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Short Piles for a Solar Power Plant in Western Rajasthan

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Abstract. Short bored cast-in-situ piles were installed for a solar power plant in western Rajasthan. The deposits at site consist of dune sand underlain by rock. The paper discusses the load-displacement behavior of 350 mm diameter 2.65-2.8 m long piles under pullout and lateral loading. To evaluate ultimate pullout capacity of piles which were not tested to failure, a hyperbolic model of load-displacement curve has been proposed. The pullout test data has been used to back-calculate the value of earth pressure coefficient, k. The lateral pile capacity has also been analyzed to evaluate the value of modulus of horizontal subgrade reaction.

Keywords: solar power plant; short piles, load tests; pullout capacity; hyperbolic model, lateral capacity, modulus of horizontal subgrade reaction.

1 Introduction

1.1 Solar Power Generation

Solar power has emerged as a major alternative and clean source of energy in India to augment power generation. Solar energy is the most readily available source of non-polluting renewable energy resources. India is moving towards an ambitious target of making renewable energy generation at par with thermal plants.

Sunlight can be utilized in two ways viz. direct conversion into electricity through solar photovoltaic (PV) cells or indirect conversion through generating high temperatures by concentrating collectors and thereby run a steam turbine in line with a conventional thermal power plant.

In solar photovoltaic (PV) plants, thousands of solar panels are installed which are usually supported on single short piles. Being lightly loaded, the pullout and lateral capacities of the piles under wind loading are the critical loading condition.

1.2 Project Details

The paper presents case study of a solar PV plant in Jodhpur district of western Rajasthan. The project area covers about 600 hectares. The area is blessed with good sun-

light over most parts, and the number of clear sunny days in a year is quite high. About 300 MW of power generation is planned.
A map of India showing the project location is illustrated on Fig. 1.

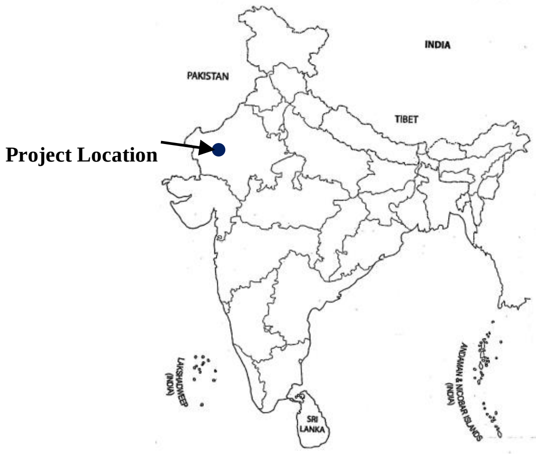

Fig. 1. Vicinity Map

2 General Site Conditions

2.1 Regional Geology

A large tract of western and south - western Rajasthan and Sindh, 640 km long and 160 km wide, constitutes the Thar Desert [1]. The aeolian accumulations of the Thar is a wide expanse of windblown sand and bare rock stretching from the west of the Aravalis to the basin of the Indus and from the southern confines of Punjab to the basin of the Sutlej.

The sands cover an irregular rocky floor, but occasionally local prominences and ridges rise above the levels of the sand. Over the greater part of the area, the sands are piled up into dunes.Dune sands are of recent age

Rocks younger than the Marwar Super group occur in northwestern part of Jodhpur district. These cover a small area and include the Badhaura sandstone and Bap boulder bed of Permo-Carboniferous age, Lathi sandstone of Jusassic age and Kapurdi sandstone of Eocene age.

2.2 Geotechnical Investigation

The project area was investigated by over 100 boreholes in addition to trial pits, electrical resistivity tests, etc. The boreholes were drilled to 5-7 m depth through soil and rock. Fig. 2 shows typical boreholes in progress at site.

Fig. 2. Boreholes in progress. Photo on left illustrates soil boring in progress using mechanized shell and auger. Photo on right illustrates rock coring being done using hydraulic rotary rig

2.3 Stratigraphy and Geotechnical Characterization

At the project site, dune sands of the Thar Desert are underlain by sandstone.In general, the sands are poorly graded with an insignificant proportion of coarse and medium sized sand grains. The stratigraphy at the site may be divided into two generalized strata as given below:

Stratum-I : Fine sand &silty fine sand

Stratum II : Sandstone

The depth to rock varies across the site from less than 1m to more than 7 m depth. Groundwater was not encountered to the depths investigated and is expected to be fairly deep. Contours of depth to rock are presented on Fig. 3.

