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Uplift Capacity Of Anchor Piles In Sand Under Axial-Pulling Loads

by

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Introduction

Structures like transmission towers, mooring systems for ocean surface or submerged platforms, tall chimneys, jetty structures and underground tanks transmit not only heavy compressive loads but they are also subjected to considerable amount of uplift forces. These structures need footings which can anchor them with the competent strata. Under-reamed piles and anchor piles are being extensively used in such cases depending on the insitu conditions. Belled cylindrical piles are generally used in expansive soils to transmit the loads to a stable zone. When the loads are compressive the bulb serves to increase the bearing area while under tension it serves as an anchor for the pile. These piles are also used in other types of soils to resist uplift forces.

Uplift resistance of a pile with base enlargement is a complicated phenomenon involving variables like length of the pile, shaft diameter of the base enlargement, pile friction angle, density of the foundation medium and the angle of shearing resistance of the soil. The ultimate uplift resistance of such piles is usually predicted by considering the shearing resistance mobilised along the rupture surface in addition to the weight of the soil bounded by rupture surface. For the design of these piles certain methods are available Sharma et al. (1978), Meyerhof and Adams (1968), Khadilkar et al. (1971) and Tomlinson (1977). However, many of them either underestimate or overestimate the uplift capacity values. The authors, therefore, have proposed an analytical approach to estimate uplift capacity. However, the validity of any method can be established only by comparing

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the estimated values from the analytical approach with the field and model test results. Herein model testing was undertaken to study the behaviour of anchor piles under axial pulling and to examine the merits and demerits of the proposed method vis-a-vis other available theories.

Scope of Investigation

Tests have been conducted on two types of piles viz. straight shafted piles and piles with base enlargement. By varying the parameters like base enlargement to shaft diameter ratio and surface roughness the following types were obtained. The base enlargement to shaft diameter ratio of 1 corresponds to a straight shafted pile.

Shaft Dia cm	Ratio of Base Enlargement to Shaft Diameter	Surface characteristic
1.27	1	smooth
1.27	2	smooth
1.27	3	smooth
1.27	1	rough
1.27	2	rough
1.27	3	rough
1.905	1	smooth
1.905	2	smooth
1.905	3	smooth
1.905	1	rough
1.905	2	rough
1.905	3	rough

Each such pile was tested under four embedment depths. The theoretical results have been compared with model test results (authors) as well as the field test results (Chandra Prakash, 1980). Some of the available methods considered for this purpose are briefly described elsewhere along with the proposed method.

Experimental Set-Up And Test Procedure

The schematic diagram of test set-up, loading arrangement and details of model pile are shown in Fig.1. A steel tank of size 91.4 cm x 76.2 cm x 91.4 cm deep filled with dry Ennore sand as foundation medium has been used to perform the tests. Pouring of sand has been done by means of slot

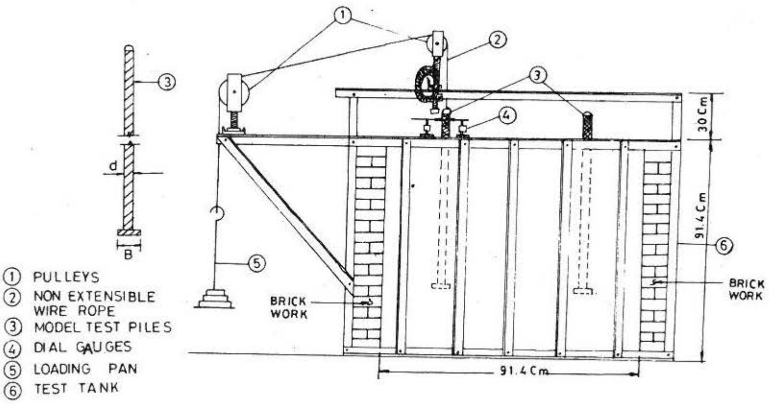


FIGURE 1. Model Pile and Test Set-up

hoppers maintaining a constant height of sand fall of 45 cm to obtain uniform and constant density for all the fillings. Pulling loads were applied vertically on the pile-top through a double pulley and flexible wire arrangement. Dial gauges placed equidistant from the pile axis in three direction making an angle of 120° with one another in the horizontal plane were used to measure axial displacements.

Model piles were made up of mild steel rods. The shaft diameters considered were 12.7 mm and 19.05 mm. Enlargement at the bottom of the shaft was provided by means of circular plate of 8 mm thickness and diameters 25.4 mm, 38.1 mm and 57.15 mm so that B/d ratios obtained were 2 and 3, where B = diameter of the base enlargement and d = diameter of the shaft. The plate is fastened to the shaft bottom by means of thread and bolt arrangement. These piles are of two surface characteristics designated as rough and smooth for convenience. The friction angle between rough pile and the foundation medium as obtained from direct shear test was 35° and for smooth one it was 30°.

The specific gravity and uniformity coefficient of the foundation material were 2.67 and 1.1 respectively. The sand grains were subangular and limiting void ratios were e_{min} = 0.59, e_{max} = 0.92 corresponding to maximum and minimum dry densities of 1.667 gm/cc and 1.395 gm/cc respectively. The placement density during the test was 1.6 gm/cc at relative density of 78.5%. The corresponding angle of shearing resistance was 39°.

Each pile was tested under various embedment depths of 25.4 cm, 38.1 cm, 50.8 cm and 63.5 cm. Pulling loads in increments were applied on piles upto failure and corresponding pile displacements were recorded.

Experimental Results And Discussion

For all the piles the observed load displacement response is practically similar. A typical set of load displacement curves for B/d = 2, d = 1.27 cm under various values of L is shown in Fig. 2, where L = embedment depth. The ultimate uplift resistance is assumed to be mobilised when the load settlement curve becomes asymptotic to the displacement axis. For smooth piles relatively higher movements have occurred before ultimate capacity is reached.

