BUILDING DIGEST

CENTRAL BUILDING RESEARCH INSTITUTE, INDIA

BORED COMPACTION PILES

Introduction

These are in-situ concrete piles in which the compaction of the concrete as well as of the soil surrounding is effected simultaneously by driving in the reinforcement cage through the freshly laid concrete. They are normally single under-reamed (Fig. 1) but they can be of uniform diameter or under-reamed with two bulbs also. The compaction increases the load carrying capacity of the piles by 75 to 100 per cent over normal piles. These are particularly suitable in loose to medium sandy and silty strata with or without water table close to the ground surface. Normal reinforcement cage can be placed even in smaller diameter piles avoiding its contact with bentonite slurry in under water construction.

In under-reamed piles, the bearing of bulbs is increased considerably as the reinforcement drags the concrete down with it and more and more concrete is forced to the sides and into the bulb, thereby compacting the whole mass. These piles can also withstand heavy uplifts and lateral loads due to under-reamed bulb.

Presently, more than 10,000 bored compaction under-reamed piles have been used for widely varying structures, such as multi-storeyed buildings including factory and laboratory buildings, antenna towers, overhead and under-ground tanks, transit sheds and gantry foundations. These have also been codified in Indian Standards.*

Design of Piles, Beams and Caps

For the design of pile foundations, information regarding loading data, bearing capacity of each pile, size, the depth of piles to suit site conditions and likely orientation of piles is required.

Diameter of these piles can vary from 25 to 50 cms. The under-reamed diameter is kept 2 to 2½ times the shaft diameter. Number of bulbs in under-reamed compaction piles is limited to two. The length of hese piles normally used varies from 3 to 10 metres from cut-off level. There is no appreciable diff-

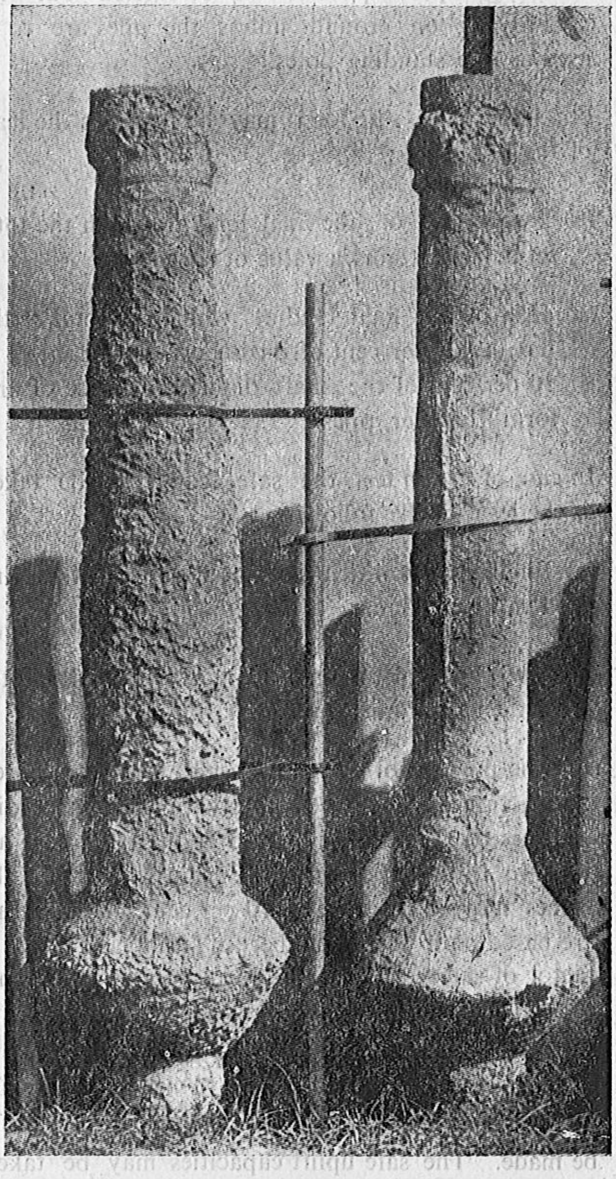

Fig. 1. Bored Compaction Pile (Left) and Normal Under-reamed Pile (Right)

* IS:2911 (Part—III)—1973, Indian Standard Code of Practice for Design and Construction of Pile Foundations Part—III, 'Under-reamed Pile Foundations'.

erence in load carrying capacity of piles with under-reams of 2 or $2\frac{1}{2}$ times the shaft diameter because the compaction in former is more effective. The former is preferred as it reduces the cap sizes considerably. For light structures, where the water table is deep, 20 cm. diameter piles may also be used. For very light structures uniform diameter compaction piles can also be used though the advantage of compaction is more in case of under-reamed piles due to bulbs.

