ON THE HOLDING POWER OF SHIP'S ANCHORS

SOME ASPECTS OF THE HOLDING ABILITIES OF ANCHORS MODEL-ANCHOR EXPERIMENTS AND THEIR CORRELATION WITH FULL-SCALE DATA

PROEFSCHRIFT

TER VERKRIJGING VAN DE GRAAD VAN DOCTOR IN DE TECHNISCHE WETENSCHAPPEN AAN DE TECHNISCHE HOGESCHOOL DELFT, OP GEZAG VAN DE RECTOR MAGNIFICUS IR. H. B. BOEREMA, HOOGLERAAR IN DE AFDELING DER ELEKTROTECHNIEK, VOOR EEN COMMISSIE AANGEWEZEN DOOR HET COLLEGE VAN DEKANEN, TE VERDEDIGEN OP DONDERDAG 12 JUNI 1975 TE 16.00 UUR

DOOR

KAREL JAN SAURWALT

WERKTUIGKUNDIG INGENIEUR,
GEBOREN TE UTRECHT

Krips Repro - Meppel

Dit proefschrift is goedgekeurd
door de promotor

Prof. Ir. J. H. Krietemeijer.

To my wife Martha and
my childern,
Wies,Frans and Jaco.

C O N T E N T S

I N T R O D U C T I O N

After an anchor vanishes under the water level it is completely impossible to see what happens next. Because the safety of life and property so often depend on the anchor, it is necessary to gain a deeper understanding of its holding abilities.

Off all factors the holding pull of an anchor depends on, the most important are:

- type, dimensions and distribution of weight;
- inclination and type of bed the anchor holds on;
- direction of the chainpull;
- the position of the anchor with respect to the surface of the bed.

Regarding the first factor, dimensions and weight are usually known.

About the other factors and their influences on the holding power we know less. Therefore selecting an anchor for a ground tackle is a very difficult choice to make from the long lists of anchor models, taking into account that it is sometimes very difficult to justify a choice once made.

In order to increase our knowledge of the phenomena concerning an anchor holding on the bottom , in this thesis the properties of different anchor types have been investigated starting from theoretical model situations.

A historical review of the development of anchors is made, considering the possibility that some anchor types may have fallen unjustly into disuse.

Studying the published results of scientific research it was evident that the aim of most research was directed to the improvement of anchors or on the development of new types and that only relatively small progress was made in the theoretical field of anchor holding power.

Therefore anchor holding abilities are analysed theoretically, considering simultaneously the practical knowledge and experiences already gained.

To check the theoretical statements made by preceding investigators and to provide usefull data for further development, some tests with model anchors were conducted at the Shipbuilding Laboratory of the Subdepartment of Shipbuilding.

The analysis of the holding abilities are subdivided in respect of impervious and soft beds, stockless and stocked anchors and finally of an anchor only penetrating the bed with its flukes or burying itself entirely.

The results are discussed and summarized in some conclusions, expecting by doing so to increase not only theoretical insight in the problems regarding holding power but also to contribute to the reduction of the hazards to men and cargo when an anchor fails to hold.

CHAPTER 1

HISTORY OF THE DEVELOPMENT OF ANCHORS

"There will be times when the anchor is the best navigational instrument in the ship, and you want to be able to rely on it."
Admiral Viscount Cunningham of Hyndhope [23]

1. INTRODUCTION

Three periods can be distinguished in the history of anchor development.
The first, the ancient period of development, comprised the process of growth up to and including the Greek-Roman period of civilization.
The second period, beginning in the Middle Ages and ending in 1821, can be characterized by its very slow progress in anchor development and even by a partial loss of acquired knowledge.
The last period, from 1821 to the present, comprises the latest and still expanding developments.

2. THE ANCIENT PERIOD OF DEVELOPMENT

The ancient period of development can be roughly divided into the prehistoric, the Egyptian, the Greek and the Roman period.
Due to the parallelism of prehistoric anchor development in several cultures and the influence upon them by the Phoenicians and others, anchor development came only gradually into being.

2.1. PREHISTORIC ANCHOR MODELS

In prehistoric times, stone-anchors, killicks and wooden anchors, weighted by means of a stone, came into being.

2.1.1. STONE-ANCHORS

Stone played a prominent role in the life of prehistoric man, ashore and afloat, due to its great unit weight. Hunting and fishing people navigated rivers and travelled from river-mouth to river-mouth, using tree-trunks, rafts, boats of papyrus, or skins stretched on to a framework of reeds.
When it appeared impossible to sound the depth of the channel with his punting-pole he used a rope, weighted with a stone, as a sounding-lead.
His fishing-nets were also weighted by means of stones. When one of these stones stuck, the system acted as a ground-tackle; the next step to a somewhat heavier rope and heavier anchor-stone could be made easily.

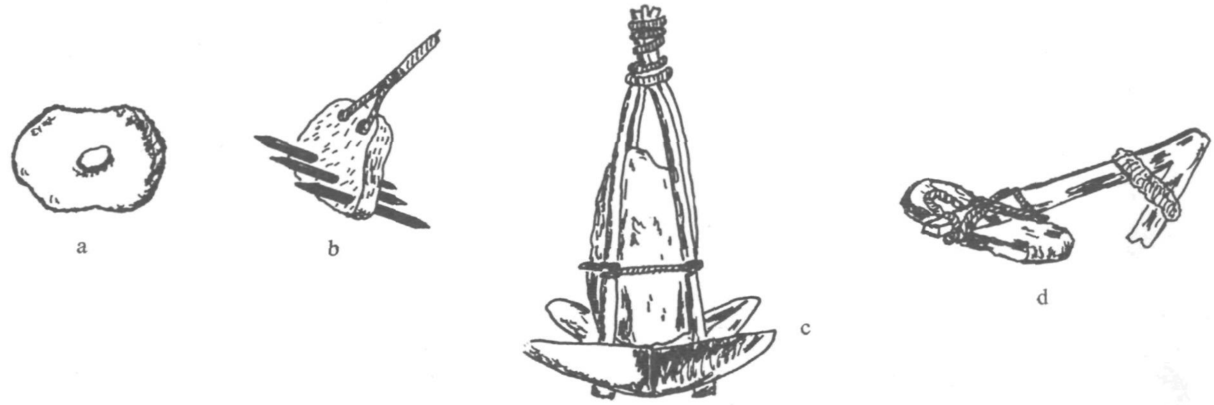


Fig. 1. Some prehistoric anchor models:
a. Anchor-stone found at Stade near Hamburg;
b. Stone-anchor with three sticks from the temple with the obelisks at Byblos, Lebanon, 19th century B.C.;
c. Killick found at Marstrand, Sweden;
d. Malayan wood anchor weighted with a stone.

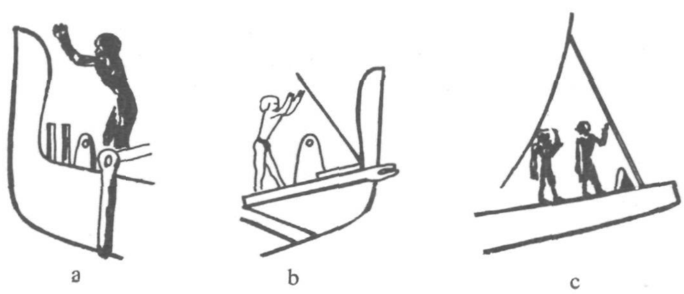


Fig. 2. Some ancient Egyptian pictures of ships with anchor-stones:
a. Fore-part of one of the ships of Pharaoh Sahure;
b. Fore-part of a ship, pictured in the sepulchral temple of King Unas;
c. Fore-part of a ship in relief, in the Mastaba of Akuhotep.

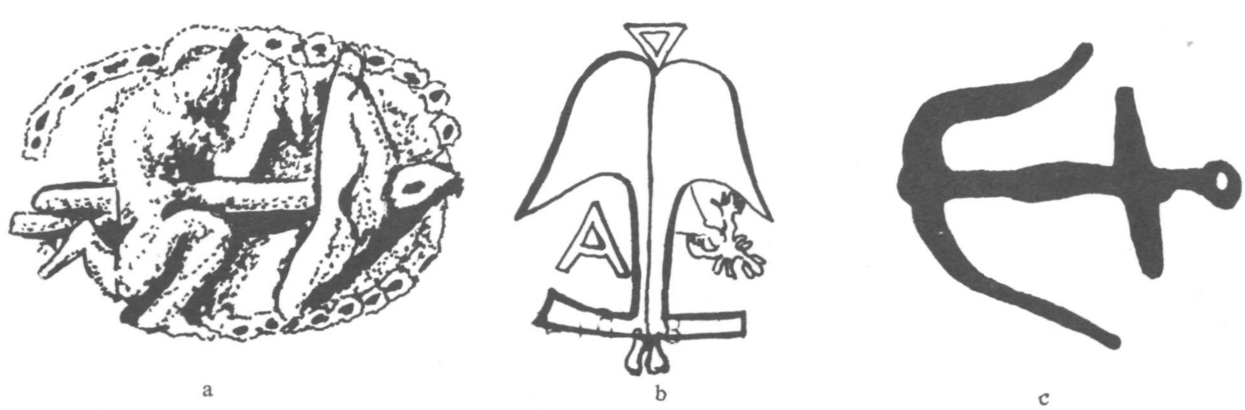


Fig. 3. Some Greek pictures of anchors:
a. A carpenter doing the final shaping on his anchor, picture on a gem of circa 500 B.C. from Sardinia;
b. Anchor indicated on a coin from Greece, Appollonia of the fourth century B.C.;
c. Hook anchor as a shield emblem in an Attic vase painting of the late sixth century.

At Stade, near Hamburg, an anchor-stone of about 12 kg, was found, figure 1a, with a bore-hole of 4 cm, made for the fastening of an anchor rope in its centre [1a].
Although stones only develop a small holding pull in relation to their weight, their holding capacity is so reliable that even now, the holding capacity of massive concrete blocks is preferred when executing large coastal engineering works. The holding capacity of stone-anchors appeared to be improved by fitting additional sticks in specially made bore-holes. Figure 1b [2].

2.1.2. KILLICKS

Prehistoric man drew-up with difficulty, a tree-stump in his fishing net.
The use of such a stump as an anchor followed logically. The next step, the construction of a wooden block with one or more stones as weights, with points extending in several directions, offered such a cheap and reliable anchor model that these "Killicks" were still used in 1925 on the Breton coast.
That in figure 1c shows a killick with four arms, and was found at Marstrand, Sweden. It dates from around 650 B.C.

2.1.3. WOOD WITH A STONE-WEIGHTED ANCHORS

At first, the weight of the stone only gave a holding pull; it was soon recognized that with a hook, greater pulls could be exerted. To sink onto the bed and to turn over a wooden hook into a good position, a stone was attached at the shank, as for instance was done with the Malayan anchor indicated in figure 1d [3].

2.2. ANCIENT EGYPTIAN ANCHORS

In ancient Egypt, water-transportation was so important that people could imagine their godhead Ra and other gods only sailing in a ship. To moor their ships they used stones. Figure 2a shows a pierced anchor-stone on the fore-part of one of the four ships Pharaoh Sahure sent in about 2550 B.C. to plunder the Syrian coast.
On a relief in the tomb of Pharaoh Akuhotep, fifth dynasty, an anchor-stone is also shown forward. Figure 2c [4].

A picture in the sepulchral temple of Hotepherachet at Saqqarah indicates on the stern of a vessel a man besides the steersman weighing an anchor-stone circa 2400 B.C. [5].
In the tomb of Toetanchamon, about 1345 B.C., a funeral fleet of eighteen model ships were found. Fastened to the starboard steering paddle of one of the models, is a miniature stone anchor, shaped almost after the fashion of a T square, with one of the arms slightly pointed.
Herodotus mentioned that Anchyronpolis on the Nile, "the city of anchors", sixty miles south of Memphis, derived its name from the presence in the vicinity of quarries from which stone-anchors were cut [1b].

2.3. ANCIENT GREEK ANCHORS

As the Greek men-of-war, at the time of the Trojan wars were very small, they were moored by means of ropes attached to mooring-stones, "Eunai", mentioned in the Odyssey for Telemachus's ship.
The word "ankyra" appears in Greek about 600 B.C. on a fragment of Alcaeus.
The original meaning of the word is connected with the words curved and hook [1a and 6]. A picture on a gem, circa 500 B.C., figure 3a, found in Sardinia indicates a carpenter doing the final shaping on his anchor. The picture is encircled by an anchor chain. The result was that the basic shape of the classical, "common", or "old-fashioned" anchor, used all over the world till 1850,

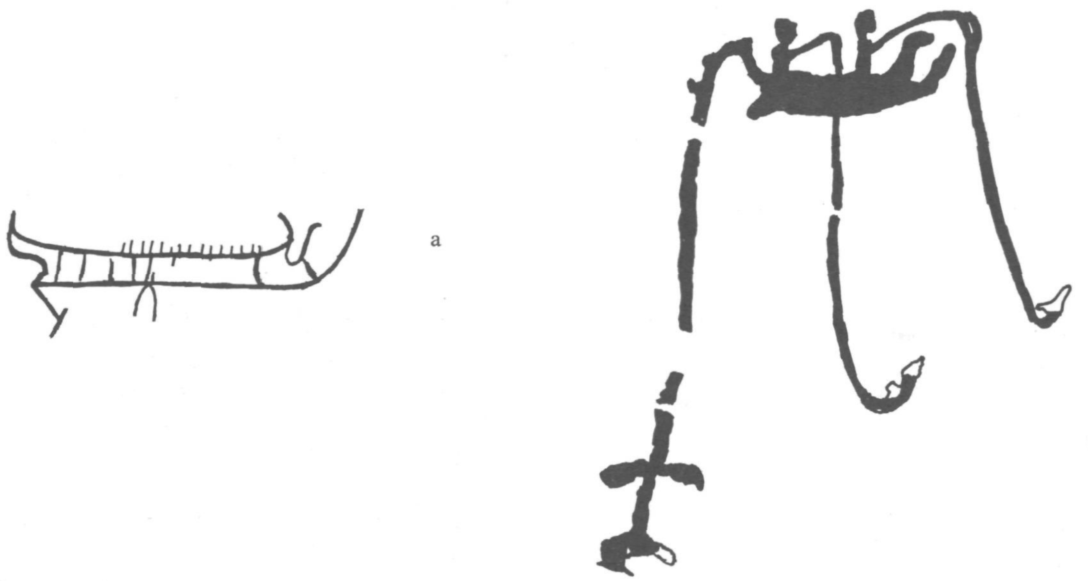


Fig. 4. Some pictures on rock-faces in Sweden:
a. A vessel on a rock-face at Himmelstadlund;
b. Fisherman on a rock-face at Kville.

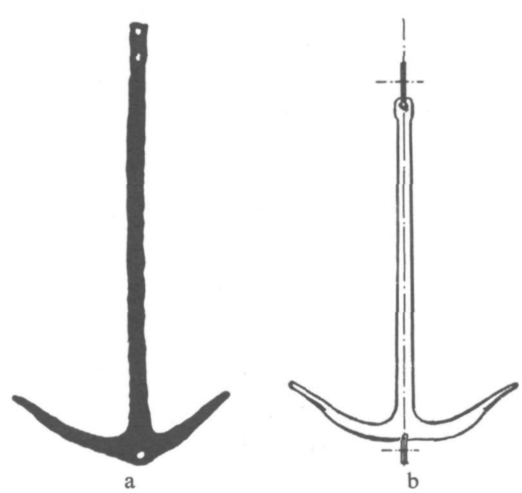


Fig. 5. Some Viking anchors:
a. Anchor with removable stock found at Bulbury Camp in Dorset;
b. Anchor of the Oseberg ship.

with shank, stock, arms and flukes, became known.
On a coin from the Greek city Apollonia, fourth century B.C., figure 3b, a stocked anchor with extended flukes is engraved.
Figure 3c shows a hook anchor as a shield emblem in an Attic vase painting of the late sixth century.
Official reports of a navy yard at Athens indicate a Greek trireme was equipped with four light and four heavy ropes for mooring and anchoring, together with two iron anchors each less than 25 kg and, if necessary, weighted by means of stones or pieces of lead.

2.5. ROMAN ANCHORS

On a monument commemorating of the Roman victory over the Carthaginian fleet at Mylae, 260 B.C., classical anchors with flukes, shank and arms are shown, evidence of the use of these anchors in the Roman fleet. During excavation of the two Caligula pleasure-barges at Lake Nemi two anchors were found in the vicinity. Figure 27 and 28 chapter 5.
About ninety meters from the starboard side of one of the barges a forged iron anchor, figure 28, was found with a weight of about 500 kg.
Arms and shank had been sheathed with wood, held by means of wrought iron bands. The iron stock, which appeared to be removable, lay horizontal in the bed and could be fastened into the shank and be held in position with a cotter pin.
On one of the arms, covered by the wood sheath the original weight MCCLXXC, 1275 Roman pounds, about 420 kg had been indicated. The length of the shank appeared to be 3.45 meters and the length of the removable stock 2,97 meters. Because all forged parts had been highly finished, probably the wooden sheath was made to improve the holding capacity of the anchor in the bed of Lake Nemi.

The second anchor, with a total weight of about 1450 kg, figure 27, was made of oak beams and had a shank with a length of 5.5 meters. At the level of the 2.4 m lead stock, the beam forming the shank is crossed by sticks of green chestnut wood, round which lead has been cast in an open mould. The diameter of the mooring rope was 14.6 cm.
In the Mediterranean Sea many lead stocks are found with weights up to 360 kg. At Cartagena a lead stock, with a length of more than two meters, was found weighing 675 kg. The oldest dated stock, sixth century B.C., was found near an Etruscan ship-wreck.
Besides lead stocks, many lead collar pieces were found, which probably enclosed arms and shank, figure 38 of chapter 5. The huge grain carrier that "Heron of Syracuse" presented to Ptolemeus III, 246-221 B.C., was equipped with eight iron and four wooden anchors.

The ship St. Paul travelled with to Rome and that ran ashore at Malta was equipped with at least six anchors.
At the isle Giannutri, near a mid-second-century B.C. ship-wreck, four wooden anchors with a lead stock and three iron anchors were found.
A ship that ran aground near Taranto, circa 100 A.D. had been equipped with five anchors, each weighing approximately 600 kg [7b].
Near Yassi Ada, in the remains of a ship that sank c. 625 A.C., having a length of about 62 feet and a beam of 16 feet, eleven iron anchors and two stocks were found. Six of the anchors had weighed about 73.5 kg (250 Roman pounds) each, three about 129 kg (450 Roman pounds) each and the other two were of some unknown intermediate weight [7c]. The calculated weight of one stock proved to be 14.5 kg (50 Roman pounds); the other 31.4 kg (100 Roman pounds).
Estimating the anchor weights 250+50, 350 + 75 and 450 + 100 Roman pounds, this ship was equipped with a total anchor weight of 1.26 tons.

About 56 B.C. the Classical anchor model was known in Northern and Western Europe. The Venetians, defeated at sea by Julius Caesar used iron anchors attached to iron chains. Such an anchor, figure 5a, dating to the beginning of our era, was discovered in a prehistoric hill-fort called Bulbury Camp at Lytchett Minster, in Dorset.

2.5. DEVELOPMENT IN NORTHERN EUROPE

Rockdrawings form the oldest sources of information about Scandinavian shipping. A drawing on a rock near Himmelstadlund in Sweden, c. 1200 B.C., shows a vessel with perhaps a ground tackle, indicated as a sloping line below the vessel (figure 4a). On a rock-wall of a rock near Kville, also in Sweden, two fishermen are indicated, with their vessel moored with a stock-anchor, figure 4b, [10]. The oldest excavated anchor is the stockless anchor of the Oseberg ship, c. 850 A.D., with a shaft length of 1.02 meters and weighing only 9.9 kg. In view of the good condition of the anchor when it was found, it must have been nearly-new when it was buried with the ship. Figure 5b. Near the Gokstad-ship, only a wooden anchor stock was found with a length of 2.75 m [11].
Thus the Viking ships were equipped with stock and stockless anchors.
The anchor of the Oseberg ship appeared to be similar to the anchor discovered at Bulbury Camp, but it is missing the removable stock.

3. FROM THE MIDDLE AGES TO 1821

3.1. STANDSTILL AND DECLINE

From the Middle Ages until 1821, the Classical stock anchor was commonly used. The shape of the stock-anchors remained unchanged, only the dimensions increasing with the dimensions of the ships. The knowledge of anchors with a removable stock became lost; this form was re-invented by the Dutch in the eighteenth century [8]. Although a chain with a length of at least 10 meters was found, attached to the shadow-ship of Ladby, tenth century, the anchorchain also fell into disuse.

As shown in the Bayeux tapestry, in 1066 William the conqueror used, during his crossing to England, small iron Viking stock anchors, attached to ropes.
In 1340, the first painting of a ship with a hawse-hole was made in the St. Eusorgio at Milan. Besides the classical anchor, the grapnel was used on board small vessels. On a drawing of a Byzantine Dromon, fourth century A.D., grapnels instead of stock anchors are shown. These anchors were especially used in the Mediterranean area among others, on the galleys. Also on the drawings of huge mediaeval men of war, grapnels with three to eight arms are indicated. These anchors were thrown into the decks or behind the bulwarks, of the enemy ships so it could be hauled to boarding distance. After the introduction of the widened points (the flukes wrought to the arms), development of the stock anchor came to a standstill for centuries.

The ratios between the anchor dimensions and the dimensions of a ship were taken over from generation to generation and at last codified in Holland in the comprehensive books of "van YK" and "Witsen" [12,13]. Dutch men of war were equipped with four equal anchor rigs, each rig consisting of one stock anchor and one anchor rope. Dutch merchantmen were equipped with four different anchor rigs, differing in size and strength. The sheet-anchor rig was the heaviest; it could be put into use at a moment's notice. For every day use, there was a "every day anchor rig" with dimensions of 7/8 of the sheet-anchor rig.
The remaining two rigs, with dimensions of 7/8 of the "every day anchor rig" were used for mooring in rivers.

The shank length of the sheet-anchor was chosen equal to 4/10 of the breath of a ship. "Van Yk" already calculated that the anchor weight (in Dutch pounds) is equal to the third power of the length (in Dutch feet) of the shank.
The cost of anchor testing, inclusive of a certificate, amounted to a half penny per hundred pounds anchor weight [12]. Per hundred pounds, the maximum allowed difference in price (including Municipal weighing and testing) between the more expensive anchors manufactured in Rotterdam and the anchors made in Amsterdam was twelve pennies [14].

3.2. TRANSITION FROM ANCHOR ROPE TO ANCHOR CHAIN

Hempen cables are strong and able to absorb impact loads. For a long time, puddled-iron chain of equal strength appeared to be many times heavier than hempen cables, until, due to the increase of quality of wrought iron combined with the increase of ship dimensions, this advantage became lost.
Lt. S. Brown, of the British Navy, fitted the "Penelope" with the first modern anchor chain in 1809. Previously, in the winter of 1808, a merchant vessel called "Ann and Isabella", of 221 tons, owned by J. Donkin, had saved a whole tier of ships that made fast to her, their hempen cables having been cut by a great flood of ice in the river Tyne. She was one of the first vessels to be supplied with iron cable. This development in favour of the iron anchor chain continued, hence c. 1834 on all large ships, the anchor ropes had been exchanged for iron chain cables [15].

3.3. IMPROVEMENT OF THE CLASSICAL STOCK ANCHOR

A general letter of the Navy board, dated 18th of November 1800, circulated to all the dockyards in the United Kingdom concerned to the frequent breakages of anchors. "Richard Pering", a clerk of the Exchequer at Plymouth dockyard, commenced investigations on his own. In January 1801, less than two months after the letter, he submitted plans and models to the Navy board, proposing an anchor model which avoided the vulnerable welding of the arms direct onto the shank at the crown.

A test anchor was manufactured in 1813 and after successful trials, by 1815 the Navy Board adopted it for the British Navy. Further development of the classical stock anchor continued. In 1844 the iron stock was introduced into the British Navy. In 1851, R.N. Rodgers patented a classical stock anchor with a removable iron stock. The anchor was on show during the Great Exhibition.
After introduction into the British Navy, figure 6a, this model was called "Admiralty stock anchor"; a name up to the present in common use with the name "Common stock anchor". In the meantime, in 1821, Hawkins patented and started the development of the stockless anchor, an anchor pattern that superseded the Classical stock anchor models almost completely.

4. DEVELOPMENT SINCE 1821

4.1. BEGINNING OF THE DEVELOPMENT

In 1821 the Hawkins anchor was patented, specifying that "the arms are movable in a plane at right angles to the shank, so that both flukes enter the ground simultaneously, ..., a stock is not required for anchors of this description. It was remarkably modern in principle and born before its time.
It was not extensively patronised and fell into disuse. Another less successful invention of H. Bessemer concerned the production of cast steel anchors, patented in 1855. Later, others were successful, so development of many anchor forms commenced and is continuing in full swing up to the present.

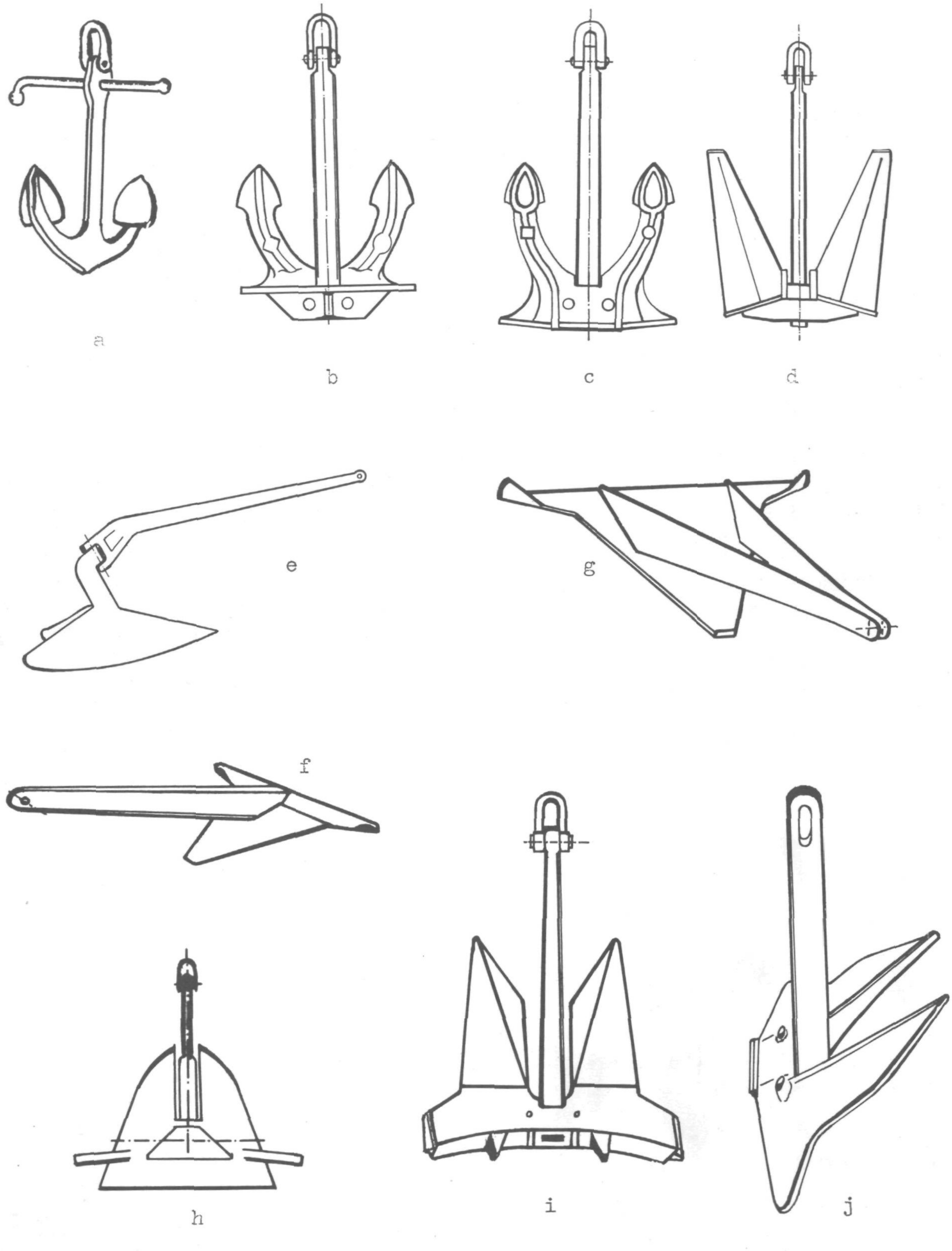


Fig. 6. Some anchor models.

a. Admiralty anchor
b. Hall anchor
c. Spek anchor
d. Pool anchor
e. Plough or C.Q.R. anchor
f. Delta anchor
g. Delta twin-shank anchor
h. Stevin anchor
i. A.C.14 anchor
j. Stokes anchor

Broadly, the development of the following anchor forms can be distinguished; the development of the stock anchors with moving hand and arms, (moving in a symmetrical plane through arms, hands and shank) : stockless anchors : grapnels : anchor forms penetrating the bottom in a particular manner : plough anchors : anchors with a stock near the shackle end of the shank : anchors with a stock at the crown and lastly, stable stockless anchor forms.