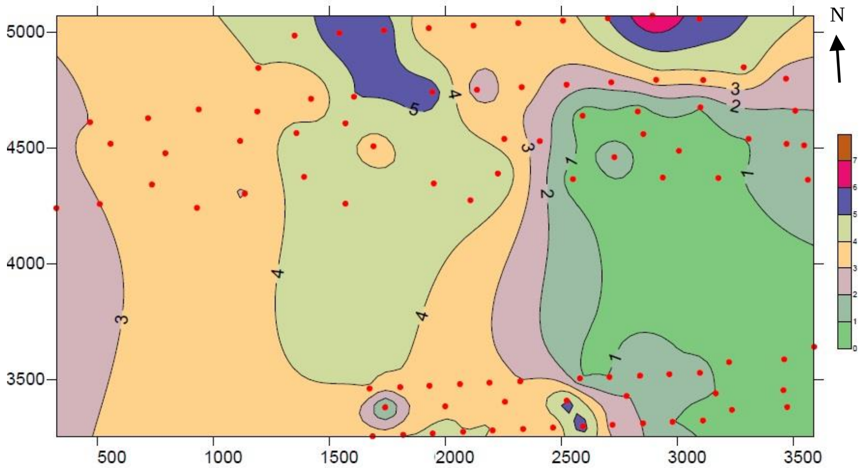

Fig. 3. Contours of Depth to rock

In general, rock is met at shallow depth on the eastern side and outcrops in the southeastern portion. In the central and western part, the depth to rock exceeds 3-4 m.

Alam Singh et al. [2] classify dune sand as a meta-stable or collapsible soil that goes through radical re-arrangement of particles and loss in volume upon wetting with or without load application. The SPT values and relative density of the soil are a function of the overburden.

Sanjay Gupta and Ravi Sundaram [3] found that the trend of SPT values is an important feature ofaeolian depositions. The soils with N-values less than about 10 to 12 may be treated as unstable portion of the dune.

Typical boreholes are illustrated on Fig. 4 and 5.

