Anchors for Offshore Structures—Geotechnical Aspects

by

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Introduction

For the recovery of ocean resources, fixed offshore platforms are being currently installed in water depths upto 250 m. Since these structures become prohibitively expensive when water depths exceed 250 m, new concepts such as guyed towers and tension leg platforms are being developed. These new structures will be held in position by foundations anchored to the sea-bed. As the offshore activity moves into deeper waters, the emphasis is likely to shift completely from fixed offshore structures to anchored floating structures, for providing a steady base at sea. Already, the worlds first guyed tower has been installed in 1983 in 300 m of water in Lena Field in the Gulf of Mexico (Ocean Industry 1983a) and the first tension leg platform is being installed in 1984 in 140 m of water in Hutton Field in the North Sea (Ocean Industry, 1983b).

Figure 1 shows a typical guyed tower. Anchors are provided at the ends of guylines to resist horizontal pulls ranging from 100 to 300 t or more per anchorage point. For tension leg platforms, (Figure 2) the applied pull is vertically upwards and each anchorage point must be able to resist a vertical pull of 2000 to 7000 t (Le Tirant (1979), Gibson and Dowse (1981)). As more deep water structures are conceptualised, it is likely that anchoring systems will be required to resist large forces in vertical, horizontal and inclined directions.

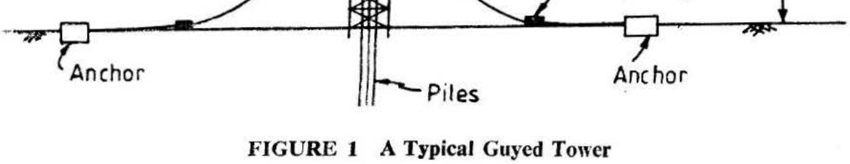

FIGURE 1 A Typical Guyed Tower

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(This paper was received in 1984, and is open for discussion till the end of July 1985)

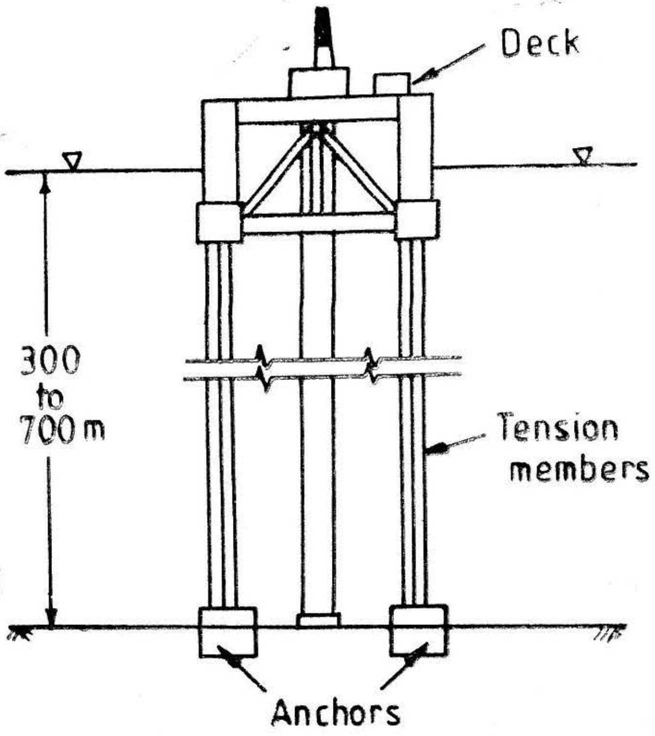


FIGURE 2. A Typical Tension Leg Platform

In the oceans, anchors have been used for centuries to hold floating vessels in position. Such conventional anchors usually have breakout capacities (often referred to as 'holding power') less than 150 t. The risk to the safety of floating vessels in case of failure, or draging, of an anchor is low. For the new types of offshore structures being envisaged, anchors with large breakout capacities will be required to operate continuously for several years, with a high risk to the safety of the structure in case of failure of an anchor. As a consequence, numerous types of new anchors are being developed. In this paper, the features, installation procedures and geotechnical aspects governing breakout capacities of various types of anchors are reviewed and their suitability for anchoring offshore structures identified.

Types of Anchors

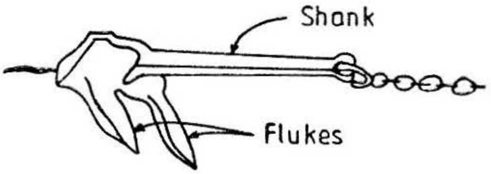
A review of literature indicates that the following types of anchors exist or are in the process of being developed for holding floating structures in position in the oceans.

Dead Weight Anchors

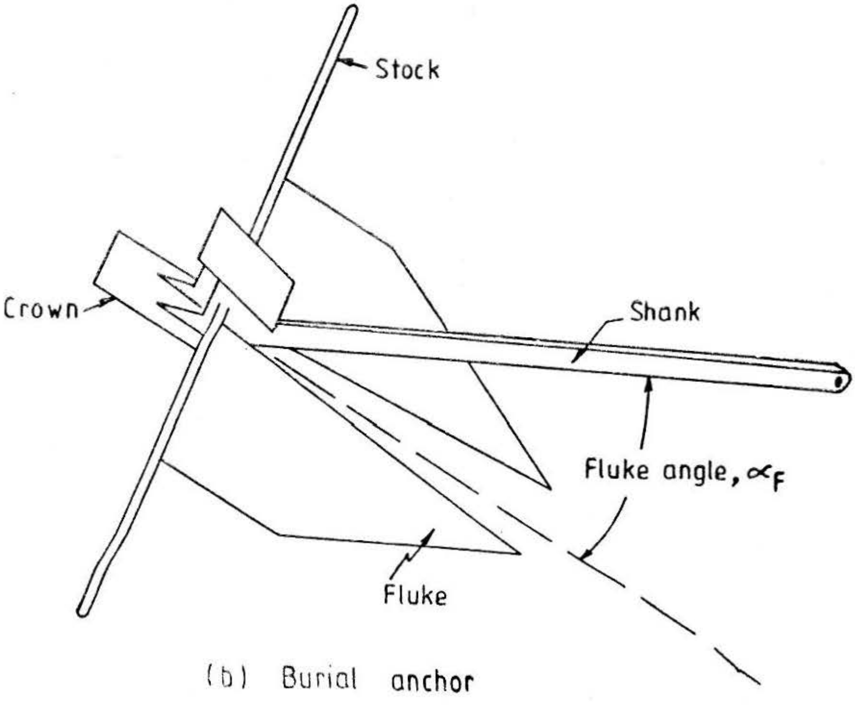
Dead weight anchors have been used since long to resist small vertical loads. They are constructed of heavy materials such as steel or concrete and rest on the seabed. Their vertical breakout capacity is essentially equal to the submerged weight of the anchor. They are used for anchoring small installations such as single point moorings.