Safe Load on a Pile/Pile Groups

These piles transfer the load to the soil by the resistance developed at its point and friction along-with surface. The load carrying capacity can be determined more reliably from in-situ load tests. Load test on groups of piles should be carried out with caps resting on ground unless the piles are to be used as free standing poles.

For single piles, safe load may be taken as the least of the following :

(a) Two thirds of the final load at which the total settlement attains a value of 12 mm.

(b) Half of the final load at which the total settlement is $7\frac{1}{2}$ per cent of the under-ream diameter or 10 per cent of the shaft diameter in case of uniform diameter piles.

In case of group test, the safe load may be taken as the least of the following :

(a) Final load at which the total settlement attains a value of 25 mm.

(b) Two thirds of the final load at which the total settlement attains a value of 40 mm.

For the purpose of design the safe load for bored compaction under-reamed piles with under-ream dia. $2\frac{1}{2}$ times the shaft dia. and 3·5 metres long, are given in Table-1. For an under-ream ratio of 2, the values may be reduced by 10 per cent. The values are based on a large number of tests and have a factor of safety 1·5 on load corresponding to 12 mm settlement. These values apply in sandy and silty soils with N values between 8 to 15. For soils with $N > 15$ these may be increased by 25 per cent and for soils with $N < 8$ a 25 per cent reduction should be made. The safe uplift capacities may be taken as half of the loads given in Table-1. Safe loads for a pile longer or shorter than 3.5 metres may also be worked out from the table. The lateral loads given in Table-1 should not be increased unless stability of the top soil (strata to depth of about 3 times the stem diameter) is ascertained.

The safe loads for bored compaction under-reamed piles for initial design purposes in soils ($N \leqslant 10$) may also be worked out from Table-1, IS : 2911 (Pt. III)—1973 by multiplying the values by 1·75 against 1.5 recommended in the said code as subsequent studies carried out at different sites clearly indicated that increase in capacity over normal under-reamed piles is about two times. The values worked out from tables referred above are still conservative in case of longer piles because of increased compaction. In such cases, and for a sizeable work, load tests may be carried out and actual values should be adopted which would normally be higher than those worked out from the tables.

Bearing Capacity from Soil Properties

The ultimate load capacity of bored compaction piles in non-cohesive soil can also be worked out from the following expression :

$$Q_u = A_a^2 \left[\tfrac{1}{2}\gamma D_u N_\gamma + \gamma d_1 N_q\right] + \pi/4\, D^2\left[\tfrac{1}{2}\gamma D N_\gamma + \gamma d_f N_q\right] + \tfrac{1}{2}\pi D \gamma K_p \tan \delta d_f^2$$

where

Q_u (kg) = Ultimate load capacity of pile

A_a (cm²) = Area of annular ring in case of under-reamed piles $= \pi/4\,(D_u^2 - D^2)$.

D_u (cm) = Diameter of under-ream bulb

D (cm) = Diameter of stem

d_1 (cm) = Depth of the centre of under-ream bulb

d_f (cm) = Total depth of pile

γ (kg/cm)³ = Average unit weight of soil (submerged weight below water table)

N_γ & N_q = Bearing capacity factor depending on the angle of internal friction.

K_p = Coefficient of Passive earth pressure $= \tan^2(45 + \phi/2)$

δ (degrees) = Angle of wall friction (may be taken equal to ϕ).

For uniform diameter pile the first term is neglected.

The compaction increases both the unit weight and shearing strength of soil. The increased ϕ is $(\phi_1 + 40)/2$ where ϕ_1 is the angle of internal friction of virgin soil. The above expression is based on the assumption that there is no appreciable increase beyond $\phi_1 = 40°$ on account of compaction. The values of N_γ, N_q, K_p and $\tan\delta$ are then taken corresponding to ϕ calculated above. The tabu-

Table-1

Safe loads on 3.5 m long Bored Compaction (Single Under-reamed) Piles.