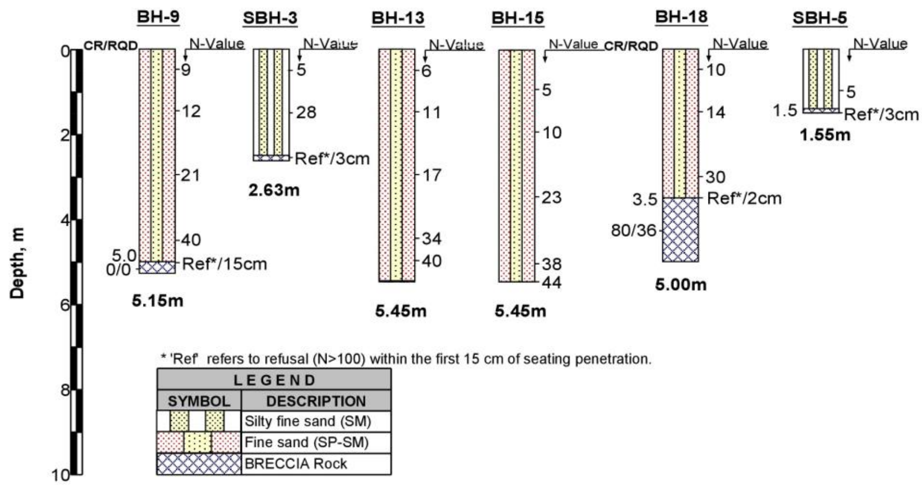

Fig. 4. Typical borehole profiles in northern side of plor

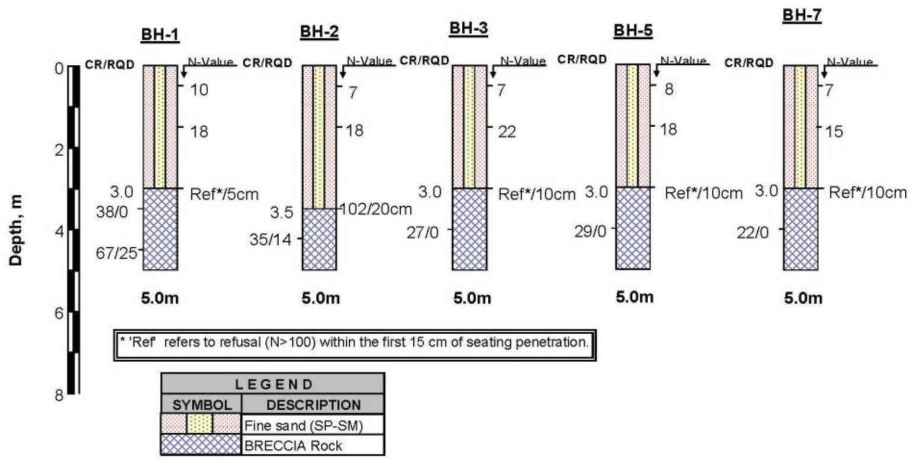

Fig. 5. Typical borehole profiles in southern side of plot

3 Foundation Type and Design

3.1 Solar PV Module Mounting Structure

Solar PV modules are mounted on a structure that is called module mounting structure (MMS). This MMS is an arrangement of rafters and purlins that transfers the load through bracings and column post to the foundation. The column post is generally embedded in the foundation. A typical isometric viewshowing different elements of MMS is placed at Fig. 6.

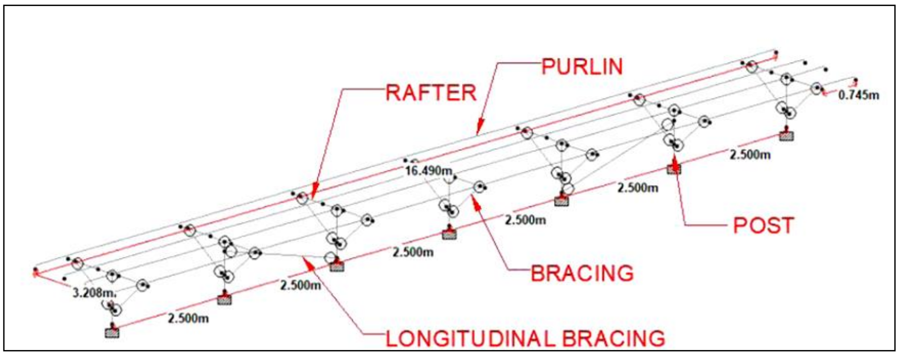

Fig. 6. Typical Isometric view of MMS

The module surface area is large compared to its weight; therefore the dead weight of structure is comparatively less. In view of large surface area and angle of module, wind load plays a predominant role in designing the structure and in turn foundation.

Due to wind loads, the dominant reactions obtained at the top of foundation are uplift and lateral. This necessitates design of foundation for pullout and lateral load resistance. A typical sketch showing the MMS table and foundation is placed at Fig. 7.

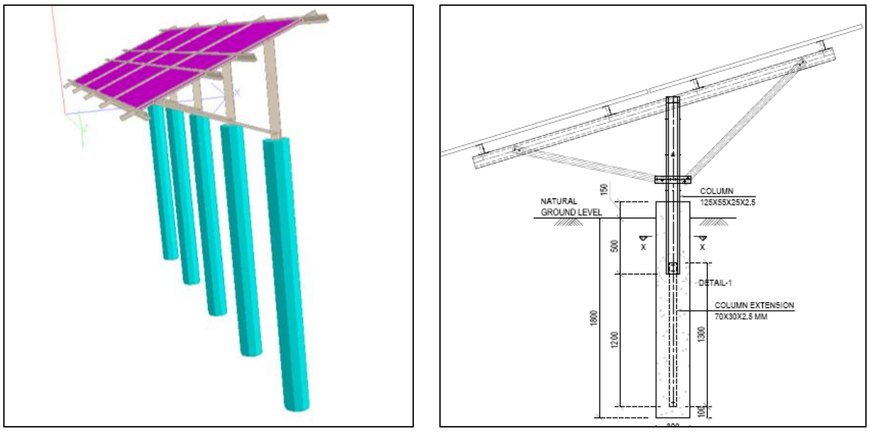

Fig. 7. MMS table with foundation: 3D rendered view on left photo and sectional view on right

3.2 Foundation type

Based upon the structural analysis considering the site-specific loads, the obtained reactions at each column location were in the range of 1.5-2.25 T in case of uplift and 0.8-1.5 T in case of lateral load. The load variations were due to the different table sizes/arrangement considered to maximize generation. The columns were generally spaced at 2.5m apart below a table. The load variation range for foundation design is placed at Table-1.