Anchors with Flukes

Fluke anchors are best suited to resist horizontal loads. They consist of a stem or shank, which is the main element of weight and flukes which cause the anchors to bury in the soil (Figure 3). Heavy anchors with small flukes are referred to as drag anchors (Figure 3a) and relatively light anchors with large flukes are referred to as burial anchors. These anchors are installed by placing them on the seabed with the flukes facing downwards and then pulling the anchor line horizontally. This causes the anchor to penetrate into the soil as shown in Figure 4 (a). A fluke anchor developes

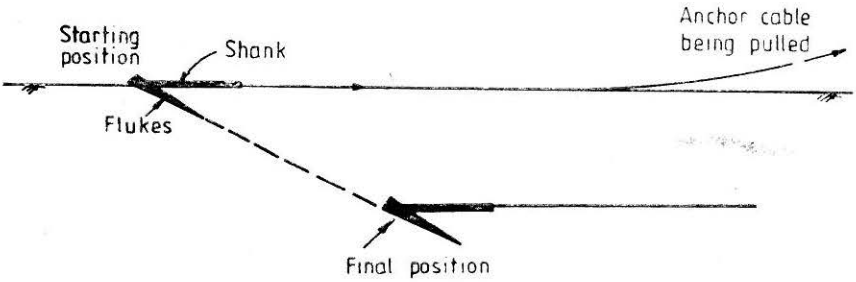


(a) Drag anchor

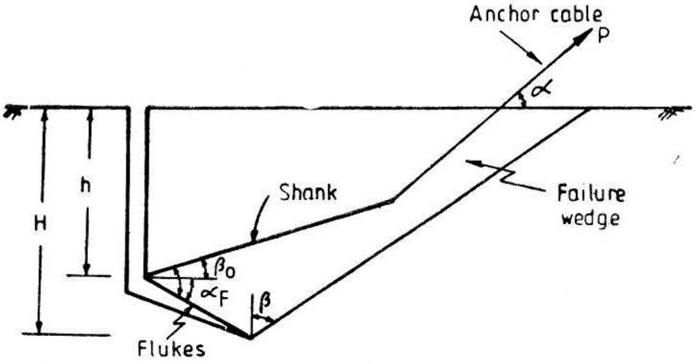


(b) Burial anchor

FIGURE 3. Features of Anchors with Flukes



(a) Anchor installation



(b) Soil failure wedge

FIGURE 4. Anchor with Flukes : Installation and Soil Failure Wedge

its full breakout capacity, if it becomes fully buried in the seabed. In some cases, factors such as overturning or rotation of the anchor may prevent burial, resulting in improper functioning of the anchor. The optimum fluke angle, $(\alpha_f+\beta_o)$, generally varies between 30 to 35° for sands and upto 50° for clays (Le Lievre and Tabatabee, 1981). Sometimes wo fluke anchors may be used in tandem to give increased horizontal breakout capacity (Taylor, 1981).

Mushroom Anchors

Mushroom anchors are cup or bowl shaped heavy anchors (Figure 5) made of cast iron or reinforced concrete. In soft fine grained soils they penetrate by sinking under their own weight (Ling, 1972) whereas in other soils external force is required to bury them. They are used for resisting vertical loads.

Hydropin Anchors

Typical features of a hydropin anchor are shown in Figure 6. It is essentially a plate which is installed by jetting water into the soil beneath the plate and pumping up the resulting slurry through a hollow

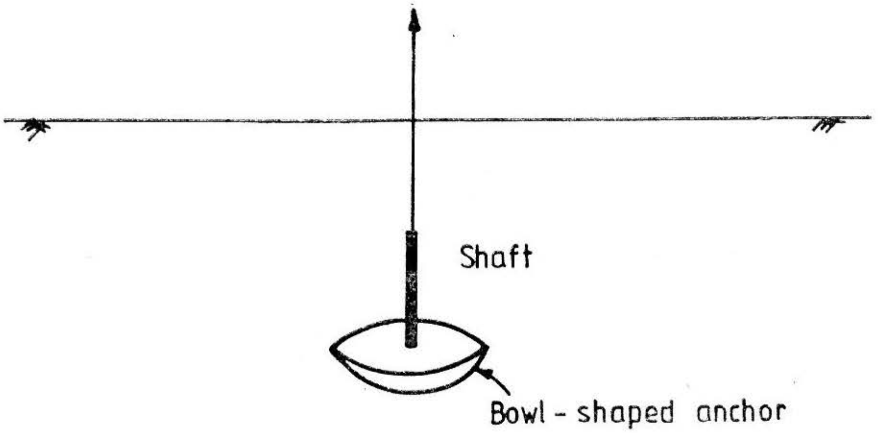


FIGURE 5. Mushroom Anchor

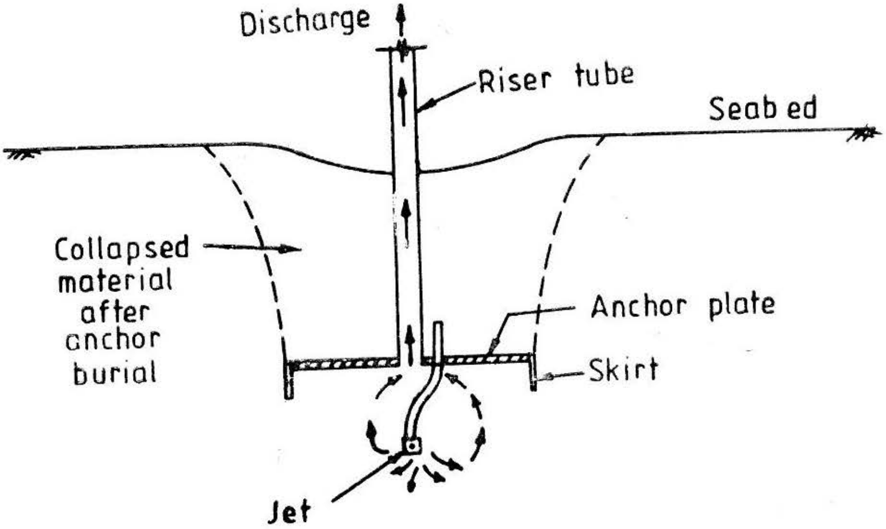


FIGURE 6. Hydropin Anchor (as per Kerr, 1976)

tube attached to the centre of the anchor. The plate sinks continuously under self weight into the hole thus created. Only model tests have been conducted on such anchors in sand as reported by Kerr (1976). When fully developed, hydropin anchors will be used for resisting vertical loads.

Propellant Embedment Anchors

Propellant embedment anchors are propelled into the seabed at a high velocity by means of a launching gun (Taylor and True, 1976 and True and Link, 1979). Such anchors consist of a fluke assembly and a

