structures built on loose/ soft soils where shallow foundations would undergo excessive settlements or have low bearing capacity. Piles are slender, having high length to width ratio, and are mainly designed to resist axial loads. However, some structures such as high rise buildings, offshore structures, tall chimneys, wind turbines, earth retaining walls are subjected to horizontal or lateral pressure caused by wind force, wave force, traffic movement, earthquake etc. Thus, piles are used as foundation to transmit vertical and lateral loads to the surrounding soil media. Pile foundations near the slope are often required to resist lateral loads. This is particularly important for piles at the abutments of bridges, dolphins etc.*

Key Words: **laterally loaded pile, sloping ground**

1. INTRODUCTION

Deep foundations are a form of foundation used to bypass weak layers of soil and bear on a dense stratum or develop sufficient skin friction around the shaft to support the structure above. Deep pile foundations are also used in locations where the use of shallow foundations would lead to unacceptably low factors of safety against shear. In addition to the gravity loads, piles are often subjected to lateral loads and moments. High rise buildings, offshore platforms, bridges, defence structures, dams, metro projects, transmission towers, earth retaining structures, wharfs and jetties were few important structures, where pile foundation were frequently used to support vertical and lateral loads. Nevertheless, in all these structures, piles had to carry not only the axial loads, but also the lateral (horizontal) forces and moments. More precisely, in structures like oil production platforms, earth retaining structures, wharfs and jetties, the primary function of piles is to resist the lateral loads for safety of the structure. For tall buildings and transmission towers, wind action may be regarded as the main source of horizontal loading, while, in case of offshore structures, oil extraction platforms, quays, harbors, wharfs and jetties, wave action has the significant contribution as horizontal force.

Dolphin structures constructed in ports are supported on pile groups that are subjected to lateral loads from mooring pull of the berthing vessel. In the deltaic area of the Netherlands, characterized by the harbours and the inland waterways to supply Western-Europe, the banks along the waterways are full of dolphins. A large part of these dolphins are located in the slopes of banks. Nevertheless, there is a lack of design rules in the current regulations for dolphins located in sloping ground. Dolphins have two functions; either they can be breasting dolphins to protect a structure (e.g. a pillar of a bridge), or mooring dolphins to secure a ship by ropes. A dolphin, loaded by an impact force or a mooring force, leads to a soil-structure interaction problem between a long vertical pile, which is laterally loaded, and the surrounding soil. Often, these dolphins are constructed in sloping ground. This changes the pile-soil interaction, particularly when the pile is loaded towards the slope. This is the case for mooring dolphins. Typical highway bridge foundation is shown in figure 1.

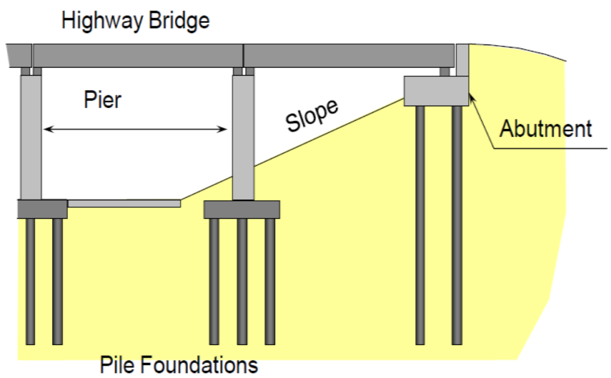

Figure 1. Typical highway bridge foundation

2. LATERALLY LOADED PILES IN HORIZONTAL GROUND SURFACE

A laterally loaded pile is a typical soil-structure interaction problem. Both the deformation of the soil and the pile need to be elaborated to find a solution for this problem. If the lateral load is applied at the pile, this will induce a lateral deformation starting at the top of the pile. This deformation will induce moments and shear forces in the pile and mobilise lateral resistance of the soil. The soil will provide resistance against the deformation of the pile. Therefore, the lateral deflection and the soil resistance have an interdependent relationship

Due to the lateral load, normal stresses in the soil will increase in front of the pile, and decrease behind the pile. This may cause a gap which arises between the back of the pile and the surrounding soil, as observed by **Davidson** [5] and later by **Gabr and Borden** [1]. Furthermore, the soil in front of the pile may fail and develop a passive wedge, which moves upwards. Further down along the pile shaft, the soil will fail by flowing around the pile, with no gap present any more. For these two failure mechanisms, schematized at the left part of Figure 2, different models are developed, which are described by **Reese and van Impe** [6] and by **Fleming** at al. [4].