Table 1. Range of foundation loads for pile design

S. No.	Type of loading, m	Load Range, T
1	Pullout	1.5-2.25
2	Lateral	0.8-1.5
3	Vertical	1.0-1.5

Different foundation systems were explored considering the cost economics as well the speed of construction. After evaluation of different options, bored cast in-situ pile appeared to be the most economical foundation system for such loads. The speed of construction was also in line with the project schedule.

3.3 Foundation Design

Based upon the geotechnical investigation carried out across the site, entire area was divided in two parts: one where sand was deposited up to the depth of investigation and the other where rock was encountered after few meters of loose sandy deposit. For both the cases bored cast in-situ pile was found suitable.

Design of pile against the pull out capacity was done based on the recommendations of IS:2911 Part-1 Sec-2-2010 [4]. The design was done considering factor of safety of 2 as the capacity was required to be validated through pull out test at site.

For the design of pile against lateral load, IS:2911 Part-1, Section 2-2010 recommendations could not be used,as due to fewer loads only short pile was required. Therefore, short pile was designed considering the Broms'approach[5].

Based on different loading conditions and different geotechnical parameters, dimensions of pile were designed. The pile details are presented in Table-2.

Table 2. Details of bored cast in-situ piles used at site

Diameter of pile, mm	Length of pile, m	Approximate number of piles	Remarks
350	1.8	20000	Minimum 1m rock socket
350	2.5	15000	Sandy soil
350	2.65	65000	Sandy soil
350	2.8	40000	Minimum 1m rock socket
350	3.1	10000	Sandy soil

The paper discusses the pullout and lateral load-displacement behavior for 2.65-2.8 long piles bearing on the dune sands.

4 Pile Testing and Results

Bored piles of 350 mm diameter were installed with about 200 mm sizechannel section embedded in it.Pile lengths ranged from 2.65 to 2.8 m. Since pullout and lateral loading are the critical loading conditions, sufficient number of vertical pullout and lateral load tests were performed to confirm the safe capacities.

Nearly 1,50,000 piles were installed at the site.About 140 initial piles were tested for compression, pullout and lateral loading to 2.5 times the design load.

4.1 Pullout Tests

Pile pullout tests were performed in accordance with IS: 2911 Part 4-2013 [4]. A hydraulic jack placed over a girder was used to apply the pullout force. Reaction was obtained from supports resting on the ground. A dial gauge was placed with reference to a stable datum bar. Fig 8 presents a schematic of the test setup and a photograph of the pullout test in progress.

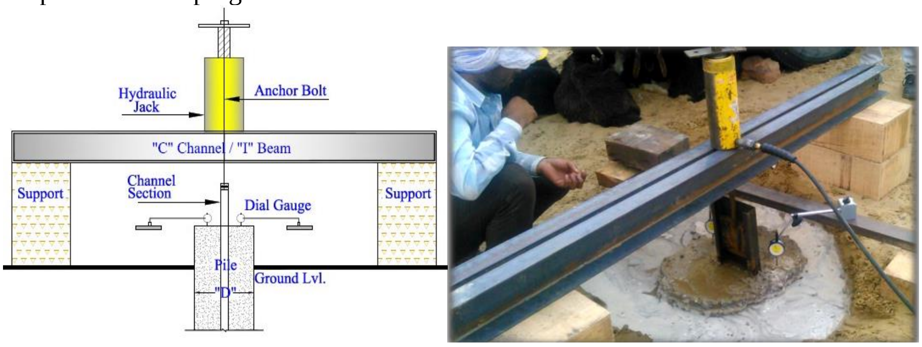

Fig. 8. Test arrangement for pile pullout test. Sketch on left is a schematic of the test setup. Photo on right shows test in progress.

Typical load-displacement curves are illustrated on Fig. 9.