4.2. DEVELOPMENT OF PORTER'S AND TROTMAN'S ANCHORS

In 1838, Porter patented an "anti fouling anchor" with arms moving in the symmetrical plane, through the arms and shank. This anchor model was already indicated in a patent issued to Piper in 1822. After the improvements of Trotman, in 1852, figure 39 chapter 5 , this design was very popular and widely used, as evidenced by the number still being recovered.
It was superseded by the stockless anchor models in c. 1890. Due to the advance of the stockless anchors, the shank could now be drawn up into the hawsepipe.

4.3. FURTHER DEVELOPMENT OF THE STOCKLESS ANCHOR

In regard to the Hawkins anchor, some improved models were developed, made and used on a small scale, though success remains moderate. In 1886, a patent was issued to J. Verity and J.F. Hall for a stockless anchor, shaped like the Hawkins anchor. After the additional improvements and patents of 1888 and 1889 issued to Hall, development of the "Hall anchor" was, for the greater part ended (figure 6b). The anchor was an immediate success with the shipping companies. In 1886, a patent was issued to Westeney and Smith; in 1887 to Byer and was enlarged upon in 1900; in 1901 to Balldt, starting a further development to which, amongst others, Dunn, Tuzack, Gruson and Mairer contributed.
For the time being, there is very evidence that this development will be continued. In the Netherlands, various stockless anchor models were invented, such as the "Spek anchor" developed by Mr. W. Speksnijder ca.1954 and the "Pool anchor" developed by Mr. L.F.J. Pommée around 1958 (figure 6c and 6d).

4.4. DEVELOPMENT OF THE GRAPNELS

To simplify the stowage of grapnels, hinges were introduced producing a more manageable idle position. It appeared that by connecting the arms in pairs to rings, rotating about the shank, an idle position of the arms could be realized with all the arms in one plane through the shank. Another form, with a movement of the arms comparable with the folding movement of an umbrella is applied to the "Umbrella-folding-grapnels". In addition to the multi-sided symmetrical grapnels, some two-sided symmetrical forms as the "Herve-anchor" were developed. At present it can be stated that the development of grapnels may be considered ended.

In 1850, the "Mushroom anchor" was patented, an anchor form that can be considered as being an "imaginary" grapnel with many arms. It was supplied to submarines and used for permanent mooring of lightships and buoys.
Without special equipment to dig it in, a mushroom anchor remains upon the bed, developing only a very small holding power. In view of this lack of holding power a mushroom anchor form - "Langston anchor" - was developed with a long pipe shank. Forcing water from the shackle end through the pipe, between the mushroom surface and the bed the anchor is washed into the soil.
Taking this development further, alternative methods can be found to force an anchor to penetrate into the soil quickly.

4.5. ANCHOR FORMS WITH ASSOCIATED EQUIPMENT, ASSISTING PENETRATION OF THE ANCHOR INTO THE SEA BED

The "Army Material Command's Engineer Research and Development Laboratories" U.S.A., developed an anchor system in which the anchor is fired into the soil with a mortar. This "embedment anchor Seastaple", is employed where the load of the mooring wire has to be held in a roughly vertical direction. A less fiery solution, "the Vibratory anchor" was developed by the "Ocean Science and Engineering Inc., Rockville". A vibrating driving head, fluidizing the bottom material around the anchor drives the fluke assembly into the seafloor.
After embedding, the driving head can be recovered. In both systems, the anchor wire is attached to the fluke assembly in such a manner that the assembly rotates (embedded), in a direction perpendicular to the load of the anchor wire. Considering the continuous increase of Offshore activities, further development of anchor forms with additional equipment for embedment can be expected.

4.6. PLOUGH ANCHOR FORMS

In 1933, a patent for the "C.Q.R. anchor was issued to G.I. Taylor.
The holding ability of this "Secure anchor" is attained by means of a crown part formed by two mirror symmetrical coulters (figure 6e). It's holding power is restricted due to its small penetration depth in the soil. It is therefore only supplied to small vessels. Closely allied to the plough anchors are the anchor forms with scoop shaped flukes, which, shifting over the bed, taking up bed material, in time penetrate the bed. Amongst others, the "Gillois, Heuss and Multisoc" anchors attain their holding power by shifting over the bed.
Development of these anchor forms may be regarded as ended.

4.7. THE MARTIN ANCHOR

At the shackle end of the shank of the Martin anchor, introduced into the French Navy about 1890, figure 40 chapter 5 , a small stock was maintained, in the belief that the stock and not the flukes hold the load. It was soon deleted, due to the troubles it caused hauling in the anchor. This in contradistinction to the anchor forms with a stock at the crown.

4.8. ANCHOR FORMS WITH A STOCK AT THE CROWN

The Chinese wooden stock anchor, figure 29 chapter 5 , already in use about 2000 B.C., is one of the oldest anchor forms. The essential difference between this Chinese anchor and the Northhill anchor, patented in 1937, is that the straight-pointed arms are replaced by plough-shaped flukes. Both anchors have a common feature in that as soon as the crown and shank have penetrated the bed, further embedment and therefore further increase of holding pull, is prevented due to the upright arm and fluke. This unfavourable behaviour does not appear with the "Delta anchor", an anchor developed about 1968 by Mr. P.J. Klaren, figure 6f. But in respect to this anchor, it is obvious that it must be put upon the bed with the fluke below the shank.

The fluke of the "Wishbone anchor", a patent issued to Piper in 1822, figure 31 chapter 5 , pivots between two shanks and differs therefore essentially from the "Twin shank" anchor, figure 6g, developed from the "Delta anchor".
In 1939, Danforth patented an anchor with a hinged shank and a stock fixed to the crown, thus a synthetic form of the basic old Chinese anchor and the stockless anchor. Due to the stabilizing influence of the stock, it soon came into general use and further development commenced. This led, amongst others to the "L.S.T." anchor, figure 32 chapter 5 , the "Budock-Stato" anchor and in 1973, by Mr. R. van den Haak introduced "Stevin" anchor, figure 6h.
The favourable influence of the stock led to further development of the stockless anchors.

4.9. STOCKLESS ANCHORS WITH STABILIZING CROWNS

By extending the crown of a stockless anchor, the extremities produce a favourable stabilizing influence when the distance between them is chosen greater than the distance between the outsides of the flukes.
In this manner, the "d'Hone" anchor; the "Stokes" anchor, figure 6j and the anchors developed by the British Admiralty, figure 6i, " Admiralty Cast Type 14", are formed [17]. The stabilizing influence of the crown extremities is about comparable with the stabilizing influence of a stock.

4.10. FURTHER DEVELOPMENTS

Development of anchors, commenced in 1821, conducted and stimulated by the Navies of many countries, may not yet be regarded as being finished.
Besides the large Admiralty Research Laboratories, many independent research workers have added good new anchor forms to the long list of well-known and well-tried types. In this way, development on large and small scale will be continued for years, stimulated by the increase of the ship dimensions, oil and natural gas exploitation offshore and on the high seas, and by the execution of large civil offshore projects.

CHAPTER 2

DEVELOPMENT OF TESTING AND SCIENTIFIC RESEARCH

1. INTRODUCTION

Anchor tests can be classified into three groups. Firstly, the usual inspection and testing of newly manufactured anchors; secondly, testing with the aim of verifying anchor behaviour under circumstances similar to general use; and thirdly the pure theoretical and analytical scientific testing.

2. INSPECTION AND TESTING OF NEW ANCHORS

In the times of the Roman Emperors new anchors were inspected on the basis of good workmanship and weight, as apparent from the weight indications found on the recovered anchors [9]. In the Dutch Golden Age anchors were tested, weighed and entered in a register and a Certificate was issued. Since the tests of Pering and his publication of the results in 1819, development of the modern anchor testing methods began, a development conducted by the offices of the Navies and Classification Societies.

3. TESTS UPON THE PRACTICAL USE OF ANCHORS

Although various Navy offices conducted these rests regularly, they became a profitable operation when the Classification Societies accepted a 25% weight reduction on the minimum required anchor-weight, (based upon tests) for their approval of "High-Efficiency" anchors. These tests usually consist of dragging full-scale anchors, hitched by wire to a tug, through some well-known and registered sea-bed. The subsequent recording of the pull being solely dependant upon the time available. Occasionally, the speed and actual movement of the tug is measured. Normally the anchor penetration, digging-in and behaviour on the sea-bed is not checked or recorded. It therefore follows that these "tests" have little scientific content and are capable of statistical analysis only.

4. SCIENTIFIC RESEARCH

In this field as the first real research worker, R. Pering has to be mentioned honourably, because he published the results of nineteen years experience and carefully conducted tests in 1819 [18]. In connection with his results the British Admiralty did a great deal of the work by conducting many tests and publishing the results in detail. Often test results are not published for reasons of secrecy, or published incomplete for commercial gain.
The latter usually results in the course of years to the loss of important data.

In 1932, R.K. James and W.E. Howard commenced, at the Massachusetts Institute of Technology, their investigations into the maximum holdingpower of anchors; these investigations were continued by W.H. Leahy and J.M. Farrin [19].
Reading a paper presented to the SNAME in 1934, Read Admiral Land mentioned in

addition to the results of full-scale anchor tests, the tests conducted with scale model anchors [15]. Discussing the paper, Mr. H. de B. Parsons mentioned that in 1907 he formulated and in 1915 published his approximate law, "The holding powers of different sized anchors are proportional to the surface of their flukes multiplied by the square of the distance they are buried in the mud" [20]. In Rear Admiral Lands reply to the discussion, he mentioned that Leahy and Farrin had already found that the holding power of an anchor should depend upon a linear dimension cubed (a volume), which is reflected in the moment.

Reading a paper presented to the SNAME in 1935, Leahy and Farrin explained the intention and the results of their tests with model anchors dragging dry or submerged in a 15' x 21" x 3'" anchor tank, in turn filled with fine sand or clay. Using their formula regarding the holding pull, $P = K.A^k$, (P holding power, A fluke area, K and k constants, $k \simeq 1.53$), their model test results in sand, corresponded with the full-scale test results of the dragging tests with the "U.S.S. Trenton" at Coronade Roads. They concluded that the static moment about the bed surface of the vertical projected fluke area, (assuming a horizontal direction of the shank) can be used to compare the holding power of different anchor types [21].

127 years after the publication of Perings book in 1936, R.A.F. Wing Commander D.F. Lucking read a paper presented to the RINA, concerning English-conducted anchor tests. With the object of developing improved anchors for seaplanes, on the beach of Felixtowe dragging tests with full-scale and model anchors were conducted. "It was found that the holding forces of the full-size and fifth-scale models, with any angle of cable, were in proportion to the weights of the models, that is, to a linear dimension cubed" [22].
Discussing the results of model tests in a 15' x 3' x 2' anchor towing tank, in connection with a remark of Prof. G.I. Taylor, it was indicated that, "it must be remembered that the simple truth of the L^3 law (L a specific length) does depend on anchors of different sizes taking up the same attitude in relation to the bed". The results of further tests carried out in 1932 indicated that the holding force of an anchor in other beds could not be predicted from the holding force measured on the Felixtowe beach.

In 1950 H.L. Dove and K.P. Farell read their papers presented to the RINA, concerning tests of model anchors at the Admiralty Experiments Works, Haslar [23]. Dragging model anchors in a 25' x 3' x 3' anchor test-tank, the holding pull decreasing influence of an upwardly directed chainpull could be proved; a decreasing influence, increasing with the depth an anchor penetrates into the bed. Ten years later, H.L. Dove and G.S. Ferris discussed, referring to model tests conducted at Haslar, the newly developed "A.C.14" and "A.M.12" anchors [24].

In 1965 J. le Bloas published the results of dragging tests with model anchors in a 5.0 x 2.0 x 0.7 meters tank of "Le Laboratoire de Mécanique des Fluides de la Faculté des Sciences" at Straszbourg [25]. The test results confirmed the suitability of the holding pull formula of Leahy and Farrin and the relation between the holding pull and the static moment of the vertical projected fluke area. Casually the earth resistance forces acting on the flukes of a dug in anchor were indicated.

In the written contributions referring to a review of H.L. Dove in 1972, concerning anchor research and development at Haslar, it appeared that with regard to theoretical determination of anchor holding pull, after the statements of Leahy and Farrin in 1935, no further developments or improvements were published [29].

C H A P T E R 3

MOVEMENTS OF ANCHORS HOLDING ON AN IMPERVIOUS PLANAR BED

1. DETERMINATION OF A THEORETICAL MODEL SITUATION

In order to determine a model situation, the anchor type, bottom, direction and magnitude of loads and forces have to be specified.
Because stockless Movable Fluke anchors are extensively used in the merchant marine, this type of anchor in figure 7 was chosen. The important parts are the crown, with the flukes forming the head and the shank with the main shackle.
The head has two symmetrical planes, one symmetrical plane between the flukes and one through the flukes. The intersection of both symmetrical planes is the centre line of the head. The shank hinged to the head can swing through degrees in the symmetrical plane between the flukes. The angle between the centre line of the shank and the centre line of the head is the fluke angle β, which can increase up to a maximum value βe.

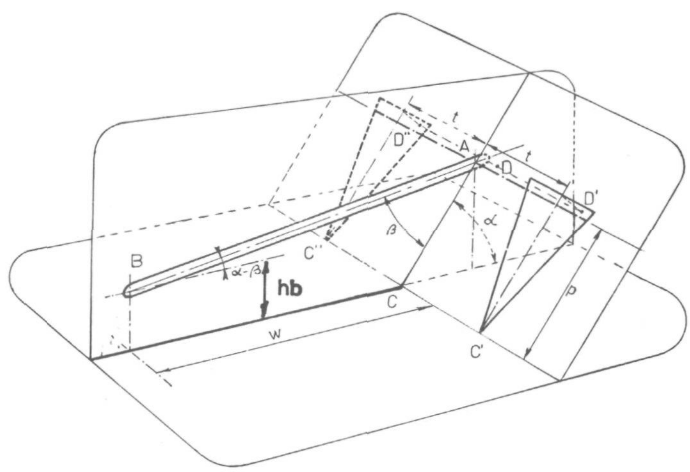


Fig. 7. The theoretical anchor model situation.

The distance between the points C' and C'' is equal to $2t$. The distance from a point of a fluke to the extended swing axis of the shank in the crown is p.
The extremities D' and D'' of the crown lie on a distance k, under the symmetrical plane through the flukes, and their projection in the symmetrical plane between the flukes D lies on a distance a, after the hinge point of the shank A. See figure 8. The length of the shank l is the distance between the centre line of the pin hole of the main shackle and the centre line of the hinge.
The friction in the hinge point will be neglected.

With respect to the hard bed, the assumptions made are:

- the points of the flukes do not slip over, or penetrate in the bed surface;
- the points hold behind an uneven area;
- further, we assume a horizontal and flat bed surface.

The important loads and forces are:

- the total weight of the anchor Ga ;
- the chainpull acting on the shank Ks;
- the vertical reaction forces of the bed acting vertically on the end of the shank Pb and on the point of the flukes Pc;
- the horizontal resistance Lb and Lc, acting on both shank and flukes.

The weight of the anchor is apportioned between the weight of the shank Gs acting at a distance $\lambda s.l$ from B and the weight of the head Gc acting at a distance $\lambda p.p$ from C. These weights can be apportioned as follows:

Gr, acting at the point of the shank B, $Gr= (1-\lambda s)Gs$,
Gp, acting at the points of the flukes C, $Gp= (1-\lambda p)Gc$ and
Gn, acting at the hinge point A, $Gn= \lambda s.Gs+\lambda p.Gc$.

Indicating Gn with $\lambda.G$ and Gr with $(1-\lambda)G$, the weight $G, G=Gr+Gn$, represents the moving weight portion. This weight applies at the centreline of the shank at a distance $\lambda.l$ from B. $\lambda=Gn/(Gr+Gn)$...... ...... (1)

With respect to the chainpull, the assumption is made that the pull is acting in the vertical symmetrical plane between the flukes, because usually an anchor will slew with the shank in the direction of the chainpull.
Kh is the horizontal and Kv is the vertical component of the chainpull.
To simplify the formulas, the assumption is made that the horizontal resistance of the point of the shank is equal to zero, when B touches the bed.
Taking all introductory made assumptions, the movement of an anchor can be analysed in the vertical symmetrical plane between the flukes.
See figure 8.

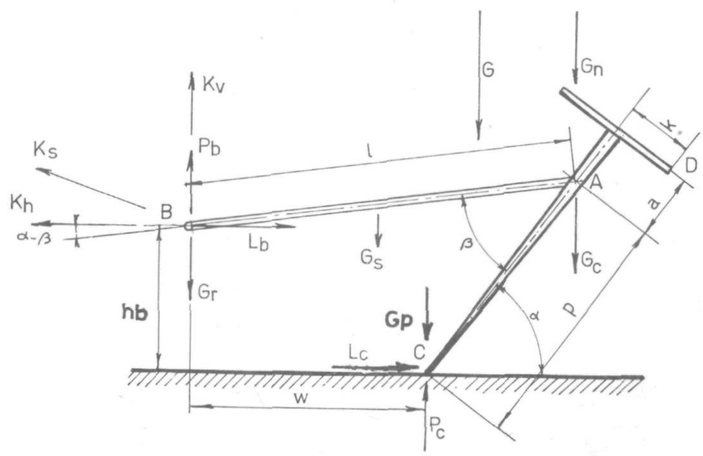


Fig. 8. The loads and forces acting on the anchor.

The inclination of the flukes α is the angle between the centre line of the head and the bottom plane. The vertical distance from the centre of the pinhole in the shank to its projection in the bottom plane is hb. The horizontal distance from the projection of the pinhole centre in the bottom, to the projection of the points of the flukes in the vertical symmetrical plane, is w.
Assuming the values of Kh and Kv change slowly, the first inertia influences of the anchor parts can be neglected.

2. THE ANALYSIS OF THE BEHAVIOUR OF AN ANCHOR

Assuming the chainpull increases, with the help of the developed model situation, the different movements and the developing transitions between the movements can be analysed.

From the starting position, when head and shank rest on the bed, the first movement starts. Movement ends when the anchor erects so that the flukes are standing on their points and the tip of the shank rests on the bed, the final position. In this situation, the angle of inclination of the flukes is αe and the fluke angle is βe.
The analysis will show that four different kinds of anchor movement are possible. Further, it appears that six characteristic patterns of movement can occur. The pattern of movements and the relating anchor chainpull depend merely upon the anchor design. The indice *b* refers to the starting position and the indice *e* to the end situation.

3. THE FOUR ANCHOR MOVEMENTS

1. The crown and the points of the flukes are resting on the bed.
   The shank whips up and point *B* lifts off the ground.
   The Whipping movement (see figure 9).

2. The shank point *B* slips over the bottom, while the crown tips over.
   Extremity *D* lifts off the bed. The Tipping movement (see figure 10).

3. The shank tilts the head, because the fluke angle is equal to the maximum value βe. Only the fluke points *C* are resting on the bed.
   The Tilting movement (see figure 11).

4. Only the fluke points are resting on the bottom. The fluke angle β is smaller than the maximum value βe, so shank and crown swing around *C*.
   The Swinging movement (see figure 12).

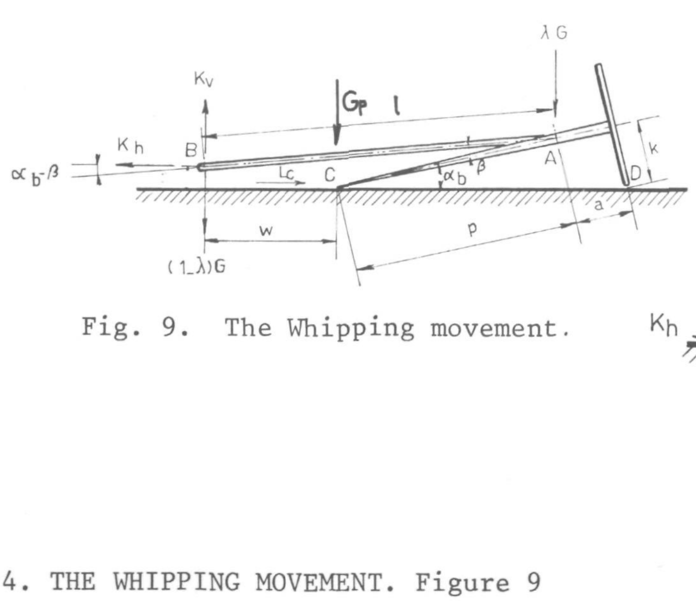


Fig. 9. The Whipping movement.

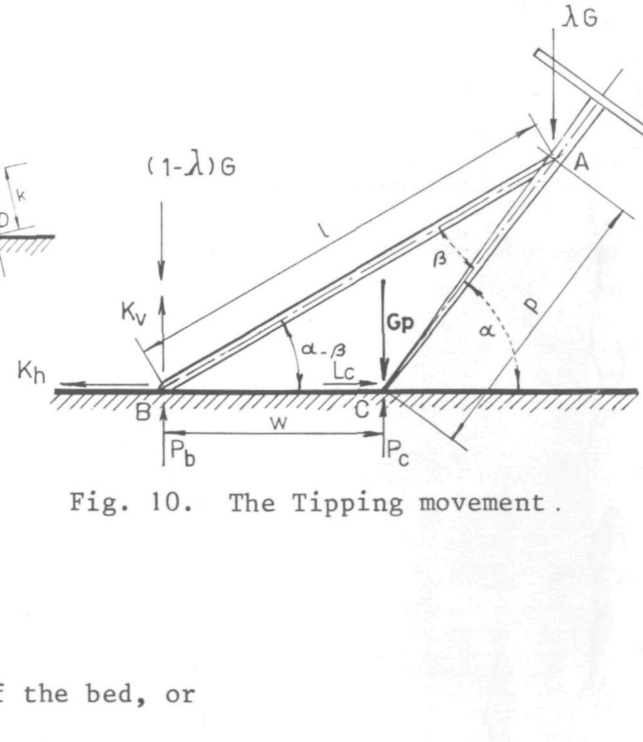


Fig. 10. The Tipping movement.

4. THE WHIPPING MOVEMENT. Figure 9

The movement starts as point *B* lifts off the bed, or

$$Kv + Kh.\mathrm{tg}(\alpha b-\beta b) > (1-\lambda)G,$$

where $\mathrm{tg}\alpha b = k/(p+a)$ and $l.\sin(\alpha b-\beta b) = p.\sin\alpha b$. βb is the value of β when point *B* rests on the bed and αb is the value of α when the points *C* and *D* rest on the bed.

When moving, providing $\beta < \beta e$, the equilibrium equation about point B gives the value of Kh in relation to Kv and β.

$$Kh.\mathrm{tg}(\alpha b-\beta) = (1-\lambda)G-Kv \quad \ldots\ldots \qquad \ldots\ldots \quad (2)$$

Extremity D is resting on the bed as long as $Kh \leq (G-Kv)/\mathrm{tg}\alpha b$.
When Kv is equal to zero, a particular case of movement occurs.
The conditions and equations are:

$$Kh \leq G/\mathrm{tg}\alpha b, Kh.\mathrm{tg}(\alpha b-\beta) = (1-\lambda)G \quad \ldots\ldots \qquad \ldots\ldots \quad (3)$$

and $(1-\lambda).\mathrm{tg}\alpha b < \mathrm{tg}(\alpha b-\beta)$.

5. THE TIPPING MOVEMENT. Figure 10

When B slips over the bed, $\beta b < \beta < \beta e$, $Pb \geq 0$ and $hb = 0$.
Thus

$$p.\sin\alpha = l.\sin(\alpha-\beta) \quad \ldots\ldots \qquad \ldots\ldots \quad (4)$$

Because, extremity D lifts off the bed, the moment equation about C indicates $G-Kv-Pb = Kh.\mathrm{tg}\alpha$ and related to the shank about A, $(1-\lambda)G-Kv-Pb = Kh.\mathrm{tg}(\alpha-\beta)$ so

$$Kh = \lambda G/\{\mathrm{tg}\alpha-\mathrm{tg}(\alpha-\beta)\} \quad \ldots\ldots \qquad \ldots\ldots \quad (5)$$

Because $Pb \geq 0$ is $Kh.\mathrm{tg}(\alpha-\beta) \leq (1-\lambda)G-Kv$.

When Kv is equal to zero, the movement continues as long as $\lambda \leq \{\mathrm{tg}\alpha-\mathrm{tg}(\alpha-\beta)\}/\mathrm{tg}\alpha$ or $p.\cos\alpha \leq (1-\lambda)l.\cos(\alpha-\beta)$, $1-\lambda \geq \mathrm{tg}(\alpha-\beta)/\mathrm{tg}\alpha$ or $\cos\beta \leq \{l^2.(1-\lambda)+p^2\}/pl(2-\lambda)$.

Because β increases and $\cos\beta$ decreases when α increases, the last condition indicates the movement continues to the final position when this movement is once commenced. During this movement Kh decreases.
In this case, the Tipping movement occurs only when $(1-\lambda) \geq \mathrm{tg}(\alpha b-\beta b)/\mathrm{tg}\alpha b$.
The maximum value of Kh, acting at the start of the movement, is $Kh = \lambda.G/\{\mathrm{tg}\alpha b-\mathrm{tg}(\alpha b-\beta b)\}$.

6. THE TILTING MOVEMENT. Figure 11

The movement occurs as soon as $\beta = \beta e$.
Shank and head rotate together, about point C.
When $Q = Kv\{p.\cos\alpha-l.\cos(\alpha-\beta e)\}$ the moment equation about C gives:

$$Kh = \frac{G.\{p.\cos\alpha-(1-\lambda).l.\cos(\alpha-\beta e)\}-Q}{p.\sin\alpha-l.\sin(\alpha-\beta e)} \quad \ldots\ldots \qquad \ldots\ldots \quad (6)$$

$Kv+Kh.\mathrm{tg}(\alpha-\beta e) \geq (1-\lambda).G$.
When Kv is equal to zero, the formula and the condition are reduced to:

$$Kh = \frac{G.\{p.\cos\alpha-(1-\lambda).l.\cos(\alpha-\beta e)\}}{p.\sin\alpha-l.\sin(\alpha-\beta e)} \quad \ldots\ldots \qquad \ldots\ldots \quad (7)$$

$Kh.\mathrm{tg}(\alpha-\beta e) = (1-\lambda).G$.