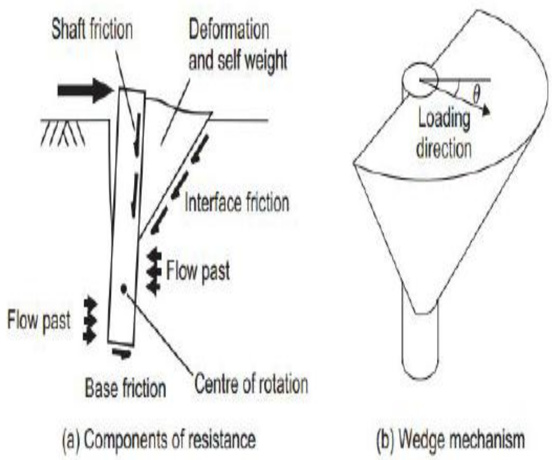

Figure 2: Collapse mechanism in the upper soil layer after Fleming et al. [4]

The strength of single piles in a horizontal soil profile is most commonly determined by modelling the soil and pile relationship with *p-y* curves. The *p-y curve* method models the pile as a beam and the soil resistance around the pile is modelled using a series of non-linear springs along the length of the pile, know as p-y curves. The lateral soil resistance per unit pile length is defined as *p* and the lateral soil deflection is defined as *y*. An illustration of this model is presented in Figure 3.

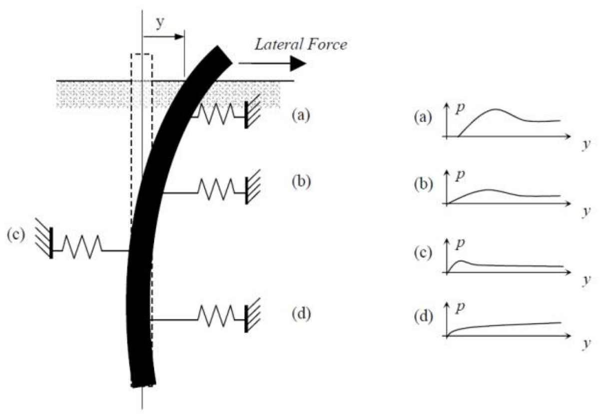

Figure 3: Illustration of p-y Curve Model.

The method, which was introduced in early 1950's, has evolved and, with the advent of computers, has become a practical means for design (Reese et al., 2000).

Broms developed his method in 1964 [8]. The method uses the theory of subgrade reaction and it was for the first time possible to calculate the deflections and bending moments of the pile with an ultimate strength model. With a range of design charts obtained by Broms a suitable pile can be chosen. Deflections can only calculated for the "working load range", which is 0.3–0.5 of the ultimate pile capacity. Broms assumes that for this range the soil behaves linearly elastic. Another simplification of the model is that for cohesive soils the subgrade modulus is assumed to be constant with depth. The method is validated by field tests; the calculated deflections are not very accurate. However, on ultimate lateral resistance the method for cohesive soil is reasonably it is conservative

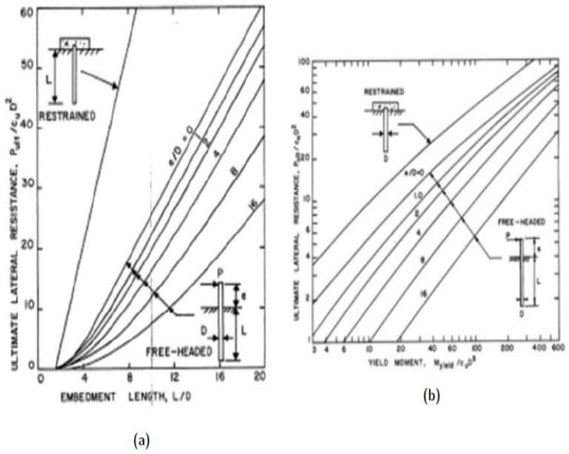

Figure 4: Design charts of Broms: ultimate resistance for cohesive soils related to (a) embedded length of pile (b) yield moment of pile