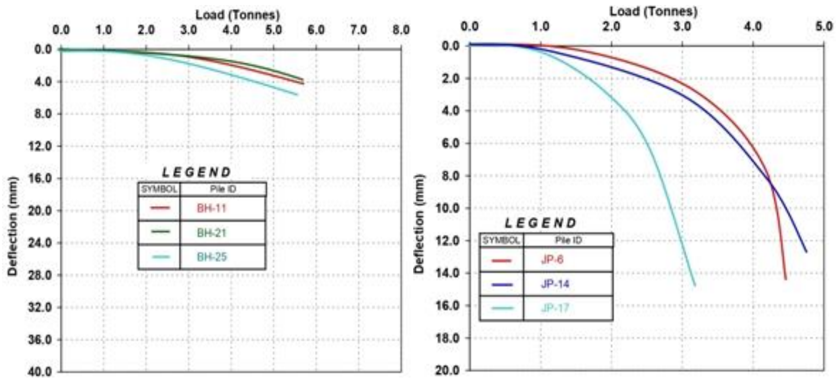

Fig. 9. Pullout Test -Typical Load-Displacement Curves.

Interpretation of Safe Pullout Capacity from Load-Displacement Graph. The safe pullout capacity of pile was considered as the lower value obtained from the following two criteria given in IS: 2911 Part 4-2013 [5]:

i. Two-thirds of the load at which pile deflection attains a value of 12 mm; and
ii. 50% of the load at which the load-displacement curve shows a clear break.

Extrapolation of Load-Displacement Curve to Assess Safe Pile Capacity. Many of the tests were not carried out to failure and were stopped on reaching twice the design load. Therefore an attempt was made to mathematically extrapolate the load-displacement curve assuming a hyperbolic correlation.

Kaniraj and Samantha [7] advocated the hyperbolic model to extrapolate results of vertical compression load tests on bored piles. The authors propose that a similar hyperbolic correlation may be used to extrapolate results of vertical pullout tests.

The basic premise is that the load-displacement curve follows a hyperbolic function expressed as follows:

$$\frac{S'}{Q'} = a + bS' \tag{1}$$

where

$S' = s/D$, ratio of measured displacement, s to pile diameter, D

$Q' = Q/Q_r$, ratio of applied load Q (corresponding to deflection s) to a reference load Q_r

$a$and b are constants

Hence, plot of S'/Q' versus S' shall be a straight line. To check the reliability of the correlation proposed in Equation 1, eight tests which had been carried out to failure(displacement of more than 12-14 mm) were analyzed. A very good match was found between the actual load-displacement curve and the predicted hyperbolic curve with error of less than 3 to 8%.

The concept was then used to extrapolate results of tests which had not been carried out till failure. For a good correlation, piles that had experienced deflection of at least 4 mm were used since for lesser deflections, the displacement may be primarily elastic and soil-movement may be small. Typical plot of *S'/Q'* versus *S'* for one test is illustrated on Fig. 10.

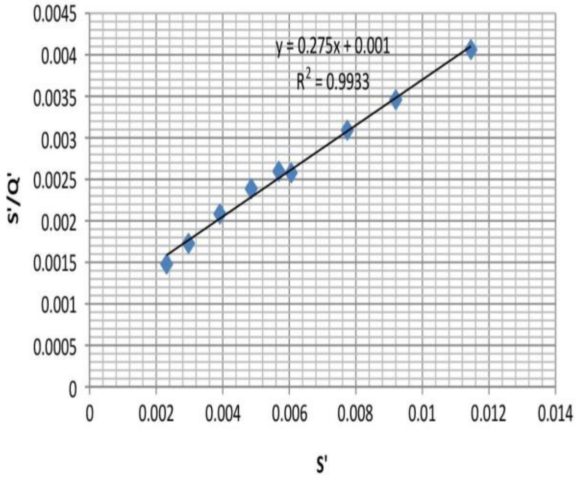

Fig. 10. Extrapolation of load-displacement plot using hyperbolic model- of *S'/Q'* versus *S'* for one test and the trendline. Please note that the error is small with R^2 value close to 1.

Typical extrapolated load-settlement curves for three tests are presented on Fig. 11.