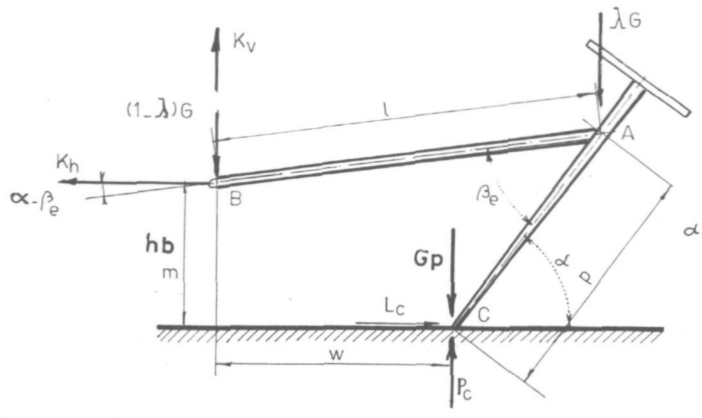


Fig. 11. The Tilting movement.

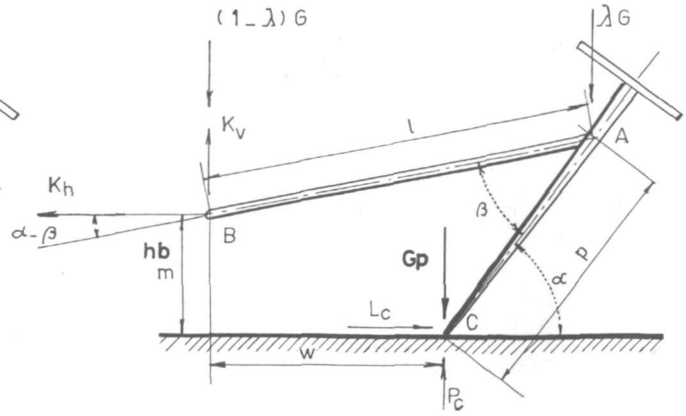


Fig. 12. The Swinging movement.

7. THE SWINGING MOVEMENT. Figure 12

The movement occurs as soon as $\beta b < \beta < \beta e$ and $hb > 0$. Thus $p.\sin\alpha > l.\sin(\alpha-\beta)$. The equilibrium equation of the head gives

$$Kh = (G-Kv)/\mathrm{tg}\alpha \ldots\ldots \qquad \ldots\ldots (8)$$

The equilibrium equation of the shank gives $Kh.\mathrm{tg}(\alpha-\beta) = (1-\lambda).G-Kv$.
Thus

$$Kh = \lambda.G/\{\mathrm{tg}\alpha-\mathrm{tg}(\alpha-\beta)\}\ldots\ldots \qquad \ldots\ldots (9)$$

Combining the formulas gives

$$(G-Kv)/\mathrm{tg}\alpha = \lambda.G/\{\mathrm{tg}\alpha-\mathrm{tg}(\alpha-\beta)\}\ldots\ldots \qquad \ldots\ldots (10)$$

which is the key formula to calculate β depending upon the value α and Kv.
In the particular case when $Kv = 0$ then

$$\mathrm{tg}(\alpha-\beta) = (1-\lambda).\mathrm{tg}\alpha\ldots\ldots \qquad \ldots\ldots (11)$$

and $\mathrm{tg}\beta = \lambda.\mathrm{tg}\alpha/\{1+(1-\lambda).\mathrm{tg}^2\alpha\}$.
So

$$\mathrm{tg}\alpha = \frac{\lambda \pm \sqrt{\lambda^2-4.(1-\lambda).\mathrm{tg}^2\beta}}{2(1-\lambda).\mathrm{tg}\beta}\ \ldots\ldots \qquad \ldots\ldots (12)$$

A point to note is that there are only practical solutions when $\mathrm{tg}\beta \leq \lambda/2.\sqrt{1-\lambda}$ or $\sin\beta \leq \lambda/(2-\lambda)$.
Further applies

$$Kh = G/\mathrm{tg}\alpha\ldots\ldots \qquad \ldots\ldots (13)$$

so that the maximum value of Kh is $G/\mathrm{tg}\alpha b$ because Kh decreases when α increases.

8. THE SUCCESSION OF MOVEMENTS

To determine what patterns of succession of movements are possible, we have to analyse systematically the conditions concerning the transitions between the movements. The transitions are:

About the starting situation,
start with the Tipping movement,
start with the Whipping-Swinging movement and
start with the Whipping-Tilting movement.

During the movements, the transitions between
the Swinging and Tipping movement and
the Swinging and Tilting movement.

About the final situation,
from the Tipping movement to the final position and
from the Tilting movement to the unstable end situation.

9. MOVEMENT ABOUT THE STARTING SITUATION

Assuming an increase of Kh two movements, Tipping or Whipping can occur. Assuming the Tipping movement starts, the movement continues until the final position is achieved. This movement forms the first pattern of anchor behaviour and is not a normal condition.
Movement starts as

$$Kh = \lambda . G/\{\mathrm{tg}\alpha b - \mathrm{tg}(\alpha b - \beta b)\} \ldots\ldots \qquad \ldots\ldots (14)$$

The head tips when $Kh.\mathrm{tg}(\alpha b-\beta b) \leq (1-\lambda).G-Kv$ or when $Kv = 0$ when

$$(1-\lambda) \geq \mathrm{tg}(\alpha b-\beta b)/\mathrm{tg}\alpha b \ldots\ldots \qquad \ldots\ldots (15)$$

Accepting a small error by substituting the tangents by the sinus values we obtain the condition

$$(1-\lambda) \geq p/l \ldots\ldots \qquad \ldots\ldots (16)$$

For most anchors $0.3 > 1-\lambda > 0.1$ and therefore $0.65 > p/l > 0.5$ applies, so this pattern of movement will never occur with these types.
When the Whipping movement occurs, there is a transition to the Tilting or to the Swinging movement. Assuming $Kv = 0$, there is a transition to the Tilting movement as

$$Kh \geq \frac{G.\{p.\cos\alpha b-(1-\lambda)\}.l\cos(\alpha b-\beta e)}{p.\sin\alpha b-l.\sin(\alpha b-\beta e)}$$

with $Kh = (1-\lambda)G/\mathrm{tg}(\alpha b-\beta e)$ and a transition to the Swinging movement as $Kh \geq G/\mathrm{tg}\alpha b$ and $Kh < (1-\lambda).G/\mathrm{tg}(\alpha b-\beta e)$.

With each movement of the flukes, there is a risk that the anchor will free, therefore the value of Kh necessary for moving the head has to be as high as possible. To determine which movement gives the highest Kh value before the head moves, the important formulas and conditions are summarized in figure 13.

For a Tipping anchor $Kh = (G-Pb)/\mathrm{tg}\alpha b$ and for a Swinging anchor $Kh = G/\mathrm{tg}\alpha b$.
The Kh value of the Tipping anchor is lower than the Swinging anchor.
For the Tilting anchor, $Kh = \{\lambda.G.p.\cos\alpha b-w.(1-\lambda).G\}/hb$ and the distance hb for a Tilting anchor will be smaller than for a Swinging anchor. The Kh value of the Tilting anchor is the largest.
The formula of the Kh value of the Tilting anchor movement indicates that a positive Kv value decreases the value of Kh necessary to lift the head.
So it is obvious that the old rule that sufficient length of chain has to be paid out to guarantee a horizontal chainpull on the anchor, is a good one.

Movement	Maximum Kh value when the head goes up	Condition
Tipping	$Kh = \lambda G/(\text{tg}\alpha b-\text{tg}(\alpha b-\beta b))$ $= (G-Pb)/\text{tg}\alpha b$	$(1-\lambda).\text{tg}\alpha b \geq \text{tg}(\alpha b-\beta b)$
Swinging	$Kh = G/\text{tg}\alpha b$ $= \lambda G/(\text{tg}\alpha b-\text{tg}(\alpha b-\beta))$	$(1-\lambda).\text{tg}\alpha b$ $< \text{tg}(\alpha b-\beta b)$ $> \text{tg}(\alpha b-\beta e)$
Tilting	$Kh = G\dfrac{p.\cos\alpha b-(1-\lambda).l.\cos(\alpha b-\beta e)}{p.\sin\alpha b-l.\sin(\alpha b-\beta e)}$	$(1-\lambda).\text{tg}\alpha b \leq \text{tg}(\alpha b-\beta e)$

Fig. 13. Summary of the formulas and conditions about the starting situation when $Kv = 0$.

10. THE TRANSITION BETWEEN THE SWINGING AND THE TIPPING MOVEMENT

When the point of the shank B touches the bed the Swinging movement changes into the Tipping movement. Then $hb = 0$ and at this moment $Pb = 0$. Therefore $Kh = (G-Kv)/\text{tg}\alpha = \{(1-\lambda)G-Kv\}/\text{tg}(\alpha-\beta)$. When $Kv = 0$ can be derived

$$\cos^2\alpha = \frac{(1-\lambda)^2.\{(l/p)^2-1\}}{1-(1-\lambda)^2} \quad \ldots\ldots \quad \ldots\ldots (17)$$

The transition occurs when the right half of the formula has a value smaller than 1 and $\alpha e > \alpha > \alpha b$. The transition is impossible when the value of $\cos^2\alpha$ is larger than 1 or, when $(1-\lambda) > p/l$ as derived from the formula. In this case there is only a Tipping movement.

11. THE TRANSITION BETWEEN THE SWINGING AND THE TILTING MOVEMENT

There is a transition between both movements when the value of β during the Swinging movement reaches the value βe. At this moment is

$$(G-Kv)/\text{tg}\alpha = \lambda.G/\{\text{tg}\alpha-\text{tg}(\alpha-\beta e)\}$$

or, when

$$A = (1-\lambda-Kv/G)/(1-Kv/G)$$

$$\text{tg}\alpha = \frac{1-A \pm \sqrt{(A-1)^2-4.A.\text{tg}^2\beta e}}{2.A.\text{tg}\beta e}.$$

For $Kv = 0$

$$\text{tg}\alpha = \frac{\lambda \pm \sqrt{\lambda^2-4.(1-\lambda)\text{tg}^2\beta e}}{2.(1-\lambda)\text{tg}\beta e} \quad \ldots\ldots \quad \ldots\ldots (18)$$

There is a transition when there is a real solution for the square root. There is no transition when $\lambda^2-4.(1-\lambda)\text{tg}^2\beta e < 0$ or $\sin\beta e > \lambda/(2-\lambda)$.

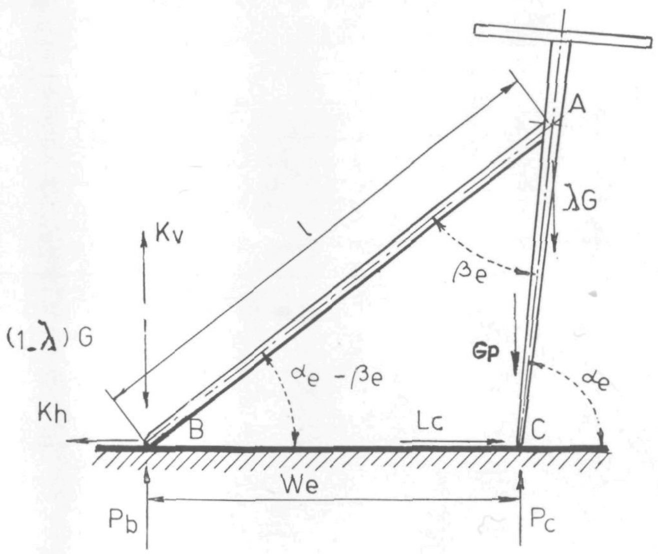


Fig. 14. The Final situation.

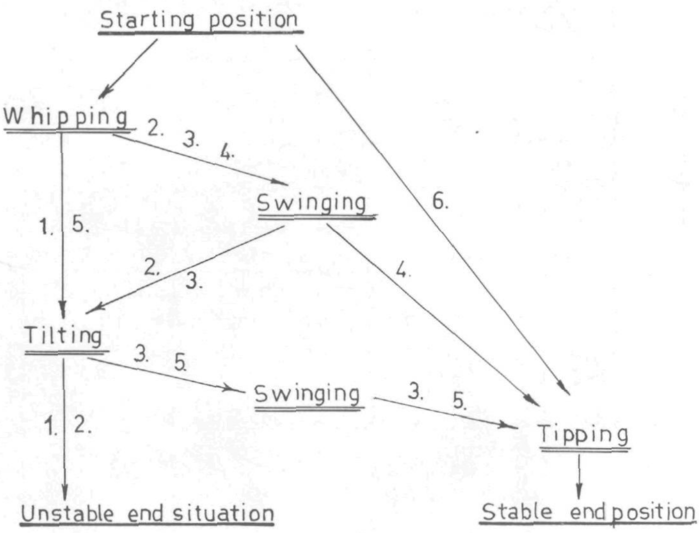


Fig. 15. The succession of anchor movements.

The numbers 1...6 concern the movements of the anchors indicated on page 25.

12. THE FINAL SITUATION. Figure 14

In this situation $hb = 0$ and $we^2 = l^2+p^2-2.p.l.\cos\beta e$...... ...... (19)
we is the distance between B and C when $\beta = \beta e$.
The equilibrium equation about C gives:

$$Kv+Pb = G\,\frac{(1-\lambda).l.\cos(\alpha e-\beta e)-p.\cos\alpha e}{l.\cos(\alpha e-\beta e)-p.\cos\alpha e} \;...... \qquad ...... (20)$$

Statically, the final position can never be reached when $Kv+Pb < 0$ or when $(1-\lambda).l.\cos(\alpha e-\beta e) < p.\cos\alpha e$ or $(1-\lambda) < \mathrm{tg}(\alpha e-\beta e)/\mathrm{tg}\alpha e$.
Such an anchor never reaches a stable final position, but rotates around C, dependent on the changes in the value of Kh or Kv. There is a stable final position when: $(1-\lambda) \geq \mathrm{tg}(\alpha e-\beta e)/\mathrm{tg}\alpha e$ or

$$\cos\beta e \leq \frac{l^2.(1-\lambda)+p^2}{p.l.(2-\lambda)} \;...... \qquad ...... (21)$$

The necessary minimum value of Kh to hold the anchor in this position is:
$Kh \geq \lambda.G/\{\mathrm{tg}\alpha e-\mathrm{tg}(\alpha e-\beta e)\}$.

At the moment $\alpha e \geq 90^\circ$, the condition changes into $Kh \leq 0$.
The anchor stands stable upon the points of the flukes. The chance the points will slip makes this very case less likely.

13. THE SUCCESSION OF MOVEMENTS AND THE ANCHOR MOVEMENT DIAGRAM

Summarizing the results of the foregoing analysis, six different successive patterns of movements are possible as represented in figure 15.
For a deeper understanding, a movement diagram figure 16 was developed, showing the different movements by means of curves. The curves indicate the relationship during the movement between the value of the angle of inclination of the flukes α, and the value of the angle of inclination of the shank β.

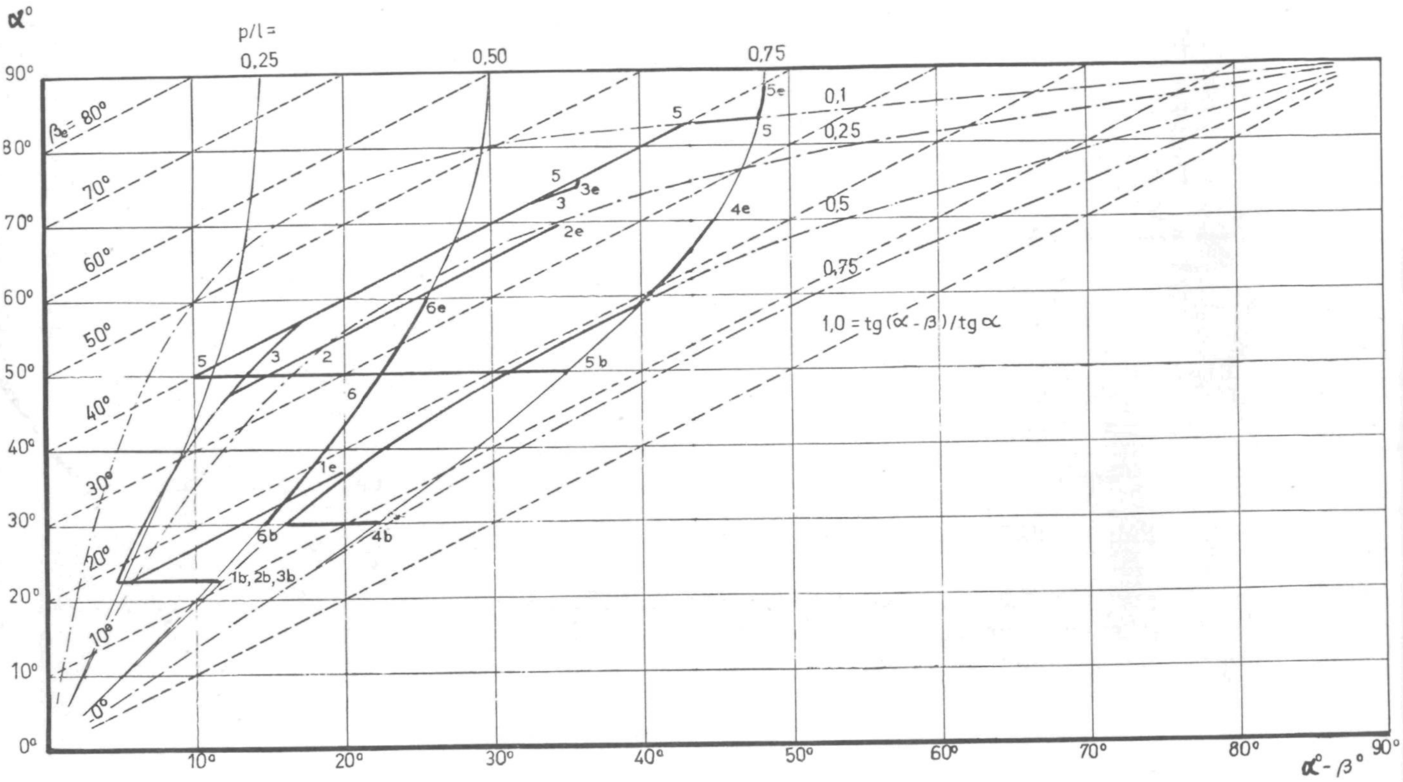


Fig. 16. The movement diagram.
Indice b relates to the starting situation and indice e to the final situation.

During the Swinging movement, the relation tg(α−β)/tgα is Constant and equal to (1−λ). The curves for (1−λ) at 0.1, 0.25, 0.5, 0.75 and 1.0 are represented.
During the Whipping movement, α remains Constant, thus a horizontal line represents this movement.
During the Tipping movement, the relation sinα/sin(α−β) is Constant and equal to p/l. The curves for p/l at 0.25, 0.50 and 0.75 are represented.
During the Tilting movement, the value of β is Constant βe. Straight inclining lines represent this movement.
In the diagram, are shown the six possible successions of anchor movements.
The main data of the six anchors are:

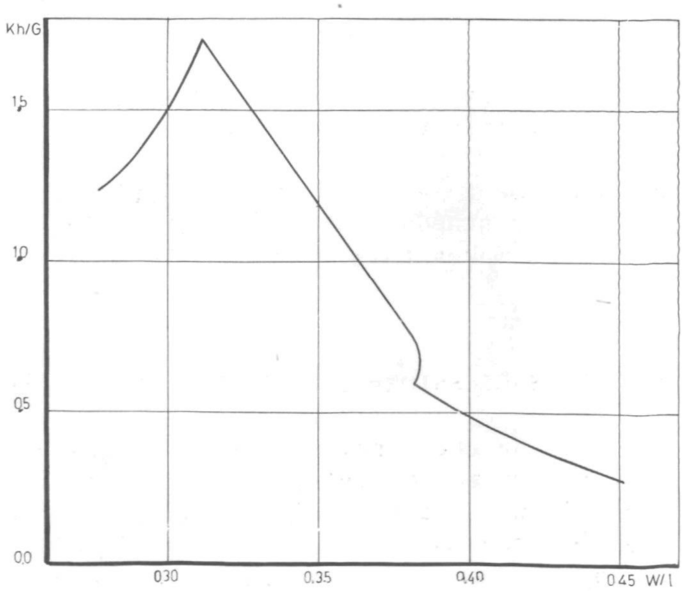


Fig. 17. The relation between w/l and Kh/G for anchor number 4 .

Anchor- and succession number	Fluke ratio p/l	Weight dist. fact. λ	Start position αb	βb	Final situation αe	βe
1	0.6	0.8	$22^{o}40'$	$9^{o}22'$	$36^{o}46'$	17^{o}
2	0.6	0.8	$22^{o}40'$	$9^{o}22'$	69^{o}	35^{o}
3	0.6	0.8	$22^{o}40'$	$9^{o}22'$	75^{o}	40^{o}
4	0.75	0.5	30^{o}	8^{o}	70^{o}	$25^{o}11'$
5	0.75	0.9	50^{o}	$14^{o}58'$	88^{o}	40^{o}
6	0.5	0.5	30^{o}	$15^{o}30'$	60^{o}	$34^{o}20'$

With the help of this diagram the behaviour of an anchor can be analysed quickly.

14. THE RELATIONSHIP BETWEEN THE ANCHOR MOVEMENT AND THE VALUE OF *Kh*

The value of *Kh* depends upon the anchor movement and the value of *Kv*. In case $Kv = 0$, the value of the ratio Kh/G can be represented on a diagram, in relation to the ratio w/l. In figure 17, for the anchor number 4, the relationship is shown. The curves of figure 18 represent the relationship for the remaining anchors. As may be seen, the value of Kh/G depends upon w/l in a very irregular way.

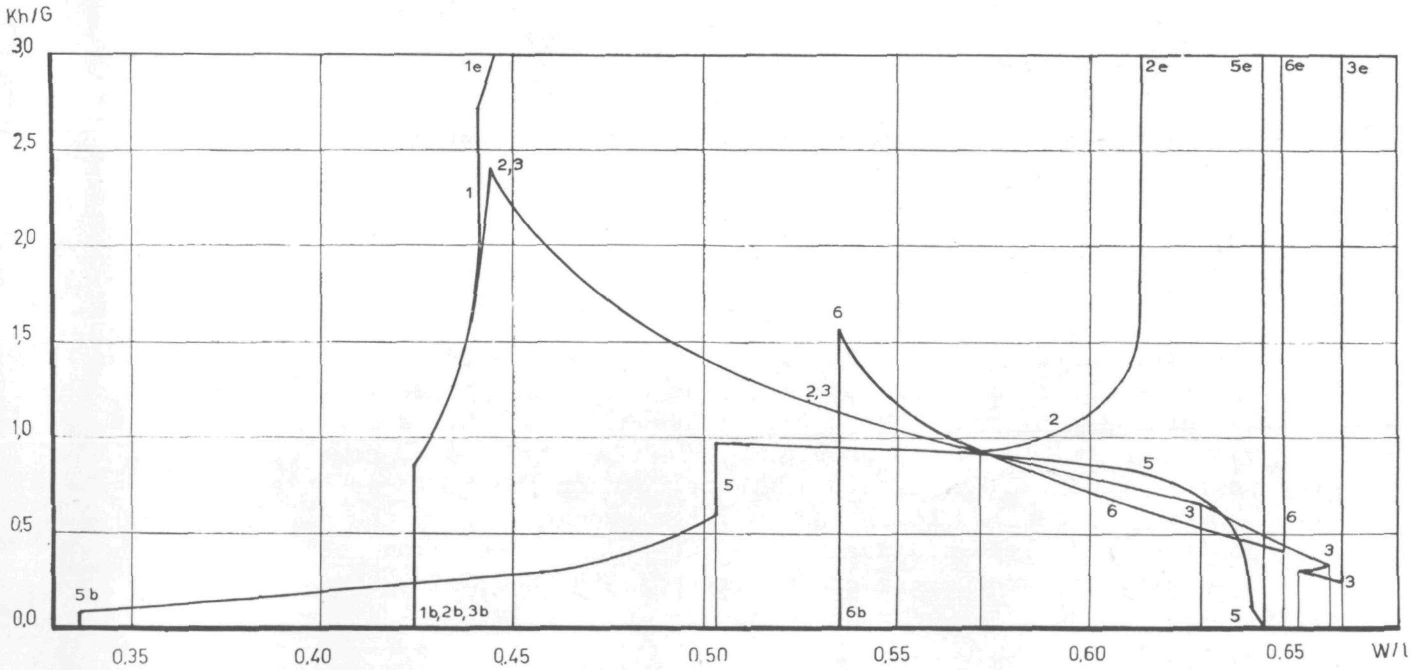


Fig. 18. The relation between w/l and Kh/G for the anchors number 1,2,3,5 and 6. Indice b relates to the starting situation and indice e to the final situation.

15. WHAT TYPE OF SUCCESSION OF MOVEMENTS IS PREFERABLE?

Before we can make a decision about this question, we have to consider what properties we require. Each movement of the flukes increases the chance that they will free. Therefore, the head has to rest on the bed as long as possible, and because movements can not be prevented they have to be reduced.

Thus to delay the beginning of the movements:

1. The value of Kh when the crown lifts off the bed has to be as high as possible.

When moving, the movement of the flukes has to be kept low. Thus:

2. The difference between αe and αb has to be small.

Dynamic acceleration effects due to an approximate Constant value of the horizontal chainpull and a decreasing Kh value during movement have to be prevented. Thus:

3. Kh/G must be increasing when w/l increases and
4. A stable final positicn is preferred because the flukes can remain stationary in this position.

Considering the relationship, figure 18, between w/l and Kh/G of the anchors 1...6 only anchors with succession of movements as anchor 1, Whipping, Tilting and unstable final situation, meet the first three requirements. By reducing the value of $\alpha e-\alpha b$ and the maximum value of hb, the movement of the flukes about the final situation can be reduced.

16. THE IMPORTANT CHARACTERISTICS OF AN ANCHOR WITH THE SUCCESSION OF MOVEMENTS WHIPPING AND TILTING

Assuming $Kv = 0$, the main condition is $(1-\lambda).\mathrm{tg}\alpha b < \mathrm{tg}(\alpha b-\beta e)$...... ...... (22)
a condition for the Tilting movement instead of the Swinging movement.
The flukes move when:

$$Kh > \frac{p.\cos\alpha b-(1-\lambda).l.\cos(\alpha b-\beta e)}{p.\sin\alpha b-l.\sin(\alpha b-\beta e)}.G \text{...... ...... (23)}$$

The value of the right part of the condition has to be as high as possible. Therefore, λ has to be high and the value of $hb = p.\sin\alpha b-l.\sin(\alpha b-\beta e)$ small. Decreasing hb reduces simultaneously the difference between αe and αb.

17. A CHOICE OF THE CHARACTERISTICS OF AN ANCHOR WITH THE SUCCESSION OF MOVEMENTS WHIPPING AND TILTING

Lloyd's Register of Shipping requires "The weight of the head, including pins and fittings, of an ordinary stockless anchor is not te be less than 60 per cent of the total weight of the anchor". So assuming $\lambda s = 0.5$ and $\lambda p = 1$, $\lambda \geq 0.8$. The value of λ may be taken as 0.8. Selecting αb low, however, a crown must be present, requiring a certain distance between the hinge point and the bed. At the same time, αb has to be chosen large enough to stop the sliding movement of the flukes over the bed against an uneven area. Assuming $\alpha b = 15^\circ$, the minimum value of Kh when the crown lifts off the bed, with the Swinging movement, would be $Kh = G/\mathrm{tg}\alpha b = 3.7G$.

The condition for the Tilting movement (22) gives $\beta e < 11^\circ 56'$ so reducing βe to 11° and introducing for p/l a value of 0.573 (the p/l value of a 30.000 lbs Danforth MK III anchor), the minimum value of Kh for moving the flukes increases upto $4.5G$, αe is 25°.
The movements of this theoretical anchor are represented in the diagram figure 19. The relationship between Kh/G and w/l is represented in figure 20.
The anchor flukes start moving when $Kh > 4.5\ G$. The movement of the flukes is a maximum of ten degrees. Under the assumed circumstances, this anchor holds the chainpull without excessive movement.

To effect a quick penetration into a soft bed the fluke angle of commercial anchor types is chosen between 32° and 45°. Therefore these anchors can make sharp movements holding on an impervious planar bed.