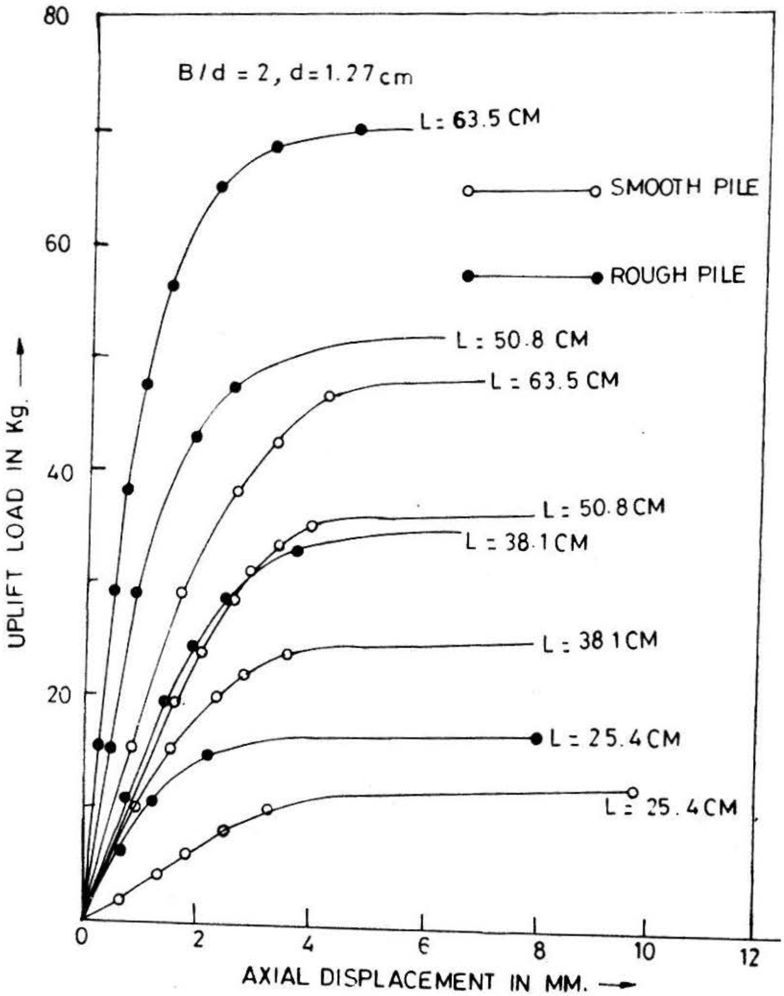
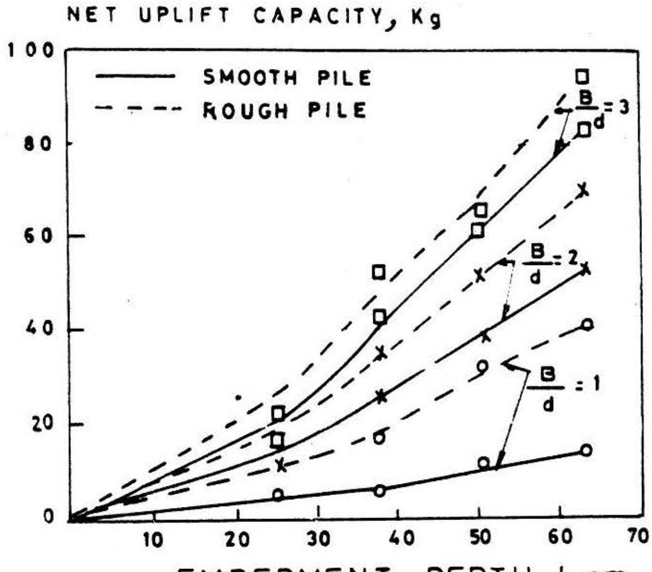
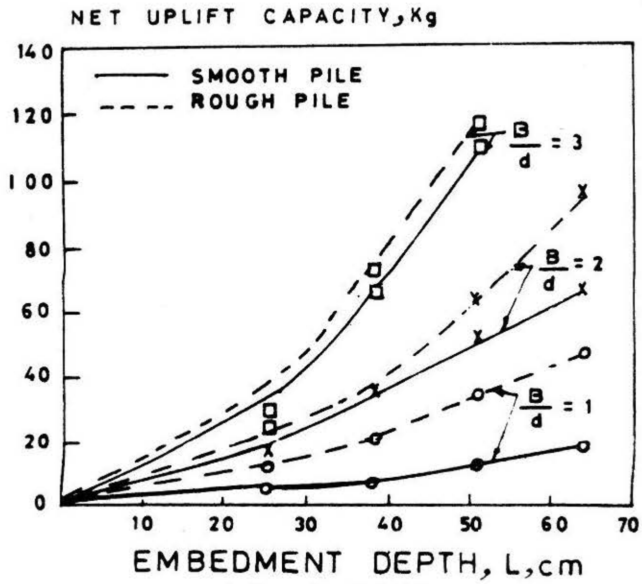