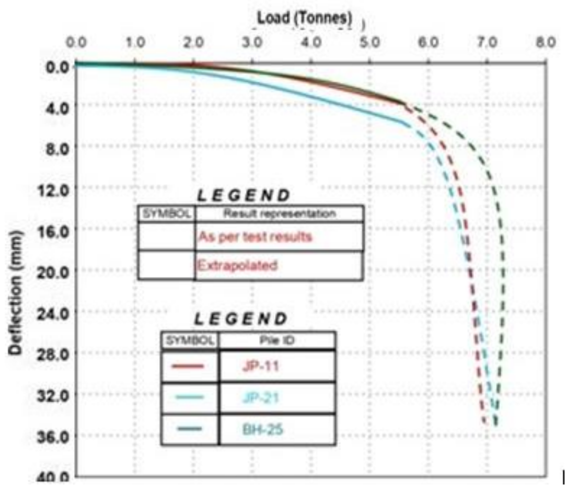

Fig. 11. Typical load-displacement curves extrapolated using hyperbolic model. The dotted lines show the extrapolated curve beyond the test data.

Table 3 presents the summary of the analysis.

Table 3. Extrapolation of load-displacement plots using hyperbolic model.

Pile No.	Maximum Load Applied, Tonnes	Measured Settlement, *s* mm	Extrapolated Ultimate Pullout Capacity, Tonnes	Interpreted Safe Pullout Capacity, Tonnes	Error in computed *s* versus measured *s*, %
JP-11	5.64	4.01	7.02	2.82	0 – 5, max 9%
JP-21	5.64	5.55	7.26	3.76	0 – 6, max10%
V5-P3	8.10	4.61	8.82	4.20	0 – 4, max 9%
V5-P11	8.10	3.95	8.84	4.40	0 –3, max 7%
V5-P18	8.10	4.50	8.73	4.40	0 – 7, max 9%
V6-P7	8.10	5.75	9.54	4.50	0 – 7 max10%
V6-P15	8.70	6.32	13.90	4.80	0 – 3 max 5%
V6-P17	8.10	5.93	19.80	5.80	0 – 3 max 6%
V6-P18	8.10	6.11	10.63	4.80	0 – 5, max 8%

Back-calculation of Soil Properties. The ultimate pullout capacity of piles installed in granular soils is computed in accordance with IS: 2911 Part 1 Section 2-2010 [4] using Equation 2 (skin friction between soil and concrete + weight of pile) as given below:

$$Q = \sigma_v \, k \tan\delta \, A_s \, L + W \qquad (2)$$

where
Q = ultimate pullout capacity of pile
σ_v = overburden pressure
k = coefficient of earth pressure
δ = angle of friction between soil and concrete (usually taken as equal to angle of internal friction of sand, ϕ, determined by laboratory tests)
A_s = surface area of pile per m length
L = length of pile
W = weight of pile

Substituting the value of ultimate capacity determined by the pullout test and ϕ value determined in the laboratory in Equation 2 above, the value of earth pressure coefficient, k maybecomputed.

It was observed that the value of k appears to increase with increase in the SPT N value. To assess the trends, Fig. 12 presents the variation of k versus field N value which shows the general trend of k with increase of N and the bandwidth of ±10% in which scatter of the data is observed.

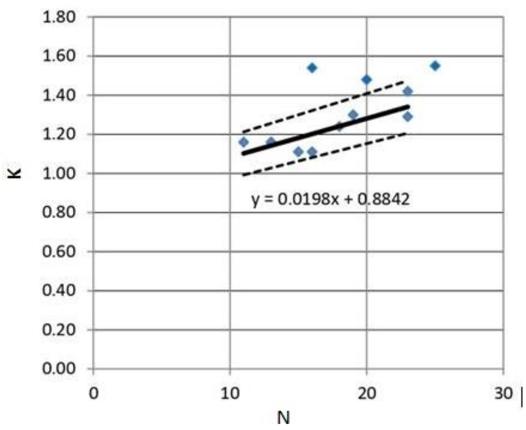

Fig. 12. Trend of field N-value versus k for dune sands. The continuous line presents the trend-line and the dotted lines present the bandwidth which is ±10%

Reviewing the trends, the authors propose the following correlation (See Table 4) between N and k, conservatively considering the lower end of the bandwidth: The lower end of the bandwidth of -10% has been proposed so as to ensure that the piles are likely to pass under the test load.