In 1946 **Hetenyi** [7] determined that a pile subjected to a lateral load can be considered as a beam. He gives a derivation in his book for a differential equation, which provides a linear relationship between the pile deflection and the soil response. This relationship is defined in Equation 1. When the pile is only loaded laterally, the second term at the left side can be eliminated

$$E_p I_p \frac{d^4 y}{dx^4} + P_x \frac{d^2 y}{dx^2} + E_{py} y = 0 \quad (1)$$

where

EpIp = bending stiffness of the pile

y = lateral deflection of the pile

Px = axial load on the pile

Epy = stiffness of the soil

In Figure 5 the response of the pile subjected to a lateral load is shown, with the corresponding mathematical relationships of **Heteyeni.** There are some limitations in the application of the above equation. To start with, the pile only can have a uniform cross section and consist of homogeneous and isotropic material. In addition, different soil layers could not be regarded. Furthermore, the soil must have a uniform modulus of subgrade reaction, which is not realistic. The largest limitations are that only static situations can be considered, in which the proportional limit of the pile material cannot be exceeded and that plasticity of the soil is not included in the model

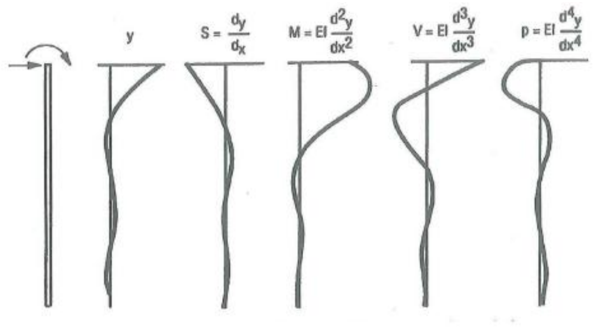

Figure 5: Response of a laterally loaded pile according to Heteyeni

According to **Reese**, two different wedge types can be distinguished, one for clay and one for sand[6]. The passive wedge for clay can be found in Figure 6. The ultimate resistance of the soil *pu*, can be determined by solving the equilibrium for *Fp* by taking the weight of the wedge, *W*, and the forces on the sliding surfaces, *Fs*, *Fn*, *Ft* and *Ff* . If one then differentiates *Fp* with respect to *H*, the ultimate resistance of the soil can be determined using Equation 2.

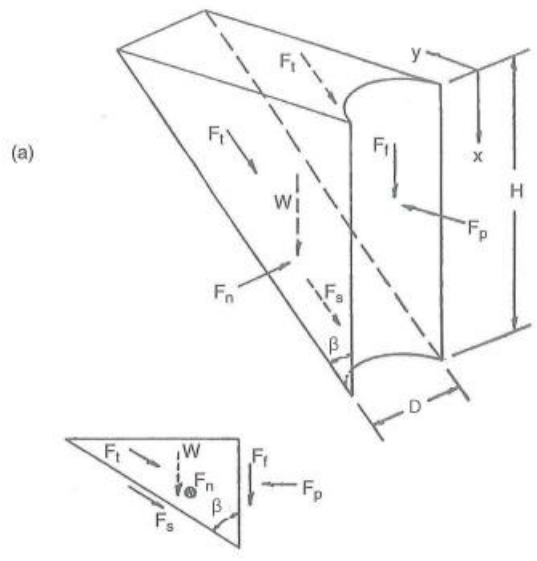

Figure 6: Assumed passive wedge-type failure for clay by Reese et al. [6]

$p_u = c_a D[\tan\beta + (1+\kappa)\cot\beta] + \gamma DH + 2c_a H(\tan\beta\sin\beta + \cos\beta)$ (2)