FIGURE 2. Uplift Load Vs Axial Displacement

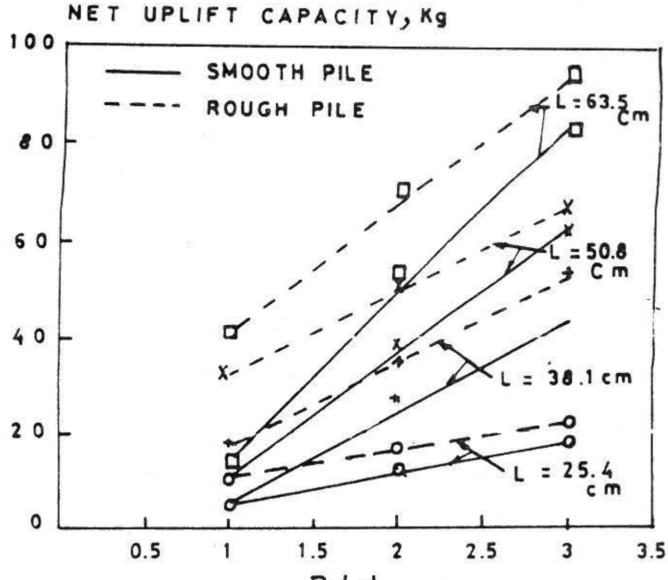


a) d = 1.27 cm

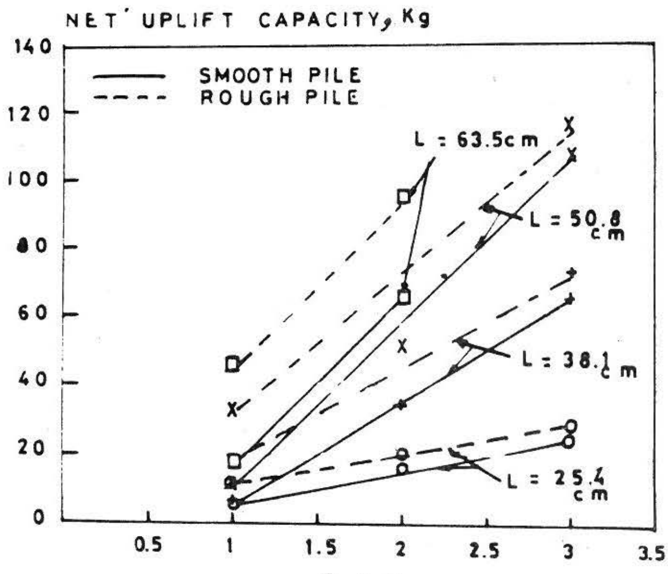


b) d = 1.905 cm

FIGURE 3. Net Uplift Capacity Vs Axial Embedment Depth



a) d = 1.27 Cm



b) d = 1.905 cm

FIGURE 4. Net Uplift Capacity Vs B/d Ratio

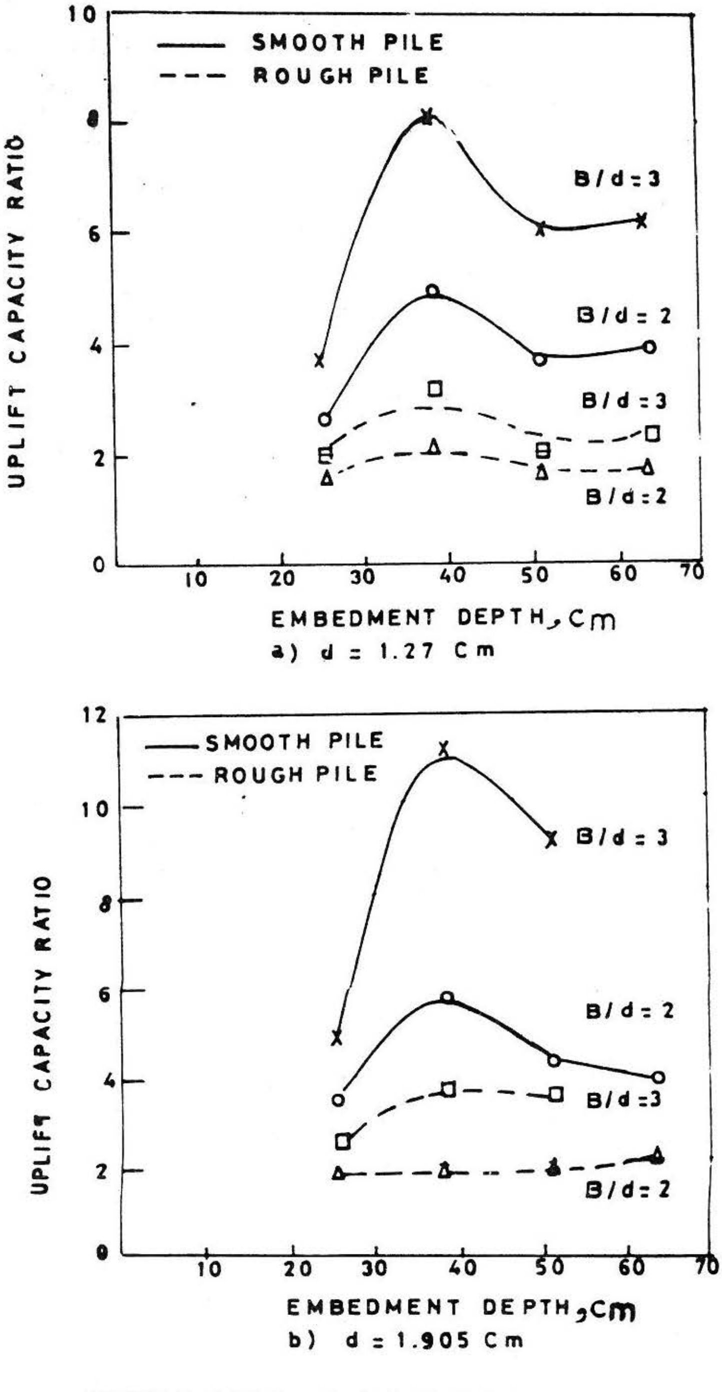
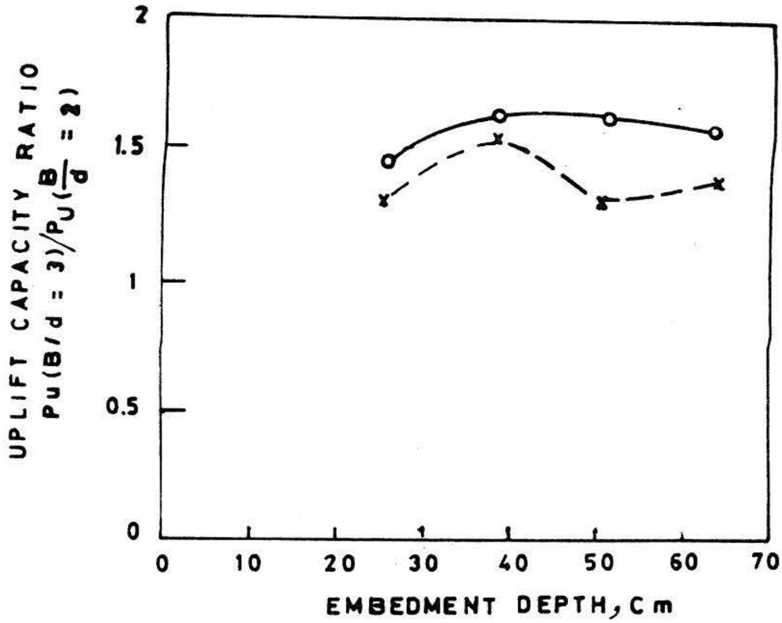
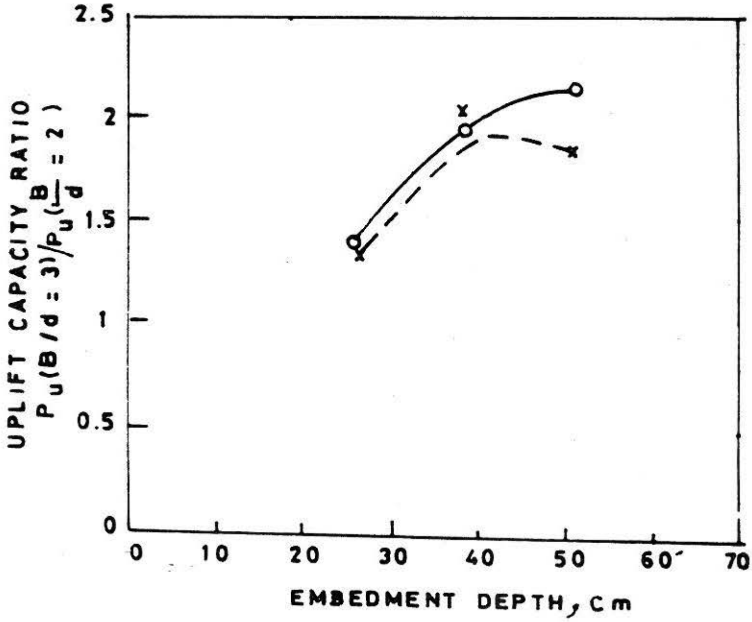