Table 4. Correlation between SPT N value and earthpressure coefficient k for pile pullout capacity computation for dune sands

Field SPTN-value	k for pullout loading
11	1.0
15	1.06
20	1.15
25	1.24

Linear interpolation may be done for intermediate N values. The authors suggest k value of 0.7 for $N \leq 5$. Further, the value of k may be restricted to 1.3 for $N \geq 30$.

4.2 Lateral Load Tests

Lateral load tests were performed in accordance with IS: 2911 Part 4-2013 [4]. A hydraulic jack placed between two piled to apply the horizontal force. One of the piles was used to take reaction force. A dial gauge was placed with reference to a stable datum bar. Fig 13 presents a schematic of the test setup and a photograph of the lateral load test in progress.

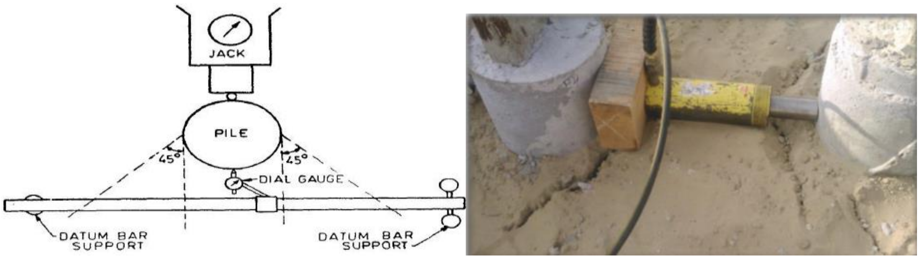

Fig. 13. Test arrangement for lateral load test on pile. Sketch on left is a schematic of the test setup. Photo on right shows test in progress.

Typical load-displacement curves are illustrated on Fig. 14.

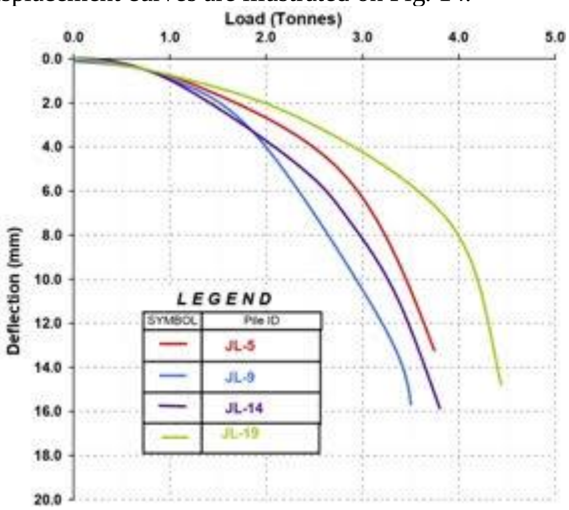

Fig. 14. Typical Load-Displacement curves for lateral load tests

Interpretation of Safe Lateral Capacity from Load-Displacement Graph. The safe pullout capacity of pile was considered as the lower value obtained from the following two criteria given in IS: 2911 Part 4-2013 [5]:

i. Load at which the deflectionattains a value of 5 mm, and
ii. Two-thirds of the load at which pile deflection attains a value of 12 mm.

Computation of Lateral Capacity. Annex-C of IS: 2911 Part 1 Section 2-2010 [4] gives the procedure for analysis of lateral capacity of long piles. The standard defines a stiffness factor, T for granular soils as follows:

$$T = \sqrt[5]{\frac{EI}{\eta_h}}$$

where

E = modulus of elasticity of concrete
I = moment of inertia of pile cross-section
η_h = modulus of subgrade reaction of soil

While piles longer than "4T" are considered as long pile, piles shorter than 2T are treated as short piles.

Since the piles of 2.65-2.8 m length classify as short piles, the procedure proposed by Broms [5] has been used. Broms gives graphical plots to compute the ultimate lateral capacity and deflection of free-head and fixed-head (restrained) short piles based on the value of η_h, ϕ and other properties of granular soils. The simplified solution is based on the assumption of shear failure in soil.

The simplified solution is based on the assumption of shear failure in soil. Broms's solution for the ultimate load resistance (P_u) and corresponding deflections for short piles in granular soil is illustrated in Fig. 15.