Where

p_u=*ultimate resistance near the surface per unit of length along the pile*

c_a=*average undrained shear strength over the depth H*

β=*angle of the inclined plane with the vertical*

γ=*unit weight of the soil*

κ=*reduction factor for shearing resistance along the face of the pile*

D=diameter of the pile

H=depth below ground surface

The passive wedge for sand can be found in Figure 3. The force *Fp* can be obtained by solving the force equilibrium with the weight of the wedge, *W*, and the forces on the sliding surfaces, *Fs*, *Fn*, *Ft* and *Fs*, and subtracting the active force, *Fa*. If one then differentiates *Fp* with respect to *H*, the ultimate resistance for the sand can be defined as:

$$p_u = \gamma H\Big[\frac{K_0 H\tan\phi\sin\beta}{\tan(\beta-\phi)\cos\Omega} + \frac{\tan\beta}{\tan(\beta-\phi)}(D + H\tan\beta\tan\Omega) + K_0 H\tan\beta(\tan\phi\sin\beta - \tan\Omega) - K_a D\Big] \quad (3)$$

Where

φ=friction angle of the soil

K_0=coefficient of earth pressure at rest

K_a=minimum coefficient of active earth pressure

Ω=angle of the wedge

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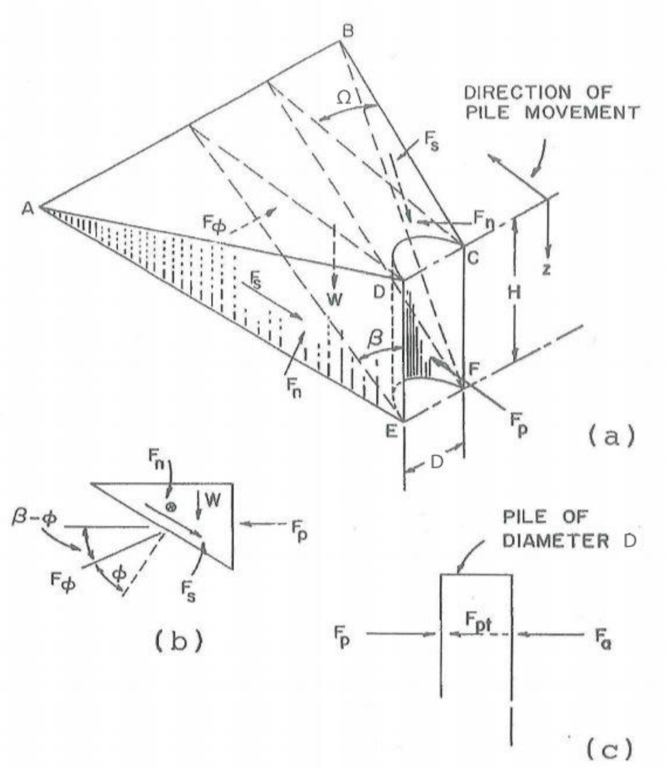

Figure 7: Assumed passive wedge-type failure for sand by Reese et al. [6]

3. TAKING THE SLOPE INTO ACCOUNT

The sloping ground may influence the soil-structure interaction between the pile and the surrounding soil significantly. The horizontal confining pressure is reduced at one side of the pile, which changes the passive wedge model. It is believed that the flow mechanism, to calculate the ultimate soil resistance at a greater depth, will not alter due to influence of the slope. However, it may develop lower down the pile than it would in horizontal surface level. The passive wedge developed by Gabr and Borden is shown in Figure 8. The model is appropriate for evaluating the ultimate soil resistance of laterally loaded piles in sloping ground consisting of cohesionless soil or soil that possess both cohesion and friction, a *c*−*φ* soil. Only the ultimate soil resistance can be determined from this model, therefore it is an ultimate strength model.