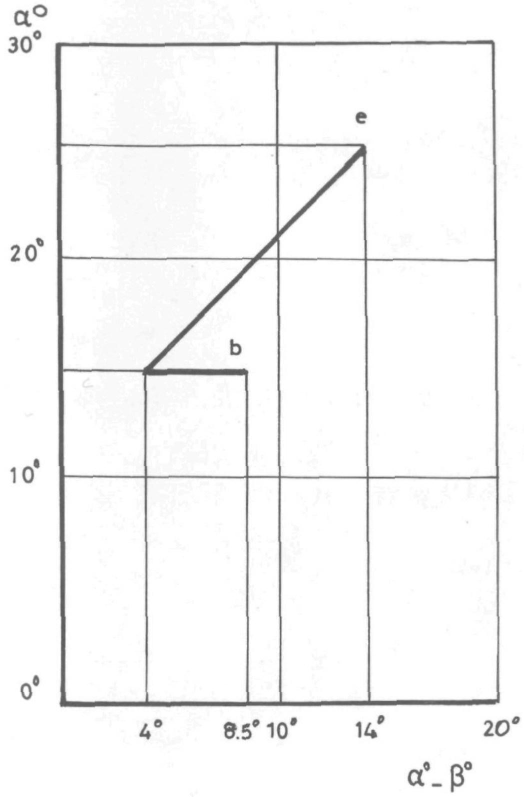


Fig. 19. Movement diagram for an anchor λ = 0.8, p/l = 0.573, αb = 15° and βe = 11°.

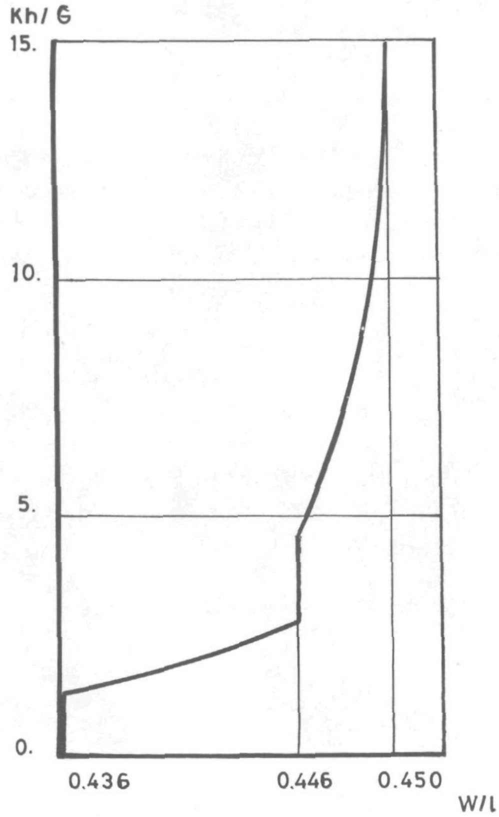


Fig. 20. The relation between w/l and Kh/G for an anchor λ = 0.8, p/l = 0.573, αb = 15° and βe = 11°.

18. DYNAMIC EFFECTS

Important dynamic effects can arise from a sudden increase of chainpull. Assuming that *Kh* increases sharply up to a further constant maximum value *Khc*, various shock movements can appear. These are powerful enough to lift the points of the flukes. Therefore, a shock movement is manifest when the shank, after leaving the bed, hits the crown at the hinge. Assuming the crown is resting on the bed and $Kv = 0$, the energy provided by *Khc*(*Ak*), is:
$Ak = Khc.l\{\cos(\alpha b-\beta)-\cos(\alpha b-\beta b)\}$ and the potential energy (*Ap*), absorbed by the shank is: $Ap = (1-\lambda).G.l\{\sin(\alpha b-\beta b)-\sin(\alpha b-\beta)\}$.
A shock movement occurs when $\beta = \beta e$ and $Ak > Ap$; thus:

$$Khc > (1-\lambda).G.\frac{\sin(\alpha b-\beta b)-\sin(\alpha b-\beta e)}{\cos(\alpha b-\beta e)-\cos(\alpha b-\beta b)}.$$

Therefore the shank of the anchor indicated in Paragraph 17 hits the crown when $Khc > 1.8G$. When the crown leaves the bed during the Swinging movement, the inclination of the shank under influence of the static *Khc*, will remain almost Constant. During the rotation of the flukes over a small angle $d\alpha$, the energy dAk provided by *Khc* is: $dAk = Khc.p.\sin\alpha.d\alpha$. The absorbed potential energy by the total anchor over a small angle $d\alpha$,dAp is: $dAp = G.p.\cos\alpha.d\alpha$.
The minimum value of *Khc* capable of lifting the head is $G/\text{tg}\alpha b$.
Thus $Khc > G/\text{tg}\alpha b$.

The energy dAa available for acceleration of the anchor movement is: $dAa = dAk - dAp$. Thus, substituting Khc,

$$dAa \geq G.p.\cos\alpha.d\alpha. \left\{ \frac{tg\alpha}{tg\alpha b} - 1 \right\} .$$

This value is positive throughout indicating an continuous acceleration of the movement. During the Tilting movement $dAk = Khc.we.d\alpha.\sin(\alpha e - \alpha)$ and $dAp = \lambda.G.p.\cos\alpha.d\alpha - (1-\lambda)G.we.d\alpha.\cos(\alpha e - \alpha)$.
The value $dAa = dAk - dAp$ can be both negative and positive so that during the Tilting movement the movement can accelerate initially and decelerate subsequently.
A heavy shock appears when the shank point at the end of the Tilting movement hits the bed. The energy provided by Khc during the complete movement Ak is: $Ak = Khc.l.(we - wb)$; $wb = l\sin\beta b/\sin\alpha b$. wb is the distance between B and C, when B,C and D rest on the bed.
The absorbed potential energy Ap is: $Ap = \lambda.G.p.(\sin\alpha e - \sin\alpha b)$.
The available dynamic energy Ad is $Ad = Ak - Ap$. The shock can be prevented when $Ad < 0$, thus $Ap > Ak$, or:

$$Khc \leq \lambda.G.\frac{p}{l} \frac{(\sin\alpha e - \sin\alpha b)}{\left\{ \frac{\sin\beta e}{\sin\alpha e} - \frac{\sin\beta b}{\sin\alpha b} \right\}}$$

For the anchor indicated in paragraph 17, when $Khc \leq 5.3G$. For the anchor number 3 indicated in paragraph 13, when $Khc \leq 1.2G$.
Assuming an elastic shock without loss of energy by deformation or friction forces, an anchor with $\lambda p = 1$ jumps over its' shank when $Ak > \lambda.G.(l - p.\sin\alpha b)$ thus when

$$Khc > \lambda.G. \left\{ 1 - \frac{p}{l}.\sin\alpha b \right\} \Big/ \left\{ \frac{\sin\beta e}{\sin\alpha e} - \frac{\sin\beta b}{\sin\alpha b} \right\}$$

For the anchor indicated in paragraph 17, when $Khc > 49G$ and for anchor number 3 when $Khc > 2{,}56G$.

Anchors in general use are commonly loaded between G and $10G$, so that shock loads may occasionally free the anchor. Therefore ship's speed has to be considerably reduced to avoid causing anchor jumping.

19. REMARKS

In the foregoing considerations sometimes the value of Kv was assumed to be equal to zero. By usual anchoring practice, sufficient length of chain has to be paid out to guarantee that the chain rests on the bed for some distance before the anchor. When the shank point is lifted, the raised part of the chain introduces a negative Kv value.

Assuming an $U2$ quality chain of d mm diameter, the weight of the required anchor in air is about $1.29\ d^2$ kg. The length of the shank is about $50d$ mm.
The weight of one meter of chain is about $0.022d^2$ kg.
Estimating that a length of chain equal to half the length of the shank will be lifted, the value of Kv will be $0.00055d^3$ or, about $0.043d$ per cent of the anchorweight. For a 100 mm chain, about 4.3%. This small amount of Kv can be neglected in most cases.
Because of various simplifying assumptions, the formulas are invalid when the bottom inclines or when the chainpull does not act in the symmetrical plan between the flukes. For these cases an additional model analysis is made in chapter 4.

20. CONCLUSIONS

Due to an increasing chainpull an anchor with tumbling flukes holding with its crown resting on the bed can make such vivid movements that it frees.
These movements, which appear without preceding warning, can be reduced by decreasing the value of the fluke angle βe.

All these vivid movements start with a rotating movement of the head about the fluke points.
Therefore the risk a loaded anchor frees unexpectedly can be reduced using a greater and heavier anchor in relation to the expected maximum chainpull.

MOVEMENTS AND STABILITY OF ANCHORS HOLDING ON AN IMPERVIOUS INCLINED UNEVEN BED

1. INTRODUCTION

Following up the analysis of anchors holding on an horizontal planar bed, the influence of an uneven bed in connection with the influence of a chainpull acting sideways to the direction of the shank can be investigated theoretically by means of an appropriate model situation.

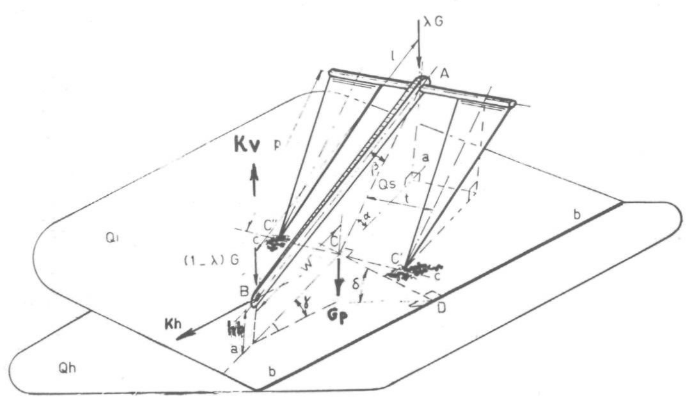


Fig. 21. The theoretical model situation concerning an anchor holding on an uneven sea bed.

The impervious inclined uneven bed is introduced with an irregular chalk, limestone or another rock-bed in mind.

2. DETERMINATION OF THE APPROPRIATE THEORETICAL MODEL SITUATION

Starting from the model situation indicated in paragraph 1 of chapter 3, the following additional assumptions are made.

- The bed is uneven and inclines, so that the line through the points of the flukes and the extended swing axis of the shank intersect the horizontal plane, *Qh*. See figure 21. The chainpull is resolved in a component *Kv* vertical to and *Kh* parallel to the horizontal plane.
- Through the points of the flukes, an auxiliary plane *Qi*, parallel to component *Kh*, is passed, which intersects the horizontal plane *Qh* with line *b-b*. The symmetrical plane between the flukes of the anchor intersects the inclined plane *Qi* with line *a-a*.
  Line *c-c* intersects line *a-a* at point *C*. The line passed through *C*, perpendicular to line *b-b*, intersects the horizontal plane in *D*.
  The angle between line *c-c* and line *CD*, is the yaw angle γ, and the angle between auxiliary plane *Qi* and the horizontal plane *Qh*, is the roll angle δ.

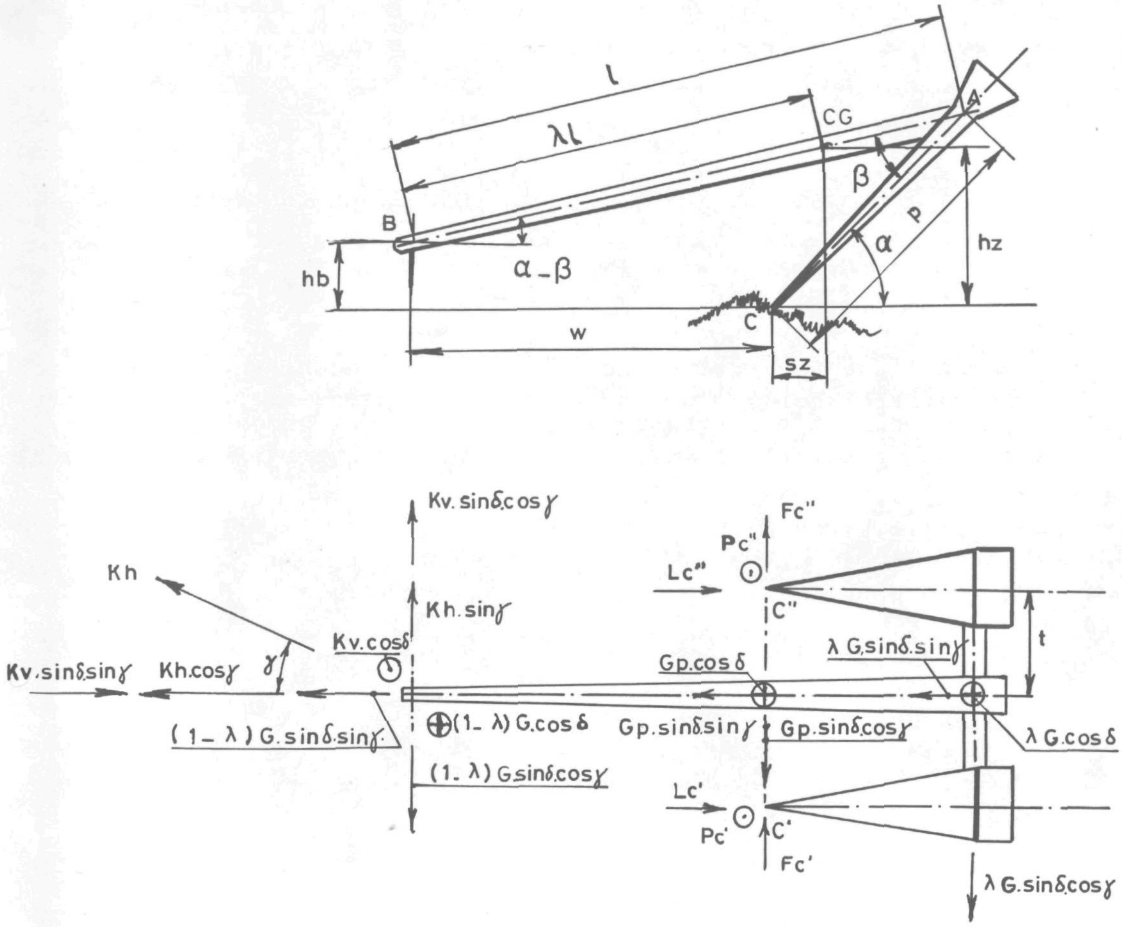


Fig. 22. The components of the loads and forces.

These angles determine the position of the anchor on the bed in conjunction with the position of the fluke points on the inclined uneven bed. Assuming an uneven impervious bed the position of *B* and the positions of the extremities of the crown in respect of the bed surface remains indeterminate. In the first instance it is therefore assumed that *B* and the crown remain above the bed surface.

All loads and forces are resolved in components parallel and perpendicular to the auxiliary plane Qi, while the parallel components are resolved further in components parallel to the symmetrical plane between the flukes and components parallel with the swing axis. See figure 22.

The loads and forces and their components are:

- The weight components of the anchor
  λG acting in point *A* and resolved in
  $\lambda G.\cos\delta$, $\lambda G.\sin\delta.\sin\gamma$ and $\lambda G.\sin\delta.\cos\gamma$.
  $(1-\lambda)G$ acting in point *B* and resolved in
  $(1-\lambda)G.\cos\delta$, $(1-\lambda)G.\sin\delta.\sin\gamma$ and
  $(1-\lambda)G.\sin\delta.\cos\gamma$.
  Gp acting in point *C* and resolved in
  $Gp.\cos\delta$, $Gp.\sin\delta\sin\gamma$ and $Gp.\sin\delta.\cos\gamma$.

- The horizontal chainpull Kh acting in point *B* and resolved in $Kh.\cos\gamma$ and $Kh.\sin\gamma$.

- The vertical chainpull Kv acting in point *B* and resolved in $Kv.\cos\delta$, $Kv.\sin\delta.\sin\gamma$ and $Kv.\sin\delta.\cos\gamma$.

- The reaction forces acting on the points C' and C'' of the flukes Pc' and Pc'', total Pc, and Lc' and Lc'', total Lc.

- The friction forces on the points C' and C'' of the flukes, acting in the direction of line c-c, Fc' and Fc'', total Fc.

3. THE EQUILIBRIUM EQUATIONS

Assuming slow movements and neglecting the inertia influences, the analysis can be started from the static equilibrium equations. Introducing sz, the distance from a line through C perpenticular to plane Qi to CG the point of application of weight component G and hz, the distance from this point to plane Qi,

$$sz = p.\cos\alpha-(1-\lambda).l.\cos(\alpha-\beta)$$
$$hz = p.\sin\alpha-(1-\lambda).l.\sin(\alpha-\beta) =$$
$$= hb + \lambda(p.\sin\alpha-hb).$$

The distance from B to plane Qi is denoted with hb comparable with the distance hb indicated in chapter 3 .
The value of sz will at all times be positive owing to the usual choice of λ, αe, p/l and βe.
The equilibrium equations are:

$$Pc = (G+Gp-Kv).\cos\delta$$
$$Lc = (G+Gp-Kv).\sin\delta.\sin\gamma+Kh.\cos\gamma$$
$$Fc = (G+Gp-Kv).\sin\delta.\cos\gamma-Kh.\sin\gamma.$$

The moment equation around a line through B, perpendicular to plane Qi is:

$$w\,(Fc-Gp.\sin\delta.\cos\gamma) + t(Lc'-Lc'') = \lambda.l.G.\sin\delta.\cos\gamma.\cos(\alpha-\beta)\ldots\ldots\ldots \quad (24)$$

The moment equation around a line through B, in the symmetrical plane between the flukes and parallel to the plane Qi is:

$$(p.\sin\alpha-hb).\lambda.G.\sin\delta.\cos\gamma + (Fc-Gp.\sin\delta.\cos\gamma).hb = (Pc'-Pc'').t\ldots\ldots \quad (25)$$

The moment equation around line c-c is:

$$hb\,.\,[\;Kh.\cos\gamma + \{\;(1-\lambda).G-Kv\;\}\;.\sin\delta.\sin\gamma\;] + w.\cos\delta.\;\{\;(1-\lambda)G-Kv\;\} =$$
$$= \lambda.p.G(\cos\delta.\cos\alpha-\sin\delta.\sin\gamma.\sin\alpha)\ldots\ldots \quad\ldots\ldots (26)$$

4. THE VALUE OF THE HORIZONTAL CHAINPULL

Assuming that neither the shank or a crown extremity rest on the bed, only phenomena related to the Tilting and Swinging movement can be analysed.
The following conversion of formula (26) may be applied for the value of during the Tilting movement:

$$Kh = \frac{Kv(hb.\sin\delta.\sin\gamma+w.\cos\delta)}{hb.\cos\gamma} +$$
$$+ G\,.\,\frac{\lambda.p(\cos\delta.\cos\alpha-\sin\delta.\sin\gamma.\sin\alpha)}{hb.\cos\gamma} -$$
$$- G\,.\,\frac{(1-\lambda)\;(w.\cos\delta+hb.\sin\delta.\sin\gamma)}{hb.\cos\gamma}\ldots\ldots \quad\ldots\ldots (27)$$

Starting from the equilibrium equation of the anchor head, the value of Kh can be derived for the swinging movement

$$Kh = Kv(\sin\delta.\mathrm{tg}\gamma - \frac{\cos\delta}{\cos\gamma.\mathrm{tg}\alpha}) + \frac{G}{\cos\gamma} . (\frac{\cos\delta}{\mathrm{tg}\alpha} - \sin\delta.\sin\gamma) \ldots\ldots\ldots \quad (28)$$

The formulas (6) and (8), chapter 3, can be simplified into:

$$Kh = \frac{w.Kv}{hb} + G.\frac{p.\lambda.\cos\alpha}{hb} - \frac{(1-\lambda)G.w}{hb} \ldots\ldots \quad \ldots\ldots \quad (6)$$

$$Kh = \frac{G}{\mathrm{tg}\alpha} - \frac{Kv}{\mathrm{tg}\alpha} \ldots\ldots \quad \ldots\ldots \quad (8)$$

Assuming $Kv = 0$ a comparison of the formula (6) with (27), and the formula (8) with (28), proves the chainpull Kh decreases dependent upon δ during the Tilting or Swinging movement. Therefore the holding pull in the horizontal direction of an anchor, holding in an inclined position will be smaller than the holding pull of the same anchor, holding with the same inclination angle of the flukes, on a horizontal plane.
When $Kv > 0$ the horizontal component of the holding pull, due to Kv, increases during the Swinging movement and during the Tilting movement when $hb > w.\mathrm{tg}\delta$.

Two particular situations arise when δ or γ is equal to zero.
When $\delta = 0$ and $\gamma \neq 0$, the anchor yaws behind the chain making a yawing movement.
When $\gamma = 0$ and $\delta \neq 0$, the anchor rolls on the chain, making a rolling movement.
The value of the horizontal chainpull for a yawing anchor is:

$$Kh = (G.zs+w.Kv)/hb.\cos\gamma \ldots\ldots \quad \ldots\ldots \quad (29)$$

during the Tilting movement
and during the Swinging movement

$$Kh = (G-Kv)/\cos\gamma.\mathrm{tg}\alpha \ldots\ldots \quad \ldots\ldots \quad (30)$$

The value of the horizontal chainpull for a rolling anchor is:

$$Kh = (G.sz+Kv.w)\cos\delta/hb \ldots\ldots \quad \ldots\ldots \quad (31)$$

during the Tilting movement
and during the Swinging movement

$$Kh = (G-Kv)\frac{\cos\delta}{\mathrm{tg}\alpha} \ldots\ldots \quad \ldots\ldots \quad (32)$$

So holding pull of a yawing anchor changes, dependent on the factor $1/\cos\gamma$ and the holding pull of a rolling anchor decreases, dependent on the factor $\cos\delta$.

For a yawing anchor, the component of Kh in the symmetrical plane between the flukes is equal to $G.sz/hb$ and during the Swinging movement, $G/\mathrm{tg}\alpha$, assuming $Kv = 0$, and $(G.zs+w.Kv)/hb$ and $(G-Kv)/\mathrm{tg}\alpha$ when $Kv \neq 0$.

Simplifying formula (6) into $Kh = (G.zs+w.Kv)/hb$ and
considering formula (8) $Kh = (G-Kv)/\mathrm{tg}\alpha$
the value of the horizontal holding pull component of a yawing anchor in the symmetrical plane between the flukes is equal to the value indicated in the formulas (6) and (8).
So the formulas concerning the Swinging and the Tilting movement, indicated in chapter 3 may be applied for a yawing anchor.

For a rolling anchor, the chainpull acts in the symmetrical plane between the flukes. The values of the chainpull Kh, indicated in (31) and (32), are a factor $\cos\delta$ smaller than the values of Kh in (6) and (8).

The values of the weight components, acting in the symmetrical plane, are also a factor $\cos\delta$ smaller than those previously indicated. Therefore the formulas with regard to the Swinging and Tilting movement of chapter 3 may also be applied for a rolling anchor.

5. THE THREE CAUSES OF INSTABILITY OF AN ANCHOR

When a point of a fluke lifts off the bed, the anchor may fall transverse, and free. After falling an anchor can slide a great distance on its side before holding again; the transverse stability of an anchor is therefore very important. When the anchor makes a slewing movement around the point of a fluke, the opposite point rotates free and one fluke holds the chainpull.
When an anchor slews instead of falling over, the anchor remains holding the chain. So it is very favourable when an anchor slews, before it can fall over. When the points of the flukes slide sideways in most cases the anchor will free.

Therefore we have to investigate the conditions relating the above mentioned movements and their mutual dependence. The aim of the considerations is to determine the particular conditions an anchor design has to meet to prevent the undesirable falling over by sliding or slewing first.

The investigation concerning stability is commenced assuming a chainpull adjusting to the position and movement of the anchor, according the formulas (27) and (28). Regarding the assumed uneven inclined sea bed, it is assumed that the end position of the anchor is one where the end of the shank is on the same level as that of point C.

6. TRANSVERSE STABILITY

An anchor stands stable as long as both points of the flukes rest on the bed. Assuming the friction forces in the direction of Pc can be neglected, the values Pc' and Pc'' can be represented as:

$$2.t.Pc' = G(t.\cos\delta+hz.\sin\delta.\cos\gamma)-Kh.hb.\sin\gamma+t.Gp.\cos\delta-Kv(hb.\sin\delta.\cos\gamma+t.\cos\delta)$$

and

$$2.t.Pc'' = G(t.\cos\delta-hz.\sin\delta.\cos\gamma)+Kh.hb.\sin\gamma+t.Gp.\cos\delta+Kv(hb.\sin\delta.\cos\gamma-t.\cos\delta).$$

An anchor rests stable in case $Pc' > 0$ and $Pc'' > 0$ thus

$$G(hz.\sin\delta.\cos\gamma+t.\cos\delta)+t.Gp.\cos\delta-Kv(hb.\sin\delta.\cos\gamma+t.\cos\delta) > Kh.hb.\sin\gamma \;......\; (33)$$

and

$$Kh.hb.\sin\gamma > G(hz.\sin\delta.\cos\gamma-t.\cos\delta)-t.Gp.\cos\delta-Kv(hb.\sin\delta.\cos\gamma-t.\cos\delta) \;......\; (34)$$

For a yawing anchor, the points of the flukes rest on the bed when $(G+Gp-Kv)t > Kh.hb.\sin\gamma > -(G+Gp-Kv)t$ or assuming $\gamma > 0$ when $Kh.hb.\sin\gamma > (G+Gp-Kv)t$.
For a rolling anchor when $(G+Gp)t.\cos\delta > -G.hz.\sin\delta+Kv(hb.\sin\delta+t.\cos\delta)$
and $(G+Gp)t.\cos\delta > G.hz.\sin\delta-Kv(hb.\sin\delta-t.\cos\delta)$.

To obtain a better understanding of these formulas they can be simplified by assuming $Kv = Gp = 0; \lambda p = 1$.

Then for a yawing anchor, the points of the flukes rest on the bed as long as:

$$/\sin\gamma/ < G.t/Kh.hb...... \qquad ...... (35)$$

or, during the Tilting movement, after substituting for Kh the terms of formula (29)

$$/\mathrm{tg}\gamma/ < t/sz...... \qquad ...... (36)$$

or, during the Swinging movement, after substituting for Kh the terms of formula (30)

$$/\mathrm{tg}\gamma/ < t.\mathrm{tg}\alpha/hb...... \qquad ...... (37)$$

As a result of the assumption of the adjusting chainpull during the Swinging movement, $sz.\mathrm{tg}\alpha = hb$ applies. Thus condition (37) is equal to (36).
For a rolling anchor, the points of the flukes rest on the bed as long as:

$$/\mathrm{tg}\delta/ < t/hz...... \qquad ...... (38)$$

7. SLEWING AROUND THE POINT OF A FLUKE

Both points rest parallel to plane Qi, against the uneven area, providing Lc'' and Lc' are both greater than zero. The values of Lc'' and Lc' can be represented as:

$$2t.Lc' = G.\sin\delta.(t.\sin\gamma+sz.\cos\gamma)+Kh(w.\sin\gamma+t.\cos\gamma)-Kv.\sin\delta.(t.\sin\gamma-w.\cos\gamma)+ +t.Gp.\sin\delta.\sin\gamma.$$

$$2t.Lc'' = G.\sin\delta.(t.\sin\gamma-sz.\cos\gamma)+Kh(t.\cos\gamma-w.\sin\gamma)-Kv.\sin\delta.(t.\sin\gamma+w.\cos\gamma)+ +t.Gp.\sin\delta.\sin\gamma.$$

An anchor rests with both points against uneven areas providing $Lc' > 0$ and $Lc'' > 0$.

$$(G+Gp)t.\sin\delta.\sin\gamma+G.sz.\cos\gamma+Kh(w.\sin\gamma+t.\cos\gamma)-Kv.\sin\delta(t.\sin\gamma-w.\cos\gamma) > 0... \quad (39)$$

and

$$(G+Gp)t.\sin\delta.\sin\gamma-G.sz.\cos\gamma+Kh(t.\cos\gamma-w.\sin\gamma)-Kv.\sin\delta(t.\sin\gamma+w.\cos\gamma) > 0... \quad (40)$$

To obtain a better understanding of these formulas they can be simplified by assuming $Kv = Gp = 0$; $\lambda p = 1$.