Initial Diameter of pile shaft (cm) (1)	Reinforcement Longitudinal No.	Reinforcement Longitudinal Dia. (mm) (2)	Spacing of 6 mm dia. rings (cm) (3)	Safe Load for one pile (Tonnes) (4)	Increase in Safe Load per 30 cm length (Tonnes) (5)	Decrease in Safe Load per 30 cm. length (Tonnes) (6)	Lateral Thrust (Tonnes) (7)
25	4	12	22	16	1.5	1.2	1.9
30	4	12	25	22	1.85	1.5	2.5
37.5	4	16	30	32	2.35	1.85	3.75
40	4	16	30	37	2.5	1.95	4.25
45	4	16	30	46	2.8	2.25	5.0
50	6	16	30	54	3.15	2.5	5.6

Notes:

1. The values are corresponding to N (SPT) values of 8 to 15. For determining the average 'N' values a weighted average shall be taken and correction for fineness below water table shall be applied where applicable.
2. The reinforcement shown is mild steel and should have a minimum clear cover of 4 cm with respect to initial shaft diameter.
3. For piles subjected to pull and/or lateral thrust, the requisite amount of steel should be provided.
4. Only 85 per cent of the above safe loads is to be taken when the bores are full with fluid during construction.
5. For working out the safe load for a group of piles, the safe load of individual pile may be multiplied by the number of piles in the group. This would be applicable for piles taking lateral thrust also.
6. Values given for lateral thrust in the table may not be reduced for reduction in pile lengths.
7. When a pile designed for a certain safe load is found just short of the load required to be carried by it, an overload of 10 per cent should be allowed on it.
8. The safe uplift resistance can be taken as half of the bearing values given in the table.
9. The capacity of a pile of length other than 3.5 m can be worked out taking into consideration increase or decrease given in columns 5 and 6.
10. The values given should be increased by 50 per cent for broken wire condition in the design of transmission line tower footing.
11. The capacity of double under-reamed pile can be worked out by increasing values of column 4 by 50 per cent.
12. For piles with under-reamed diameter equal to 2 times the shaft diameter, the table values may be reduced by 10 per cent.

Table-2

Bearing Capacity Factor N_γ and N_q Corresponding to Angle of Internal Friction ϕ.

Angle of Internal Friction ϕ (degrees)	N_γ	N_q
20	3	3.3
25	8	5.3
30	17	9.5
35	35	18.7
40	90	42.5

Table-3

Angle of Internal Friction ϕ Corresponding to Standard Penetration Resistance N

Standard Penetration Resistance N (Blows/30 cm)	Angle of Internal Friction, ϕ (Degrees)
5	29
10	30
15	32
20	33
25	35
30	36

lated value of N_γ and N_q are given in Table–2. For N_q an average of ϕ_1 is taken for the depth above the portion considered to contribute for bearing. N_γ is taken corresponding to ϕ_1 averaged over a length equal to shaft diameter or under-reamed diameter above and twice that below the bearing level for uniform and under-reamed pile respectively.

It is difficult to take undisturbed samples in case of loose soils particularly under-water, and value of ϕ_1 can be taken corresponding to N values from Table–3.

In case of c–ϕ soils, the pile capacity can be worked out considering both c and ϕ seperately the values thus obtained added. Considering angle of internal friction, the capacity may be calculated using expression and procedure described above. In case of c, to account for the effect of compaction, its values may be increased by 1.5 times and the capacity worked out from the following expression :

$$Q = A_p N_c C_p + A_a N_c C'_a + \alpha C_a A_s$$

Q (kg) = Capacity of pile

A_p (cm²) = Cross-sectional area of the pile stem at toe.

N_c = Bearing capacity factor usually taken as 9.

C_p (kg/cm²) = Cohesion of the soil around the toe after accounting for compaction.

C'_a (kg/cm²) = Average cohesion of soil around the under-reamed bulb after accounting for compaction.

α = Reduction factor usually taken as 0.5

C_a (kg/cm²) = Average cohesion of the soil along the pile stem after accounting for compaction.

A_s (cm²) = Surface area of stem.

In fine silty soils, the capacity worked out thus may be on lower side. The table values which are based on load test provide a better guide in this case.

For working out safe loads, a factor of safety 2.25 is to be applied on uniform diameter and under-reamed piles with under-reamed diameter equal to two times the shaft diameter. In piles with under-reamed diameter equal to 2·5 times the shaft diameter, the factor of safety should be increased to 2·5. An illustrative example for working out safe load on pile from tables and soil properties is given in appendix 'A'.

An increase in safe loads is to be taken for moments, wind and earthquakes as per relevant Indian Standards. However, the total increase should not be more than 50 per cent.

Spacing of Piles, Grouping and Layout

Generally the spacing between two piles is kept 2 times the shaft diameter in case of uniform diameter piles and 1·5 times the under-reamed diameter in case of under-reamed piles. The safe load for a group of piles is taken equal to the safe load for a single pile multiplied by number of piles in the group. The capacity of the group could however, be more than the individual capacity multiplied by the number of piles in the group on account of the compaction effect. The settlement corresponding to safe load in case of the group may be even less than the single pile. The pile group may also be assigned additional bearing on account of the cap resting on the ground. It may be upto 25 per cent of the allowable bearing pressure of the soil determined for 25 mm total settlement.