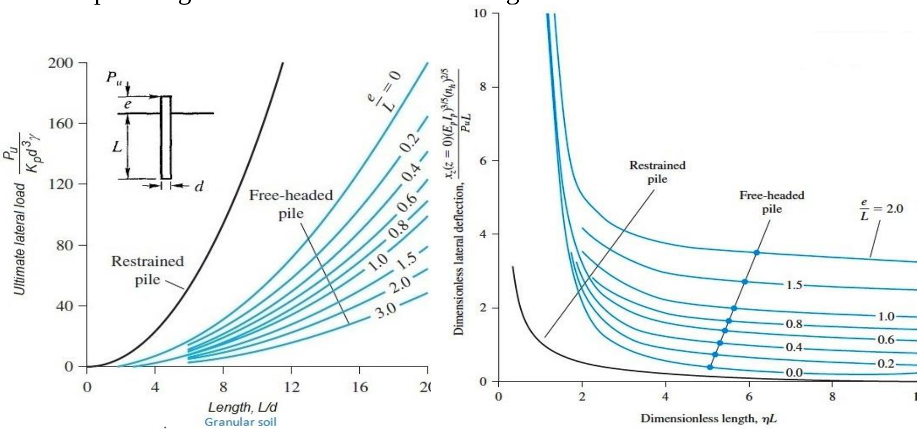

Fig. 15. Broms' solution for laterally loaded piles in cohesionless soils

A factor of safety of 3 is applied on the ultimate lateral capacity. As per the project specifications, the safe lateral load is computed for a permissible pile-head deflection of 5 mm for the free-head case. The modulus of horizontal subgrade reaction has been taken from Table 3, Annex-C of IS: 2911 Part 1 Section 2-2010 [4].

Back-calculation of modulus of horizontal subgrade reaction η_h. The lateral capacity of the free-head piles was calculated using the modulus of horizontal subgrade reaction η_h values as per IS: 2911 Part 1 Section 2-2010. It was observed that the safe horizontal capacity from the load test was substantially higher than the computed capacity. The η_h values were then changed in Broms' solution so as to match the safe capacities determined from the test.

Table 5 presents the results of the analysis for eight typical 2.65 m long piles that were tested to failure. Several additional tests in the project area tested to similar range of test loads experienced less than 4-5 mm deflectionsuggesting that the η_h values would probably be higher than the values given in Table

Table 5. Safe Lateral capacities and modulus of horizontal subgrade reaction η_h computed on basis of IS: 2911 Part 1 Sec 2and interpreted from lateral load tests

Pile No.	Field N-value	ϕ^o from lab test	Safe Lateral Capacity		η_h, MN/m^3	
			Calculated (Broms)	Test Result	IS: 2911 Part 1 Sec 2-2010	Back calcu-lated
JL5	13	30	0.63	1.83	3.1	11.0
JL9	11	30	0.56	1.59	2.7	9.0
JL11	12	30	0.60	2.01	2.9	11.9
JL14	15	31	0.71	1.73	3.5	9.7
JL17	15	31	0.71	2.14	3.5	13.5
JL24	15	31	0.71	2.09	3.5	12.3
JL26	17	31	0.79	1.61	3.9	9.1
JL23	12	30	0.60	1.74	2.9	9.7

It is evident that the η_h values back-calculated from the load tests are about 3-4 times more than the values given in the IS code. There is a need to analyze further data from more lateral load tests to conclusively develop a correlation to assess the trend of η_h with other soil characteristics.

5 Conclusions

Short piles are used for supporting the solar panels of photo-voltaic solar power plants. These panels are light-weight structures with very small downward load. But the pullout and lateral loading is significant due to the wind loads.

The paper presents a case study of a 300 MW solar power plant in dune sands of western Rajasthan. About 150,000 RCC bored-cast piles of 350 mm diameter and 1.8-3.1 m length were installed. Due to the large number of piles installed, even a 10-20 cm change in pile length can have a significant impact on the piling cost. Hence, it is necessary to optimize the pile design to economize the project cost.

The authors propose a hyperbolic correlation to extrapolate the load-displacement graph of piles tested for pullout loading in case where the test was not carried out to failure. Analyzing the ultimate pullout loads, a correlation has been developed between SPT N-value and earth pressure coefficient, k for computing the skin friction between pile and concrete. The authors also highlight the need to update the coefficient of horizontal subgrade reaction $\eta_h$for sands given in Annex-C of IS: 2911 Part 1 Sec 2-2010.

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