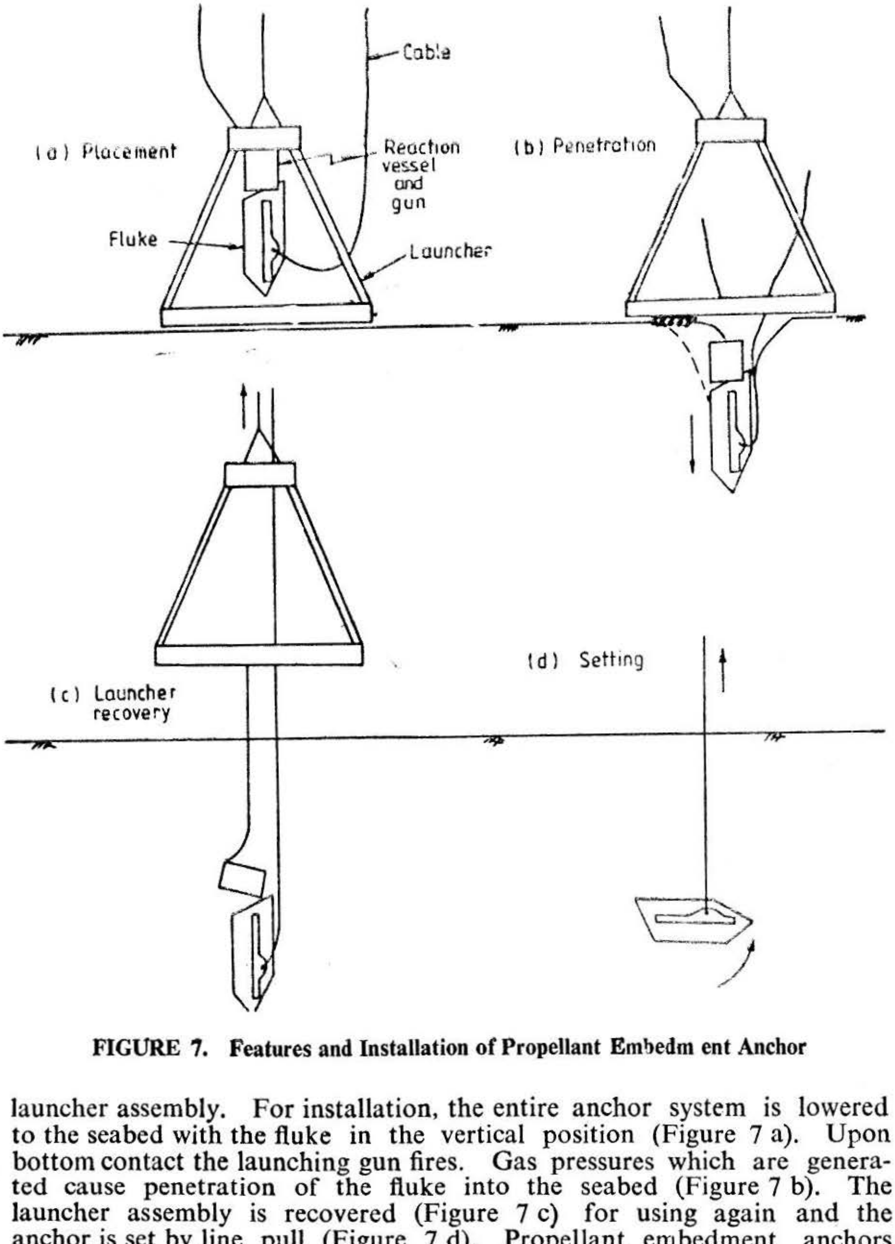


FIGURE 7. Features and Installation of Propellant Embedm ent Anchor

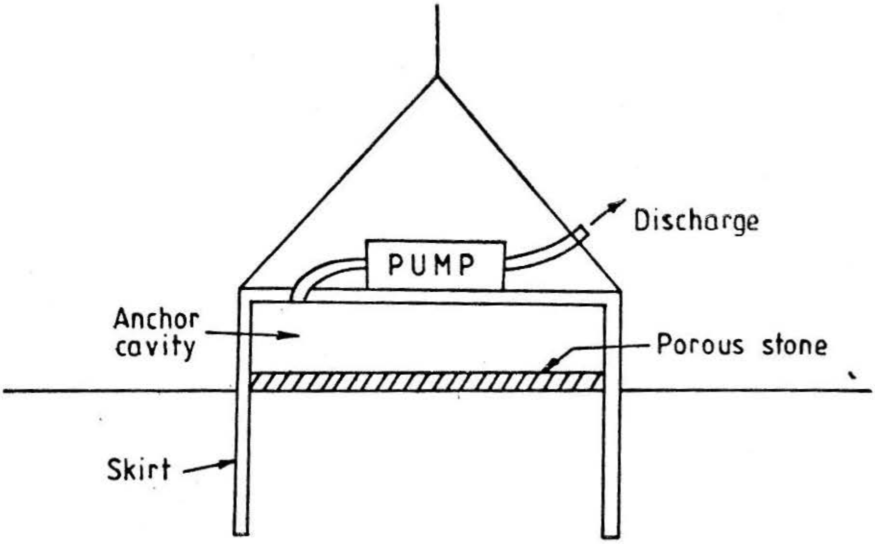
launcher assembly. For installation, the entire anchor system is lowered to the seabed with the fluke in the vertical position (Figure 7 a). Upon bottom contact the launching gun fires. Gas pressures which are generated cause penetration of the fluke into the seabed (Figure 7 b). The launcher assembly is recovered (Figure 7 c) for using again and the anchor is set by line pull (Figure 7 d). Propellant embedment anchors are used for resisting vertical loads.

Suction Anchors

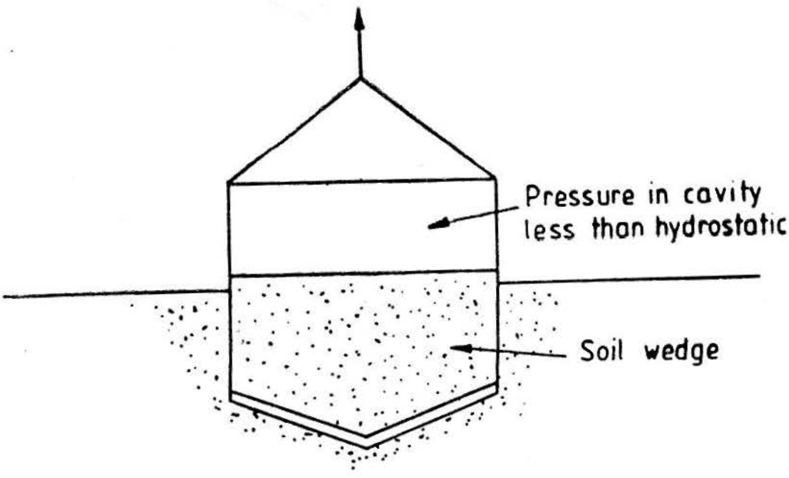
Two types of suction anchors have been described in literature, namely, (a) anchors resting on the seabed or hydrostatic anchors (Brown and Nacci, 1971) and (b) buried suction anchors (Wilson and Sahota, 1980).

Only model tests have been conducted on these anchors and they are envisaged to be used for resisting vertical forces.

The features of a hydrostatic anchor are shown in Figure 8 a. The anchor is placed on the seabed and the skirts penetrate due to self-weight into the soil. Suction is applied in the cavity by a pump which causes the pressure in the cavity to become lower than the hydrostatic pressure. This creates a hold-down force which keeps the anchor clamped to the



(a) Features

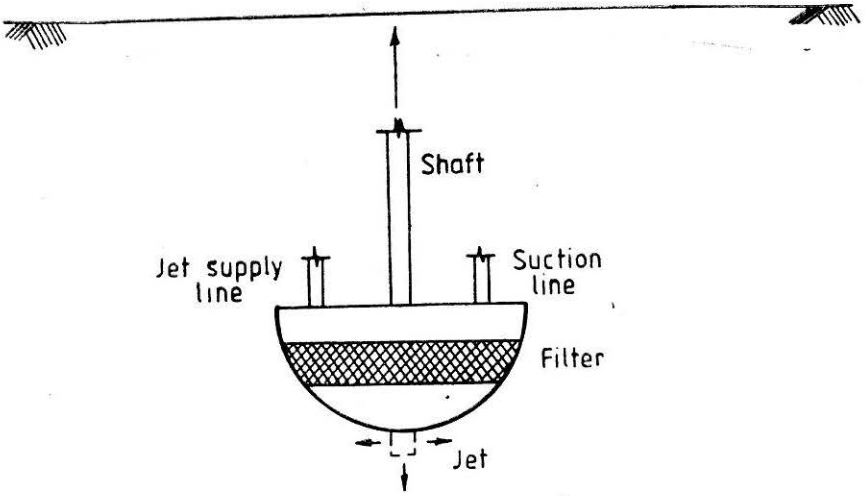


(b) Failure mechanism

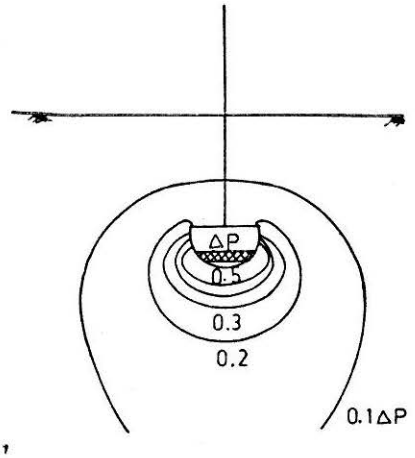
FIGURE 8. Hydrostatic Anchor (as per Brown & Nacci, 1971)

seafloor against vertical forces. Model tests indicate that hydrostatic anchors can be used in all types of soils (Wang et. al., 1978).

