Assessment of Lateral Load Capacity of Single Pile at Bettiah Site: A Parametric Study

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Pile foundations are a widely used and accepted approach to transferring superstructure load to a deeper and stronger stratum. This work has been focused on the assessment of the effects of different parameters associated with piles, such as pile diameter, pile length, grade of concrete, and pile head condition (i.e., free or fixed) on the lateral load capacity. To evaluate the lateral load capacity considering the aforementioned parameters, 'IS Code' and 'Matlock and Reese' methodologies have been utilized. Soil exploration data has been collected from ten different boreholes near the railway bridge at Bettiah site, Bihar. The results of lateral pile load at different boreholes show that the lateral load capacity of the pile significantly increases with the increase of pile diameters and grades of concrete. The lateral load capacity of the pile was increased approximately by 13%, from both the IS Code and the Matlock and Reese methods, when the grade of concrete was increased from M25 to M40. It was also found that the condition of the pile head also plays a major role in lateral load capacity. The lateral load capacity of the pile, obtained from the IS code method under fixed head conditions, was found to be higher as compared to the free head condition. It has also been observed that the lower values of safe bearing capacity for fixed heads and lower values for the free head condition were obtained by the IS Code as compared to the Matlock and Reese method.

Keywords: Pile Foundations, Lateral Load Capacity, IS Code, Matlock and Reese Method, Fixed and Free Head.

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1 Introduction

Pile foundations are a widely used and accepted approach to transferring superstructure load to a deeper and stronger stratum in most pile-supported structures such as bridges, tall fireplaces, TV towers, tall structures, high holding dividers, and seaward construction. Piles are utilized if the superstructure's load is significantly high or settlement due to the heavy load is considerably high. Piles embedded in the soil under such constructions are always subjected to lateral loads caused by wind and traffic, resulting in translation, rotation, or bending of the pile. Winkler introduced the concept of soil-pile approximation to analyze a pile under lateral load, through a spring, but it limits the coupling effect of the spring and the continuity of the soil. This limitation led to the development of the p-y curve method, which utilizes the finite difference method to model the soil resistance [1]. The P-y curve approach gives a reasonable result, and that's why the study of pile behaviour under lateral action is widely adopted in software programmers like LPILE and FBPIER [2]. The present study incorporates the use of a subgrade reaction approach through the P-y curve method. The behaviour of a laterally loaded pile is similar to that of a beam on an elastic foundation subjected to transverse loads. For a vertical pile, horizontal loads and the associated moments act at or above the ground surface only. Lateral resistance of nearby soil mobilizes lateral load; thus, lateral loading capacity is dependent on soil properties. One of the requirements for a satisfactory pile foundation under such structures is that the maximum horizontal movement of the pile should not exceed 1% of the pile's diameter [3]. The detailed investigations have been carried out by several researchers for a single vertical pile subjected to horizontal load [4, 5], utilizing the concept of modulus of subgrade reaction, which further approximates the soil medium as a series of non-linear lateral independent elastic springs that are infinitely closely spaced and represent the stiffness of soil by the decreased length of the spring down the pile (Fig. 1). At shallow depth, the spacing between pile and spring represents the displacement of soil under the action of repeated loading, and the blocks of varying sizes attached to springs take care of reaction, which increases with deflection and then reaches a maximum value (Fig. 1). Further, a generalized solution to calculate the lateral load for a vertical pile was given by Matlock and Reese (M & R)[6]. Extensive theoretical and experimental investigations have been carried out on single vertical piles subjected to lateral loads and the results have been presented in the form of bending moments and deflections [7, 8, 9]. An attempt has been made to study the behaviour of laterally loaded piles resting at various borehole locations using the Indian Standard (IS) method [10] and the p-y curve approach [6], and the results are represented in the form of Ultimate Lateral Loading Capacity (ULLC).

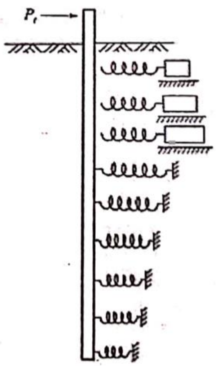

Fig. 1. Approximation of laterally loaded pile-soil system [1]

2 Study Area

The site is situated 3 km north-west of Bettiah city in the West-Champaran district of Bihar state, India (latitude 26.815483° N and longitude 84.502715° E) as presented in Fig. 2. The piles were installed at the proposed site for the construction of the railway over-bridge at Bettiah-Kumar Bagh Station or Road, and the work comes under the Samastipur Railway division.