FIGURE 5. Uplift Capacity Ratio Vs Embedment Depth



a) d = 1.27 cm



b) d = 1.905 Cm

FIGURE 6. Uplift Capacity Ratio Vs Embedment Depth

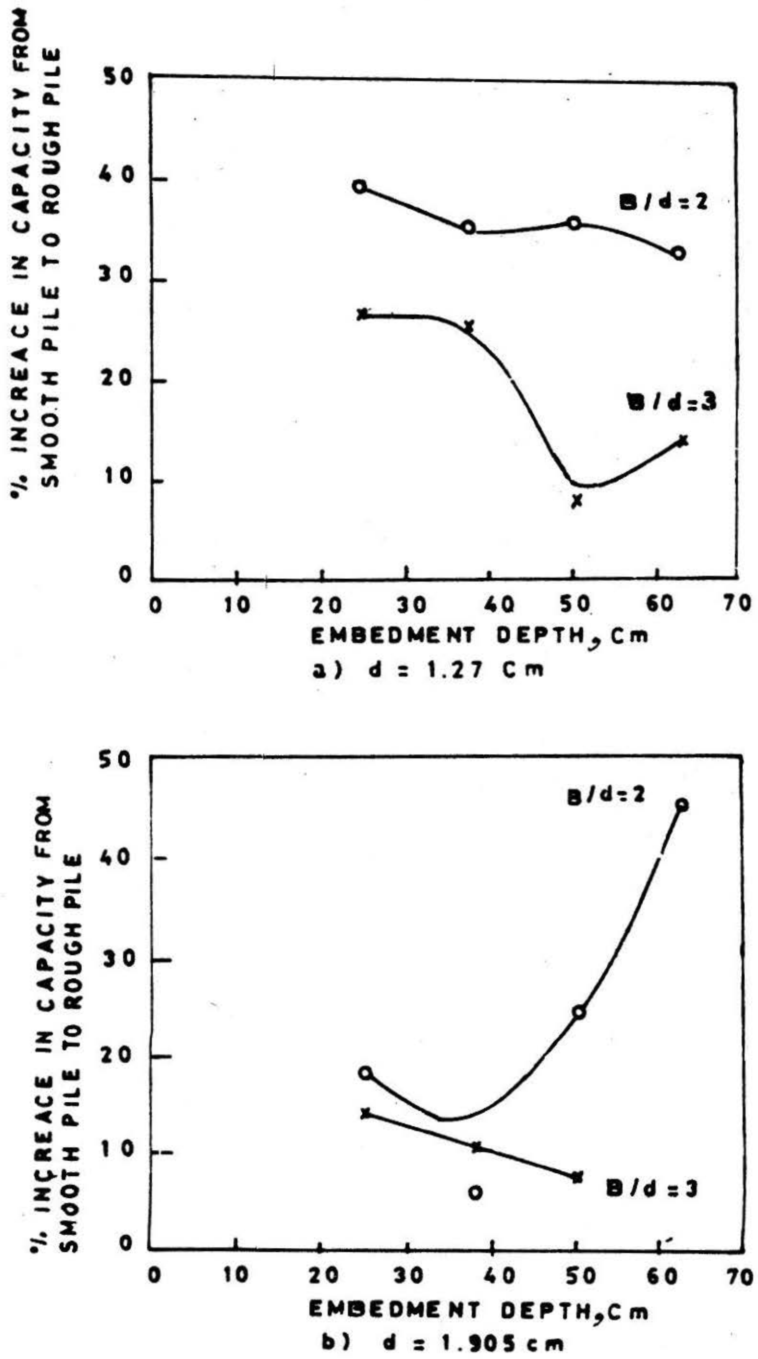


FIGURE 7. Percentage Increase in Capacity from Smooth Pile to Rough Pile Vs Embedment Depth

The test results of net uplift resistance of all the piles under different test conditions have been presented through Fig.3. Fig.4 presents the variation of net uplift capacity with B/d ratio. From Figs.3a and 3b it can be seen that P_u increases non-linearly with embedment depth and that the rough pile offers greater resistance than the smooth one. P_u also increases with B/d and the increase is maximum at larger depths. Fig.4 shows that for the same embedment depth P_u increases linearly with B/d ratio within the range of B/d ratios considered for testing.

Fig. 5 presents the variation of uplift capacity ratio (net uplift capacity of base enlarged pile/net uplift capacity of straight shafted pile) with embedment depth for different B/d ratios. Fig.6 presents variation of uplift capacity ratio (net uplift capacity of base enlarged pile with B/d = 3/net uplift capacity of the base enlarged pile with B/d = 2) with embedment depth. It can be observed from Fig.5 that the uplift capacity ratio increases with embedment depth initially and gradually falls downs with increase in embedment depth. Similar variation can be observed from Fig.6 also. In most of the cases the ratio reaches a maximum value at the same depth of embedment of about 40 cm. Though such a behaviour has invariably been observed in all the cases, no definite conclusion could be drawn with regard to the condition that would provide for maximum increase in capacity. However, some more investigation is required to come out with a definite conclusion. From the both these figures it can be seen that the ratio is always higher for a smooth pile than the corresponding rough pile. That is the increase in capacity due to increase in B/d ratio is less for rough piles than smooth piles.

