Experimental Study of Pile Resting on Sloping Ground Subjected to Cyclic Lateral Loading

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Abstract. Pile foundation has to resist lateral loads coming from moving trains, winds etc. Due to presence of sloping ground there is reduction in lateral capacity of pile because of reduction in passive resistance offered by soil. The nature of forces are dynamic and a very limited study has been done to determine the effect of dynamic lateral loading on piles resting on sloping ground. In present study, small scale physical model test were performed on sand to determine the reduction in lateral capacity of pile when subjected to 50 numbers of cycles. The relative density (30% and 60%) and ground slope (0˚ and 20˚) were the variables. Initially the static lateral capacity was determined for both the horizontal and sloping ground. The load corresponding to 5mm lateral displacement is the lateral capacity of pile. In second phase cyclic loading was given to the pile and after that its capacity was determined same as in static case and the results were compared. In static case due to presence of slope only the reduction in lateral capacity is 20%-30% depending on the relative density. Due to application of cyclic loading the reduction in lateral capacity was greater than 50%. This study shows that pile resting on sloping ground and subjected to cyclic lateral loading becomes critical case and need to be considered while designing pile foundation.

Keywords: Lateral capacity, Sloping ground, Cyclic loading.

1 Introduction

Indian Railways is planning a ‘Make in India’ touch to the super-fast bullet train project connecting Mumbai with Ahmedabad. The introduction of the bullet train, capable of hitting a speed of up to 350 kmph, will mark the country’s shift from an era of slow-speed trains to high-speed ones. These super-fast trains will travel over the bridges, exerting large lateral forces on the foundation system. He. et. al. (2013) [2] found out that the lateral force exerted due to these high speed trains can be upto 50kN. Pile foundations are generally the preferred foundation system for the bridges and designed to resist vertical structural loads. However, the pile should also be able to withstand the lateral loads, which may be caused by wind, wave action, earthquakes, or, in the case of bridges, traffic. The problem of laterally loaded piles is of particular interest, where, the ratio of lateral to vertical load is significant as in the bullet trains. The lateral resistance of a pile foundation is dependent on both the structural properties of the pile and the properties of the surrounding soil. In many practical situations, structures subject to lateral loading are located near excavated slopes or embankments. Bridge abutments, in most circumstances, are constructed on or near a slope crest to accommodate grade separations or geographical feature. Development in hilly regions often involves construction of buildings and bridges on slopes which are to be supported by piles. This situation may become critical case for the bullet train if not properly taken into consideration.

Several researchers investigated the effects of soil slope and cyclic loading separately on the lateral capacity of piles using small-scale model testing, centrifuge testing and finite element analysis. S. Mezazigh et. al. (1998) [4] performed an extensive program of centrifuge tests to study the effect of slopes on P–Y curves in dry sand. The program of tests on piles near slopes was given. It includes studies of the effect of distance to the slope, slope angle, and soil properties. Sample preparation method, model piles, and the lateral-loading device were described. Deflection versus load curves, bending-moment curves, and derived P–Y curves for piles close to slopes are compared to horizontal-ground response. F. Rosquoet et. al. (2007)[6] examined the behaviour of instrumented flexible piles in dry sand under lateral cyclic loading using centrifuged models. Considering load service conditions, the influence of the number of cycles of their amplitude and of the soil density on the pile cap displacement and the maximum bending moment of the pile was examined. The cyclic loading sequences were characterised by the number of cycles, the maximum applied load and the cycle amplitude. K. Muthukkumaran et. al. (2015) [5] performed detailed laboratory experimental model tests to study the effect of slope on laterally load pile capacity and p–y curves. The study concerns the method developed by a series of laboratory model tests (27 lateral load tests) to experimentally determine p–y curves. The study includes the effect of ground slope, relative density and embedment length on lateral load capacity, bending moment, lateral soil resistance, lateral deflection and p–y curves.

From the literature it has been found that a lot of work is done on the lateral capacity of pile for both static and dynamic loading conditions. Also static lateral capacity of pile on slopes is done but the study on the lateral capacity of pile on slopes subjected to dynamic cyclic loading is very limited. Thus the lateral capacity of pile under dynamic cyclic loading will be studied and effect of loading direction will also be considered.