Then for a yawing anchor providing

$$/\mathrm{tg}\gamma/ < t/w...... \qquad ...... (41)$$

and for a rolling anchor providing

$$/\sin\delta/ < Kh.t/G.sz...... \qquad ...... (42)$$

For a rolling anchor during the Tilting movement after substituting for Kh the terms of formula (29)

$$/\mathrm{tg}\delta/ < t/hb...... \qquad ...... (43)$$

and during the Swinging movement after substituting the terms of formula (30)

$$/\mathrm{tg}\delta/ < t/sz.\mathrm{tg}\alpha...... \qquad ...... (44)$$

This last equation is equal to (43), as a result of the assumption of the adjusting chainpull.

8. SLIDING SIDEWAYS

The maximum value Fc, the total friction force, depends upon the values of Pc and Lc and the coefficient of friction ρ of the bed.
So the maximum value of Fc is $Fc = \rho.(Lc+Pc)$.

Assuming the uneven area allows a sliding lateral movement perpendicular to the symmetrical plane between the flukes, the anchor slides upwards when
$Kh.\sin\gamma - Fc > (G+Gp-Kv)\sin\delta.\cos\gamma$ and downwards when
$Kh.\sin\gamma + Fc < (G+Gp-Kv)\sin\delta.\cos\gamma$ assuming $\delta > 0$.

An anchor rests without sliding sideways providing
$Kh(\sin\gamma - \rho.\cos\gamma) < (G+Gp-Kv)\ (\sin\delta.\cos\gamma + \rho.\sin\delta.\sin\gamma + \rho.\cos\delta)$ .... (45)
and
$Kh(\sin\gamma + \rho.\cos\gamma) > (G+Gp-Kv)\ (\sin\delta.\cos\gamma - \rho.\sin\delta.\sin\gamma - \rho.\cos\delta)$ .... (46)

To obtain a better understanding of these formulas they can also be simplified by assuming $Kv = Gp = 0$; $\lambda p = 1$.

Then for a yawing anchor, the anchor rests without sliding providing

$$Kh(/\sin\gamma/ - \rho.\cos\gamma) < \rho.G \quad \text{...... ......} \quad (47)$$

or, during the Tilting movement, providing

$$/tg\gamma/ < \rho.(hb/sz+1) \quad \text{...... ......} \quad (48)$$

or, during the Swinging movement, providing

$$/tg\gamma/ < \rho.(1+tg\alpha) \quad \text{...... ......} \quad (49)$$

The last condition is equal to (47) due to the assumption of the adjusting chainpull.
For a rolling anchor, the anchor rests without sliding providing

$$Kh.\rho > G.(/\sin\delta/ - \rho.\cos\delta) \quad \text{...... ......} \quad (50)$$

or, during the Tilting movement

$$/tg\delta/ < \rho.(1+sz/hb) \quad \text{...... ......} \quad (51)$$

or, during the Swinging movement

$$/tg\delta/ < \rho.(1+1/tg\alpha) \quad \text{...... ......} \quad (52)$$

The last condition is equal to (51) by the assumption of the adjusting chain-pull. All conditions found are summarized in figure 24.

Movements	YAWING			ROLLING		
Chainpull	Adjusting		Constant	Adjusting		Constant
Movements	Tilting	Swinging		Tilting	Swinging	
	$/tg\gamma/<$			$/tg\delta/<$		
Falling over	t/sz (36)		$\frac{t.hbd}{hb.szd}$ (56)	t/hz (38)		
Slewing	t/w (41)			t/hb (43)		$\frac{t.szd}{sz.hbd}$ (57)
Sliding	$\rho(1 + \frac{hb}{sz})$ (48)		$\rho(1 + \frac{hbd}{szd})$ (58)	$\rho(1 + \frac{sz}{hb})$ (51)		$\rho(1 + \frac{szd}{hbd})$ (59)

Fig. 24. Summary of conditions, assuming $\lambda p = 1$, $Kv = Gp = 0$.

9. THE INFLUENCE OF A CONSTANT HORIZONTAL CHAINPULL

When the curve of the anchor chain before the main shackle commences horizontal and further forms a catenary, the horizontal chain pull will remain roughly constant, after the anchor head lifts off the bed.
Therefore we have to consider the influence of a constant chainpull during the movements. To simplify the considerations $Kv = Gp = 0$, $\lambda p = 1$ is assumed. Regarding a tilting movement the formulas (29) and (31) indicate the value of Kh is proportional to the ratio sz/hb.
Introducing αg, the angle between the centerline of the flukes

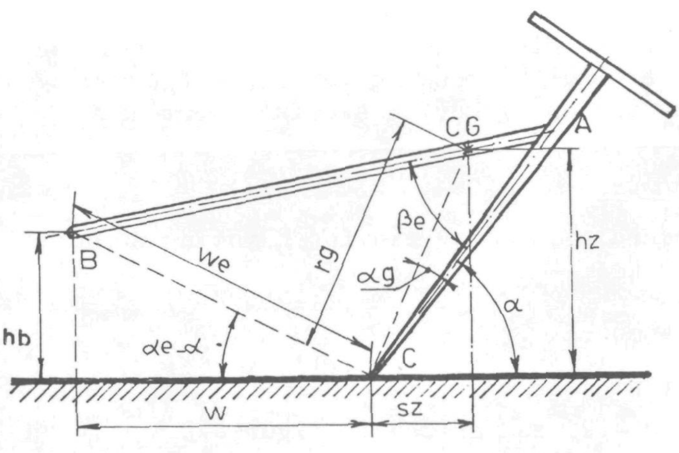


Fig. 23. The Tilting movement, assuming $\lambda p = 1$.

and the line between the centre of gravity CG and point C, and rg, the distance between C and the centre of gravity (see fig. 23), we obtain:
$hb = we.\sin(\alpha e-\alpha)$ and $sz = rg.\cos(\alpha+\alpha g)$. The value of hb/sz is:

$$\frac{hb}{sz} = \frac{we}{rg} \cdot \cos(\alpha e+\alpha g) \cdot \{tg(\alpha e+\alpha g) - tg(\alpha+\alpha g)\}.$$

When α increases, the ratio hb/sz decreases. In the case $\alpha+\alpha g < 90^{\circ}$, an unstable end situation, the value of Kh increases with α.

The formulas of the chainpull during the swinging movement (30 and 32), indicate the value of Kh decreases by an increasing value of α.
Assuming an anchor with an unstable end situation, the maximum horizontal chainpull for an anchor with the successive movements, Whipping-Swinging-Tilting, is first of all the chainpull at the moment the Swinging movements starts.
Later, during the Tilting movement, the value of the chainpull can exceed this maximum pull during a movement under adjusting chainpull, as discussed previously.
For an anchor with the successive movements Whipping-Tilting, the value of Kh increases with α when the crown leaves the bed. So this succession of movements does not allow motion under constant chainpull.

Generally, dimensions and weight distribution of anchors are chosen in such a way that an unstable end situation develops. Therefore we can confine the investigation to the case of an anchor with the successive movements Whipping-Swinging-Tilting.
The value of the chainpull when the head lifts off the bed and the Swinging movements starts is:

$$Kh = \frac{G}{\cos\gamma} \cdot \left(\frac{\cos\delta}{\mathrm{tg}\alpha b} - \sin\delta.\sin\gamma \right) \ldots\ldots \qquad \ldots\ldots (53)$$

For a yawing anchor: $Kh = G/\cos\gamma.\mathrm{tg}\alpha b \ldots\ldots$ ...... (54)

and for a rolling anchor: $Kh = G.\cos\delta/\mathrm{tg}\alpha b \ldots\ldots$ ...... (55)

For a swinging anchor, $\mathrm{tg}\alpha b = hbd/szd$ applies, assuming hbd is the value of hb and szd is the value of sz when the head lifts off the bed.
The following conditions can now be derived concerning the Swinging movement under a constant chainpull equal to the chainpull that lifted the head off the bed.
Condition (35), concerning transverse stability, indicates for a yawing anchor, after substituting (54):

$$/\mathrm{tg}\gamma/ < t.hbd/hb.szd \ldots\ldots \qquad \ldots\ldots (56)$$

For a rolling anchor the already derived general condition (38) holds good.
Condition (41) concerning the slewing movement of a yawing anchor also holds good. For a rolling anchor without a slewing movement

$$/\mathrm{tg}\delta/ < t.szd/sz.hbd \ldots\ldots \qquad \ldots\ldots (57)$$

applies.
The conditions concerning sliding are for a yawing anchor:

$$/\mathrm{tg}\gamma/ < \rho.(1+hbd/szd) \ldots\ldots \qquad \ldots\ldots (58)$$

and for a rolling anchor:

$$/\mathrm{tg}\delta/ < \rho.(1+szd/hbd) \ldots\ldots \qquad \ldots\ldots (59)$$

These conditions are also summarized in figure 18.

10. STABILITY DURING THE TRANSITIONS BETWEEN THE MOVEMENTS

Figure 24 shows all the conditions an anchor generally has to satisfy for resting with both fluke points against an uneven area, assuming an adjusting and a constant chainpull and $\lambda p = 1$, $Kv = Gp = 0$.

Assuming an unstable end situation, the behaviour of anchors with the successive movements Whipping-Swinging-Tilting, and anchors with the successive movements Whipping-Tilting can be investigated further.
Important moments during these successions of movement are the transition between the Whipping and Tilting movement, the Swinging and Tilting movement and the transition between the Whipping and Swinging movement, by which the corresponding values are indicated with the indices m, t and d.
The indice b refers to the starting position and the indice e to the assumed end situation. An indice x refers to the maximum value reached during the movements.

11. STABILITY OF AN ANCHOR WITH THE SUCCESSION OF MOVEMENTS WHIPPING-TILTING

For a yawing anchor, the conditions for falling over, slewing and sliding are: $/tg\gamma/ < t/sz$ (36), t/w (41) and $\rho.(1+hb/sz)$ (48).
The value of (36) is minimum for the transition form the Whipping to the Tilting movement, with a critical value t/szm.
The value of (41) is minimum in the end situation with a critical value t/we.
The value of (48) is minimum and equal to ρ in the end situation.
Thus $/tg\gamma/ < t/szm$, t/we and ρ to prevent falling over, slewing and sliding.
The anchor slews before falling over in situation $t/w < t/sz$ or $w > sz$.
For the transition Whipping-Tilting, the value w is minimum and the value sz maximum, so the critical condition is

$$wm > szm \text{......} \qquad \text{......} (60)$$

a condition the design of an anchor can meet.

For a rolling anchor, the respective conditions are:
$/tg\delta/ < t/hz$ (38), t/hb (43), and $\rho(1+sz/hb)$ (51).
The value of (38) is minimum in the end position t/hze and the value of (43) and (51) is minimum for the transition from the Whipping to the Tilting movement. The value of (51) is minimum during the starting situation and equal to ρ as long as the chainpull is zero.
Thus to prevent falling over, slewing and sliding $/tg\delta/ < t/hze$, t/hbm and $\rho.(1+szm/hbm)$or ρ.
A rolling anchor slews before falling over, in situation $hb > hz$.
This can not be realized because the horizontal direction of the assumed chainpull keeps hb always smaller than hz. The end of the shank will generally remain lower than the hinge; therefore there is always an imminent possibility of falling over. The best we can do is to increase the value of t to ensure the anchor slides before falling over. So $t/hz > \rho.(1+sz/hb)$.

Regarding the end situation the right half of the condition will approach infinity. It is therefore impossible to meet this condition. The value sz/hb is the ratio between the chainpull and the total anchor weight; it is reasonable to replace this ratio by the ratio of the anchor proofload Khp and the anchor weight Ga. In this case an anchor has to meet the condition:

$$t > \rho.hze.(1+Khp/Ga) \text{......} \qquad \text{......} (61)$$

see figure 25.

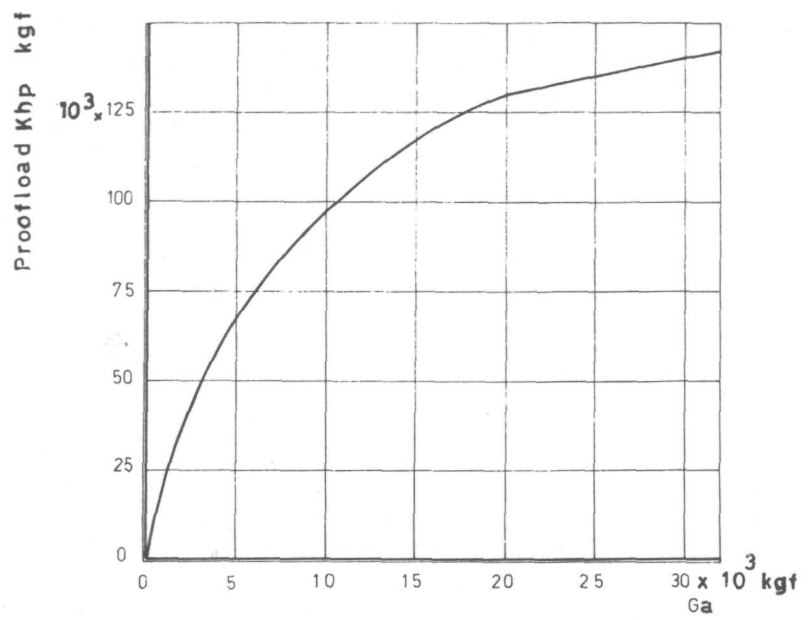


Fig. 25. The relation between the anchor weight and the proofload, as required by the classification societies.

12. STABILITY OF AN ANCHOR WITH THE SUCCESSIVE MOVEMENTS WHIPPING-SWINGING-TILTING

For a yawing anchor, falling over, slewing and sliding conditions already found apply during the Tilting movement, and during the Swinging movement, assuming adjusting chainpull. Hence $/tg\gamma/ < t/sz$(36), t/w (41) and $\rho.(1+hb/sz)$ (48). During the swinging movement under constant chainpull $/tg\gamma/ < t.hbd/hb.szd$ (56), t/w (41) and $\rho.(1+hbd/szd)$ (58). The critical values for the slewing and sliding conditions are, t/we and ρ, during the end situation.
The critical value of the condition concerning falling over, occurs for a Swinging movement during constant chainpull where hb is equal to its maximum value hbx.
At the moment, the transition between the Swinging and the Tilting movement, is $\alpha x = \alpha b - \beta d + \beta e$.
So the critical conditions are $/tg\gamma/ < t.hbd/szd.hbx$, t/we and ρ.

The anchor design meets the requirements, in that the anchor slews before falling over, in condition $t/w < t.hbd/hb.szd$ or, in the critical situations during the transitions Whipping-Swinging and Swinging-Tilting,

$$wd > szd \ldots\ldots \qquad \ldots\ldots (62)$$

and

$$wx > hbx.szd/hbd \ldots\ldots \qquad \ldots\ldots (63)$$

$$wd = l.\cos(\alpha b-\beta d)-p.\cos\alpha b$$
$$hbd = p.\sin\alpha b-(1-\lambda).l.\cos(\alpha b-\beta d)$$
$$wx = l.\cos(\alpha x-\beta e)-p.\cos\alpha x$$
$$hbx = p.\sin\alpha x-l.\sin(\alpha x-\beta e)$$
$$tg(\alpha b-\beta d) = (1-\lambda)tg\alpha b.$$

To comply with the conditions (62) and (63) can be difficult.

For a rolling anchor the conditions are during Swinging and Tilting under adjusting chainpull $/tg\delta/ < t/hz$ (38), t/hb (43) and $\rho.(1+sz/hb)$ (51).

During Swinging with constant chainpull, $/tg\delta/ < t/hz$ (38), $t.szd/sd.hbd$ (57) and $\rho.(1+szd/hbd)$ (59).
Condition (38) is critical to the end situation t/hze. Where hb is maximum, condition (43) is critical. This can be either hbd or hbt.
$hbt = p.\sin\alpha t - l.\sin(\alpha t-\beta e)$
$tg(\alpha t-\beta e) = (1-\lambda).tg\alpha t$.
Condition (57) is critical with a value t/hbd. Condition (51) is critical during the transition from the Swinging to the Tilting movement, because $1/tg\alpha t < 1/tg\alpha d$. The right half of condition (51) is minimum and equal to ρ during the starting situation without chainpull.
Assuming the maximum value of hbd and hbt is $hbdt$, the critical conditions are $/tg\delta/ < t/hze$, $t/hbdt$ and $\rho.(1+szt/hbt)$ or ρ. An anchor will fall over primarily, instead of slewing round because $hb < hz$.
The anchor slides before falling over as $t/hz > \rho.(1+sz/hb)$.
This condition can be replaced by (61) to make a practical condition.

13. SUMMARY OF THE CONDITIONS

Succession of movements	Whipping-Tilting	Whipping-Swinging-Tilting
Yawing anchor		
Slewing before falling over	$wm > szm$ (60)	$wd > szd$ (62) $wx > hbx.szd/hbd$ (63)
Rolling anchor		
Sliding before falling over	$t > \rho.hze(1+Khp/G)$ (61)	

Stability conditions

	Whipping-Tilting $/tg\gamma/<$	Whipping-Tilting $/tg\delta/<$	Whipping-Swinging-Tilting $/tg\gamma/<$	Whipping-Swinging-Tilting $/tg\delta/<$
Falling over	t/szm	t/hze	$\frac{t.hbd}{szd.hbx}$	t/hze
Slewing	t/we	t/hbm	t/we	$t/hbdt$
Sliding	ρ	$\rho.(1+\frac{szm}{hbm})$ or ρ	ρ	$\rho.(1+\frac{szt}{hbt})$ or ρ

14. NUMERICAL EXAMPLE

To obtain an impression regarding the importance of the conditions already found, some critical values of an anchor with the successive movements Whipping and Tilting and of an anchor with the successive movements Whipping, Swinging and Tilting are calculated.

The main data of the anchors are: $\lambda p = 1$.

Anchor	Number	λ	p/l	αb	βe	t/l
	1	0.8	0.573	15^{o}	11^{o}	0.355
	2	0.8	0.573	15^{o}	15^{o}	0.355

The value of ρ is assumed to be 0.1.

The calculated values are:

Anchor number	1		2	
	$/tg\gamma/<$	$/tg\delta/<$	$/tg\gamma/<$	$/tg\delta/<$
Falling over				
value tg	1	2.65	0.762	1.4
value angle	45^{o}	69.3^{o}	37.3^{o}	54.4^{o}
Slewing				
value tg	0.8	4.53	0.755	2.96
value angle	38.6^{o}	77.5^{o}	37.1^{o}	72.3^{o}
Sliding				
value tg	0.1	0.552 or 0.1	0.1	0.338 or 0.1
value angle	5.7^{o}	28.9^{o} or 5.7^{o}	5.7^{o}	21.2^{o} or 5.7^{o}
(60) and (62)	$wm/l = 0.444 > szm/l = 0.354$		$wd/l = 0.444 > szd/l = 0.354$	
(63)			$wx/l = 0.454 < hbx.szd/hbd.l = 0.466$	
(61)	$Khp < 17Ga$		$Khp < 13Ga$	

The possibility of an anchor freeing by sliding appears greatest. It is therefore useful to consider the aspects of the sliding movement in greater detail.

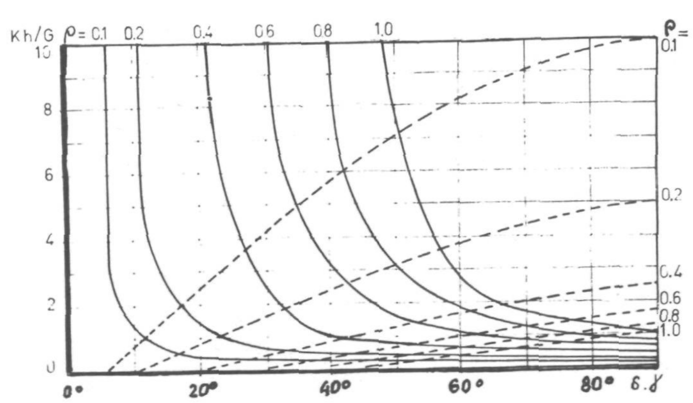


Fig. 26. Curves concerning the sliding conditions (47) and (50).

——— sliding during the yawing movement
- - - - - sliding during the rolling movement

15. SLIDING MOVEMENT

Regarding sliding, in figure 26 the curves relating to the critical *Kh*, δ and γ values of the formulas (47) and (50) are represented. The curves decreasing by an increasing value of γ, show the relationship between *Kh* and γ of a yawing anchor.

$Kh/G = \rho/(/\sin\gamma/-\rho.\cos\gamma)$.

The curves increasing by an increasing value of δ, show the relationship between *Kh* and δ of a rolling anchor.

$Kh/G = (/\sin\delta/-\rho.\cos\delta)/\rho$.

During the yawing movement $Kh/G < \rho/(/\sin\gamma/-\rho.\cos\gamma)$...... ...... (47)

During the rolling movement

$$Kh/G > (/\sin\delta/-\rho.\cos\delta)/\rho \text{......} \qquad \text{......} (50)$$

It is remarkable that the critical ratio *Kh/G* increases for a yawing anchor and decreases for a rolling anchor, by an increasing value of ρ.
The allowable value of γ is equal to the allowable value of δ when $tg\delta = tg\gamma = 2.\rho.(1-\rho^2)$.

In practice, we may expect that the roll angle of an anchor holding on a sea bed will be smaller than the yawing angle. The yawing angle arises under influence of the unknown sea bed area, wind, direction of the waves and current.
The rolling angle only arises under influence of the uneven sea bed area.
It is noticeable that the decisive influence of the yawing movement is by an increasing chainpull.

Commonly, the value of ρ will be smaller than *t/we*, value related to slewing. Therefore in the end situation, sliding will occur most often. The anchor will free as a result of the yawing movement of the ship, behind the anchor.
It is therefore advisable under dangerous circumstances to lay out a stern anchor to reduce the yawing movement of the ship, behind the bower anchors.
Assuming a constant value of ρ, holding a specified chainpull, an increase of the allowable yawing angle can only be realized by increasing the anchor weight to a large degree.

16. CONCLUSIONS

The greatest risk of an anchor freeing by sliding is during the yawing movement of a ship behind an anchor. It is less difficult to meet condition (60) than conditions (62) and (63). Taking into account the value of *hze* will always be smaller in condition (61), an anchor with the succession of movements Whipping-Tilting will be the most stable. Therefore preference is given to anchors which make only two movements, the Whipping of the shank and Tilting of the complete anchor.

By means of a particular choice of the weight distribution, the distance between the flukes and other dimensions, sometimes a stockless movable fluke anchor will slide before falling over. In case the uneven area does not allow a sideways movement, a rolling stockless, movable fluke anchor will fall over.
Therefore the risk of a stockless anchor falling over during rolling can not be remedied by constructive measure. A yawing stockless movable fluke anchor, that meets the conditions (60) or (62 and 63), will slew, holding the chainpull on one fluke only.

It will be disadvantageous to make a great distance between the fluke points for increasing the rolling stability, because it decreases the possibilities that the fluke points hold simultaneously after an uneven area.

With the help of a stock, the risk that an anchor might fall over may be reduced; by decreasing the distance between the fluke points simultaneously, an anchor will also slew earlier. Therefore the behaviour of the old fashioned and modern stock anchors, are investigated in chapter 5.

17. REMARKS

All conditions summarized in figure 24 are related to anchors with $\lambda p = 1$ and assuming $Kv = 0$.
When $\lambda p < 1$ and $Kv = 0$, the derived conditions may be used to obtain a rough impression of the anchor stability because the centre of gravity of these anchors lies below the centre of an anchor with $\lambda p = 1$.
In all other cases the stability conditions with respect to a particular anchor, have to be derived from the general conditions indicated in the paragraphs 6, 7 and 8.

CHAPTER 5

STOCKED ANCHORS HOLDING ON AN IMPERVIOUS BED

1. THE DIFFERENT STOCKED ANCHOR TYPES

Of the oldest anchors we know, the anchors of the Greeks, Romans and Chinese were stocked and as stocked anchors were extensively used through all ages, the question concerning their advantages and disadvantages, with respect to stockless anchors arises.
The most important difference between the various types is the position of the stock with respect to shank, flukes and crown. The Roman anchors found near the hulks of two galleys built by the Emperor Caligula in 40 A.D., have stocks which were located at the end of the shanks, opposite the crowns. See figures 27 and 28 [9] .

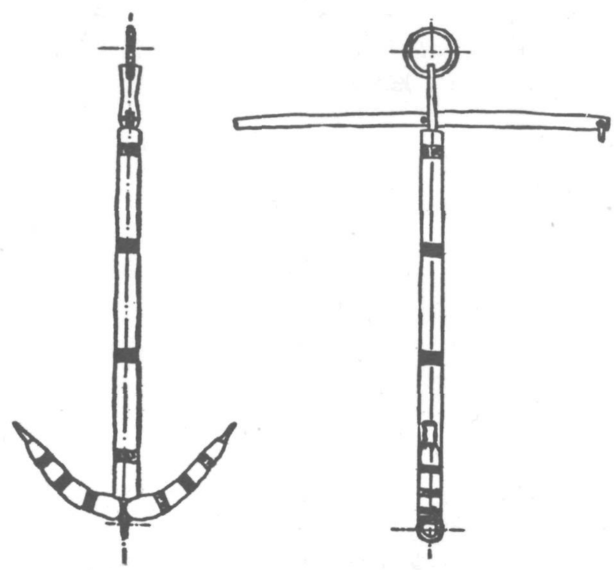


Fig. 28. Roman anchor with curved arms and removable iron stock, found near the "Caligula" galleys.

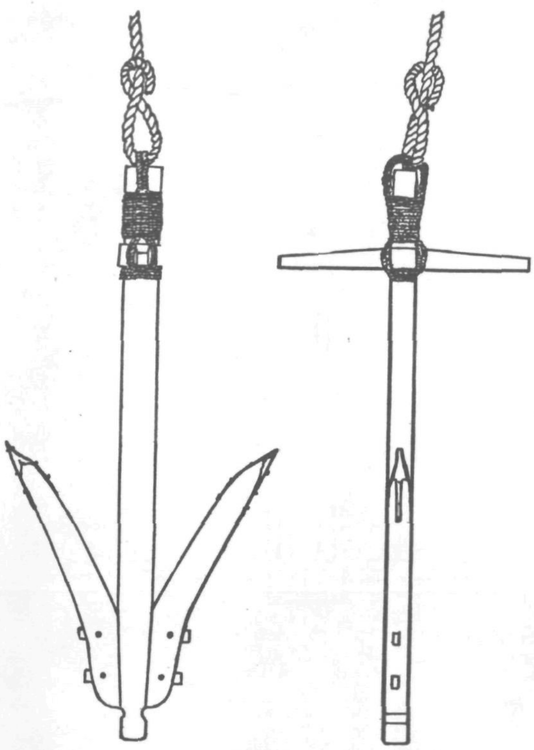


Fig. 27. Roman anchor with straight arms and lead stock, found near the "Caligula" galleys.

This general type, referred to as "Old Fashioned" or "Common" continued to be used by the British and U.S. Navies in the 1800's.
The stock of the Chinese anchors is located at the crown, perpendicular to the plane through the arms and the shank.

See figure 29. This anchor type was used as early as 2000 B.C. and is still efficiently holding Chinese junks. The Northill anchor, basically of the Chinese anchor model, was patented in 1937. See figure 30.

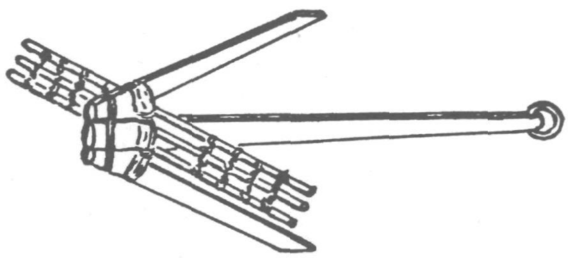


Fig. 29. Chinese anchor.