Percentage increase in capacity from smooth pile to rough pile versus pile embedment depth for B/d ratios of 2 and 3 is shown in Fig.7. It can be observed that increase in capacity is higher when B/d = 2, than when B/d = 3. That is increase in capacity with increase in pile friction angle, δ is less for piles having higher B/d ratio i.e. influence of δ decreases as (B/d) increases.

Methods Of Analysis

Method 1

Tomlinson (1977) has suggested to use the analysis developed by Meyerhof and Adams (1968) regarding the uplift capacity of foundations in partially cohesive (C - ϕ) soil which was based on observations and test data. The theory has been proposed for a strip footing and has been extended to circular and rectangular footings and for group action.

For granular soils at shallow depth (L < H) gross uplift resistance P_g is expressed as

$$P_g = S(\pi/2)\,\tau\,B\,L^2\,K_u \tan\phi + W \quad (1)$$

at greater depths (L > H)

$$P_g = S(\pi/2)\,\tau\,B\,(2L - H)\,H\,K_u \tan\phi + W \quad (2)$$

Net uplift capacity,

$$P_u = P_g - W_a \quad (3)$$

where L = depth of embedment

H = vertical extent of failure surface

B = diameter of the base of the footing

S = shape factor

W = weight of the soil mass and anchor pile uplifted.

W_a = weight of the anchor pile.

τ = effective unit weight of the soil

ϕ = Angle of shearing resistance

K_u = Nominal uplift coefficient on a vertical plane through the footing edge. The value of K_u for a granular soil is relatively constant for a wide range of ϕ and may for all practical purposes be taken as 0.95 for a strip footing.

Shape factor is given by

$$S = 1 + m(L/B) \quad (4)$$

with a maximum of

$$S = 1 + m(H/B) \quad (5)$$

Where (H/B) is given in Table 1 and the coefficient 'm' has values given in Table 2.

TABLE 1
Values Of (H/B) For Square And Circular Footings

ϕ	20^0	25^0	30^0	35^0	40^0	45^0	48^0
H/B	2.5	3	4	5	6	9	11

TABLE 2
Values Of Coefficient 'm'

ϕ	20^0	25^0	30^0	35^0	40^0	45^0	48^0
m	0.05	0.1	0.15	0.25	0.35	0.5	0.6
S_{max}	1.12	1.30	1.60	2.25	3.45	5.5	7.6

Method 2

Sharma et al. (1978) have suggested to evaluate the ultimate uplift capacity of under-reamed piles by computing skin friction along the shaft and bearing pressure on the annular area of the under-reamed bulb using the following expression.

$$P_u = (\pi/2)\, d\, k\, \tau \tan\delta \left(d_1^{\,2} + L^2 - d_n^{\,2}\right) + \pi/4 \left(B_1^{\,2} - d^2\right)\left(1/2\, n\, \tau\, B_1\, N_\tau + \tau\, N_q \sum dr\right) \qquad (6)$$

where d = Diameter of the pile shaft

d_1 = Depth of centre of the first under-reamed bulb.

d_n = Depth of the centre of the last under-reamed bulb.

B_1 = Diameter of under-reamed bulb

n = Number of under-reamed bulbs

dr = Depth of the centre of different under-reamed bulbs.

k = Coefficient of earth pressure, usually taken as 1.75 for sandy soils.

δ = Pile friction angle

N_γ, N_q = Bearing capacity factors depending on ϕ are given in the said reference. δ may be taken equal to ϕ.

For single under-reamed pile the above expression reduces to the form

$$P_u = (\pi/2)\, d\, k\, \gamma \tan\delta\, L^2 + \pi/4\left(B_1^2 - d^2\right)\left(1/2\, B_1\, N_\gamma + \gamma\, N_q\, d_1\right) \quad (7)$$

Method 3

The above equation has been modified (Chandra Prakash, 1980) as

$$P_u = (\pi/2)\, d\, k_{ul}\, \gamma \tan\delta\, L^2 + \pi/4\left(B_1^2 - d^2\right)\left(\gamma\, N_q\, d_1\right) \quad (8)$$

where

K_{u1} = Limiting uplift coefficient (Meyerhof, 1973)

N_q = bearing capacity factor reduced to 1/3 of the value given by Vesic (1963).

Method 4

Based on the model test results the authors observed that (i) the uplift capacity of the anchor pile increases with L, B/d and δ, (ii) δ has substantial influence upon the uplift capacity even if the pile has a base enlargement. However, the influence of δ decreases as B/d ratio increases. That is when B/d is small the contribution to the uplift resistance from the pile surface friction will be of considerable magnitude. Therefore in this method suggested by the authors the net uplift capacity is calculated, albeit approximately, by summing up the resistance offered by the shaft of the pile and resistance offered by the annular area of the base enlargement. They are estimated independently by using the analysis of Chattopadhyay and Pise (1986a) and (1986b) for axial uplift capacity of vertical piles and horizontal anchors respectively.

Chattopadhyay and Pise (1986a) proposed a generalised theory to evaluate uplift resistance of a circular vertical pile embedded in sand, the failure surface is assumed curved and passing through the surrounding soil. Net uplift capacity is predicted considering different parameters like $\lambda = (L/d)$ = slenderness ratio, ϕ and δ and is expressed at limiting equilibrium condition as

$$P_u = A_1 \tau \pi d L^2 \tag{9}$$

where

A_1 = net uplift capacity factor

A_1 depends on λ, ϕ and δ . Design charts have been given for the uplift capacity factor, A_1 for different values of ϕ, δ and λ of practical interest (Chattopadhyay and Pise, 1986c).

The ultimate uplift capacity of circular anchor plate embedded in sand has been expressed by Chattopadhyay and Pise (1986b) as

$$P_u = \tau L N_{q1} A \tag{10}$$

where L = depth of embedment

A = area of the anchor

N_{q1} = breakout factor

N_{q1} is a function of relative depth, L/B and ϕ. Chattopadhyay and Pise (1986b) presented values of N_{q1} for different values of ϕ and L/B.

The net uplift capacity of the anchor pile is taken as the sum of the resistance given by equation 8 and resistance offered by the base enlargement given by equation 9. This can be expressed as

$$P_u = A_1 \tau \pi d L^2 + \tau L N_{q1} A \tag{11}$$

In the above expression A is the annular area of the base enlargement i.e. $A = \pi/4\ (B^2 - d^2)$.