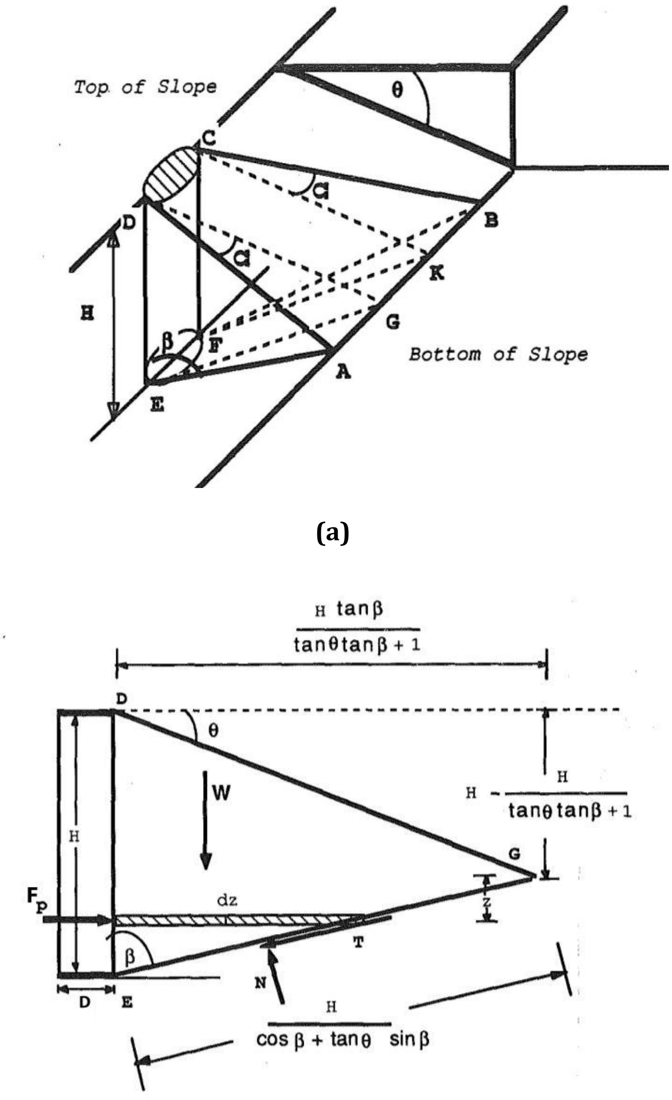

Figure 8: Assumed failure wedge with plane failure surface (a) and assumed wedge in equilibrium (b) of Gabr and Borden

$$p_u = \gamma H\left[H\left(S_{1\phi} + 3K_o S_{3\phi}\right) + DS_{2\phi} - K_a D\right] + c\left[H\left(S_{1c} + S_{3c}\right) + DS_{2c} - 2DK_a^{0.5}\right] \quad (4)$$

in which

H = depth below ground surface

Ko = coefficient of at-rest earth pressure

Ka = coefficient of active earth pressure

c = cohesion of the soil

D = diameter of the pile

*S*1_ − *S*3_ = parameter of Gabr and Borden

$S1c - S3c$ = parameter of Gabr and Borden

Reese published his modification of the formula to obtain the ultimate soil resistance. The formula is shown for both clay and sand.

Clay

The ultimate resistance of clay near the ground surface if the pile is pushed downhill slope, which has an angle θ, is expressed as:

$$p_u = (2c_a D + \gamma DH + 2.83 c_a H)\frac{1}{1 + \tan\theta} \quad (5)$$

Sand

The ultimate resistance of the sand near the ground surface if the pile is pushed downhill, with an angle smaller than the friction angle φ, is expressed as:

$$p_u = \gamma H\left[\frac{K_o H \tan\phi \sin\beta}{\tan(\beta-\phi)\cos\Omega}(4G_1^3 - 3G_1^2 + 1) + \frac{\tan\beta}{\tan(\beta-\phi)}(DG_2 + H\tan\beta\tan\Omega G_2^2) + K_o H \tan\beta(\tan\phi\sin\beta - \tan\Omega)(4G_1^3 + 3G_1^2 + 1) - K_A D\right] \quad (6)$$

Where

$$G_1 = \frac{\tan\beta\tan\theta}{\tan\beta\tan\theta + 1}$$
$$G_2 = 1 - D_1$$
$$K_A = \cos\theta\frac{\cos\theta - (\cos^2\theta - \cos^2\phi)^{0.5}}{\cos\theta + (\cos^2\theta - \cos^2\phi)^{0.5}}$$

Sivapriya and Gandhi presented the study of single pile in the sloping ground under different static lateral loading conditions in which the pile is subjected to forward and reverse loading at ground level and slope level. Laboratory experiments are conducted in a test tank with cohesive soil by embedding a semi-infinite pile. The behaviour of the pile is studied by considering three different slopes (1V:3H, 1V:2.5H and 1V:2H) with varying positioning of pile in-terms of relative stiffness factor (R). Relative stiffness is found by conducting lateral load test in horizontal ground condition for the same soil properties. Lateral load corresponding to 5 mm displacement is taken as the ultimate lateral load. The deformation and bending characteristics of the pile are observed for different conditions and compared with pile loaded at the levelled ground. Numerical studies are performed to validate the test results and to assess the effect of water table on pile-slope behaviour. Parameters such as optimum distance from slope crest towards the embankment where the effect of slope becomes void were also studied. The ultimate lateral capacity of the pile decreases linearly with an increase in slope angle when loaded towards the slope. The lateral load behaviour of the pile under reverse loading is almost similar to the horizontal ground condition for the various slopes.