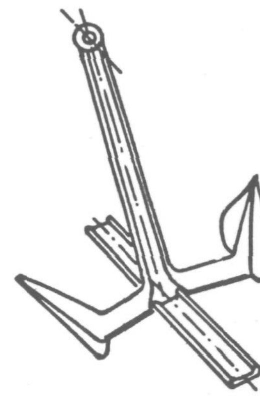


Fig. 30. Northill anchor.

Next to the "Common" shank-stocked and the Chinese crown-stocked anchor types, with arms fixed to the shank, there are many different stocked anchor models with movable arms and flukes. Most of these were invented during the nineteenth century.
So the shank-stocked, hinged arm type of Porter, patented in 1838 and introduced by Trottman in 1852, the arm can rotate about a hinge at the crown end of the shank, in a plane through the shank perpendicular to the stock. See figure 39.
The axis of rotation of the fluke of the first pivoting single fluke, crown-stocked "Wishbone" anchor, patented by Piper in 1822, coincides with the axis of the stock.
See figure 31.

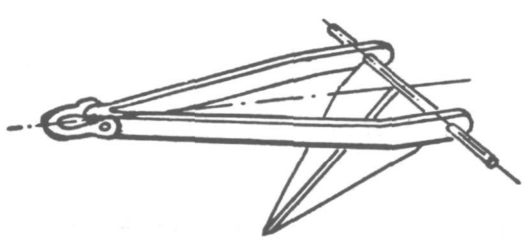


Fig. 31. Wishbone anchor.

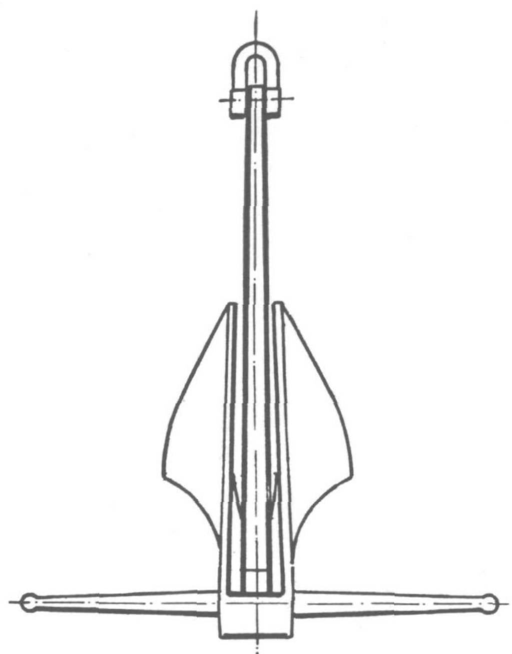


Fig. 32. L.S.T. anchor.

A very important group is the double fluke, crown-stocked anchor model. The main characteristic of this group is that both flukes pivot about an axis, coinciding with the axis of the stock. See figure 32.

Summarizing, the following groups of anchor types have to be investigated further:

- The Common anchors with stocked shank and arms fixed to the crown.
- The shank-stocked types with movable arms and flukes.

- The crown-stocked anchors with arms fixed to the crown.
- The crown-stocked, movable arm and fluke anchor types.

The addition of a stock to an anchor often leads to an improvement of the anchor stability. However, this enlarges the risk that the anchor will rest with the crown and stock alone touching the bed. In such a position, the flukes or the fluke points often cannot touch the bed. In this respect, the properties of the stockless grapnel anchor is considered in relation to the crown-stocked anchors.

2. THE COMMON ANCHOR

The two lake Nemi, Roman common anchors are not similar. The one with the lead stock has straight arms and the iron stocked has curved arms.
Therefore, the influence of straight and curved arm forms are investigated successively.
The centre of gravity of common anchors lies on the centre line of the shank. Therefore related to common stocked anchors $\lambda p = 1$ and $G = Ga$.

2.1. THE ROMAN ANCHOR WITH STRAIGHT ARMS

The Roman anchor, assuming a horizontal even bed, can be represented in theoretical form as indicated in figure 33.

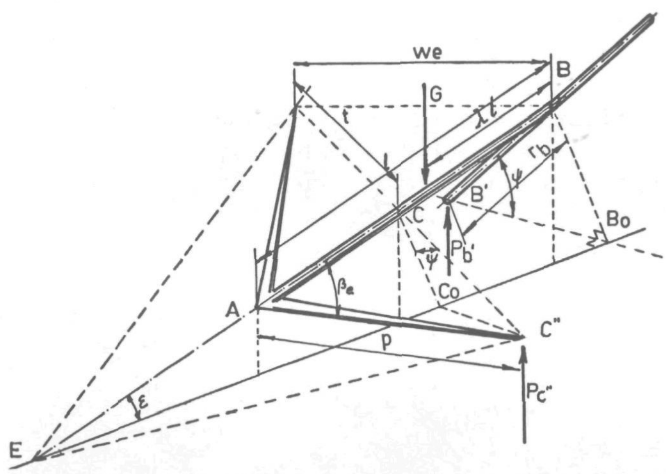


Fig. 33. Model situation of a "Common" anchor with straight arms.

It is holding when the stock rests parallel to the bed and B coincides with Bo. It would be very useful if the anchor, resting otherwise, would rotate itself immediately into the desirable holding position. Assuming in the starting position point A rests on the bed; the anchor will rotate immediately until an arm touches the bed. Because there is a direction of shank rotation, the centre of gravity falls. Rotating further, after fluke point C'' hits the bed, the point of the crown A lifts off the bed. This happens (neglecting dynamical influences), only when the anchor, resting on A, C'' and B', is unstable.

Assuming ψ the inclination angle of the stock, measured in a plane through the centre line of the stock, perpendicular to the shank and ε is the inclination angle of the shank to the bed

$$tg\varepsilon = (rb.\sin\psi - t.\cos\psi)/(l - p.\cos\beta e) \quad \ldots\ldots \quad \ldots\ldots (51)$$

rb is half the shank length.

A lifts off and the shank rotates when the forces *Pb'* and *Pc"* cause a moment about the centre line of the shank $Pb'.rb.\cos\psi > Pc''.t.\sin\psi$ or when

$$\mathrm{tg}\psi < \frac{rb}{p.\sin\beta e} \cdot$$

$$\cdot \frac{l^2+p^2-2.l.p.\cos\beta e-\lambda.l(l-p.\cos\beta e)}{rb^2+\lambda.l(l-p.\cos\beta e)} \text{ .... } (52)$$

During rotation to the holding position, ψ and also $\mathrm{tg}\psi$ decrease.

There is a critical situation when *A*, *C"* and *B'* rest on the bed, or when

$$\mathrm{tg}\psi = l.\mathrm{tg}\beta e/rb \text{ .... } (53)$$

Substituting this value of $\mathrm{tg}\psi$ in condition (52), the anchor rotates automatically into its holding position when

$$l < \frac{rb^2.(we^2-\lambda.l.q)\cos\beta e}{p.\sin^2\beta e.(rb^2+\lambda.l.q)} \text{ .... } (54)$$

Assuming $q = l-p.\cos\beta e$ so that $we^2 = p^2.\sin^2\beta e+q^2$.

2.2. THE COMMON ANCHOR WITH CURVED ARMS

This Roman type, holds when the stock rests parallel to the bed and *B* coincides with *Bo*. See figure 28 and 34.
Resting otherwise, the anchor can make two different movements; rolling over the bed with the curved arm or, rotating about the point of a fluke.
Concerning the arm rolling movement, additional formulas and conditions can be derived with the help of the theoretical situation of the anchor as represented in figure 34.

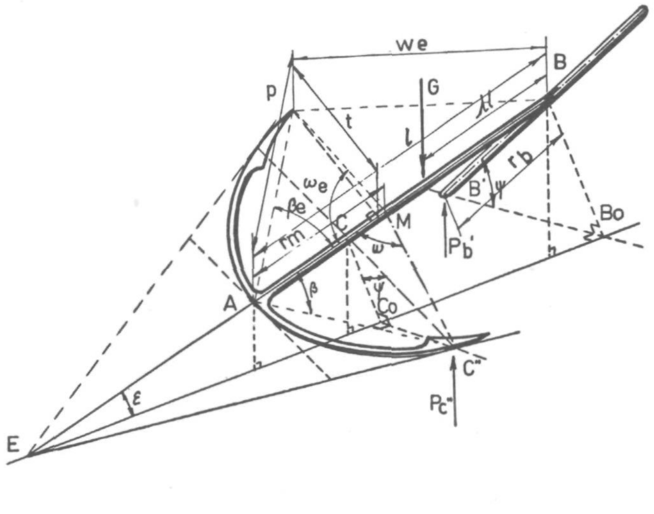


Fig. 34. Model situation of a "Common" anchor with circular curved arms.

Assuming circular curved arms with radius *rm*, and one arm resting with point *C"* on the bed, the attitude of the anchor is determined by an auxiliary angle ω, relating to the angle about which the arm rolls over the bed, and the angle of inclination of the shank ε.

$tg\varepsilon = (rb.\sin\psi - rm.\sin\omega.\cos\psi)/\{l - rm.(1-\cos\omega)\}$.
Because the line EC'' is tangential to the arm, applies $tg\varepsilon = \cos\psi/tg\omega$ too.
Eliminating ε,

$$rb.tg\omega = \{(l-rm).\cos\omega + rm\}/\sin\omega \qquad (55)$$

A lifts off and the shank rotates when the reaction forces in B' and C'', Pb' and Pc'' cause a moment about the centre line of the shank, in the direction of the holding position, so that

$$Pb'.rb.\cos\psi > Pc''.rm.\sin\omega.\sin\psi \qquad (56)$$

or

$$\lambda < rb^2.(l-rm)/\{rb^2 + rm^2 + rm.\cos\omega.(l-rm)\}.l \qquad (57)$$

The right part of this condition is minimum, as $\cos\omega$ is maximum, or as A rests on the bed. Then the condition is

$$\lambda < rb^2.(l-rm)/l.(rb^2 + rm.l) \qquad (58)$$

The transition from the arm rolling movement into the fluke point rotating movement happens when C'' coincides with the point of the fluke, $\omega = \omega e$ and if λ meets condition (57) for $\cos\omega = \cos\omega e$.
Denoting the value of ψ at the position of transition by ψt,

$$tg\psi t = \{(l-rm).\cos\omega e + rm\}/rb.\sin\omega e \qquad (59)$$

Substituting, $tg\beta e = \sin\omega e/(1-\cos\omega e)$ and
$p = rm.\sin\omega e/\sin\beta e$,
condition (53), relating the anchor with straight arms, applies to this movement of rotation about the fluke point C''.
Assuming $q = l - rm.(1-\cos\omega e)$, the movement continues when

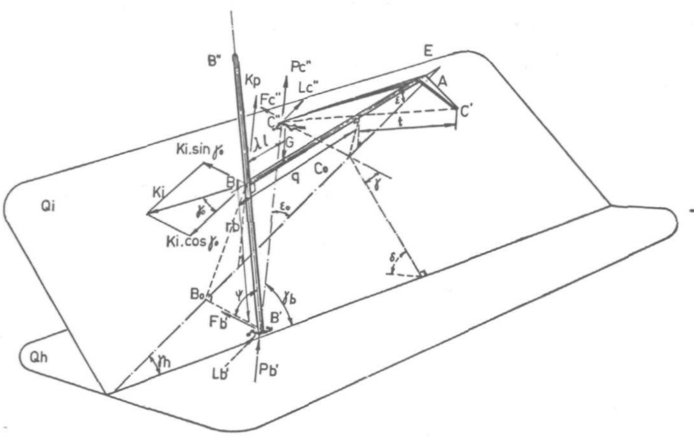
$$tg\psi t < \frac{rb}{rm.\sin\omega e} \cdot \frac{\omega e^2 - \lambda.l.\{l - rm.(1-\cos\omega e)\}}{rb^2 + \lambda.l.\{l - rm.(1-\cos\omega e)\}} \qquad (60)$$

When an anchor does not rotate itself into the holding position, the anchor chain is the only means that can help. Therefore, the influence of the chainpull in connection with the influence of an inclined bed has to be investigated further.

2.3. MOVEMENT OF A COMMON ANCHOR ON AN INCLINED BED

It is assumed the anchor rests on an inclined sea bed Qi, resting with fluke point C'' and the end of the stock B' on the bed. The chainpull is resolved into a component Ki, parallel to the bed and a component Kp, perpendicular to the bed. See figure 35. The position of the anchor is determined by the angles γb and δ. Angle δ, the inclination angle of the plane, and γb the angle between a horizontal line of the plane and the line through the two points B' and C'' the anchor rests on. Dependent on the inclination angle ψ of the stock, the projection of the shank perpendicular to plane Qi, line EBo, makes an angle γh with a horizontal line.

Assuming the component of the chainpull Ki, makes an angle γo with a line through point B, parallel to line EBo, the anchor rotates to the holding position when the sum of the moments, due to the chainpull and the anchor weight, acts in the direction concerned. The different forces and their components are indicated in figure 36.



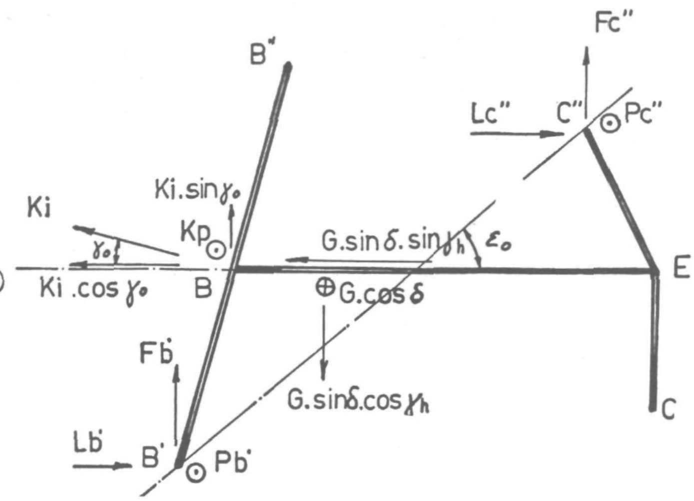


Fig. 35. "Common" anchor with straight arms resting on an inclined plane.

Fig. 36. The forces acting on a "Common" anchor resting on an inclined plane.

The value of the auxiliary angles ε and εo can be determined with the formulas $\mathrm{tg}\ \varepsilon = (rb.\sin\psi - t.\cos\psi)/q$ and $\mathrm{tg}\varepsilon o = \cos\varepsilon.(t.\sin\psi + rb.\cos\psi)/q$.
For an anchor with circular curved arms $t = rm.\sin\omega e$. For an anchor with straight arms $t = p.\sin\beta e$.

The moment about line $B'C''$ is

$$Mbc = Ki.rb.\sin\psi.\cos\varepsilon.(\cos\gamma o.\sin\varepsilon o + \sin\gamma o.\cos\varepsilon o) + \\ + G.\cos\delta.\sin\varepsilon o \left\{ \frac{q.rb.\cos\psi}{\cos\varepsilon.(rb.\cos\psi + t.\sin\psi)} - \right. \\ \left. - rb.\sin\psi.\sin\varepsilon - \lambda.l\cos\varepsilon \right\} + \\ + G.\sin\delta.(\sin\gamma h.\sin\varepsilon o - \cos\gamma h.\cos\varepsilon o). \\ (rb.\sin\psi.\cos\varepsilon - \lambda.l.\sin\varepsilon) - Kp.rb.\cos\psi.\cos\varepsilon o \ldots\ldots \qquad \ldots\ldots (61)$$

Eliminating the values ε and εo and assuming $a1 = rb.\cos\psi + t.\sin\psi$ and $a2 = rb.\sin\psi - t.\cos\psi$, the condition, indicating rotating to the holding position, simplifies to

$$0 < Ki.rb.\sin\psi.\{a1.\cos\gamma o + (a2^2+q^2)^{\frac{1}{2}}.\sin\gamma o\} + \\ + G.\sin\delta.\{a1.\sin\gamma h - (a2^2+q^2)^{\frac{1}{2}}.\cos\gamma h\}.(rb.\sin\psi - \lambda.l.a2/q) + \\ + G.\cos\delta.(q^2.rb.\cos\psi - q.\lambda.l.a1 - rb.t.a2)/q - \\ - Kp.rb.(a2^2+q^2).\cos\psi/q \ldots\ldots \qquad \ldots\ldots (62)$$

Rotating on a horizontal sea bed, the value of δ is equal to zero, so condition (62) is

$$0 < Ki.rb.\sin\psi\{a1.\cos\gamma o + (a2^2+q^2)^{\frac{1}{2}}.\sin\ \gamma o\} + \\ + G.(q.rb.\cos\psi - \lambda.l.a1 - rb.rm.a2/q) - \\ - Kp.rb.(a2^2+q^2).\cos\psi/q \ldots\ldots \qquad \ldots\ldots (63)$$

The influence of Ki in this condition is always positive, so an increasing chainpull, due to the ship movement, can rotate the common anchor into the holding position. If the angle γo is positive, the value of Kp practically zero or negative, and if fluke C'' holds.
The movement becomes impossible for $Kp = 0$ when $a1.\cos\gamma o + (a2^2+q^2)^{\frac{1}{2}}.\sin\gamma o \leq 0$ or when $\mathrm{tg}\gamma o < -a1/we$ or $\gamma o < -\varepsilon o$.

Because the value of γo has been negative, the chainpull will be able to rotate the anchor into the opposite holding position, with fluke point C' holding on the bed. The anchor cannot rotate into a holding position when the crown continues to slip over the bottom and the fluke points do not touch the bed.

2.4. THE EQUILIBRIUM EQUATIONS

The analysis of the stability of a Common anchor, holding on an inclined sea bed can be started from the static equilibrium equations, assuming $Kp = 0$ and the stock rests on the bed on the outer ends B' and B'' only. See figure 37.

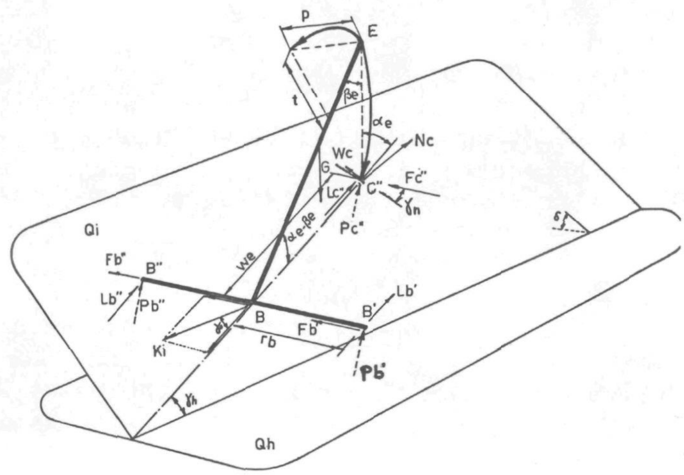


Fig. 37. "Common" anchor holding on an inclined plane.

The equations are:

The equations relating to the forces:

Holding equation $Lc'' = Ki.\cos\gamma o + G.\sin\delta.\sin\gamma h - Lb' - Lb''$.

Sliding equation $Fb' + Fb'' + Fc'' + Ki.\sin\gamma o = G.\sin\delta.\sin\gamma h$.

Weight equation $G.\cos\delta = Pc'' + Pb' + Pb''$.

The equations relating to the moments:

Yawing equation $(Lb' - Lb'').rb + Fc''.we = G.\sin\delta.\cos\gamma h.\lambda.l.q/we$.

Equation relating to rotation about the axis of the stock

$$Pc''.we + G.\sin\delta.\sin\gamma h.\lambda.l.t/we = G.\cos\delta.\lambda.l.q/we.$$

Falling over equation

$$(Pb' - Pb'').rb = G.\sin\delta.\cos\gamma h.\lambda.l.t/we.$$

2.5. THE VALUE OF THE CHAINPULL

The value of the chainpull Ki depends on the direction and the value of the friction forces, acting on the points of the stock B' and B''.

Assuming a maximum coefficient of friction between stock and plane equal to ρb and assuming $a3 = (rb^2 + we^2)^{\frac{1}{2}}$ the friction forces can be determined.

When the friction forces are acting in a direction against a slewing movement of the anchor, about point C, in a direction where the value of γ increases, the forces are:

$$Lb'' = -\rho b.rb.Pb''/a3 \qquad Fb'' = -\rho b.we.Pb''/a3$$
$$Lb' = +\rho b.rb.Pb'/a3 \qquad Fb' = -\rho b.we.Pb'/a3$$

Substituting these values in the equilibrium equations, the condition indicating where the anchor starts slewing is

$$we.Ki.\sin\gamma o - G.\sin\delta.\cos\gamma h.(we-\lambda.l.q/we) > \frac{\rho b.G}{we}.\left(1+\frac{rb^2}{a3.we}\right).$$

$$.\{(we^2-\lambda.l.q).\cos\delta+\lambda.l.t.\sin\delta.\sin\gamma\}.$$

The condition relating to the beginning of a slewing movement in opposite direction is:

$$we.Ki.\sin\gamma o+\frac{\rho b.G}{we}\left(1+\frac{rb^2}{a3.we}\right).\{(we^2-\lambda.l.q)\cos\delta+\lambda.l.t.\sin\delta.\sin\gamma\} <$$

$$< G.\sin\delta.\cos\gamma h.(we-\lambda.l.q/we).$$

Introducing the values sz, hz and $a4$:
-sz, the distance of the centre of gravity to a line vertical on the bed through point C'', the point on which the fluke is holding, $sz = we-\lambda.l.q/we$,
-hz, the distance of the centre of gravity to the bed, $hz = \lambda.l.t/we$ and
-$a4 = (1+rb^2/a3.we)/we$, the condition relating to the holding force Ki, the anchor does not slew when

$$sz.G.\sin\delta.\cos\gamma h-\rho b.a4.we.G(sz.\cos\delta+hz.\sin\delta.\sin\gamma h) \leq we.Ki.\sin\gamma o \leq$$
$$\leq sz.G.\sin\delta.\cos\gamma h+\rho b.a4.we.G(sz.\cos\delta+hz.\sin\delta.\sin\lambda h) \qquad \ldots\ldots. (64)$$

A slewing movement, once started by a change of the value $Ki.\sin\gamma o$, varies the value of γh and γo simultaneously and stops in a new position that complies with condition (64).

2.6. TRANSVERSE STABILITY

The anchor rests stable so long as both points of the stock B'' and B' are resting on the bed. The values of the reactions Pb' and Pb'' are:

$$Pb' = \frac{G}{2.rb.we}.\{rb.sz.\cos\delta+hz.(rb.\sin\gamma h+we.\cos\gamma h).\sin\delta\} \qquad \ldots\ldots.. (65)$$

and

$$Pb'' = \frac{G}{2.rb.we}.\{rb.sz.\cos\delta+hz.(rb.\sin\gamma h-we.\cos\gamma h).\sin\delta\} \qquad \ldots\ldots.. (66)$$

A point lifts off the bed when either Pb' or Pb'' is negative, therefore the anchor rests stable as long as $-rb.sz/hz.(rb.\sin\gamma h+we.\cos\gamma h) < \mathrm{tg}\delta <$
$< rb.sz/hz.(we.\cos\gamma h-rb.\sin\gamma h)$.
The value of $/\mathrm{tg}\delta/$ is minimum when $\mathrm{tg}\gamma h = -rb/we$ or rb/we..... ...... (67)

Then $/\mathrm{tg}\delta/ < \dfrac{rb.sz}{hz.(we^2+rb^2)^{\frac{1}{2}}}$ applies. ...... (68)

As was expected, the values of Ki and G are cancelled out.

2.7. SLIDING SIDEWAYS

It is assumed fluke point C'' holds against an uneven area in a position where line BC'' makes an angle γn, with a line in plane Qi, perpendicular to the line formed by the intersection of the surface of the uneveness and plane Qi.
See figure 37.
Introducing the friction coefficient ρc, acting between the bed and the point of the fluke, the condition relating to the normal holding force Nc and the tangential friction force Wc the point does not slide when:

$$Wc \leq \rho c(Nc+Pc'')\ldots\ldots \qquad \ldots\ldots (69)$$

Introducing $Wc = Lc''.\sin\gamma n + Fc''.\cos\gamma n$ and $Nc = Lc''.\cos\gamma n - Fc''.\sin\gamma n$.
The value of Pc'' is

$$Pc'' = G.\lambda.l(q.\cos\delta - t.\sin\delta.\sin\gamma h)/we^2 \ldots\ldots \qquad \ldots\ldots (70)$$

When the point slides sideways, the stock will also slide.
To simplify the formulas, a sliding movement of the anchor without slewing, a translation movement, is assumed. Then $Lb'+Lb'' = \rho b.(Pb'+Pb'').\sin\gamma n$ and $Fb'+Fb'' = \rho b.(Pb'+Pb'').\cos\gamma n$.

Condition (69) can be written, after substituting Wc and Nc and after eliminating Fc, in the form:

$$Ki.\{\rho c.\cos(\gamma n-\gamma o)-\sin(\gamma n-\gamma o)\} \geq Pc''(\rho b-\rho c) +$$
$$+ G.\sin\delta\{\cos(\gamma h-\gamma n)-\rho c.\sin(\gamma h-\gamma n)\}-G.\rho b.\cos\delta \ldots\ldots \qquad \ldots\ldots (71)$$

If $tg(\gamma h-\gamma n)$ is equal to $-\rho c$, the right half of the condition is maximum.
When $Ki = 0$ and $\rho b = \rho c$ for $\gamma h = \gamma n$ condition (71) is $tg\delta \leq \rho b \ldots\ldots \ldots\ldots$ (72)

When $\gamma n = 0$ and $Ki = 0$ and $\rho b = \rho c$ the anchor will not slide, as
$O \geq \sin\delta.(\cos\gamma h-\rho b.\sin\gamma h)-\rho b.\cos\delta$, or $O \geq tg\delta.(1-\rho b.tg\gamma h)$, or $1/\rho b \leq tg\ h \ldots$ (73)

2.8. THE BEHAVIOUR OF A WOOD-STOCKED COMMON ANCHOR

In order to gain a deeper understanding of the behaviour of a wood-stocked Common anchor, some critical values, neglecting the shape of the flukes, are calculated relating to an old Common anchor of 1100 old Dutch pounds as indicated by Nicolaes Witsen in 1671 [13].

The main dimensions are indicated in old Dutch feet.

l = 10.5' rm = 4.77' $\beta e = 60^\circ$
we = 9.1'
p = 4.77' rb = 6.5' $\omega e = 60^\circ$

The value of λ of this anchor type will have been about 0.45.
Equation (59), regarding the situation of transition between the arm rolling and the fluke point rotating movement, indicates a value of ψt about 58.5°.
On dry land, condition (60) indicates for this ψt value, λ must be smaller than or equal to 0.3, the anchor will rotate automatically to its holding position.
The anchor will roll over the arm in the opposite direction, and the point of the crown A will hit the bed, as the value of λ is greater than 0.3.
The fluke point the anchor was resting on will lift off the bed.
Condition (60) indicates the chain-pull has to rotate the anchor to a value of $\psi t < 41^\circ$, before the anchor will rotate itself to the holding position on a horizontal bed.

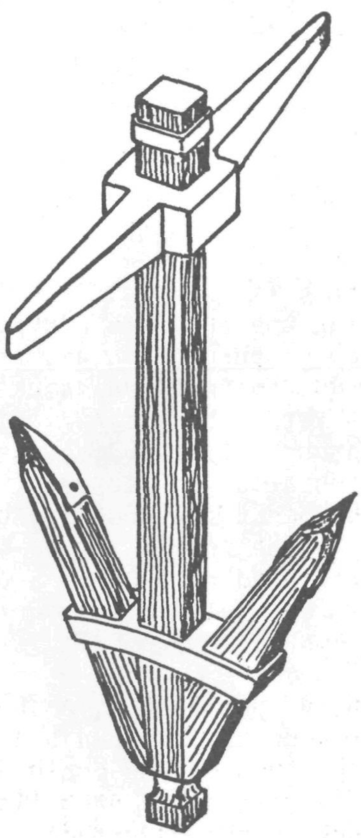


Fig. 38. Roman anchor with a lead collar round the arms and shank to the crown.