In case of load bearing walls, the piles are provided under wall junctions to avoid point loads on beams. Positions of intermediate piles are then decided trying to keep the door openings fall in between two piles as far as possible.

The number of different pile sizes under one structure should generally be restricted to three. The top of pile cap and grade beams should be kept flush. If possible, this level should be kept flush with proposed ground level.

Grade Beams

The grade beams are to be designed for panel action. The minimum height to span ratio should be 0.6. The beams are designed for a maximum bending moment of $wl^2/50$ where w is the uniformly distributed load per metre run (taken up to a maximum of two storeys in multi storey constructions) and l is the effective span in metre. The minimum depth of beam should be 15 cm and it should not normally exceed 20 cm for normal spans of about 3 metres. Where the beam is resting on natural ground advantage of bearing provided by beam may also be taken in designs as in case of pile caps. In such cases, a levelling course of mass concrete of about 8 cm thickness is provided.

Pile Caps

The pile caps should be designed in accordance with IS:2911 (Pt-III)-1973. Load from column is dispersed at 45° to the mid depth of pile cap from the face of column or pedestal if any. The reaction offered by piles is also taken to be distributed at

45° from the face of pile upto mid depth of pile cap. The shear force is worked out at the critical section which is located at a distance equal to half the pile cap depth from the face of column or pedestal. The maximum bending moment is then worked out. It will be either at the critical section described above or at the section where shear force is zero.

Construction Technique*

Boring, under-reaming and concreting is carried out in the normal manner**. A boring guide is fixed in position and bore hole of the required size is made. For dry bores, normal spiral auger is used. In ground with high water table where caving in is likely in bores, boring and under-reaming may be carried out by using suitable drilling fluid (generally solution of upto 5 per cent bentonite in water). For boring, normal spiral auger or bucket auger with gravity valves and modified under-reaming tool which avoid back suction is used. In very unstable soils, it is preferable to maintain continuous circulation of drilling fluid. For concreting, a high slump concrete (about 20 cm) of required grade (not less than 1:2:4 nominal mix) is needed. When the bores are full of drilling fluid or water, displacement method involving the use of a tremie pipe is employed for concreting. Immediately, after placing concrete, the reinforcement cage with a heavy driving pipe is held centrally on the bore. The reinforcement cage is prepared by welding so as to withstand the driving stresses. For easy driving it is preferable to use mild steel reinforcement. The reinforcement assembly is driven through the freshly laid concrete to the full depth by a suitable drop weight. For efficient and easy driving heavy drop weights (about 500 kg) with mechanical operated winches may be used with advantage depending on site conditions, pile sizes etc. The reinforcement assembly during driving may be guided either engaging it from bottom to a central mild steel rod kept in the bore hole or it can be guided suitably otherwise. As the assembly is driven, it pushes the concrete on all the sides, thereby compressing it along with the soil around. Extra concrete is simultaneously poured in to keep it level with the ground. After driving is completed, the pipe is also filled with fresh concrete and withdrawn.

In place of hollow steel pipe, a suitable diameter precast concrete unit or timber pile may be used which is left in position after driving. It is particularly advantageous for speeding up the work on major projects. Precast units with projections of suitable size may also be used in place of reinforcement assembly. In this case the required steel is placed in the precast units. It is particularly suitable for speeding up the work in areas with subsoils having large amount of harmful salts. In case of 20 cm diameter piles only precast unit or timber pile is used in place of hollow driving pipe.

In case of very heavy structures where longer piles are required and cut off level is sufficiently deep, it is desirable to excavate ground upto a depth of about 0.3 metre above the cut-off level before construction of piles.

The amount of concrete required for these piles normally varies from 1.2 to 1.4 times of the normal uniform diameter or under-reamed piles. However, the volume of concrete actually placed may be observed in the case of few piles initially cast and the average figure obtained may be used as a guide for working out the quantities of the concrete and cement for subsequent piles.

Overall Cost

The cost of bored compaction piles ranges from Rs. 12.00 to Rs. 18.00 per tonne of safe load carried by the pile. No establishment charges and profits have been included. These may vary from place to place, depending upon the nature of work and agency.