Comparison Of Theoretical And Experimental Studies

Model Test Results of Authors

Comparison of the experimental values with theoretical predictions is presented through Figs 8 to 11. The ratio of theoretical predications to test results under different test conditions for each method has been presented through Figs.12 and 13.

Referring to figures 8 to 11, it can be observed that the test results are in closer agreement with the values of uplift capacity estimated by the proposed approach (Method 4) than those predicted by other methods discussed in the paper. From Fig. 13b it can be observed that Method 4 predicts values which are off by ± 20% from test results. From Figs. 12a and 13a it can be seen that Method 1 and Method 3 predict conservative values. From Fig. 12b it can be observed that the predictions by Method 2 are scattered over a large range i.e. theoretical predictions vary from 0.5 to 1.5 times the test results.

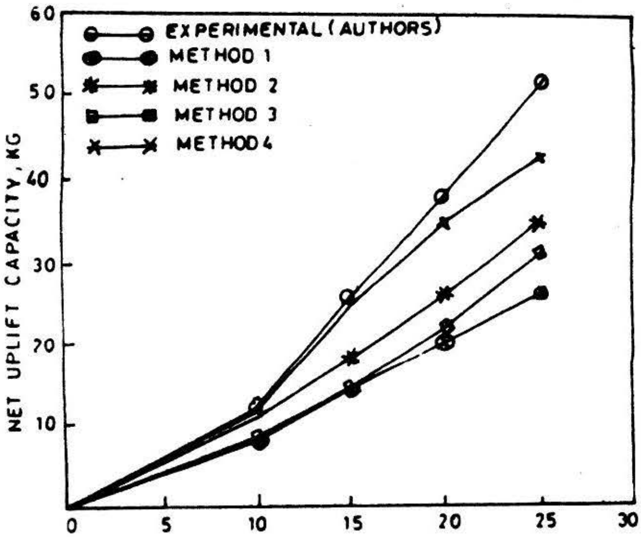
Field Test Results of Chandra Prakash

Chandra Prakash reported uplift test results of two fullscale isolated similar 3.5 m long single under-reamed piles of 30 cm diameter with under-reamed diameter of 75 cm (centre of under-ream is at a depth of 2.88 m below GL) in uniform silty sand. The average values of ϕ and τ were taken as 30° and 1.6 gm/cc respectively over a depth of 3.5 m. The ultimate uplift capacity from the load test was found to be 19.0 ton. Comparison of these field test results with theoretical predictions is shown in Table 3.

TABLE 3
Comparison With Field Test Results

Method	Net ultimate uplift capacity, ton		
	Fictional Component	Base Resistance	Total
Load Test			18.17*
Method 1			18.70
Method 2	9.3	28.8	38.10
Method 3	7.5	16.5	24.00
Method 4	4.98	11.97	16.95

* uplift resistance obtained from load test - self weight of pile.



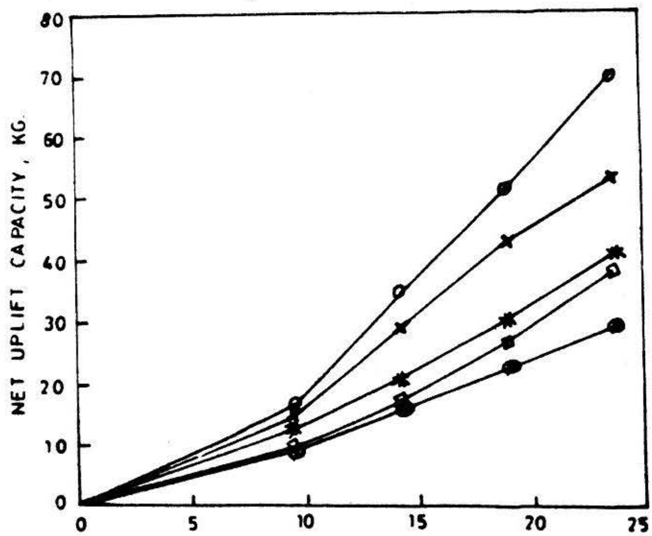
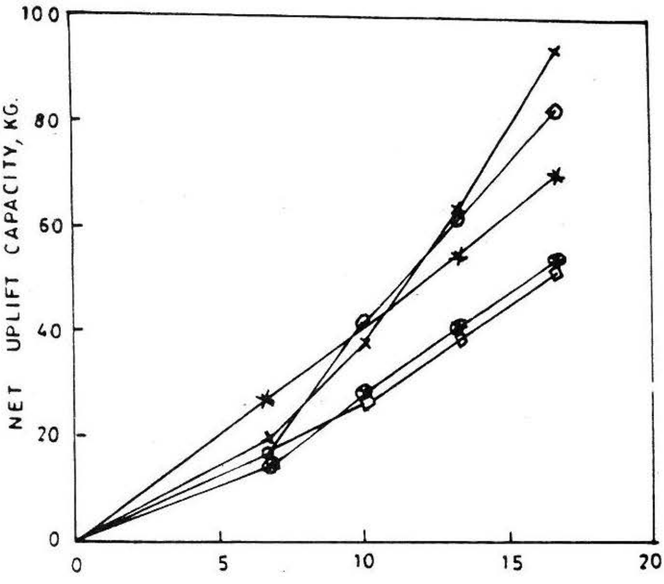
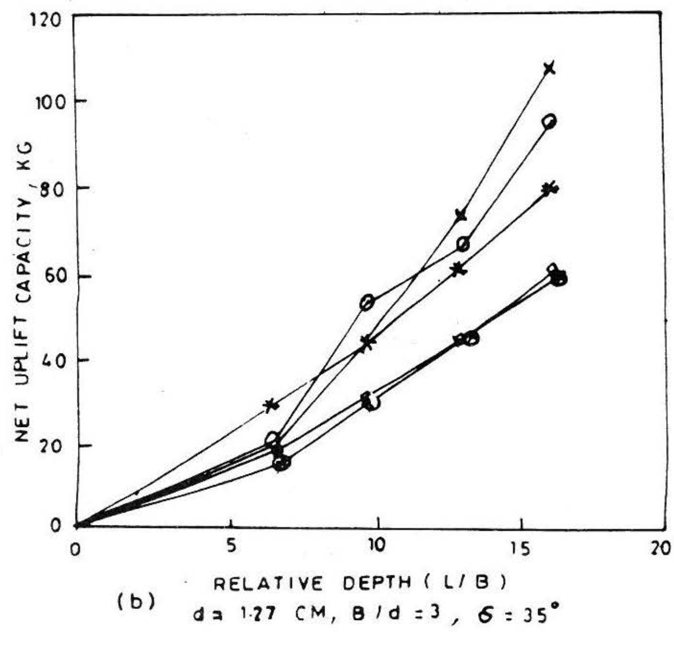