Fig. 2. Location of the study area

3 Soil Exploration

Soil exploration is required to ascertain various sub-soil characteristics, stratification data, and engineering properties. Figure 3 presents the locations of ten boreholes. The entire exploration programme has been divided broadly into two parts: fieldwork and laboratory tests. Fieldworks reveals the sub-surface deposit types and their characteristics through the samples obtained by advancing the boreholes of 150 mm in diameter by auger and rotary equipment up to 40 m depth [11]. The Standard Penetration Test (SPT) value is one of the indicators of the strength of soil [12, 13]. Thus, the scope also included conducting SPT [14], collecting disturbed samples at regular intervals for identification and logging purposes, collecting undisturbed tube samples at suitable intervals of 1.5 m or at the change of strata, whichever is earlier, and testing these in the laboratory.

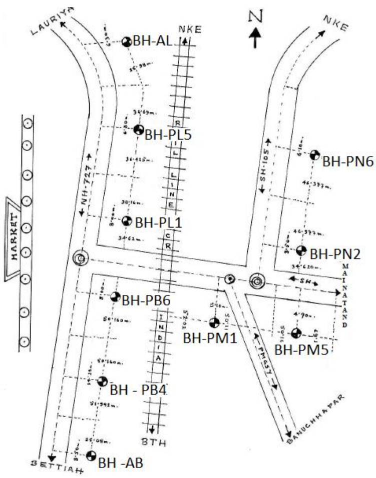

Fig. 3. Location of boreholes

Laboratory tests were performed at NIT Patna laboratory to determine water content, bulk density, specific gravity, and strength parameters (Table 1 and 2). The water table was at an average depth of 1.2 m from the top of the ground level. During the investigation, it was found that the SPT value at PB-0 and AB site (Fig. 4) changes drastically after 20 m, which is also reflected later in the ULLC of the pile. Based on the visual classification and investigation results of field and laboratory tests on the samples recovered, we divided the proposed site into six layers. The overall soil profile can be described as stiff clay to dense sand and the geotechnical properties of these profiles are presented in Table 1.

Table 1. Major soil strata available at the proposed site

Layers	Thickness (m)	Field N value	IS Classification	Bulk Density (gm /c.c.)
1	0.0 – 1.4	-	CL-ML	1.82
2	1.4 – 5.5	4 – 9	CL, ML, CL-ML	1.83 – 1.86
3	3.65 – 13.45	10 – 18	SM, SM-SP	1.84 – 1.86
4	4.2 – 12.2	15 – 34	SP, SM-SP	1.86 – 1.88
5	6.0 – 13.7	32 – 53	SP, SM-SP	1.87 – 1.89
6	6.6 – 15.25	55 – 100	SP, SM-SP	1.88 – 1.91

Table 2. Average boreholes properties.

Borehole	NMC (%)	Bulk Density (gm/cc)	Specific Gravity (G)	Cohesion (c) (kg/cm²)	ϕ (degree)
PM-1	18.44	1.88	2.65	0.255	32.330
PB-0	18.92	1.88	2.65	0.380	33.125
PB-4	18.72	1.87	2.65	0.290	32.890
AB	18.42	1.88	2.66	0.435	32.780
PM-5	18.56	1.89	2.65	0.293	32.500
PL-1	18.30	1.88	2.65	0.423	32.875
PL-5	18.12	1.90	2.66	0.340	32.750
AL	19.48	1.87	2.65	0.323	33.125
PN-2	18.46	1.90	2.65	0.335	32.330
PN-6	18.60	1.89	2.66	0.370	33.110

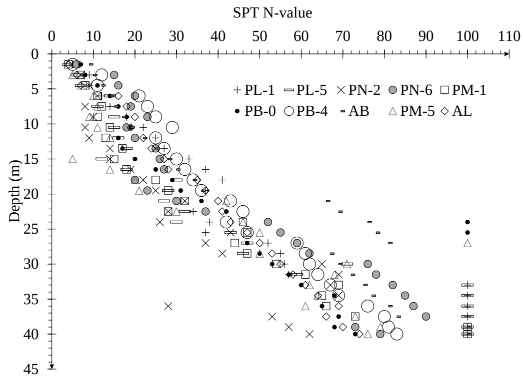

Fig. 4. Scatter of SPT *N*-value

4 Methodology

To study the behaviour of laterally loaded piles different methodologies such as the Sub grade Reaction approach, Ultimate Limit State method, Continuum approach, and Finite Element approach have been reported in the literature [2]. The present study utilizes the sub grade reaction approach utilized by the Indian standard method and the M&R method for the calculation of ULLC. Further, results obtained from both the methods were varied against the various combinations of length, diameter, head condition, and concrete grade of the pile to understand the respective influence on the ULLC.