Muthukkumaran and Begum had done series of laboratory model test had on the instrumented pile on horizontal ground, 1V: 2H slope and 1V: 1.5H slope with the relative density of sand at 30%, 45% and 70% and varying embedment length to diameter ratio of 25, 30, and 35. From the experimental results, the behaviour of the pile was studied by its lateral load – pile head displacement response and bending moment profile along the pile shaft. From the load-deflection and bending moment behaviour, a correction factor for the lateral load capacity and the maximum bending moment for the sloping ground was obtained. An equation for the depth of fixity for the cohesionless soil including the effect of ground surface, relative density and embedment length was obtained. The lateral load capacity is significantly reduced when the ground surface changes from horizontal to slope. The increase in relative density of soil increases the lateral load capacity. The increase in embedment length of the pile increases the lateral load capacity. The maximum bending moment increases with increase in slope when comparing to horizontal ground. This is due to the reduction in soil mass at the top portion, which decreases the mobilization of passive resistance in-front of the pile. The maximum bending moment decreases with increase in relative density of the soil. This is due to the increase in pile-soil relative stiffness against the lateral load and hence the depth of fixity reduces for increase in relative density.

Chong Jiang et al had done series of three-dimensional finite element analyses, performed to study the behavior of piles in sloping ground under undrained lateral loading conditions. .e analyses have been conducted for slopes with different angles and two loading directions, the obtained results show that as the slope increases, it can cause greater lateral displacement and internal force of the pile. In addition, the increase of the slope ratio will cause the position of the maximum bending moment and soil resistance zero point of the pile to move downward, further increasing the pile deflection. Furthermore, when the pile distance from slope crest B < 7D, the displacement and internal force development of the pile under toward loading is more obvious. When the pile distance from the slope crest exceeds 7D, the effect of loading direction on the pile can be neglected.

Bhishm Singh and Sawant had discussed about the investigation of 22 laboratory tests in dense sand at 72% relative density. The main motive of their study was to examine the effect of slope angle and edge distance on the pile response. Ground slope was varied as 1V:1.5H, 1V:1.75H and 1V:2H for sloping ground condition. Pile response was obtained for seven different positions of pile from the crest of the slope for a specified relative density. Then pile response for horizontal ground condition was obtained for quantification of effect of sloping ground. Displacement and bending moments in the pile increased significantly when the ground surface changes from horizontal to slope. An increase in the edge distance from the slope crest causes reduction in the pile displacement and maximum bending moment

4. CONCLUSIONS

Although a general agreement exists between the results of the different studies, the factors quantifying such effects vary significantly from study to study. The differences can be attributed to the many factors involved such as the type of materials used in the laboratory tests and the assumptions made in analytical models that differ between studies. However, without an adequate amount of full-scale field tests to verify the methods, it is difficult to come to a consensus on the method to be used in analysis and design of piles in or near sloped soil profiles.

Reduction of the confining soil, due to a slope decreases the lateral capacity of the pile. Parameters that influence the amount of decline are the slope angle, the soil parameters, the pile properties and the roughness of the pile-soil interface. Moreover, all the full scale tests demonstrate the formation of a gap, which is observed in both cohesive and cohesionless soil and opens further as the lateral load increases. The gap suggests that over the length of the gap there is no active pressure that does contribute to the pile-soil interaction. It can therefore be concluded that the size of the passive wedge and its offered resistance determine the pile-soil interaction. Another key finding is the fact that the lateral response of piles depends mainly on the soil properties of the soil layers in the first 8D-10D, where D is defined as pile diameter.

The lateral load carrying capacity increases with increase in length to diameter ratio This may be due to the increase of frictional resistance with length

As the slope angle decreased lateral load carriying capacity of the pile increased to a certain extend

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