FIGURE 8. Comparison of Uplift Capacity of Anchor Piles by Different Theories

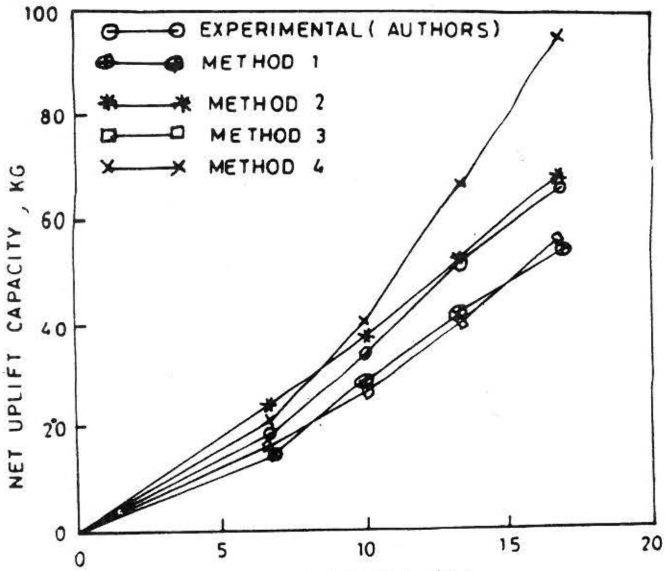


(a) d = 1.27 CM, B/d = 3, δ = 30°

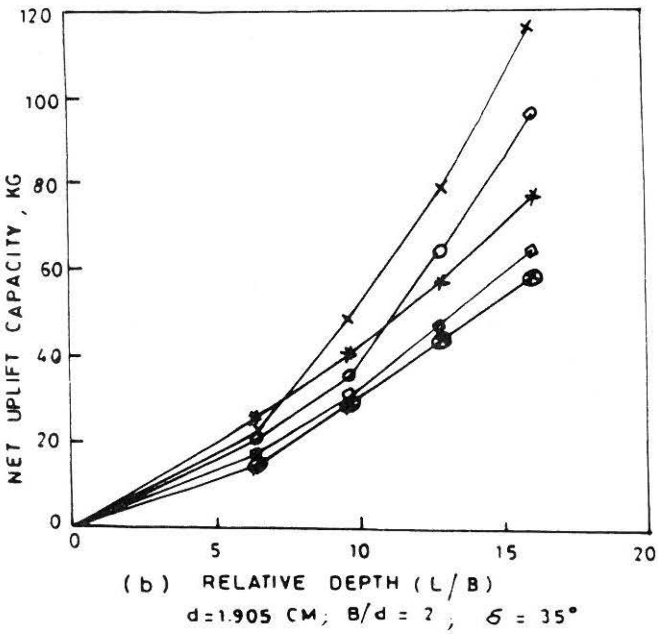


(b) d = 1.27 CM, B/d = 3, δ = 35°

FIGURE 9. Comparison of Uplift Capacity of Anchor Piles by Different Theories

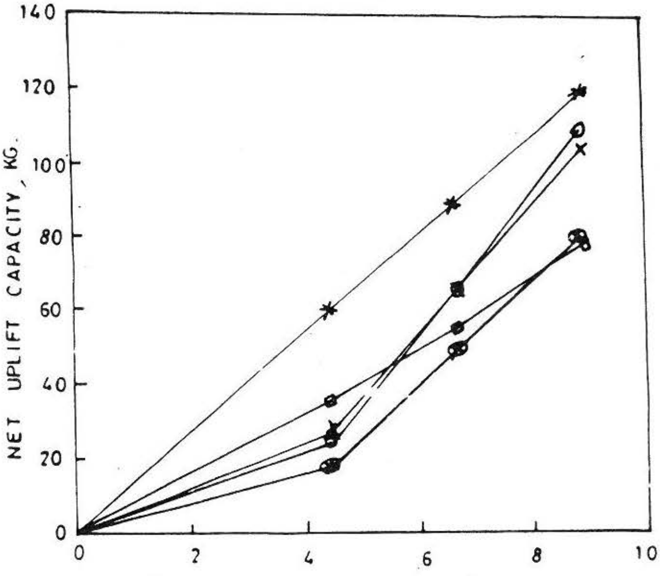


(a) d = 1.905 CM, B/d = 2, δ = 30°

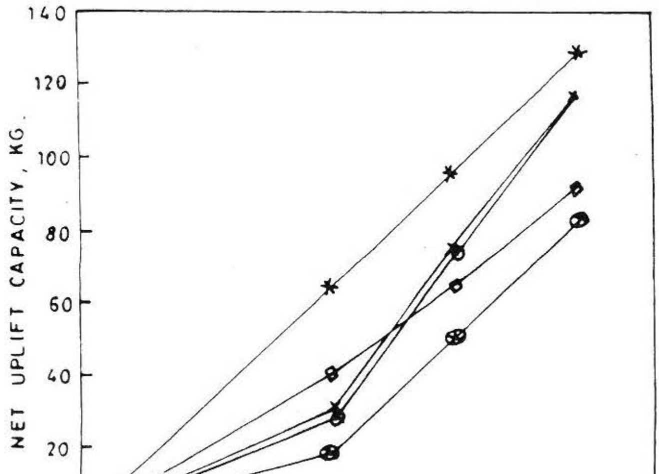


(b) d = 1.905 CM; B/d = 2; δ = 35°

FIGURE 10. Comparison of Uplift Capacity of Anchor Piles by Different Theories



(a) d = 1.905 CM, B/d = 3, δ = 30°



(b) d = 1·905 CM, B/d = 3, δ = 35°

FIGURE 11. Comparison of Uplift Capacity of Anchor Piles by Different Theories

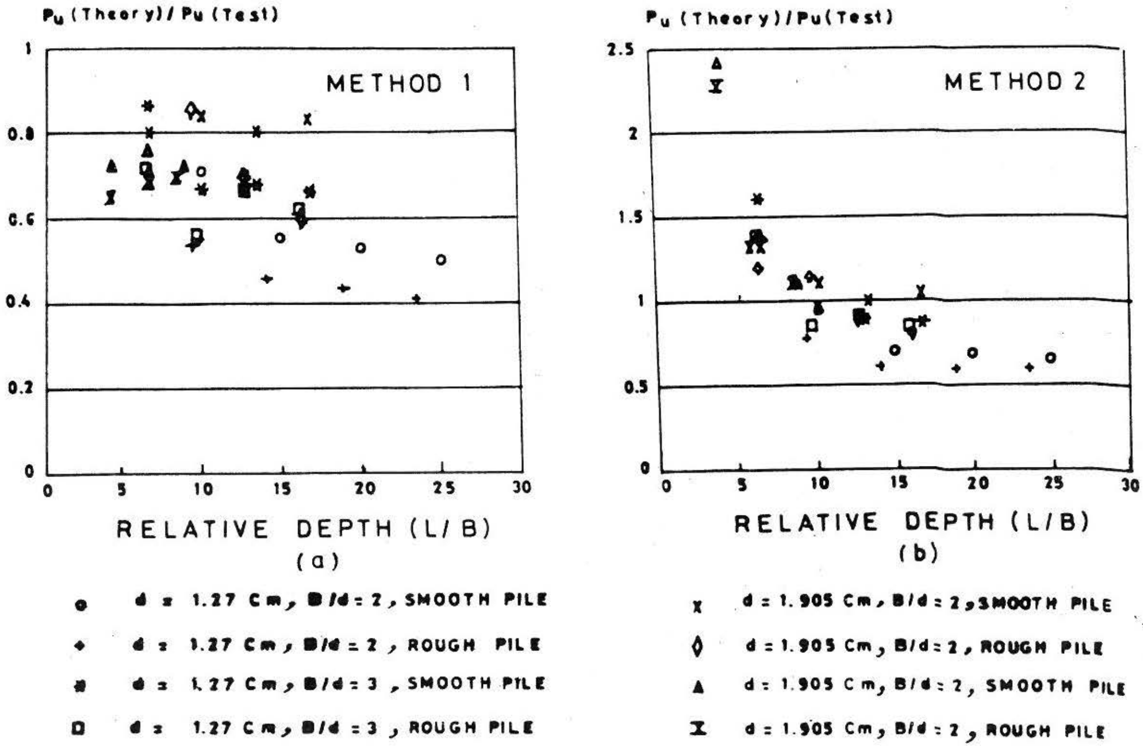


FIGURE 12. P_u (Theory) / P_u (Test) Vs. Relative Depth

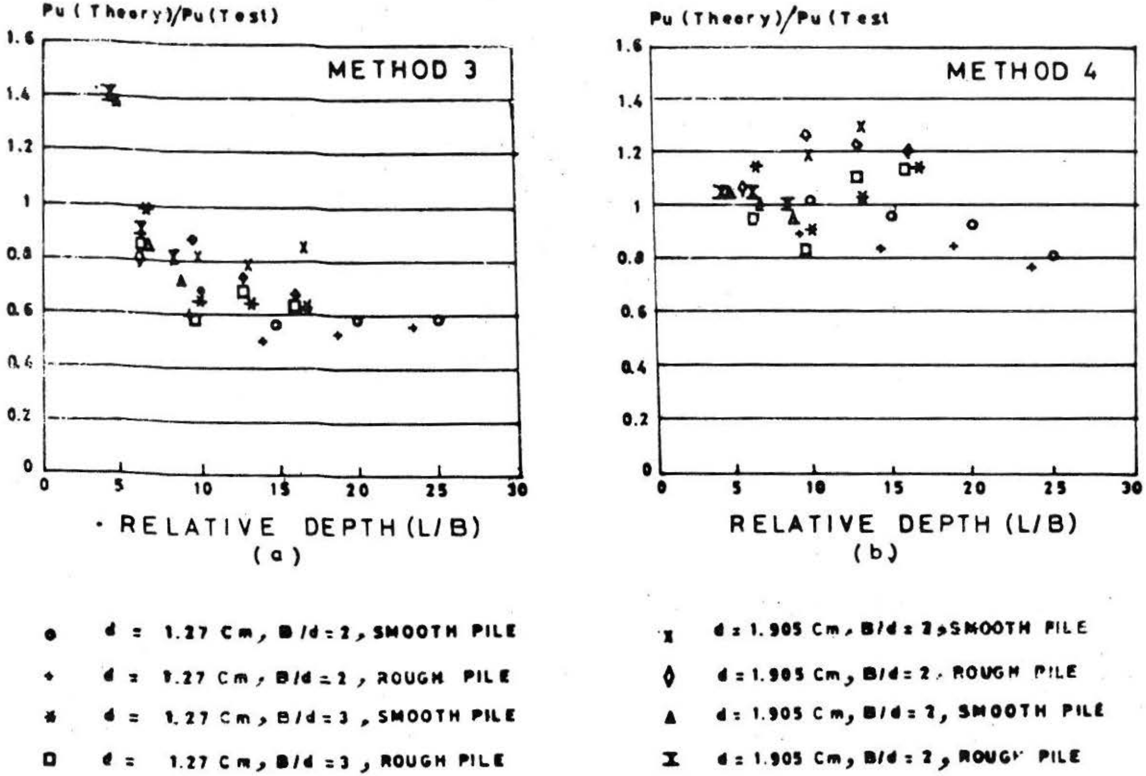


FIGURE 13. P_u (Theory) / P_u (Test) Vs. Relative Depth

Uplift capacities estimated from Meyerhof and Adams (1968) (Method 1) and the proposed method (Method 4) are closer to the test value compared to other predictions.

Conclusions

Based on the results and discussions given above the following conclusions are drawn.

Smooth piles require relatively higher displacements compared to the rough piles to mobilise the ultimate resistance. Uplift resistance increases with depth of embedment as also with B/d ratio. Rough piles offer more resistance than smooth piles. However, increase in uplift capacity with increase in pile friction angle, δ is less for piles having higher (B/d) ratio. i.e. influence of δ decreases as (B/d) increases.

The proposed method gives better estimates of uplift capacity compared to other methods. The true potential of the proposed method could not be explored adequately within the limited scope of the investigation undertaken by the authors. However, further investigation may be taken up to reinforce the applicability of the proposed method.

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