4.1 Indian Standard (IS) Method (2010)

This method is performed in accordance with Indian Standard [10] & it provides an approximate solution due to the complexity of the problems. The procedure starts with the determination of the behaviour of piles considering a flexible member of infinite length or a short rigid pile [4, 10, 15]. Firstly, the Stiffness Factor (T/R) is computed for the specific combination of pile and soil which is further linked to the grade of concrete, dimension of the pile, and Modulus of Subgrade Reaction whose values are taken from IS 2911 which is listed in Table 3. The site in the present study consists of sand primarily; thus, stiffness factor (T) is calculated (Eqn. 1). As per IS criteria (Table 4), all pile comes under the range of long pile. Thus, the present study encompasses the behaviour of long piles. Virtual Fixity depth indicates a specific profundity below the ground surface where piles are fixed and not meant to yield under lateral load application. Further, the Depth of virtual fixity is used in calculating the lateral deflection of piles and bending moment in the conventional elastic analysis. Further, the cantilever distance between the ground and the point of application of lateral load is calculated. Further, Eqn. 2 and Eqn. 3 has been used to calculate the ULLC for piles with free head and fixed head, respectively.

$$T(m) = \sqrt[5]{\frac{EI}{\eta_h}} \tag{1}$$

$$H(kN) = \frac{3EIy}{\left(e + z_f\right)^3} \times 10^{-3} \tag{2}$$

$$H(kN) = \frac{12EIy}{\left(e+z_f\right)^3} \times 10^{-3} \quad (3)$$

where, E stands for modulus of elasticity of pile material in kN/m², I is the moment of inertia of the pile cross-section, in m⁴, η_h is the modulus of sub grade reaction (MN/m²), 'z_f' is depth to point of fixity, 'y' is the maximum pile head deflection in mm and 'e' is the cantilever length above the ground surface to the point of application of load in meter.

Table 3. Modulus of sub grade reaction for granular soil η_h (kN/m³) [11]

SI. No.	Soil type	SPT N-value (Blows/30 cm)	Range of η_h (kN/m³)	
			Dry	Submerged
1	Very loose sand	0 – 4	< 0.4	< 0.2
2	Loose sand	4 – 10	0.4 – 2.5	0.2 – 1.4
3	Medium sand	10 – 35	2.5 – 7.5	1.4 – 5.0
4	Dense sand	> 35	7.5 – 20	5.0 – 12.0

Table 4. Criteria for the behaviour of pile based on its embedded length [11].

SI. No.	Type of pile behaviour	Relation of embedded length with stiffness factor	
		Linearly increasing	Constant
1	Short (rigid) pile	$L \leq 2T$	$L \leq 2R$
2	Long (elastic) pile	$L \geq 4T$	$L \geq 3.5R$

4.2 Matlock and Reese Method (1961)

Reese and Matlock [4] proposed to use the principle of dimensional analysis to establish the non-dimensional relationships for piles. Further, Matlock and Reese [15] proposed equations for the determination of deflection, slope, shear force, bending moment, and soil reaction at any point along the depth of the pile and M&R [6] introduced a non-dimensional Deflection Coefficient for calculating the lateral deflection of the pile. For very long piles, it is observed that the total length 'L' loses its significance because the deflection is almost zero for much of the length of the pile [4]. It is convenient to introduce some characteristics length as a substitute. A linear dimension 'T' is therefore included in the analysis. Since T in the analysis expresses a relationship between the soil stiffness and the flexural stiffness of the pile material, it is called the relative stiffness factor. For an applied lateral load and moment, the outcome for the deflections of the elastic curve will include the relative stiffness factor and be expressed as Eqn. 4. An elastic behaviour can be assumed for minor deflections concerning the pile dimensions, for which the principle of superposition can be applied. By applying the principle of superposition, the effects of imposed lateral load (H_t) (case A) and imposed moment (M_t) (case B), if considered separately, give rise to deflection. Total deflection at any point x from top of the pile, having flexural rigidity EI can be accessed as per Eqn. 5. The solution for the two cases of deflection may be expressed in the following forms of Eqn. 6 and Eqn. 7., where y_A and y_B are deflection due to H_t and M_t respectively.