2 Physical Modelling

In the present study we performed physical modelling under normal gravity (1-g model tests) to study the behavior of pile subjected to static and cyclic lateral loads on the sloping grounds.

2.1 Materials and equipment

The details about the materials and equipment used for testing will be discussed in this section.

Sand. Relatively uniform sand was used in the study. The specific gravity of the soil is 2.611. Physical properties of the sand is shown in Table.1. The sand is classified as poorly graded sand (SP) according to USCS classification system. All the tests were performed as per Bureau of Indian Standards (BIS).

Table 1. Physical properties of soil.

Property of sand	Value	Property of sand	Value
Specific Gravity (G)	2.61	Coefficient of curvature (Cc)	0.76
Effective size of particle (D10), mm	0.21	USCS[1] classification	SP
Mean size of particle (D50), mm	0.70	Minimum unit weight (γ_{min}),kN/m^3	14.87
Coefficient of uniformity (Cu)	4.76	Maximum unit weight (γ_{max}), N/m^3	17.87

[1]unified soil classification system [2]poorly graded sand

Model pile. The current project considers prototype pile made up of concrete having diameter and length of 0.5m and 10m respectively. The modulus of elasticity of concrete was assumed equals to 30 GPa. D. Wood [7] mentioned that correct physical modeling can be obtained for piles under lateral loading if we maintain the dimensionless ratio ϕ identical for model and prototype, where

$$\phi = \frac{GL^4}{EI}$$

G= Shear modulus of soil, L= Length of pile, EI= Flexural rigidity of pile.

Assuming soil stiffness G identical in model and prototype and considering length scale (nl) equals to 30, we get a concrete model pile having length and diameter equals to 0.33 m and .016 m respectively. The pile casted is shown in Figure 1. As concrete model piles takes time for curing and also a single pile can only be used once due to formation of cracks thus alternative pile made up of CPVC is used in present study as shown in Figure 2. The detail of model and prototypes decided by performing calculations is shown in Table 2. Due to unavailability of solid section, the hollow section of PVC was used for testing purpose.

Model Box. A cubical box of size 610mm×610mm×610mm was prepared to conduct lateral test on piles. The dimensions of the box were selected by considering the boundary effects from the pile. Three sides were made up of steel plates (1.02mm thickness) and fourth side was made up of acrylic glass sheet (6mm thickness) to check the relative density distribution throughout the depth.

Table 2. Detail of model and prototype considered for study

Type	Material	E (GPa)	μ	Length (m)	Diameter (m)	Thickness (m)
Prototype	Concrete	30	0.150	10	0.5	-
Model	Concrete	30	0.150	0.33	0.016	-
Model	CPVC	2	0.386	0.578	0.029	-
Model (Hollow)	CPVC	2	0.386	0.578	0.0325	0.0035

Fig. 1. Concrete model piles with mould.

Fig. 2. CPVC model piles used in testing.

Shake table. Uni-directional shake table was used to generate cyclic displacement to the pile. It can traverse distance from -50mm to +50mm with maximum vibratory motor frequency of 50Hz. The frequency of vibration of table and rotating motor was different thus, calibration chart was prepared for various range of frequencies of shake table. This chart was used to determine the required vibration frequency of table. The wave pattern was found out to be linearly varying. . In the present study table frequency of 0.5Hz was used so that inertia effect can be avoided.

2.2 Methodology

In the previous section we discussed about the materials and equipment used for the testing purpose, in this section we will discuss about the methodology adopted for testing. The following section will cover the sand placement method, test setup for static and cyclic loading.

Methodology for placement of sand. The sand bed was prepared by weight-volume method. The sand was filled in layers of thickness 5cm and compacted by using roller of 2.16 kg. A total of 11 layers were constructed by this method for each test. The detail of procedure is shown in Table 3. The density for each relative density was determined from,

$$R.D. = \left(\frac{1}{\gamma min} - \frac{1}{\gamma}\right) / \left(\frac{1}{\gamma min} - \frac{1}{\gamma max}\right)$$

For generating sloping ground, calculated amount of sand was removed after filling the whole tank. The detail of sand quantity is shown in Table 3.