When $\lambda < 0.25$, as indicated by condition (58), the anchor will rotate to its holding position from $\psi t = 90^{\circ}$. Influenced by the wood of the stock under water, the value of λ will be about 0.56. Therefore the anchor will come to its holding position only with the help of the chainpull. Thus the ship drags the anchor over the bed until one of the fluke points gets a hold on the bed, causing an increasing chainpull, which introduces the rotating movement to the holding position. The problem is how long will an anchor slide before this happens. Preventing continuous sliding by paying out a great length of anchor rope, as already described by "Van Yk" [12] in 1697, is sometimes impossible. So "is 't wel gebeurd dat een schip op lager wal verlooren ging, dat anders geschapen stond sijn Meesters groten dienst te sullen doen", "it happened a ship got lost piled up on a lee shore, a ship that was built to give good service to its master" [12].

In the critical position, when $\gamma h = 35.6^{\circ}$ and the value of δ causes the anchorstock to lift off the bed, δ can be determined with formula (68).
On dry land $\delta \geq 61^{\circ}$ and on the sea bed $\delta \geq 49^{\circ}$.
Changes in the value of Ki or angle γo cause a slewing movement of the anchor, introducing a risk the anchor will free. There is a reasonable chance that the fluke point will hold in a small pit that allows a slight slewing movement of the sharp point of the Common anchor.
When $Ki = 0$ and $\rho b = \rho c = 0.1$, sliding can occur when $\delta > 5.7^{\circ}$.
See condition (72).
The chance that the anchor does not slide because the value of γh is larger than 84.3°, as indicated by condition (73), is negligible.

2.9. THE BEHAVIOUR OF THE CALIGULA ANCHOR WITH STRAIGHT ARMS

The lead stocked anchor, found near the "Caligula" barges is missing the lead collar. See figure 27. These often found lead collars belonged to Roman anchor models as indicated in figure 38.
The dimensions of the "Caligula" anchor were estimated as follows:
$l = 4.2$ m, $p = 2.79$ m, $rb = 1.17$ m, βe about 27.5°. The weight of the lead stock will be about 710 kg. The total weight about 1450 kg and the value of λ on land about 0.29. Condition (53) indicates for a resting anchor on land a rotation to the holding position when $\psi < 33.5^{\circ}$.
In the position with A, C'' and B' resting on the bottom, $\psi = 62^{\circ}$, so that on land, the anchor does not rotate itself automatically in the holding position. Condition (54) indicates only anchors with $\lambda \leq 0.08$ will do this.
Assuming the specific gravity of the wooden parts about equal to the specific gravity of the sea water, the value of λ of the immersed anchor will nearly be zero, due to the lead stock. So, resting on a sea bed, this Roman anchor will always rotate by its own weight to the holding position, a property the old Common anchors missed, owing to the reversed weight distribution of wood stock and iron arms and flukes.
At the moment the Romans added the lead collar to the crown, this property was lost, by the increasing of λ. Probably they added this collar for strengthening the crown and to achieve a crown weight sufficient to sink the arm on the bed.

2.10. CONCLUSIONS

Common, shank-stocked, anchors with arms fixed to the crown are stable, holding immersed on an inclined bed with an inclination angle $\delta \leq$ about 49°.
The magnitude of the chainpull and the direction of the chainpull do not directly effect the stability of the holding anchor.
A change in the magnitude or the direction of the chainpull, will often start a small slewing movement, thus introducing the risk that the anchor will free.
The anchor will not yaw, but slews immediately. So sliding sideways, due to a yawing movement of the ship will not occur, because the anchor will slew about the holding fluke point.

Sliding due to the inclination of the sea bed will occur when the coefficient of friction is smaller than tgδ. The anchor rotates only in the holding position by the chainpull, effected by the movement of the ship. It needs the help of the chainpull and an uneven area of the bed to move from the resting position with the fluke points lifted from the bed, into the holding position.
Therefore, there is a great risk the anchor will slide over a long distance on the bed, before one of the flukes takes hold. This risk increases, as the length of the chaincable paid out is short and the stock will be lifted off the bed, during the sliding movement.

2.11. COMPARISON WITH THE STOCKLESS, MOVABLE FLUKE ANCHORS

As the dimensions and the weight distribution of the iron, shank-stocked Common anchors are about the same as the old wood-stocked models, we may compare the properties already found for stockless, movable fluke anchors with the properties of the Common wood-stocked anchors.

Comparing the Common anchors with the stockless, movable fluke anchors, there is no important difference relating to the risk of falling over, when resting on an inclined bed. The risk of falling over of a yawing, movable fluke anchor will be about the same as the risk the Common anchor will free, by the slewing movement introduced by a change in direction or magnitude of the chainpull.

Without chainpull, the risk of sliding sideways on an inclined plane is the same for both anchor types. Considering the results of the comparison, the risk that the Common anchors will fail to hold in time, the unfavourable situation of the stock for stowing the anchor and the great risk of fouling when the chain hits the upwards anchor arm, it is understandable that the Common, shank-stocked, anchor fell into disuse.

3. SHANK-STOCKED ANCHOR MODELS WITH MOVABLE ARMS AND FLUKES

There are two important shank-stocked anchor models with movable arms and flukes.

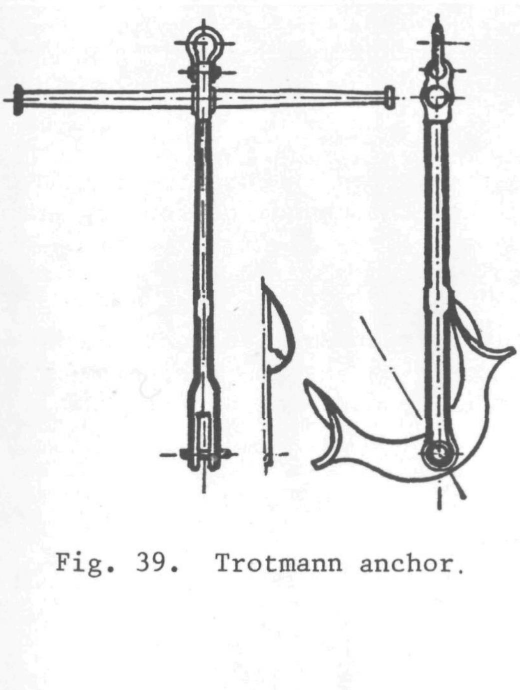


Fig. 39. Trotmann anchor.

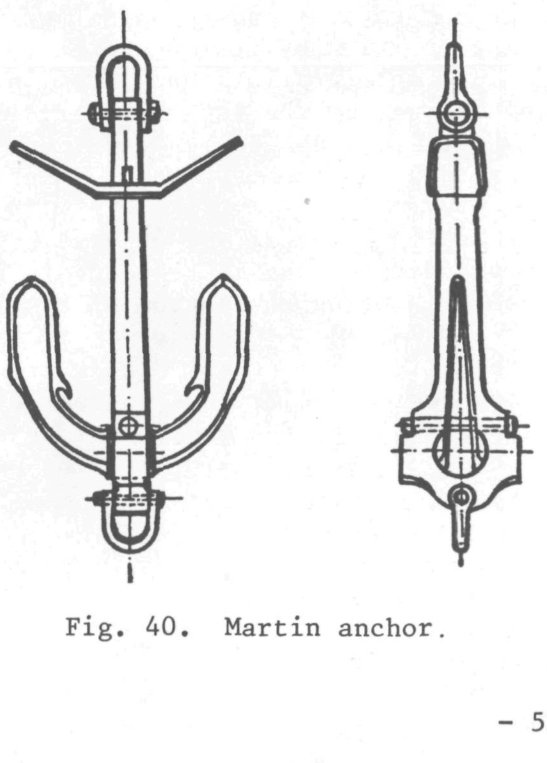


Fig. 40. Martin anchor.

The first model is the Porter of 1838, see figure 39. This was improved and introduced by Trotmann in 1852. Arm and flukes form one part that can rotate in a plane, through the shank perpendicular to the stock, around a hinge pin, situated at the crown's end in the shank. The second, is the Martin anchor. See figure 40.
Arms and flukes, forming one part, can rotate in the crown about an axis parallel to the stock. Both models have different properties and therefore they have to be considered separately.

3.1. THE PORTER-TROTTMANN ANCHOR MODEL

Derived from the Common anchor model, the Porter-Trotmann anchor rotates and folds immediately into a resting position with the stock resting on and parallel to the bed. In the situation where the anchor rests on a planar sea bed, and stock and shank form together two lines in a plane perpendicular to the bed, the height of the centre of gravity above the bed is about 0.25 times the length of the shank. With one fluke folded under the shank, with the stock resting parallel to the bed, the centre of gravity is about 0.10 times the length of the shank above the bed. Therefore, assuming the hinge works properly, the anchor rotates and folds always unloaded, to the end position due to its own weight.

In all probability, the fluke point (under the shank) when dragged over the bed, will fix very quickly. Then induced by the chainpull, arm and flukes rotate, in a plane perpendicular to the bed, about the pin in the shank and hence lifts the crown. During this movement there is an additional possibility that the anchor will free.
At the moment the upper fluke touches the shank, the movement is finished and the holding position is reached. In this position the centre of gravity of the anchor lies under the shank.

Condition (64) already relating to the chainpull of the Common anchor, may also be applied to the Porter-Trotman anchor; and equation (70), condition (71) may also be so related. Therefore properties relating chainpull, stability and sliding sideways of the Porter-Trotman anchor are practically equal to the properties of the Common anchor.

The risk the anchor will free is greater than for a Common anchor, because the flukes and arm make an additional rotating movement about the pin in the crown and also about the point of the fluke, on the bed where the anchor holds.
The anchor rotates and folds, after being lowered on to the bed, into the resting position by its own weight. Therefore the Porter-Trotman anchor will hold in a shorter time than a Common anchor. It is an important, improved. model rising out the long list of old-fashioned anchor models.
This "anti fouling" design was very popular as evidenced by the number still being recovered from the beds of Europe's ports.

"Anti fouling" so called, because holding in a soft bed the upper fluke lies down against the shank, reducing in this position the chance of fouling and the chance of hitting the bottom of a ship.

But there is an important disadvantage, as A. Hauser wrote in 1866 [26].
"L'inconvénient majeur est la mobilité des pattes quand on les rentre à bord, elle peut donner lieu a des accidents". This disadvantage and the unfavourable situation of the stock for stowing were the main reasons the anchor fell into disuse.

3.2. THE MARTIN ANCHOR MODEL

The Martin anchor, ancestor of the stockless anchors, is provided with a small stock at the chain end of the shank. See figure 40. As long as the stock and shank remain free of the bed, it has the same properties as a stockless anchor. The value of λ of the Martin anchor will be smaller than the λ value of a stockless anchor, due to the weight of the stock.
Holding on an inclined bed, the properties of the Martin anchor differ by the stabilizing influence of the stock.
Assuming $Pb'' = 0$.
$(Gp+G)\cos\delta = Pc'+Pb'+Pc''$.
See figure 41.

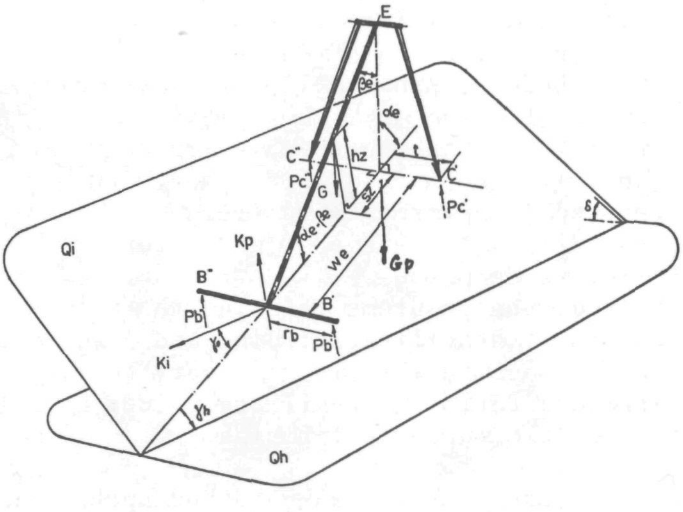


Fig. 41. Model situation of a shank-stocked anchor resting on an inclined plane.

As $Pb'.we = sz.G.\cos\delta + hz.G.\sin\delta.\sin\gamma h$ and $Pb'.rb + t.(Pc'-Pc'') = G.hz.\sin\delta.\cos\gamma h$, the value of Pc'' can be determined. After eliminating the values Pb' and Pc' we find:
$2.we.t.Pc'' = G.hz.\sin\delta.\{(rb-t).\sin\gamma h - we.\cos\gamma h\} + G.\cos\delta\{sz.(rb-t) +$
$+ we.t\} - t.we.(Kp - Gp\cos\delta)$.
Assuming $Gp = 0$ the value of Pc'' is minimum as $\mathrm{tg}\gamma h = (t-rb)/we$.
Then the anchor rests stable as $Pc'' > 0$ or as

$$/\mathrm{tg}\delta/ < \frac{t.we + (rb-t).sz}{hz.\{we^2 + (t-rb)^2\}^{\frac{1}{2}}} \quad ...... \qquad ...... \quad (74)$$

In the holding position the usual value of sz is small; therefore the influence of the added stock also. Due to this small effect and the unfavorable situation of the stock for stowing, the stock was omitted during the course of time.

3.3. CONCLUSIONS

The stabilising influence of the stock in the shank-stocked anchor models with movable arms and flukes in the holding position is very small. This appears from the conditions (68) and (74). The influence of the stock, expressed by the term rb, is determined by the ratio sz/we in both conditions.

The influence of the stock is minimal because sz is usually very small in the holding position. In other words, the stock is situated at the wrong end of the shank. It is therefore very useful to further investigate the properties of the crown-stocked anchor models.

4. THE CROWN-STOCKED ANCHORS WITH FIXED ARMS

Characteristic for the crown-stocked anchors is the stock perpendicular to the symmetrical plane through the arms and shank and located at, or near the crown. The differences between the Chinese anchor, with a fixed stock and pointed arms and the Northill anchor with plough flukes and removable stock, to simplify stowing, do not affect the behaviour of the anchors holding on an impervious inclined bed. See figures 29 and 30.

Therefore, a crown-stocked anchor can be represented in a simplified way as indicated in figure 42. The anchor rests in the holding position with the points B, C and D'' on the inclined bed Qi. Line BDo is the intersection of plane Qi with a plane through the shank, perpendicular to plane Qi. The chainpull in B has been resolved in a force Kp, acting perpendicular to plane Qi and a force Ki acting in plane Qi.
To study the problems relating to chainpull, stability, sliding and slewing movements it is necessary to introduce following auxiliary values to obtain manageable formulas.

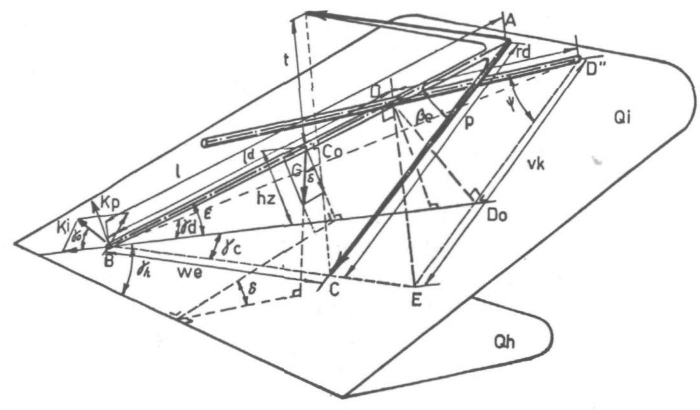


Fig. 42. Model situation of a crown-stocked anchor resting on an inclined bed.

As assumed for the shank-stocked anchors the distance between C and Co equal to $t = p.\sin\beta e$ and the distance between B and Co equal to $q = l-p.\cos\beta e$.
The distance between B and D is denoted with ld. The distance between D and E with $re = t.ld/q$. The distance between E and D'' with $vk = (rd^2+re^2)^{\frac{1}{2}}$, rd half the length of the shank. The distance between B and Do with $vb = (ld^2+re^2.rd^2/vk^2)^{\frac{1}{2}}$.
The angle between the line through the fluke point and the shank end and the intersecting line of the plane, through the shank, perpendicular to the inclined plane Qi is denoted with γc. The angle between the line through the resting end of the stock and the intersecting line of the plane, through the shank, perpendicular to the stock is denoted with γd. The other values are chosen in the same way as with the preceding anchor models.

4.1. THE EQUILIBRIUM EQUATIONS

The starting point for further investigations form the equilibrium equations.
They are:

The weight equation $\quad Kp+Pb+Pc+Pd'' = G.\cos\delta$ .... (75)

The holding equation $\quad Ki.\cos\gamma o+G.\sin\delta.\sin\gamma h = Lb+Lc+Ld''$.

The sliding equation $\quad Ki.\sin\gamma o-G.\sin\delta.\cos\gamma h+Fb+Fc+Fd'' = 0$.

The moment equation about line BDo:

$$hz.G.\sin\delta.\cos\gamma h+Pd''.rd.\cos\psi = Pc.t.\sin\psi \qquad (76)$$

The moment equation about an axis through B, parallel to line $D''E$:

$$\lambda.l.G.\cos\delta.\cos\varepsilon-G.hz.\sin\delta.\sin\gamma h = (Pc.q+Pd.ld)/\cos\varepsilon \qquad (77)$$

The slewing equation about point C:

$$(Ki.\cos\gamma o+G.\sin\delta.\sin\gamma h-Lb).t.\sin\psi-(Fb+Ki.\sin\gamma o).q/\cos\varepsilon+G.\sin\delta.\cos\gamma h.(q-\lambda.l)/\cos\varepsilon-$$
$$- Ld''.(t.\sin\psi+rd.\cos\psi)+Fd''.(vb-q/\cos\varepsilon) = 0 \qquad (78)$$

4.2. THE CHAINPULL

The value of the component Ki of the chainpull can be determined with the slewing equation (78). Assuming the friction between anchor and bed equal to zero in the points B and D'', the equation can be further simplified in:

$$Ki.(q^2.vk.vb.\sin\gamma o-t^2.ld^2.\cos\gamma o) =$$
$$= G.\sin\delta.\{t^2.ld^2.\sin\gamma h+q.(q-\lambda.l).vk.vb.\cos\gamma h\} \qquad (79)$$

The formula indicates the anchor slews in the same manner as the Common and Porter-Trotman anchors about point C, in the direction of the chainpull component Ki. The slewing movement ends when equation (79) applies, due to the changes of the angles γo and γh.

4.3. TRANSVERSE STABILITY

The anchor rests stable as the point C and D'' of the fluke and the stock are resting on the bed. From the equations (76) and (77) can be derived:

$$Pc = \frac{G.\lambda.l.rd.ld}{q.vb.vk}\left\{ \sin\delta.\cos\gamma h.\sin\psi + \frac{\cos\psi}{vb}.(ld.\cos\delta - rd.\sin\delta.\sin\gamma h.\sin\psi) \right\} . \quad (80)$$

and

$$Pd = \frac{G.\lambda.l.\sin\psi}{vb.vk} . \left\{ \frac{re}{vb}.(ld.\cos\delta - \sin\delta.\sin\gamma h.\sin\psi.rd) - rd.\sin\delta.\cos\gamma \right\} \ldots\ldots\ldots \quad (81)$$

So fluke point C lifts off the bed as

$$\sin\delta.\cos\gamma h.\sin\psi + \frac{\cos\psi}{vb}.(ld.\cos\delta - rd.\sin\delta.\sin\gamma h.\sin\psi) < 0$$

or

$$\mathrm{tg}\delta.(rd^2.\sin\gamma h - vb.vk.\cos\gamma h) \geq rd.q.vk/rc \ldots\ldots \quad\ldots\ldots (82)$$

For $\gamma h = 0$ the critical value of δ can be determined with $\mathrm{tg}\delta \leq -rd.q/t.vb$.
Stock point D'' lifts off as

$$\mathrm{tg}\delta.(t^2.ld^2.\sin\gamma h + q^2.vb.vk.\cos\gamma h) \geq t.q.vk.ld^2/rd \ldots\ldots\ldots\ldots \quad (83)$$

For $\gamma h = 0$ the critical value of δ indicated is $\mathrm{tg}\delta \geq t.ld^2/rd.q.vb$.
The critical value of δ indicated with condition (82) is minimum as
$\gamma h = 180^\circ - \gamma d \qquad \mathrm{tg}\gamma d = rd^2/vk.vb$.
The critical value of δ indicated with condition (83) is minimum as
$\gamma h = \gamma c \qquad \mathrm{tg}\gamma c = t^2.ld^2/q^2.vb.vk$.
So the minimum stable value of δ, if $\gamma h = 180^\circ - \gamma d$, can be determined with

$$\mathrm{tg}\delta.t.(vb^2.vk^2 + rd^4)^{\frac{1}{2}} < rd.q.vk \ldots\ldots \quad\ldots\ldots (84)$$

and, if $\gamma h = \gamma c$, with

$$\mathrm{tg}\delta.rd.(t^2.re^2.ld^2 + q^2.vb^2.vk^2) < t.vk^2.ld^3.we \ldots\ldots \quad\ldots\ldots (85)$$

4.4. REARWARD STABILITY

Rotating about the line CD'' the anchor can lift B off the bed.
This happens only when Pb is equal to or less than, zero. Substituting the values of Pd and Pc in equation (75) and assuming $Kp = 0$, the following condition can be derived, relating to the situation as B lifts off the bed:

$$\lambda.l \geq \frac{vb^2.q^2.vk^3}{\mathrm{tg}\delta.\cos\gamma h.t.rd.ld.vk.vb.(ld-q) + (ld.vk - rd.re.\mathrm{tg}\delta.\sin\gamma h).q.(ld.rd^2 + q.re^2)} .$$

On a horizontal bed, $\delta = 0$

$$\lambda.l \geq \frac{vb^2.q^2.vk^2}{ld^2.(q.rd^2 + ld.t^2)} \ldots\ldots \quad\ldots\ldots (86)$$

4.5. SLEWING AFTER SLIDING INTO THE HOLDING POSITION

Sliding over a horizontal planar sea bed without holding, the chainpull will be acting at the anchor in the direction of the centre of gravity; thus, in a plane perpendicular to the horizontal plane through line BDo.

Assuming the friction forces in D'' and B are equal to zero, the anchor will slew over the angle γc, about point C, the moment point C takes hold.

$$\operatorname{tg}\gamma c = t^2.ld^2/q^2.vb.vk \text{......} \qquad \text{......} \; (87)$$

The movement ends when the chainpull acts in a vertical plane through fluke point C.

4.6. THE CHINESE ANCHOR

To obtain an impression regarding the importance of the conditions already found, some values of a Chinese anchor are calculated. See figure 29.
Assuming $p = 0.5l$, $ld = 0.85l$, $rd = 0.5l$ and $\beta e = 30^\circ$ the following values are:

$\gamma c \simeq 14^\circ$	$t = 0.25l$	$we = 0.619l$	$q = 0.566l$
$\gamma d \simeq 24^\circ$	$re = 0.357l$	$vk = 0.625l$	$vb = 0.901l$

For $\gamma h = 0$ the critical values regarding the transverse stability are:
$-51^\circ \leq \delta \leq +35^\circ$.
If $\gamma h = \gamma c$ condition (85) indicates $\delta < 34^\circ$ and if $\gamma h = 180^\circ - \gamma d$ condition (84) indicates $\delta < 49^\circ$.
Condition (86) regarding the rearward stability indicates the anchor rests stable as $\lambda < 0.72$.
The difference between the critical δ values regarding the transverse stability is notable. The Northill anchor model equalizes both critical δ values.

4.7. THE NORTHILL ANCHOR

If the maximum δ value of condition (84) is equal to the maximum δ value of condition (85), regarding both directions of the transverse stability, the following equation must apply to the anchor dimensions.

$$rd^4.(re^2+ld^2) = re^4.(rd^2+ld^2).$$

The only solution is $rd = re$, the solution the Northill anchor fulfills.
See figure 30. The conditions (84) and (85) are $\operatorname{tg}\delta < ld/(ld^2+rd^2)^{\frac{1}{2}}$, so that the maximum values of δ regarding the transverse stability will always be smaller than 45°.
If $rd = re$, than $rd = p.\sin\beta e.ld/(l-p.\cos\beta e)$.
Condition (86) regarding the reaward stability can then be simplified into

$$\lambda.l \geq \frac{q.(2.ld^2+rd^2)}{ld.(ld+q)} \text{......} \qquad \text{......} \; (89)$$

Assuming for a Northill anchor model $ld = l$, $q = 0.8l$ and $rd = re = 0.5l$ the anchor rests stable corresponding to condition (88) when $\delta \leq 41.8^\circ$.
Condition (89) indicates, if $\lambda \geq 1$, the anchor will fall backwards.
The exact value of λ equal to one occurs when $ld^2 = q.(ld^2+rd^2)$.
The rearward stability of the assumed Northill anchor model is noticably more favourable than that of the assumed Chinese model.
However, what occurs when the anchors are resting on the crown upon the bed?

4.8. RESTING ON THE CROWN, WITH THE SHANK UPRIGHT

In the holding position, the anchor rests with the points B, D'' and C on the bed. But there is another resting position with the points A, D'' and C resting on the bed. With the help of equilibrium equations can be derived the anchor rests stable in this upright position if

$$\lambda . l > l - \frac{p^2.(va^2+rd^2)}{p.\cos\beta e.(va^2+rd^2)+va.p^2} \quad ...... \qquad ...... (90)$$

assuming $va = l-ld$.

The assumed Chinese anchor falls into the holding position from the unstable crown resting position when $\lambda < 0.56$. The Northill falls when $\lambda < 0$.
The Northill anchor rests very stable on the crown. Therefore a ship has to turn over a Northill anchor when it is resting with the crown upright on the bed. There is a probability that the chainweight acting at the anchor ring of a Chinese anchor, resting with the crown upright on the bed, turns the anchor over into the holding position, without the help of the ship movement.

4.9. ROLLING MOVEMENT AND TRANSVERSE STABILITY

When the anchor falls over transverse, about line *BD″*, point *C* will free and the anchor will lose hold. Conditions (82) and (84). When the anchor rolls about line *BC*, the end of the stock *D″* lifts off the bed, but point *C* maintains hold. Conditions (83) and (85).
The last movement will be preferred to the first movement.
Therefore the critical values of δ, indicated in the conditions (82) and (84) should be greater than the critical values indicated in the conditions (83) and (85).

The Chinese anchor form will therefore be preferable to the Northill model. Disadvantageous to both models is the risk that point *C* frees during a rolling movement. Further, due to the two opposite holding positions of the anchor, the flukes must be shaped with points, causing point loads on the bed material, and therefore there is a risk the bed gives way when the necessary holding force increases.

4.10. CONCLUSIONS

The stabilising influence of the stock of Crown-stocked Anchors is important. The stock introduces two fluke-point holding positions. Therefore a fluke must have a point: however, this may give rise to a high local load on the bed, with consequent bed collapse.

The Chinese anchor model will be preferred because the transverse stability relating to lifting of the fluke points can be made greater than the transverse stability of the Northill anchor.
The rearward stability of a Chinese anchor is smaller than that of a Northill anchor, but this also implies that the Chinese anchor resting on the crown turns over easier into the holding position.
The chance that a Northill anchor after lowering is resting in the holding position is slight, so the ship has to turn over the anchor.

5. THE GRAPNEL

In favourable circumstances, a grapnel can hold with two points simultaneously. Holding with one point only, the formulas relating to the Northill anchor model apply to a four-arm grapnel also.
One fluke is holding, the other arm is acting as a stock half. So condition (88) and (89) apply.
Resting on the crown, with the shank upright, the grapnel is very stable.
The ship has to turn over the anchor into the holding position.
The possibility that the grapnel will hold is twice that of a Northill anchor.