$$y = f_y\left(x,\ T,\ L,\ E_s,\ H_t, M_t\right) \tag{4}$$

$$y = y_A + y_B \tag{5}$$

$$\frac{y_A}{H_t} = f_A(x, T, L, E_S, EI) \tag{6}$$

$$\frac{y_B}{M_t} = f_B(x, T, L, E_S, EI) \tag{7}$$

f_A & f_B represents two different functions of similar terms and the value of non-dimensional coefficients A_y and B_y for case, A and case B respectively can be determined as a function of depth coefficient (z) (Eqn.8).

$$z = \frac{x}{T}, A_y = \frac{y_A EI}{H_t T^3}, B_y = \frac{y_B EI}{M_t T^2} \tag{8}$$

$$y_x = \frac{H_t T^3}{EI} A_y + \frac{M_t T^2}{EI} B_y \tag{9}$$

Total deflection y at any depth x can be given Eqn. 9. Where E_s is the elastic modulus of soil, EI is flexural rigidity of pile, A_y and B_y are deflection coefficients and its values can be chosen from the table provided by M&R [6] for a given depth coefficient (z).

Free Head Pile: When the pile head is free to rotate, the corresponding equations for deflection at ground level are expressed as Eqn. 10. In the free head case, the pile head is in pinned condition thus moment due to fixity will not develop (Eqn. 11).

$$y_g = 2.435\frac{H_t T^3}{EI} + 1.623\frac{M_t T^2}{EI} \tag{10}$$

$$y_g = 2.435\frac{H_t T^3}{EI} \tag{11}$$

Pile Head Fixed Against Rotation: When Degree of Freedom is zero for a pile at its head then the general equation of deflection is expressed as Eqn. 12 and Moment developed at ground level due to fixity is given by Eqn. 13. Using the value of Deflection coefficient A_y and B_y for zero-depth coefficient is 2.435 & 1.623, respectively [6], the lateral load can be reported in form of Eqn. 14.

$$y_x = \frac{H_t T^3}{EI} C_y; where, C_y = A_y + \frac{M_t}{H_t T} B_y \tag{12}$$

$$M_t = M_g = -0.93 H_t T \tag{13}$$

$$H_t = \frac{EI y_g}{0.93 T^3} \tag{14}$$

5 Results and Discussion

ULLC was calculated for all the ten boreholes by using IS code [10] & Matlock & Reese method [6] and considering variation in several parameters like diameter, length, grade of concrete, and pile head condition.

5.1 Comparison between Results of IS Code and Matlock & Reese Method

M & R [6] gives a better representation of field test results [16]. Reese [7] utilized the concept of M & R for lateral load calculation and found very less variation when compared with actual field results. Overall, the Highest value of ULLC was 483 KN (M&R), obtained at PB-0, for a pile of 1.2m diameter and 25 m length and the lowest value was 17.5 KN (IS 2911) at borehole PL-5, for the pile having 0.4 m diameter and 15m length (Fig. 5). This can be attributed to a sudden increment of N-value after 20 m for PB-0. The highest & lowest value of ULLC was obtained corresponding to the L/D ratio of 20.83 & 37.5, respectively, for all of the borehole sites but PL-1. PL-1 exhibits a higher SPT N-value at a lesser depth of the pile (15m & 18m) and a lower value of that at a greater depth of the pile (21 m & 25 m), due to which it shows the highest & lowest value of ULLC for L/D ratio 15 & 52.5 respectively. It was observed that the range of ULLC was largest for the calculation with the M&R method for the fixed head. M&R gives ULLC value higher than IS code method for both head conditions.

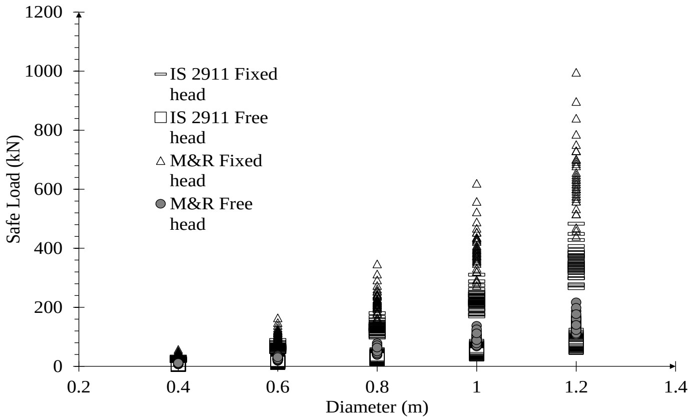

Fig. 5. Scatter of ULLC (M25; L = 15 m)