Buried suction anchors can be conical or hemispherical in shape. Model tests have been performed on them in sand only (Wilson and Sahota, 1980). Typical features of a hemispherical anchor are shown in Figure 9 a. They are installed by jetting water into the underlying soil to achieve the required penetration. After burial to the desired depth has been achieved by jetting, suction is applied within the anchor. This causes a flow of water from the surrounding soil into the anchor resulting in increased breakout capacity.



(a) Features



(b) Influence of suction on pore pressure

FIGURE 9. Buried Suction Anchor (as per Wilson & Sahota, 1980)

Pile Anchors

Long steel tubular piles (Figure 10 a) are being extensively used as foundations of jacket type offshore structures. Apart from resisting large compressive forces, such piles offer significant vertical breakout capacity and horizontal breakout capacity and can be used for providing anchorage in any direction. With increasing water depth, the method of installation requires special attention. Underwater hammers have been used for installing piles in water depths upto 300 m and can perhaps be used upto 500 m (Mayfield et. al., 1979 and Low and Yin, 1979). Collip and Johnson (1979) have reported installation of long piles in soft soil, in water depths greater than 200 m by jetting. McLamore et. al. (1982 a) have described a new technique by which steel piles can be installed by drilling and then grouted in-place in a single operation. In this technique a drill-string is lowered to the seabed and a hole 15 cm larger than the pile diameter is drilled to the desired depth. A tubular steel pile is lowered over the drill string into the hole. With the pile in position, cement is pumped by a special method through the drill-string to fill up the annular space between the pile wall and the drilled hole. The drill string is then picked up slowly to fill the inside of the pile with cement till the seabed level. A pile installed by this method is shown in Figure 10 b.

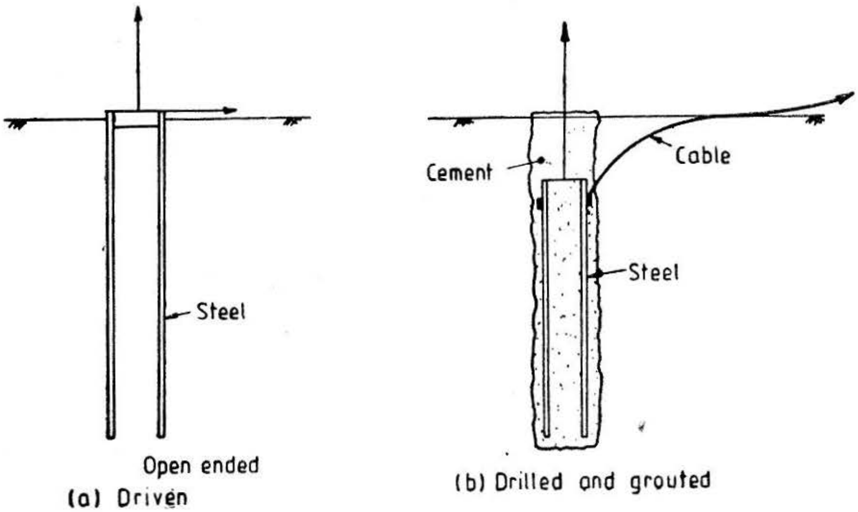


FIGURE 10. **Long Steel Tubular Piles**

Hogervorst (1980) has suggested the use of large diameter short steel piles which can be installed by suction, for anchoring offshore structures. Each pile consists of a hollow steel cylinder 3 to 5 m in diameter and 5 to 10 m long, with a closed top and two pumps which can apply suction inside the pile. The installation technique is depicted in Figure 11. The pile is lowered to the seabed and allowed to rest on it under self weight. The pumps are then started to cause the pressure inside the pile to become less than hydrostatic. A net downward force causes the pile to penetrate

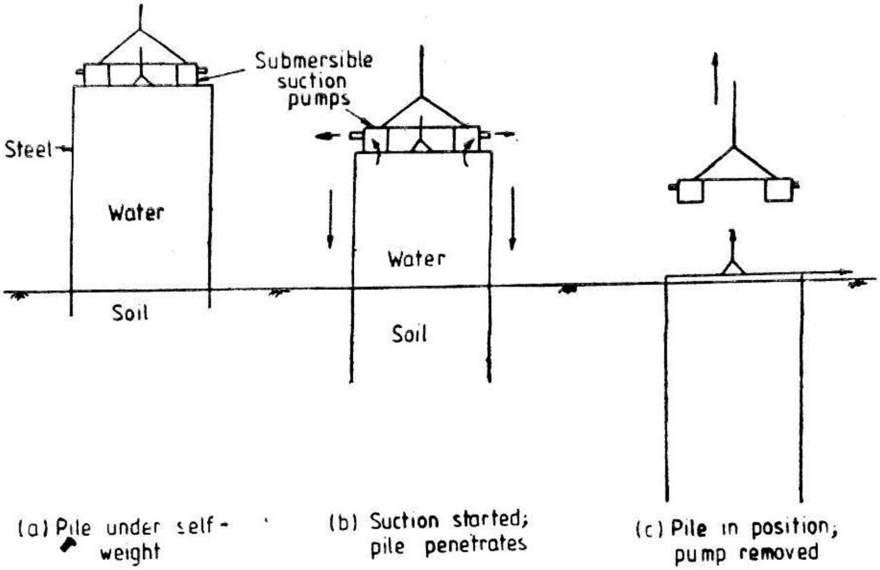


FIGURE 11. Short Steel Tubular Pile Installed By Suction

into the seabed. Once the desired penetration is reached, the pumps are stopped and removed from the pile top. Satisfactory performance of such piles for resisting horizontal loads in sand has been reported by Hogervorst (1980) and Senpere and Auvergne (1982).

Gravity Anchors

Gravity anchors are larger versions of dead weight anchors. They are being developed to provide the high vertical anchorage required for tension leg platforms (Le Tirant, 1979). A gravity anchor will comprise of an envelope which will be constructed in protected waters and floated into position where it will be filled with ballasting material such as sand or concrete or heavy residue causing it to sink to the ocean floor. The gravity anchor may rest on the seabed or may become buried depending on the strength of the soil. Such anchors will offer vertical breakout capacity on account of their self weight. To increase the horizontal breakout capacity they may be provided with skirt walls at the base (Figure 12).

Mass Chain Anchors

In some areas, the thickness of soil cover over rock on the ocean floor may be smll. Anchors which rely on burial depth for their breakout capacity will be ineffective in such cases. Mass chain anchors can be used with advantage for resisting horizontal loads in such areas as they can conform to the seabed topography and develop their full horizontal breakout capacity. Ramsden and Watts (1982) have described the use of a mass chain anchors installed by free fall technique in water depth of 1500 m. Essential features of the chain anchor used by them are shown in Figure 13.