Actual Use and Cost Economics

Bored compaction under-reamed pile foundations have successfully been used for widely varying structures subjected to vertical loads (both compression and uplift), lateral loads, moments due to crane loads, winds and seismic forces etc. Some of the major projects where these piles have been used are listed below :

1. Residential Buildings
   - (i) CPWD Staff Quarters, New Delhi.
   - (ii) LIC Staff Quarters, Shahdra.
   - (iii) Residential Quarters, Shri Harikota.
2. Factory and Office Buildings
   - (i) M/s. Brewries Pvt. Ltd., Factory Building, Paradeep Port, Orissa.
   - (ii) G.C.F. Factory, Jabalpur.

* This is a patented process of this Institute and has been licensed.

** 1. CBRI Building Digest No. 56–Under-reamed Pile Foundations.

2. IS:2911 (Pt—III)–1973, Indian Standard Code of Practice for Design and Construction of Pile Foundations Part–III 'Under-reamed Pile Foundations.'

(iii) Fire Research Laboratory, Roorkee.

3. Other Structures

(i) Transit Shed, Paradeep Port, Orissa.

(ii) Substation Gantry Foundation at Kashipur and Khurja.

4. Overhead Tank

(i) Seemapuri (Delhi), Exhibition Ground (Delhi), Faridkot (Pb.) etc.

5. Larger Under-ground Tanks at Delhi.

6. 100 Metres High Antenna Towers at Roorkee, Haldia, Paradeep Port etc.

7. Road Bridge, Khurja.

The use of these piles is recommended for high rise buildings, port structures, very high towers etc.

Apart from being safe and providing speedy construction, these foundations have proved economical 25 to 40 per cent over deep piles, 20 to 25 per cent over open footings, 25 to 30 per cent over rafts and 10 to 15 per cent over normal under-reamed piles (in loose soils).

Appendix 'A'

Illustrative Example for Safe Load on Pile

Pile Details—Type—Bored compaction single under-reamed

Initial diameter of shaft = 40 cm
Under-reamed diameter = 80 cm
Length of Pile = 500 cm

Soil type—Silty sand (SM)

N (Average for 6 metres length) = 10
Water table close to Ground level

Safe Load on Pile

From Table–1

Safe Load of 40 cm dia. 3·5 m long single under-reamed (under-reamed dia = $2\frac{1}{2}$ times the shaft dia. = 100 cm). = 37.00t (Col. 4)

Increase due to increased length of 1·5 m (5—3·5 m) @ 2·5t per 30 cm length = 12·50t (Col. 5)

Total = 49·50t

Safe load considering bore full of bentonite solution during construction i.e. 49·50 × 0·85 = 42.00t (Note 4)

Reduction @ 10 per cent for under-reamed diameter equal to twice the shaft diameter (i.e. 80 cm instead of 100 cm) = 4·2t

Safe load = 37·8t

From IS:2911 (Pt-III)—1973

Safe load of 40 cm dia. 3·5 m long normal single under-reamed pile = 28·00t (Table–1.Col. 6)

Increase due to increased length of 1·5 m @ 1·9t per 30 cm length = 9.50t (Col. 8. Note 12)

Total = 37·5t

Reduction @ 25 per cent for loose soil ($N \leqslant 10$) = (–) 9·4t (Clause 3·1)

= 28·1t

Reduction @ 15 per cent for bore full with bentonite solution during construction = (–) 4·2t (Table–1. Note 8)

= 23·9t

Safe load of bored compaction pile using multiplying factor 1·75 = 41.8t

Reduction @ 10 per cent for under-reamed diameter equal to two times the shaft dia. (i.e. 80 cm instead of 100 cm) = (–) 4·18t

Safe load = 37·62t

From Soil Properties

For N = 10, ϕ_1 = 30 degrees (Table–3)

$\phi = (30+40)/2$ = 35 degrees (both for friction and point bearing)

$A_a = \pi/4\ (80^2-40^2) = 3768$ sq cm, $D_u = 80$ cm

$D = 40$ cm, $d_1 = 425$ cm $d_f = 500$ cm

$\gamma = 0.95$ kg/cm² (submerged weight)

Table—2, for $\Phi = 35$ degrees

$N_\gamma = 35$

$N_q = 18{\cdot}7$

$K_p = \tan^2(45+35/2) = 3{\cdot}7$

$\tan\delta = \tan\Phi = \tan 35 = 0.7$

Using the above values

$Q_u = 33500 + 12000 + 38600$ kg
$= 84100$ kg $= 84{\cdot}1$t

Safe load $= 84{\cdot}1/2{\cdot}25 = 37{\cdot}4$t

Note—Due to limitations in obtaining reproduceable soil data, the values from soil properties may vary considerably.

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