Table 3. Detail of weights for sand placement.

Relative Density (%)	Unit Weight (kg/m^3)	Volume of each layer (m^3)	Weight of soil for each layer (kg)	Weight of soil to be removed for 20° slope (kg)
30	1566.73	0.0186	29.15	15.39
45	1609.34	0.0186	29.93	16.07
60	1654.33	0.0186	30.77	16.62

Static loading. After preparation of sand bed, the pile was inserted into the sand by providing blows with hammer having weight of 5kg. For the case of sloping ground, the pile was first inserted and then the sand was removed to generate slope. In slopes the pile was inserted at a distance of 50mm from the crest of the slope to avoid any disturbance to the pile while removing sand.

The static lateral capacity of pile was determined by measuring the load corresponding to lateral deflection of 5mm as mentioned in IS 2911 [1]. The test set-up used to measure lateral capacity is shown in Figure 3. A multi-speed loading frame having load cell of capacity 1-ton capacity with precision of 0.1kg was used for applying lateral load to pile. A linear variable displacement transducer (LVDT) having precision up to ±0.01mm was used to measure the lateral deflection of pile. The vertical movement of loading shank is converted into lateral motion with the help of pulley and steel wire arrangement.

Cyclic loading. Displacement controlled lateral loading was given to the pile head with the help of shake table. Long, J H, and Geert Vanneste.(1994) [3] mentioned that effect of cyclic loading is greatest for the first cycle and with consequent loading the effect of cycles reduces. Considering the mentioned finding, 50 numbers of cycles were decided. The frequency of vibration considered is such that the effect of repeated loads is important and effect of inertia is minimal. Two types of loading conditions are studied i.e. one-way loading and two-way loading. In one-way loading the displacement varies from 0mm to 5mm linearly and in two-way the displacement varies from -5mm to 5mm linearly.

i. ii.

Fig. 3. Static loading test set up for i) horizontal ground and, ii) sloping ground.

The test set-up used to perform cyclic loading is shown in Figure 4. The sand placement method and pile installation method is same as in static loading. The lateral cyclic movement of shake table is transferred to the pile head with the help of rigid bar which is bolted firmly to the shake table and pile head. It was ensured that the rigid bar only moves to and fro and there is no rotation of the bar so that the piles moves the exact distance as the input given to shake table. During testing the shaking of the test box was not observed ensuring the suitability of box dimensions for preventing the boundary effect.

After the pile was subjected to desired number of cycles, the pile was disconnected from the shake table by loosening the bolts. The degradation in the lateral capacity of pile was determined by making alternative arrangement as shown in Figure 5. The displacement and load was measured with LVDT and load cell. As loading frame was not available to generate loading, sand was used to give load to the pile head. The sand was poured into the plastic container with the help of special pouring apparatus as shown in Figure 6, so that uniformity in pouring can be obtained with proper measurement from LVDT and load cell. The sand was filled until the lateral deflection reached 5mm which is the lateral capacity of pile after the cyclic loading.

Fig. 4. Cyclic loading test arrangement with connections.

Fig. 5. Test arrangement after cyclic loading.

Fig. 6. Sand pouring cylinder.

3 Results and discussions

3.1 Static test results

The static lateral capacity of pile was determined first as mentioned in section 2.2. A total of 4 numbers of tests were performed as shown in Table 4.

Table 4. Parameters for static loading.

Relative Density (%)	Slope of ground (˚)
30%	0 ˚
	20 ˚
60%	0 ˚
	20˚

The Load-Deflection curve of pile head for 30% and 60% relative density is shown in Figure 7 and Figure 8.