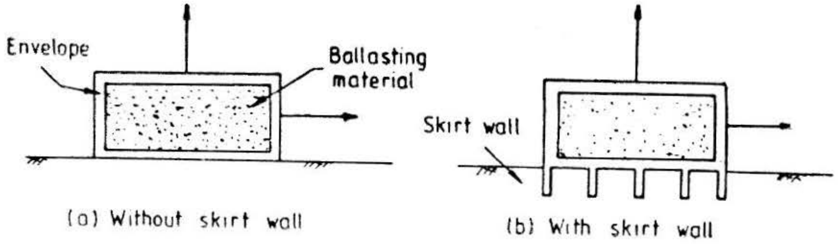


FIGURE 12. Gravity Anchors

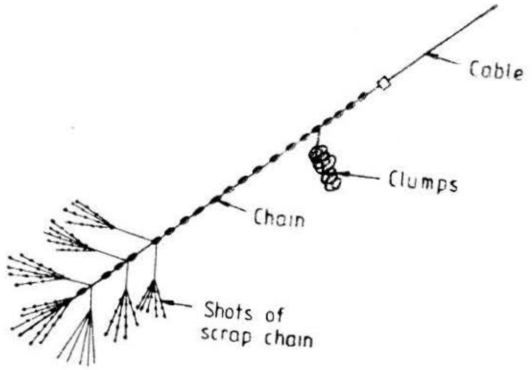


FIGURE 13. Features of Mass Chain Anchor (as per Ramsden & Watts, 1982)

Factors Affecting Breakout Capacity of Buried Objects

Factors affecting breakout capacity of buried objects under static loading in (*a*) vertical, (*b*) horizontal and (*c*) any direction are discussed in the following first three subsections after which the influence of cyclic loading on breakout capacity is identified.

Vertical Breakout Capacity

Fig. 14 (*a*) shows the various forces which act on an object buried at a depth, *D*, below mudline when it is pulled vertically upwards under static load. The ultimate vertical breakout capacity can be expressed as

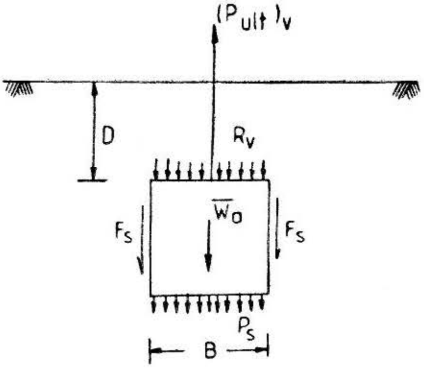
$$(P_{ult})_v = W_a + F_s + R_v + P_s. \qquad \text{... (1)}$$

where

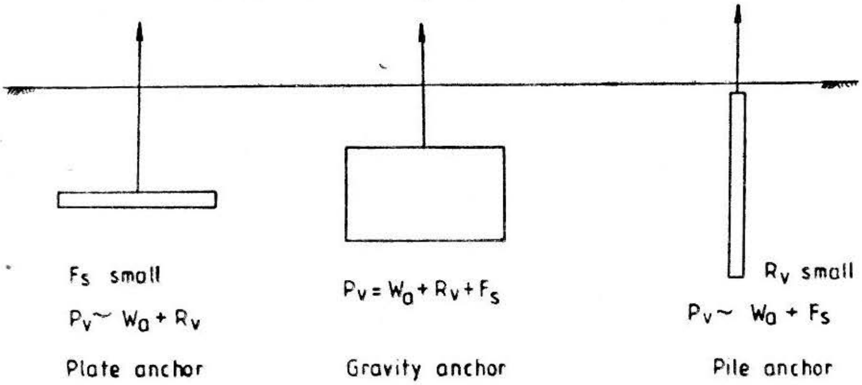
$(P_{ult})_v$ is the ultimate vertical breakout capacity,

W_a is the submerged weight of the buried object,

F_s is the total skin friction acting on the sides of the object,



(a) Factors affecting breakout capacity



(b) Influence of shape on breakout capacity

FIGURE 14. Vertical Breakout Capacity of Buried Objects

R_v is the vertical breakout resistance offered by the soil, and

P_s is the soil suction force.

F_s can be evaluated using standard soil mechanics formulae available for estimating skin friction.

Evaluation of R_v has been the subject of study by numerous investigators in the recent past. Balla (1961), Meyerhof and Adams (1968), Vesic (1971), Bemben et. al. (1973), Bemben and Kupferman (1975) and others have developed thories on the basis of laboratory expriments for estimating R_v. Their investigations have revealed that R_v can be expressed as :

$$R_v = \gamma_b D \times N_{bs} \times \text{Area} \qquad \text{(for sands)} \qquad \ldots (2)$$

and $$R_v = S_u \times N_{bc} \times \text{Area} \qquad \text{(for clays)} \qquad \ldots (3)$$

where

N_{bs} is the breakout factor in sands,

N_{bc} is the breakout factor in clays,

$\gamma_b D$ is the effective overburden stress,

and S_u is the undrained shear strength of clay.

Two distinct types of failures are observed when an embedded object is pulled upwards. When the burial depth is small, a well defined failure surface develops from the object till the mudline. For deep burial depths, no well defined failure surface developes but the behaviour is more like punching failure (Vesic, 1971). This transition from shallow to deep behaviour occurs when the depth to width ratio exceeds 4 to 10 in loose to dense sands and when the ratio exceeds 2 to 5 for soft to stiff clays. The theories proposed by various investigators mentioned above can be used to evaluate N_{bs} and N_{bc}.

In sands, N_{bs} is a function of the depth to width ratio, D/B, angle of shearing resistance, $\bar{\phi}$, and relative density. The breakout factors evaluated using different theories for sands, show as wide a variation as is typically observed in bearing capacity factors. Bemben and Kupferman (1975) have reviewed the various theories and proposed a simplified method for evaluating N_{bs} in sand. For D/B ratios exceeding 10, N_{bs} reaches upper limiting values of 10 for $\bar{\phi} = 35°$ and 40 for $\bar{\phi} = 45°$.

In clays, evaluation of N_{bc} as per different theories does not yield as wide a variation as in sands. N_{bc} is a function of D/B and reaches an upper limiting value of 9 for D/B greater than 5.

It is important to note that the equations for evaluating breakout resistance, R_v, i.e. Eqs. (2) and (3) are similar in nature to the equations one uses for evaluating end bearing resistance in piles. In fact Vesic (1971) has observed that for deep burial depths the magnitude of breakout resistance is comparable to magnitude of end bearing resistance offered by soils to piles in both sands and clays.

The soil suction force, P_s is not developed in sands because of their high permeability. In clays the suction force is relevant only for short term loading. Le Tirant (1979) suggests that the suction force should be taken as half the undrained strength. Bemben and Kupferman (1975) have presented data which shows N_{bc} increases by 6 when suction is present. More data is required before the suction force can be used with confidence in evaluating breakout capacity.

Fig. 14 (*b*) shows that different components contribute differently to the breakout capacity depending upon the shape of the object. In the case of plate anchors, F_s is negligible and $(P_{ult})_v$ comprises primarily of R_v with some contribution from W_a. For buried gravity anchors F_s, R_v and W_a all contribute towards the ultimate vertical breakout capacity. In pile anchors, R_v is negligible and $(P_{ult})_v$ comprises primarily of F_s with some contribution from W_a.