5.2 Effect of Diameter

To check the effect of pile diameter on ULLC, the different pile diameters such as 0.40 m, 0.60 m, 0.80 m, 1.0 m, and 1.20 m were considered. Fig. 6 and Fig. 7 shows the response of pile diameter on ULLC at each borehole using IS code for fixed & free pile head respectively. It is seen that the lateral capacity to carry safe load increases with an increase in pile diameter. An approximate increment of 150% & 140% was observed in ULLC for fixed and free head conditioned pile respectively, for 200% increment in diameter. This is attributed to the increase in moment of inertia, stiffness factor, surface area, and depth of fixity which relies upon the diameter of the pile. It was observed from the increasing slope of the curves in Fig. 6 & Fig. 7 that the rate of increment of the lateral capacity of the pile increases with an increase in diameter and a similar response was reported by Salini et al.[17]. The average variation between ULLC calculated by IS 2911 and M&R method increases from 55% to 75% for a diameter change from 0.4m to 1.2 m respectively.

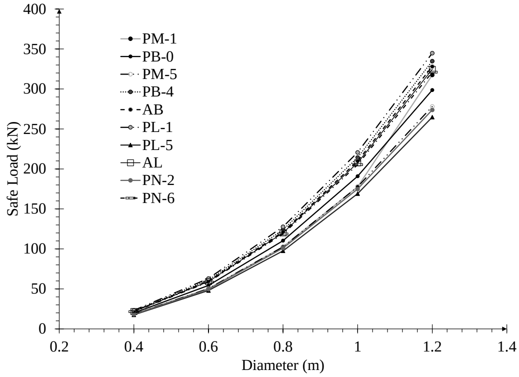

Fig. 6. ULLC evaluated as per IS 2911 [10] approach (Fixed head M25 15m)

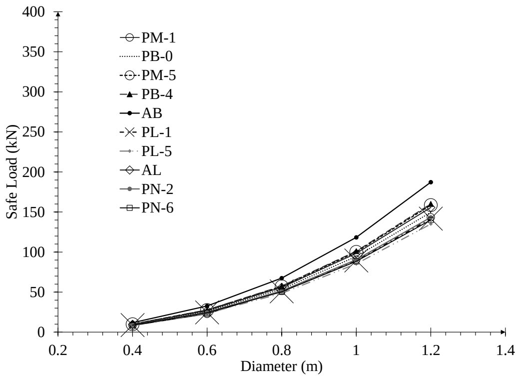

Fig. 7. ULLC evaluated as per M&R [7] approach (Free head; M25; L = 21 m)

5.3 Effect of Length of the Pile on ULLC

To examine the impact of the length of the pile on ULLC, distinctive pile lengths such as 15 m, 18 m, 21 m, and 25 m were considered in the present paper, and a typical result is presented in Fig. 8. The figure shows non-linear behaviour at a lesser depth and becomes relatively flattered at a higher depth. This behaviour is associated with the fact that the ULLC of a pile increases at a high rate for the initial increment in length, but later on, it increases linearly [17]. At lesser depths, the pile behaves nonlinearly with the depth, but as the depth increases, it starts behaving more linear [4]. Due to the mobilisation of passive resistance on the extended length of the pile (15 to 25 m), ULLC increases with an increase in the pile length [18]. Evaluation of bearing capacity for the laterally loaded pile condition: curve fitting methods are also useful to understand the behaviour of the pile [19, 20]. Changing the length from 15 m to 25 m leads to the lowest increment of 4% for the borehole PL-1 and the highest increment of 78% for PB-0. The percentage increment in ULLC due to length varies between 4%-78% for fixed head condition and between 3.8% and 67% for free head condition at all of the borehole sites, and this can be attributed to the non-uniform SPT N-value distribution along with the depth. It is also obtained that the percentage change in ULLC due to length increment is higher for the M & R approach.