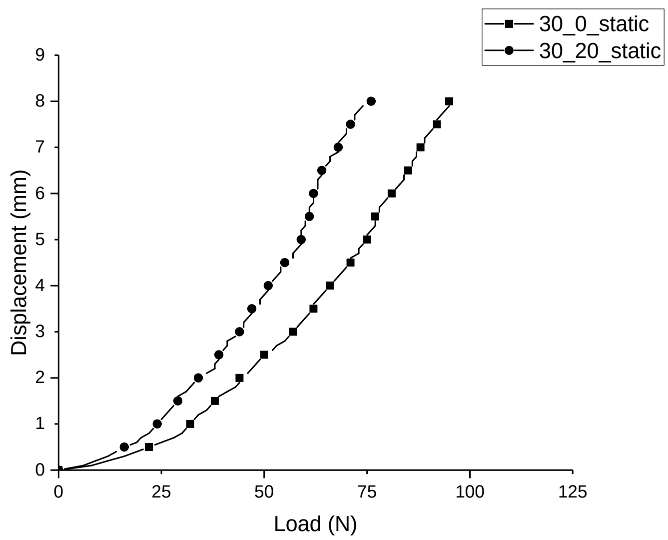

Fig. 7. Load-Deflection curve for 30% relative density for horizontal and sloping ground.

From the curves it can be seen for both the relative densities that there is reduction in lateral capacity due to sloping ground. The main reason for this reduction is less passive resistance offered by the sloping ground due to unavailability of soil. The reduction in capacity of pile for 30% and 60% relative density due to slope, considering the 5mm failure criteria is 21.33% and 31.57% respectively. It is observed that for medium dense sand there is more reduction in capacity compared to the loose sand.

3.2 Cyclic results

The cyclic tests were performed as mentioned in section 2.2. with the help of shake table. The detail about the shake table and methodology of testing adopted is already discussed in section 2. The parameters considered for cyclic tests are shown in Table 5. A total of 10 cyclic tests were performed for current study.

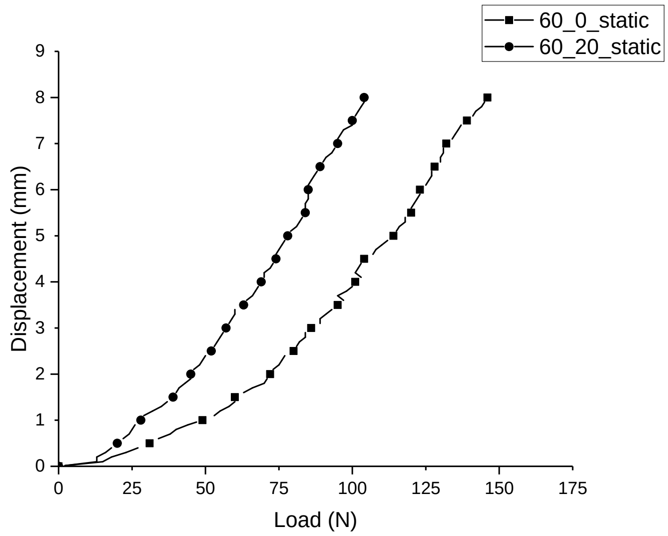

Fig. 8. Load-Deflection curve for 60% relative density for horizontal and sloping ground.

Table 5. Parameters considered for the cyclic tests.

Relative Density (%)	Slope of ground (˚)	No. of cycles	Loading type
30%	0˚	50	One-way, Two-way
	20˚	50	One-way, Two-way
60%	0˚	50	One-way, Two-way
	20˚	50	One-way, Two-way
	0˚	500	Two-way
	20˚	500	Two-way

The results for the mentioned parameters are shown in Figure 9 and Figure 10 for 30% and 60% relative density respectively. These results are for both horizontal and sloping ground when subjected to 50 numbers of cycles with one-way and two-way loading. The format used to depict the different combination is as follows,

Relative density _ Slope _ Loading type

Thus 30_20_1 means piles in 30% relative density having sloping ground of 20˚ and subjected to two-way cyclic loading.

It can be observed from the load-deflection curve that for horizontal ground there is slight effect of loading type. The lateral capacity for two-way loading is higher than the one-way loading for both relative densities but for sloping ground the effect of loading type is insignificant. This shows that the characteristics of load can be a significant parameter when behavior of piles subjected to cyclic loading is considered.

The reason for higher reduction in case of one-way loading is greater cumulative deformations compared with two-way loading. Due to absence of sand because of slope the accumulated deformations are same for the one-way and two way-loading, therefore the difference is insignificant.