Horizontal Breakout Capacity

When a buried object is pulled in the horizontal direction, the ultimate horizontal breakout capacity can be expressed as (Fig. 15 *a*).

$$(P_{ult})_h = F_f + R_h + P_s \qquad \dots (4)$$

where

$(P_{ult})_h$ is the ultimate breakout capacity in the horizontal direction,

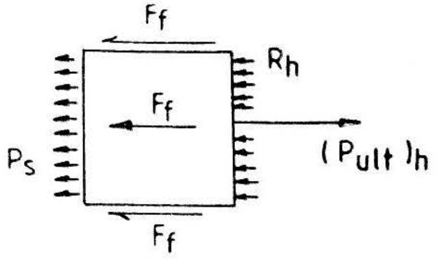
F_f is the total friction resistance acting on the surfaces parallel to direction of pull,

R_h is the breakout resistance offered by the soil in the horizontal direction, and

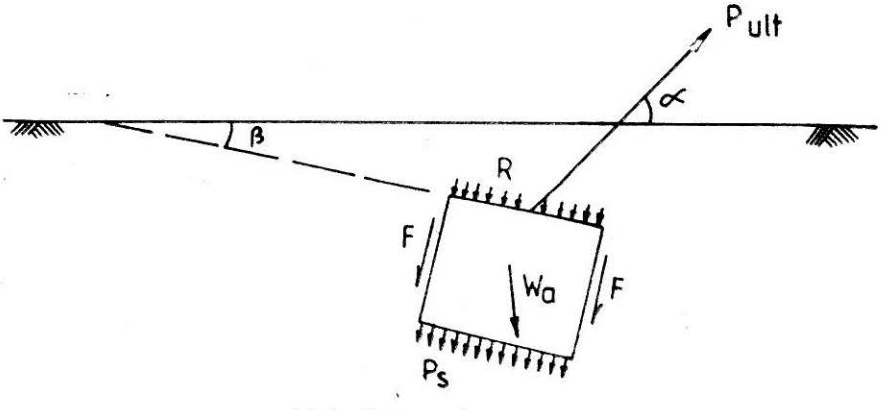
P_s is the soil suction force.

F_f can be evaluated using standard soil mechanics formulae available for estimating sliding friction.

Evaluation of R_h has not been studied in detail. For shallow depth, R_h can be estimated using lateral earth pressure theories developed for deadman anchors of flexible sheet piles (Teng, 1965). For deep burial



(a) Horizontal direction



(b) General case

FIGURE 15 Breakout Capacity of Buried Objects depths, R_h is approximately equal to the bearing capacity of a footing whose base is located at a depth corresponding to the middle of the object as per Terzaghi (1943). More investigations are required to verify the applicability of these theories for submarine soils.

The soil suction force, P_s, is zero for sands and is usually neglected in clays.

Breakout Capacity in any Direction

Fig. 15 (*b*) depicts the general case of pull out force applied to a buried object in any direction. From the observations made for vertical and horizontal breakout capacities and from Fig. 15 (*b*) it may be noted that the breakout capacity in any direction of a buried object depends upon (*a*) submerged weight of the object ; (*b*) burial depth of the object ; (*c*) soil type and shear strength ; (*d*) shape and dimensions of the object ; (*e*) orientation of the object i.e. angle β and (*f*) direction of pull i.e, angle α. The last two factors have been less than adequately studied. Colp and Herbich (1975) made some studies on horizontal plates embedded at shallow and deep depths and pulled at angles varying from 0 to 45° from the vertical. They observed that in clays, breakout capacity under inclined loads was not very different from vertical breakout capacity. In sands, the breakout capacity was initially observed to increase with inclination of applied load. This trend was observed to reverse beyond a certain angle of inclination. More studies are however required to clearly identify the influence of direction of pull and of object orientation on breakout capacity.

Breakout Capacity Under Cyclic Loading

The pull-out forces which are transmitted to the anchors of floating offshore structures have a significant cyclic component. Only a few investigators (Bemben et. al., 1973 Bemben and Kupferman 1975, Andreadis et. al., 1981, have attempted to identify the influence of cyclic loading on breakout capacity. These studies have been confined to vertical cyclic loading applied to plate-like buried objects.

The results of these studies show that under cyclic loading, upward movement of a buried object accumulates. The rate of movement is a function of the ratio of the magnitude of the cyclic load to the static breakout capacity and the number of cycles. If the cyclic loading magnitude is kept low, the rate of movement reduces as the number of cycles increases but the movement never ceases. For high magnitude, the rate of movement may increase with the number of cycles leading to failure. This happens more rapidly in the case of objects buried to shallow depths, where accumulation of upward movement causes the static breakout capacity to reduce progressively, leading to failure. For a given cyclic loading magnitude, the response of objects buried to deeper depths is superior because the ratio of the cyclic loading magnitude to static breakout capacity decreases with increasing depth.

The concept of failure under cyclic loading has not yet been evolved for buried objects, though it is evident that it will have to be a strain dependent criterion. It is also apparent that as the amplitude of cyclic loading increases, burial depths of embedded objects will have to be increased significantly to obtain satisfactory response.

Breakout Capacities of Different Types of Anchors

Having identified the various types of anchors in use or being developed for future use and having looked into the factors which influence the breakout capacity of embedded objects, attention is now focussed on evaluation of breakout capacities of various types of anochors. Till the recent past, the breakout capacity of an anchor has been expressed as a function of the weight of the anchor. The term 'holding efficiency' which is the ratio of breakout capacity to the weight of an anchor, has been used as an index of performance of an anchor. A higher holding efficiency indicates a superior anchor because, for a required breakout capacity, an anchor with higher holding efficiency is lighter and easier to handle. Attempts have been made only in the recent past to estimate breakout capacities in sands and clays using soil mechanics principles. These are reviewed hereafter. In the following sub-sections, the breakout capacities of various types of anchors have been evaluated in sands and clays using the following properties.

Sand :

$\bar{\phi} = 35°$, $\gamma_t = 1.8\ g/cc$.

Normally consolidated clay :

$S_u = 0.25, \overline{\sigma_v}\ \gamma_t = 1.8\ g/cc$.

where

γ_t = total unit weight and

$\bar{\sigma}_v$ = effective overburden

Anchors with Flukes

Drag anchors rely on their weight and some soil resistance against their small flukes for their breakout capacity. They have holding efficiencies of about 2 in clay and 5 in sand and breakout capacity usually less than 50 t. On the other hand the breakout capacity of relatively light weight burial anchors is derived almost entirely from the breakout resistance offered by the soil against the large flukes. Burial anchors exhibit holding efficiencies greater than 10 and sometimes as high as 30 with breakout capacities ranging from 100 to 400 t in sands and 50 to 200 t in clays.

Le Tirant (1979) has suggested that the breakout capacity of fluke anchors can be approximated by

$$(P_{ult})_h = c\ W_a^b \qquad \ldots(5)$$

where c and b are dimensionless coefficients which vary between 2.6 to 110 and 0.76 to 1.15 respectively for different soils.

Puech *et. al.* (1978) have studied behaviour of various types of fluke anchors in different soil conditions and have illustrated the insufficiency of the concept of efficiency and of trying to empirically relate breakout capacity with the weight of anchor. They observed that the breakout capacity of fluke anchors was mainly a function of burial depth, area of flukes and strength properties of the soil. Le Lievre and Tabatabee (1981) conducted model tests on fluke anchors buried in sand and developed a method for evaluating breakout capacity on the basis of a soil wedge analysis. The failure wedge used for analysis is shown in Figure 4 (*b*).

Using the theory of Le Lievre and Tabatabee (1981), the breakout capacities of three types of anchors in sand has been evaluated by Singh (1984). Some of his results are presented in Table 1. One notes from Col. (5) in the table that a breakout capacity of greater than 100 *t* can be easily obtained in sands at small burial depths. The breakout capacity reduces significantly when the direction of pull is not horizontal as can be observed by comparing cols. (5) and (6) in Table 1. The breakout capacity does not change significantly if the weight of anchor is taken as zero (col. (7)), indicating that for anchors with large fluke areas, weight of anchor makes a small contribution to breakout capacity.