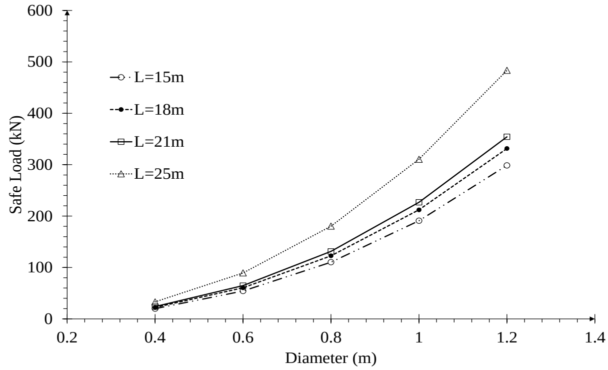

Fig. 8. Effect of length on ULLC (PB0; IS2911 [10]; Fixed head; M25)

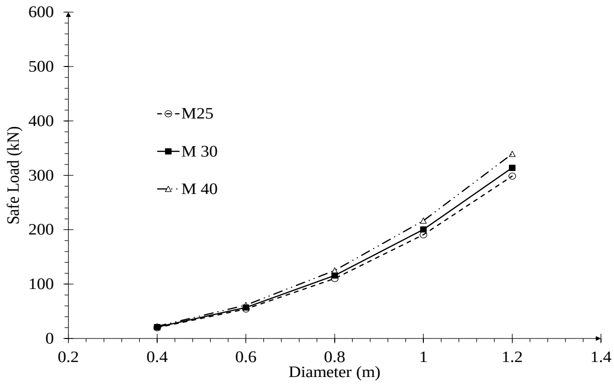

Fig. 9. Change in ULLC with concrete grade (PB0, IS 2911 [10], Fixed head, L= 15m)

5.4 Influence of Grade of Concrete on ULLC

Evaluation of the influence of grade of concrete on ULLC is carried out by selecting three different grades of concrete, i.e., M25, M30, and M40. The result shows the least increment in ULLC for an increase in grade of concrete when compared with other variable parameters (Fig. 9). When the grade of concrete is increased from M25 to M40, the capacity increases by 13% approximately for both methods and both head conditions at each of the borehole sites.

5.5 Influence of Pile Head Condition on Lateral Load Capacity

Free head and fixed head conditions were undertaken to understand the impact of pile head conditions on ULLC. It was obtained that the pile head condition has a significant impact on the lateral load-bearing capacity due to the fixity of the pile, which caused an additional moment. When the head condition is changed from free head to fixed head, the ULLC increases by approximately 320% for both methods. The percentage increment in ULLC due to head condition increases with an increase in diameter but more or less remains constant for every borehole site at a particular diameter. The variation is shown in Fig.10 for borehole PB0, and an approximately similar variation pattern was reported for other borehole sites.

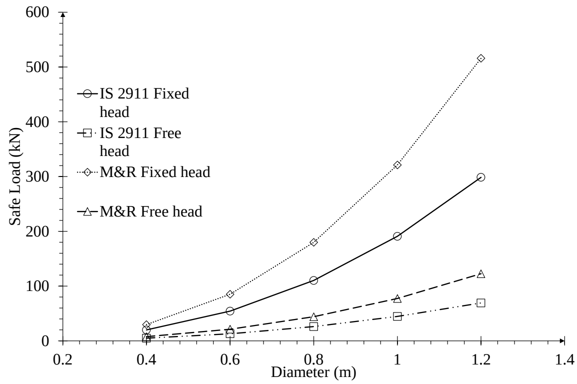

Fig. 10. Effect of Head condition on ULLC (PB0; M25; L = 15 m)

6 Conclusions

The ULLC for piles in a cohesionless soil stratum is evaluated for both fixed and free head conditions, using the IS Code method [10] and the Matlock & Reese [6] method, considering piles of various diameters, lengths, and concrete grade, and the results are represented in terms of lateral loading capacity, unlike moment and deflection, which are relatively lucid for practical applications. The average variation between both methods (for a fixed head condition) increases from 55% to 83% for a diameter change from 0.4 m to 1.2 m, respectively. This variation confirms the results obtained by Jayasree [16]. While for free-head conditions, this variation ranges between 63% and 84%. According to the results, IS 2911: 2010 provides a conservative value of ULLC of approximately 70% for the fixed-headed pile and approximately 75% for the free-headed conditioned pile. The diameter has a maximum and the grade of concrete has a minimum influence on the ULLC. Previous studies also found the IS code method of lateral load analysis uneconomical [16, 18], and the present study is also in agreement. Since the public and private construction departments are currently considering the conventional IS:2911 method for the design of laterally loaded piles in bridges, they are underestimating the capacity of the pile by adopting an uneconomical design method. Thus, it is recommended to adopt an improved method for designing the piles exposed to lateral loads.

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