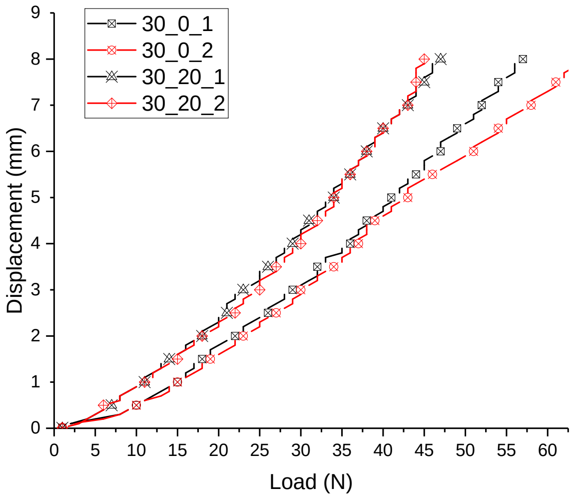

Fig. 9. Load-deflection curve for 30% relative density for cyclic tests.

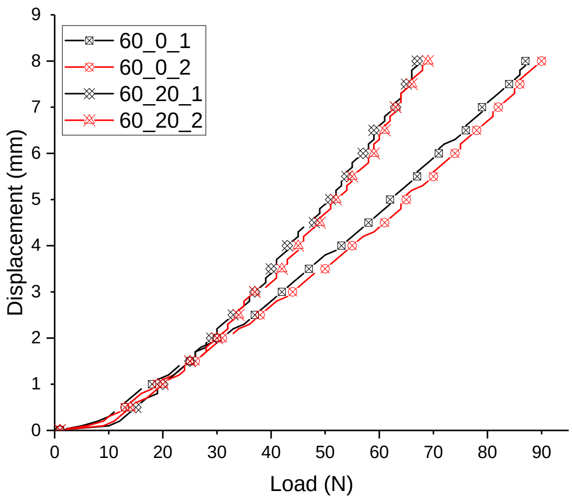

Fig. 10. Load-deflection curve for 60% relative density for cyclic tests.

The reduction in capacity due to slope and the nature of cyclic loading is summarized in Table 6. It shows the lateral capacity of pile corresponding to 5mm deflection for all the static and cyclic tests performed. The percentage reduction is found out with reference to lateral capacity for horizontal ground and under static loading. It can be concluded from the data that the reduction in capacity is much significant for medium dense sand compared with the loose sand. The critical case becomes when the pile is installed near sloping ground and subjected to one-way cyclic loading. The static lateral capacity method overestimates the pile capacity and cyclic or dynamic nature of load needs to be considered for proper design of pile foundations.

Table 6. Summary of the reduction in lateral capacity for tests performed.

Relative Density (%)	Slope (˚)	Loading Type	Lateral capacity (Newton)	Percentage reduction (%)
30	0	Static	75	-
	0	Two-way	43	42.66
	0	One-way	41	45.33
	20	Static	59	21.33
	20	Two-way	34	54.66
	20	One-way	34	54.66
60	0	Static	114	-
	0	Two-way	65	42.98
	0	One-way	62	45.61
	20	Static	78	31.57
	20	Two-way	52	54.38
	20	One-way	51	55.26

4 Conclusions

In present study small scale physical modeling of pile constructed near slopes subjected to static and cyclic loading was done. From the results we can conclude the following:

- The presence of slope causes reduction in lateral capacity of pile due to absence of soil there is less passive resistance offered by soil to pile. The reduction in capacity due to slopes compared to horizontal ground can be 20% to 30% depending on the relative density.
- The pile subjected to dynamic lateral forces can reduce the lateral capacity by 56% depending on the ground slopes and relative density.
- The nature of cyclic loading (one-way and two-way loading) also influences the lateral capacity of pile.

As High speed trains can exert large lateral force with cyclic nature which may cause damage if pile is not designed considering its dynamic nature. The situation worsens if slope is also present as in abutments thus further study such as more number of tests with variable slope is required for better design.

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