TABLE 1

Breakout Capacity of Fluke Anchors in Sand as per Singh (1984)

Anchor Type	Anchor wt. (*t*)	Fluke Area (m^2)	Burial Depth (*m*)	Breakout Capacity (*t*)		
				$\alpha^* = 0$	$\alpha = 30°$	$W_a^{**} = 0, \alpha = 0$
(1)	(2)	(3)	(4)	(5)	(6)	(7)
Danforth: *D*−5000	2.27	1.95	2	44.3	23.4	40.0
			4	136.5	65.5	132.5
Stato: *S*−12 000	5.45	4.77	2	86.4	48.4	78.8
			4	225.8	116.6	217.4
Danforth: *D*−30 000	13.6	6.49	2	113.1	66.9	95.4
			4	273.9	148.4	253.8

* α = Direction of applied pull to horizontal.

** W_a = Weight of anchor.

Singh (1984) extended the theory of Le Lievre and Tabatabee (1981) to fluke anchors buried in clay. The breakout capacities of three anchors in normally consolidated clay are given in Table 2. On comparing Tables 1 and 2, one notes that breakout capacities in clay are much lower than those in sand and that 100 *t* capacity can just be achieved in clay at burial depth of 10 *m*.

TABLE 2

Breakout Capacity of Fluke Anchors in Clay as per Singh (1984)

Anchor Type	Burial Depth (*m*)	Breakout Capacity (*t*) $\alpha^* = 0$
Danforth: $D-5000$	2	8.4
	4	14.3
	10	32.0
Stato: $S-12000$	2	19.9
	4	32.8
	10	71.7
Danforth: $D-30000$	2	31.7
	4	50.6
	10	107.1

$^*\alpha$ = Direction of applied pull to horizontal.

For satisfactory performance, a fluke anchor must penetrate into the seabed and remain stable after attaining the required burial depth. Factors affecting penetration and stability of a fluke anchor are (*a*) fluke angle, (*b*) fluke spacing (*c*) presence of stabilizers such as stocks and (*d*) geometric symmetry (Puech *et al.*, 1978, Beck, 1974). Limited data in literature suggests that fluke anchors may bury upto 12 *m* in soft clays whereas in sands penetration is more difficult and hence burial depth is much smaller. Research is in progress to improve pentration and stability characteristics of fluke anchors (Ura and Yamamoto, 1981).

Mushroom Anchors, Propellant Embedment Anchors and Hydropin Anchors

Mushroom anchors, propellant embedment anchors and hydropin anchors are essentially plate anchors. Their vertical breakout capacity depends primarily on the breakout resistance offered by the soil along with a small contribution from the weight of the anchor. Table 3 shows a comparison between observed values of breakout capacities for propellant embedment anchors in sand and clay reported by True and Link (1979) and for hydropin anchors reported by Kerr (1976) with the range of theoretical values obtained from different theories. One observes from the table that a fairly good agreement exists between observed and theoretical values.

Table 4 gives an idea of the range of breakout capacities which may be obtained using plates anchors having areas of 1, 4 and 16 m^2 embedded at depths of 5, 10 and 20 *m* in sand and clay. One observes that the vertical breakout capacities in clay are much lower than those in sand. Capacity of 200 *t* or more can be easily obtained in sand but not in clay. For developing high vertical breakout capacity, large area plates must be embedded to deep depths. At this juncture, only the propellant embedment anchors offer this advantage.

TABLE 3

Comparison Between Observed and Theoretical Values of Vertical Breakout Capacity for Propellant Embedment Anchors and Hydropin Anchors.

Anchor Type	Anchor wt. *(t)*	Fluke Area (m^2)	Soil Type	Burial Depth *(m)*	Vertical Breakout Capacity *(t)*	
					Observed	Range of Theoretical Values
Propellant: CEL 300 k	1.9	5.9	Clay	5	66	53 to 75
				10	160	106 to 150
				20	365	210 to 300
Propellant: CEL 300 k	1.9	3.0	Sand	5	115	85 to 100
				10	350	240 to 400
Hydropin	0.2	0.3	Sand	3	13	7 to 13
				6.1	30	26 to 56
	0.5	1.1	Sand	7.6	80	71 to 128

TABLE 4

Vertical Breakout Capacity of Plates in Sand and Clay

Burial Depth *(m)*	Vertical Breakout Capacity *(t)*					
	Sand			Clay		
	$A = 1$	$A = 4$	$A = 16$	$A = 1$	$A = 4$	$A = 16$
5	40 to 80	64 to 112	128 to 192	9 to 11	36 to 43	80 to 96
10	80 to 320	320 to 1280	640 to 896	18 to 22	72 to 86	288 to 345
20	160 to 640	640 to 2560	2560 to 5120	36 to 43	144 to 173	576 to 691

A = Area of plate in m^2.

Suction Anchors

Hydrostatic anchors develop breakout capacity on account of the pressure reduction in the anchor cavity due to suction applied by the pump (Figure 8 (*a*)). Model pull-out tests results reported by Brown and Nacci (1971) and Wang *et. al.* (1978) reveal that a soil wedge remains attached to the bottom of the anchor after pull out (Figure 8 (*b*)), which may resemble a cone in the case of sand but may not be so regular in the case of clay. Brown and Nacci (1971) proposed that estimation of breakout capacity in sand could be done on the basis of force equilibrium. However, Wang *et. al.* (1978) have subsequently developed a method for estimating the vertical breakout capacity in all types of soils using the Mohr—Coulomb failure theory in terms of effective stress-strength parameters. Using this method, typical values of vertical breakout capacities that can be developed by hydrostatic anchors having diameters of 1 and 4 *m* with suction pressures of 0.25 and 1 kg/cm^2 are given in Table 5 for sand and clay. From the table it is evident that for developing vertical breakout capacity of 100 *t* or more, anchors having a diameter of more than 4 *m* will be required.

In buried suction anchors, flow of water takes place from the surrounding soil towards the anchor. This causes reduction in the porewater pressure (Figure 9 (*b*)) and hence an increase in the effective stress in the soil surrounding the anchor. Increase in effective stress results in an increased strength of the soil and consequently a larger breakout capacity. Wilson and Sahota (1980) have evolved an equation to estimate breakout capacity of buried suction anchors in sand on the basis of model tests. The equation is empirical in nature and not based on soil mechanics principles.

On the assumption that the equation proposed by Wilson and Sahota (1980) can be used for large diameter anchors, Singh (1984) evaluated the vertical breakout capacities that can be developed by 0.5 *m* and 4.0 *m* diameter anchors buried at 1 to 8 *m* depth, with suction pressures of 0.25 kg/cm^2 and 1.0 kg/cm^2. His results are presented in Table 6. The table also lists the vertical breakout capacities which can be developed by *a* plate anchor without suction, evaluated by using Vesic's (1971) theory. From the table one can observe that suction in buried anchors increases the vertical breakout capacity significantly when the suction pressure is of the order of 1 kg/cm^2.

TABLE 5

Vertical Breakout Capacity of Hydrostatic Anchors

Anchor Diameter (*m*)	Vertical Breakout Capacity (*t*)			
	Sand		Clay	
	$\Delta p = 0.25$	$\Delta p = 1.0$	$\Delta p = 0.25$	$\Delta p = 1.0$
1	1.0	3.4	0.8	2.6
4	28.9	66.6	24.7	52.9

Δp = Suction pressure in Kg/cm^2

TABLE 6

Vertical Breakout Capacity of Buried Suction Anchors in Sand

Burial Depth (m)	Vertical Breakout Capacity (t)					
	$B = 0.5\,m$			$B = 4.0\,m$		
	Buried Suction anchor		Plate anchor	Buried Suction anchor		Plate anchor
	$\Delta p=0.25$	$\Delta p=1.0$	$\Delta p=0$	$\Delta p=0.25$	$\Delta p=1.0$	$\Delta p=0$
1	1.6	4.6	0.6	45.7	102.3	11.5
2	4.0	12.2	2.8	81.0	146.1	32.1
4	11.3	37.9	11.3	162.5	253.9	91.1
8	34.2	118.6	22.6	353.5	547.8	321.8

B = Anchor diameter

Δp = Suction pressure in Kg/cm^2.

At this point of time there is absence of performance data on large full scale suction anchors—both hydrostatic and buried. Suction anchors offer the advantage of being reusable but can suffer from mechanical breakdowns and can, at present, be envisaged for use in future for short term low-risk anchorage.

Pile Anchors

Methods for estimating axial and lateral capacity of piles are well established—API (1980), Broms (1964 *a, b*), Matlock (1970), Reese *et. al.* (1974), *Matlock and Reese (1975). These can be used for evaluating the* vertical and horizontal breakout capacities of long steel tubular piles. These piles typically have diameters varying from 0.75 to 1.5 m with well thickness of 0.025 to 0.075 m. Typical values of vertical and horizontal breakout capacities offered by such piles in sand and clay are given in Table 7. These have been calculated using API method for vertical breakout capacity and Broms (1964 *a, b*) method for horizontal breakout capacity. One notes from the table that uplift capacities of more than 1000 *t* can be achieved in both sands and clays. Horizontal capacities upto 450 *t* in sand and 300 *t* in clay are possible. The horizontal breakout capacities are independent of pile length for long piles since they are governed by the moment of resistance of the pile section. For resisting horizontal loads, it is advantageous to attach the anchor cable well below the pile top. This reduces the pile deflection and increases the horizontal breakout capacity. McLomore *et. al.* (1982 *b*) have presented some curves for vertical and horizontal capacities of drilled-then-grouted long steel piles of different lengths in sand and clay.

TABLE 7

Range of Breakout Capacities of Long Tubular Steel Piles

Pile Length (*m*)	Breakout Capacity (*t*)*			
	Sand		Clay	
	Vertical	Horizontal	Vertical	Horizontal
30	200 to 500	*100 to 450*	*150 to 350*	*50 to 300*
60	800 to 1800	100 to 450	450 to 1000	50 to 300
90	1600 to 3200	100 to 450	1000 to 2000	50 to 300

* For pile diameters of 0.75 to 1.5 m and pile wall thickness of 0.025 to 0.075 m.

The vertical breakout capacity of large diameter short steel piles installed by suction can be calculated by the same method as that used for long steel piles. However, the method for determining horizontal breakout capacity of short piles is distinct from that of long piles. The method proposed by Broms (1964 *a*, *b*) and Brinch Hansen (1961) for short stiff piles can be used for estimating horizontal breakout capacity. Table 8 lists the vertical and horizontal breakout capacities which can be developed by piles having diameters of 3 to 5 m and 10 m. The table clearly indicates that large diameter short piles can be used with advantage for resisting horizontal loads in sand.

Dead Weight Anchors, Gravity Anchors and Mass Chain Anchors

Dead weight anchors, gravity anchors and mass chain anchors rely primarily on their weight for breakout capacity. They may either rest on the seabed surface or sink beneath it depending upon the type and strength of the soil.

TABLE 8

Range of Breakout Capacities of Large Diameter Short Tubular Steel Piles

Pile Length (m)	Breakout Capacity (*t*)*			
	Sand		Clay	
	Vertical	Horizontal	Vertical	Horizontal
5	53 to 89	100 to 180	47 to 79	20 to 45
10	163 to 334	350 to 600	151 to 314	100 to 180

* For pile diameter varying from 3 to 5 m.

The horizontal breakout capacity of mass chain anchors can be evaluated as

$$(P_{ult})_h = f\,(\triangle L)\,\overline{W_L} \qquad \ldots(6)$$

where f is the coefficient of friction between the chain and soil,

$\triangle L$ is length of chain resting on the seabed, and

$\overline{W_l}$ is the submerged linear weight of the chain.

The coefficient of friction between soil and chain as reported by Le Tirant (1979) varies between 0.75 to 1.0 for sands and 0.35 to 0.6 for clays respectively. Ramsden and Watts (1982) have been able to achieve breakout capacity of 150 t in water depth of 1500 m using mass chain anchors.

Gravity anchors usually remain on the seabed surface in case of sands and overconsolidated clays. However, they may become buried in normally consolidated clays. The depth of burial of a gravity anchor can be evaluated by applying the method proposed by Small et. al. (1971) for estimating sinking of submarine pipelines into the seabed. As per this method an object will continue to sink in the soil till the bearing capacity of the soil is adequate to resist the bearing pressure transmitted by the object. This method has been developed on the basis of model tests on submarine pipelines only and is yet to be verified for objects of other shapes. Having established the burial depth, the vertical and horizontal breakout capacities can be determined as per equations (1) and (4). Tables 9 and 10 list the burial depths, vertical and horizontal breakout capacities for different sizes of concrete gravity anchors in sand and clay. The anchors rest on the seabed surface in sand but become completely buried in clay. The vertical and horizontal breakout capacities in sand and clay are of the same order of magnitude. The last column in Table 9 depicts that significant increase in horizontal breakout capacity can be achieved in sands by

TABLE 9

Breakout Capacity of Gravity Anchors in Sand

Dimensions (m)			Burial Depth (m)	Breakout Capacity (t)		
B	*L*	*H*		Vertical	Horizontal	Horizontal (with 2 m deep skirts)
6	6	3	0	151	87	187
6	6	6	0	302	174	292
9	9	6	0	680	392	615
12	12	6	0	1209	693	1089

B = Width, *L* = Length, *H* = Height

TABLE 10

Breakout Capacity of Gravity Anchors in Clay

Dimensions (m)			Burial Depth (*m*)	Breakout Capacity (*t*)	
B	*L*	*H*		Vertical	Horizontal
6	6	3	4.0	187	83
6	6	6	6.75	390	176
9	9	6	7.50	875	413
12	12	6	8.00	1498	662

B = Width, *L* = Length, *H* = Height

providing skirt wall at the base of the anchor. From Tables 9 and 10 it is evident that large sized gravity anchors can provide high breakout capacities in clays and sands in both vertical and horizontal directions.

Conclusions

For breakout capacities of the order of 400 t or more, long steel piles and large gravity anchors seem most suitable. Anchors comprising of pile groups or a combination of gravity anchors and piles are likely to be developed for future use as foundations of tension leg platforms in deep waters.

Large diameter short steel piles and anchors with large fluke areas can be used to resist horizontal loads less than 400 t in sands and less than 200 t in clay. For resisting vertical loads upto 400 t, plate anchors must be embedded to depths of the order of 20 m; only the propellant embedment anchor can achieve such penetration. Suction anchors are still in the developmental stage and can only be used for resisting short term vertical loads.

More attention should be focussed on studying the following aspects :

(*a*) Estimation of horizontal breakout resistance offered by soil to buried objects,

(*b*) Estimation of depth of penetration of anchors with flukes.

(*c*) Estimation of sinking of various types of anchors into soft soils near the seabed.

(*d*) Influence of cyclic loading on breakout capacity.

Results of such studies would help in the development of rational design procedures for anchors of offshore structures.

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