6. THE CROWN-STOCKED MOVABLE-FLUKE ANCHORS

The investigation of the properties of crown-stocked movable-fluke anchors has reference to two holding situations. The situation where both points and the shank end are resting on the bed, so that the stock is free of the bed, is indicated as the normal holding position.
See figure 43. When one point, a stock end and the end of the shank are resting on the bed, the anchor holds in the tilted holding position.

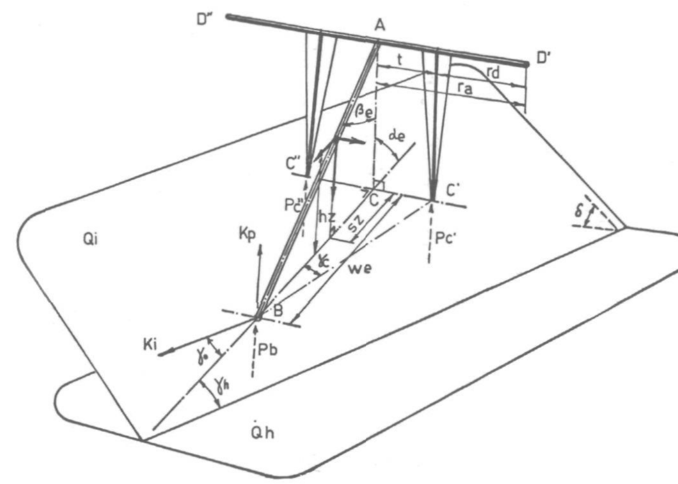


Fig. 43. Model situation of a crown-stocked movable-fluke anchor resting on an inclined plane .

6.1. THE NORMAL HOLDING POSITION

When both fluke points are resting on the bed and the stock is free of the bed, the formulas relating to the transverse stability of the shank-stocked anchors apply, assuming the value of rb is equal to zero.
Thus applies $2.we.t.Pc'' = G.\cos\delta.t.(we-sz)-G.hz.(t.\sin\gamma h+we.\cos\gamma h).\sin\delta -$
$- t.we(Kp-Gp.\cos\delta)$.
Assuming $Kp = Gp = 0$; $\lambda p = 1$; the anchor holds stable as $t.(we-sz).\cos\delta -$
$- hz.(t.\sin\delta.\sin\gamma h+we.\cos\gamma h) > 0$.
The minimum critical value of δ appears when the value of γh is equal to γc.
$\mathrm{tg}\gamma c = t/we$.
Then the condition is

$$/\mathrm{tg}\delta/ < t/(we^2+t^2)^{\frac{1}{2}}.\mathrm{tg}(\alpha e-\beta e)...... \qquad ...... (91)$$

The moment one point frees, the anchor slews over, about γc degrees, to the resultant of the chainpull and the weight of the anchor itself is acting in the plane through the holding point C' and perpendicular to Qi.
Now the holding point has slewed also, over angle γc, relating to the uneven area of the bed the point holds on. So there is a high risk the anchor will free by sliding sideways.
Decreasing the value of γc decreases the risk of sliding under these circumstances.
Introducing γc condition (91) changes into:

$$/\mathrm{tg}\delta/ < 1/\mathrm{tg}(\alpha e-\beta e).(1+1/\mathrm{tg}^2\gamma c)^{\frac{1}{2}}...... \qquad ...... (92)$$

indicating the important influence of the angle between shank and bed on stability, and indicating the stabilizing influence of an increasing γc value. So there is a contradistinction between the desirability of decreasing the slewing angle γc, and the equal desire to increase the minimum critical δ value relating to the transverse stability.
A compromise has to be made.

6.2. THE TILTED HOLDING POSITION

In the tilted holding position, figure 44, the anchor can make three movements:

- Rotating about line $D'B$, through the shank end and the stock end. The anchor turns over, losing its stability and hold.

- Rotating about line $C'B$, through the shank end and fluke point. The anchor retains hold and returns to the normal holding position, holding with one fluke point only.

- Crown, flukes and stock rotate about line CD', through the holding fluke point and the shank end.

To simplify the formulas necessary to investigate the above mentioned three types of movement, the following auxiliary values are introduced.

αf the angle between the bed and the centre line of a fluke perpendicular to the stock, measured in a plane through the centre line perpendicular to the stock.
ra the length of a total stock half, $ra = rd+t$.

$$vo = p.\sin\alpha f/\cos(\alpha f-\beta e)$$

$$vb = \left\{ l^2 + \frac{ra^2.vo^2}{(rd^2+vo^2)} \right\}$$

$$vd = (rd^2+vo^2)^{\frac{1}{2}}$$

The main relationship between αf and βe is formed by the equation

$$l.rd/ra = p.\sin\alpha f/\sin(\alpha f-\beta e) \qquad (93)$$

To gain manageable formulas $\lambda p = 1$, $Gp = 0$ is assumed.

6.3. TRANSVERSE STABILITY,

relating to turning over and losing hold.
With the help of the moment equation about line $D'B$, can be derived the formula that the anchor turns over when $\mathrm{tg}\delta.vo.(vb.vd.\cos\gamma h+ra.rd.\sin\gamma h) > vd.rd.l$.
The critical value of δ is minimum when $\gamma h = \gamma d$; $\mathrm{tg}\gamma d = ra.rd/vb.vd$.
γd the angle between line $D'B$ and line $G'B$.
Then the anchor turns over when

$$\mathrm{tg}\delta > rd.l/vo(l^2+ra^2)^{\frac{1}{2}} \qquad (94)$$

6.4. TRANSVERSE STABILITY,

relating to returning into the normal holding position.
With the help of the moment equation about line $C'B$, can be derived the formula that the anchor returns into the holding position when

$$\mathrm{tg}\delta.(\cos\gamma h+\sin\gamma h.\mathrm{tg}\gamma c).ra.vo < l.vd.\mathrm{tg}\gamma c \qquad (95)$$

$$\mathrm{tg}\gamma c = \frac{vo.(t.rd-vo.p.\sin\beta e)}{vd.vb.\left\{ vo-\frac{rd}{ra}.p.\cos\beta e.\mathrm{tg}(\alpha f-\beta e)\right\}} \qquad (96)$$

The critical value of δ is minimum when $\gamma h = \gamma c$.
Then the anchor turns over when

$$\mathrm{tg}\delta < l.vd.\sin\gamma c/ra.vo \qquad (97)$$

When resting in the horizontal plane, the anchor returns when $\mathrm{tg}\gamma c > 0$ as can be derived substituting $\delta = \gamma h = 0$ in the moment equation about line $C'B$ (96).
Or $t.rd > vo.p.\sin\beta e$ or

$$ra > \frac{p^2.\sin\alpha f.\sin\beta e+t^2.\cos(\alpha f-\beta e)}{t.\cos(\alpha f-\beta e)} \qquad (98)$$

Condition (98) indicates for Pipers Wishbone anchor, with $t = 0$, $ra > \infty$ as was expected.

6.5. STABLE TILTED HOLDING POSITION ON AN INCLINED BED

As $\gamma d > \gamma c$ there is a possibility that the anchor holds in a stable position. But what happens when $\gamma d > \gamma c$?
Then the position of C' must be chosen on the other side of line BD', or $p > l.rd/ra$. See figure 44. Then point C' lies above plane $AD'B$, and the value of βe becomes negative. The shank is blocked in the opposite position by the crown so that $\beta = -\beta e$.

Due to this movement of the shank about the hinge a new possibility of holding in a stable, tilted position has arisen. The anchor is always unstable in the very particular case $\gamma d = \gamma c$ and when C' lies on the line $BD'.p = l.rd/ra$.
For every other value of p, a tilted, stable holding position, by particular combinations of δ and γ values are possible.

6.6. ROTATING ABOUT A LINE THROUGH THE HOLDING FLUKE POINT AND THE STOCK END THAT THE ANCHOR RESTS ON

The equations regarding the rotation of the crown, about line $C'D'$ are long and very complicated.
See figure 44. Confining the study to the case of an anchor resting on a horizontal bed appeared to be necessary.
In the theoretical case $\alpha f = 0$, $tg\gamma c = t/(l-p)$ applies.
In the tilted holding position, the value of $tg\gamma c$ has been determined with equation (96). So the value of γc changes with the value of αf.
The anchor slews when the crown rotates about line $C'D'$.
Therefore it is necessary to investigate this rotation of the crown further, assuming for simplification the anchor holds on a horizontal bed.

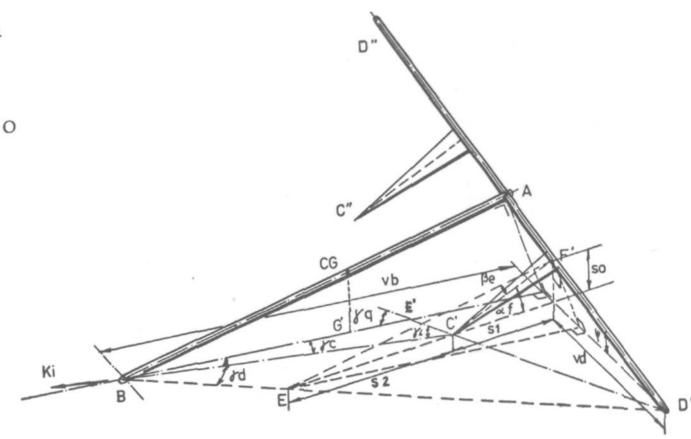


Fig. 44. Movable crown-stocked fluke anchor holding in a tilted position on an inclined plane, assuming $Gp = 0$, $\lambda p = 1$.

If $\alpha f > 90^0$ and $\gamma c < 0$ and $\gamma d > 0$ the anchor can rest stable even when the chainpull is zero. As the line of action of the weight intersects the horizontal plane on the side of B, from line $C'D'$ a horizontal chainpull can hold the anchor in a tilted, holding position. When the intersection lies on the other side, point B will be lifted off the bed.
So a horizontal chainpull can hold the anchor if $BG' < BE'$ or

$$\lambda.l^2 < v2.\frac{l^2.rd^2+l^2.vo^2+ra^2.vo^2}{v2.vo^2+rd^2.(v1+v2)} \;\;...... \qquad ...... \;(99)$$

$v1 = p.\cos\beta e/\cos(\alpha f-\beta e)$, $v2 = p.\sin\beta e/\sin(\alpha f-\beta e)$.
When in the holding position the value of the chainpull Ki will be too small to hold the anchor, the value of αf will decrease by rotation of the crown, about line $C'D'$.

The rotating movement once started, assuming constant chainpull, stops in the normal starting position of the anchor, with the crown resting on the bed, because the value of the needed chainpull to hold the anchor increases as αf decreases. So the anchor returns from a tilted, holding position into a normal position, holding with one fluke only.

6.7. SLIDING OVER THE UNEVEN AREA IN THE TILTED POSITION

Assuming point C' holds the anchor, line BC' represents the direction of the chainpull Ki, acting on an anchor holding on a horizontal bed.
As line $D'C'$, the intersection of the surface of the fluke and the bed, does not stand perpendicular to the chainpull there is a possibility of sliding sideways.

The angle γi between line BC' and line $D'C'$, can be determined with γc and the angle γq line $D'C'$ makes with line BE'; $\gamma i = \gamma q - \gamma c$.

$$\text{tg}\gamma q = l(rd^2+vo.p.\sin\beta e)/p.\cos\beta e.vb.vd \qquad (100)$$

There is a reasonable chance the anchor will hold if the fluke is pointed.
If the ends of the flukes have been formed by two parts of the line $C'C''$, the chance decreases, because this materialised line parts do form a sledge that can slide over the uneven area, freeing the anchor.

6.8. THE TILTED HOLDING POSITION ON A HORIZONTAL BED

Holding on a horizontal bed, the anchor holds stable in the tilted position when the direction of the weight of the anchor intersects the bed, between the line BC' and BD'. Then, because the weight acts in plane ABE', the direction of line BE' must be between the lines BC' and BD'. Thus $\gamma c < 0 < \gamma d$.
When $\gamma c < 0$ then $t.rd < vo.p.\sin\beta e$ or $t.ra(l-p.\cos\beta e) < l.(p^2.\sin^2\beta e+t^2)$.
When $\gamma d > 0$ then angle $\psi < 90^{\circ}$. $\text{tg}\psi = vo/rd = l.p.\sin\beta e/(rd.l-ra.p.\cos\beta e)$.
So $\gamma d > 0$ when $rd.l > ra.p.\cos\beta e$ or $rd > t.p.\cos\beta e/(l-p.\cos\beta e)$.
At the same time $\alpha f < 90^{\circ} + \beta e$.

When $\gamma c > 0$ the anchor returns to stable holding position.
When $\gamma d < 0$ the anchor, unstable, rotates first about line BD' and falls over, while the shank rotates about the crown hinge. So the anchor turns over completely.
Commonly, stockless anchors can turn over easily because the value of rd of a stockless anchor is near zero.

6.9. THE TILTED POSITION OF A STOCKLESS ANCHOR ON A HORIZONTAL BED

The value rd of most of the stockless anchors is positive, due to the dimensions of the crown hinge construction. When a stockless anchor falls over, the crown touches the bed in a situation comparable with the tilted holding position of an anchor with a stock. Then three movements can occur.
Firstly, the tilted position is unstable, because $\gamma d < 0$. The anchor turns over completely and comes into a new starting situation, sliding with both fluke points over the bed.
Secondly, the tilted position is stable and the flukes are so made that the fluke point still can hold the anchor in this position.
Thirdly, the tilted position is stable, but the form of the fluke is so broad that the fluke side rests on the bed and the fluke point is lifted above the bed. In this position, such an anchor can slide long distances over the bed without any chance of holding again. Therefore, preference is given to stockless anchors which have an unstable tilted position.
The behaviour of a stockless anchor in the tilted position can be examined very easily by situating such an anchor on its side, with the maximum value of its fluke angle. When the anchor turns over it is unstable.

6.10. NUMERICAL EXAMPLE

To obtain an impression regarding the importance of the conditions already found, some critical values of a modern stock anchor design are calculated.

Assuming $p = 0.6\ l$
$t = 0.085l$
$ra = 0.467l$
$rd = 0.382l$
$\beta e = 32^{\circ}$
$\lambda p = 1$

the maximal theoretical γc value when $\alpha f = 0^{\circ}$ is 12.1°.
In the normal holding position the minimal γc value is 8.3°, so that the anchor slews about a very small angle, about 3.8°, holding with one fluke point, when the chainpull acts and the crown rises from the normal starting position into the normal holding position.
Regarding the transverse stability condition (91), this indicates for $\gamma h = \gamma c$ that the anchor holds stable so lang as $/\delta/ < 12.5^{\circ}$. In the tilted holding position $\gamma d = 10.1^{\circ}$ and $\gamma c = -25.5^{\circ}$. When $\gamma h = \gamma d$ the anchor holds stable as long as $\delta > -50.2^{\circ}$, as indicated by condition (97).

The chainpull can hold the anchor in the holding position, with B resting on the bed, when $\lambda < 0.92$, as indicated by condition (99). When the anchor tilts from the normal holding position, into the tilted holding position, the possibility of the anchor freeing is great, because during this movement the anchor slews about $8.3^{\circ}+25.5^{\circ} = 33.8^{\circ}$. The value of γq is 39.4° and γi is 64.5°, so the chainpull makes an angle of $90^{\circ}-64.5^{\circ} = 25.5^{\circ}$ with the direction perpendicular to the intersecting line of the plane the anchor rests on and the plane through holding fluke point and stock.

Assuming the coefficient of friction between stock and bed equal to zero, the anchor slides sideways and frees when $\rho c < \mathrm{tg}\ 25.5^{\circ} = 0.477$.
Generally, a smaller value of ρ can be expected so the flukes must be pointed to retain hold in a pit of the bed.

7. CONCLUSIONS

- Stockless anchors have to hold in the normal holding position only.
  To obtain stability, the distance between the fluke points has to be chosen with the greatest possible width, to reduce the possibility of falling over. However, this decreases the possibility that both fluke points find hold simultaneously and therefore the anchor holding.

- Stocked anchors can hold in the tilted position also. The angle through which the anchor slews must be kept as small as possible, to reduce the possibility of the anchor freeing, when falling over from the normal holding position, into the tilted holding position. Therefore, the distance between the fluke points has to be small; reducing simultaneously the chance of sliding sideways, holding with one fluke in the normal holding position and, in the tilted holding position. However, the minimum distance between the fluke points is limited by the dimensions of the shank and the minimum distance between the shank and the inner sides of the flukes necessary to reduce the possibility that stones or other debris on the bed get jammed between fluke and shank.

- The tilted holding position of a stockless anchor must be unstable.
  The anchor has to fall back into the normal holding position or has to turn over completely by its own weight during sliding over the bed, due to the chainpull, after the friction forces acting on the crown have decreased the fluke angle.

- The flukes of a stocked anchor must be pointed and the anchor must be capable of holding the chainpull, required for holding the ship with one fluke point in the tilted holding position as well.

- The flukes of a stocked anchor have to be so shaped that a single fluke point rests on the bed in the tilted holding position.

- Stocked anchors with a great distance between the fluke points behave in the normal holding position, comparable to anchors without stock.
  If stocked anchors fall over sideways, the stock prevents the anchor turning over; but the additional induced slewing movement about the holding point will generally free the anchor by sliding sideways. Therefore, the increased probability, that the stocked anchor, with a small distance between the fluke points, will find hold with both points simultaneously results in the increased risk the anchor will free by sliding sideways during the falling-over movement into the tilted holding position.

It is therefore obvious that there is only minimal difference between the possibilities of stocked and stockless anchors both finding and keeping hold upon an impervious bed.

CHAPTER 6

ANCHORS PENETRATING AND HOLDING ON A SOFT PLANAR BED

1. INTRODUCTION

Following the analysis of the phenomena regarding anchors holding on an impervious bed, it follows that the phenomena regarding anchors holding on a soft bed has to be investigated. Sliding over the surface of a soft bed the flukes will penetrate the bed first. The shank and the crown remain above or resting on the surface.
Due to the deformation of the bed material a mould rises above the flukes stimulating deeper penetration. The increasing earth resistance acting on the flukes increases the holding pull and induces additional movements of the shank and the anchor crown and flukes. The phenomena with respect to this penetrating anchor movement will be investigated in this chapter.
In chapter 7 the phenomena when the shank and the crown also penetrate into the bed, so that an anchor digs in entirely, will be investigated.

2. THE MODEL SITUATION

Starting from the model situation as represented in figure 45; this differs from the preceeding model situation of an anchor holding on an impervious bed in that the flukes penetrate into the bed changing, due to the earth resistance, the magnitude and the position of the reaction forces of the bed.

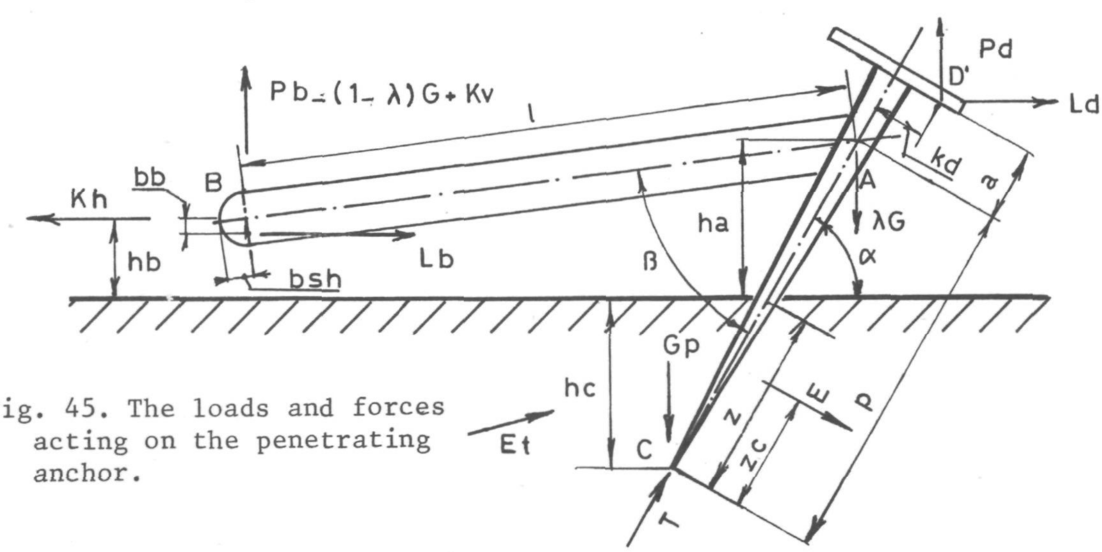


Fig. 45. The loads and forces acting on the penetrating anchor.

The earth resistance force *Et* acting on the flukes can be resolved in two directions; a direction perpendicular to line *CA* and in the direction of line *CA*.
Component *E* acting perpendicular applies to a distance *zc* from *C*.
Component *T* coincides with the symmetrical line *AC* between the flukes.

The forces *Pb*, *Lb*, *Pd* and *Ld* are earth resistance forces acting in the situations where the anchor rests with the shank end or crown upon the bed.

Pb and *Lb* apply in *D'* at a distance *kd* from line *CA*.
Pd and *Ld* apply in *B'* at a distance *bb* below *B*, see figure 45.
The diameter of the shank head is denoted with *bsh*.

Assuming the direction of the hinge axis parallel to the planar surface of the bed, the resultant of the forces perpendicular to the symmetrical plane through the shank between the flukes is assumed to be equal to zero.
The forces *Lb* and *Ld* are frictional forces acting in the situations where the anchor rests with the points *B* and *D* upon the bed. Point *C* of the flukes lies a distance *hc* below the level of the bed, due to the penetration of the flukes over a distance *z* into the bed.
The anchor holds stable if the value of the forces *E* and *T* required to hold the anchor are less, or equal to, the ultimate value the soil can produce without continuous deformation.

If these ultimate values of the bearing forces are exceeded, the anchor will penetrate deeper into the bed or, will rotate about the top of the flukes sliding upwards. The last combined rotation and translation will occur due to the rotation and translation of the soil wedge, broken away from the rest of the soil, before the anchor.
Therefore the holding pull of a penetrating anchor depends on:

- the shape and the dimensions of the anchor parts penetrating into the bed,
- the position and attitude of the penetrating anchor to the bed, and
- the nature of the bed.

With regard to the bearing earth resistance forces acting on an anchor, there has not yet been published a theory or a practical formula. Therefore the direction and magnitude of the earth resistance forces can only be determined exactly by testing anchors and model anchors.

Measuring the holding pull and the related anchor position the resistance forces *E* and *T* and the distance *zc* can sometimes be calculated when during the penetrating movement crown and shank do not touch the bed.
The succession of the movements is determined by the *E*, *T* and *zc* values during the movements. Therefore the different types of penetrating movements have to be analysed.

3. MOVEMENTS OF A PENETRATING ANCHOR

Similar to an anchor holding on an impervious bed, a penetrating anchor can make several movements, see figure 46.
The movement of the crown in relation to the bed, sliding over or lifting off is of importance during the Tipping movements.
Therefore in contradistinction to the movements of an anchor on an impervious bed, we have to distinguish seven penetrating movements as:

- The crown Sliding-Tipping movement, figure 46a;
  crown and shank slide over the bed surface while β remains smaller than βe.
- The Rotating-Tipping movement, figure 46b;
  the shank slides over the bed surface while the crown is lifted upwards and β remains smaller than βe.
- The crown Sliding-Whipping movement, figure 46c;
  the crown slides over the bed surface and the shank is lifted upwards while β remains smaller than βe.
- The Rotating-Swinging movement, figure 46d;
  crown and shank are both lifted above the bed surface while β remains smaller than βe.

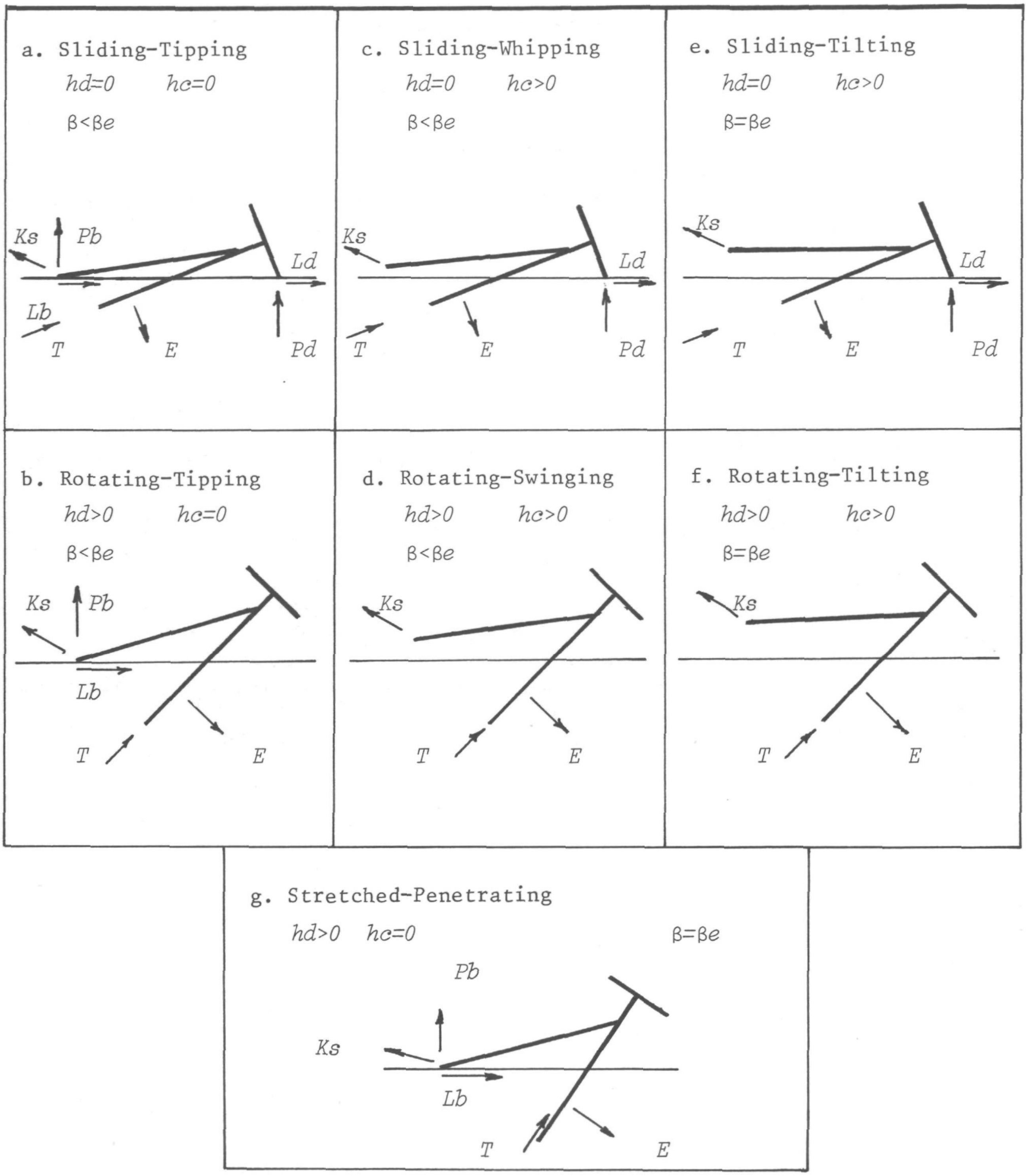


Fig. 46. The penetrating movements.

- The crown Sliding-Tilting movement, figure 46e;
  the crown slides over the bed while the shank is lifted above the bed surface in its extreme position $\beta = \beta e$.
- The Rotating-Tilting movement, figure 46f;
  the crown and the shank are lifted above the bed surface while the shank remains in its extreme position $\beta = \beta e$.
- The Stretched-Penetrating movement, figure 46g;
  the shank in its extreme position $\beta = \beta e$ slides with its shackle end over the bed surface while the crown is lifted above the bed.

In the final position of the penetrating movements the crown and the shank in its extreme position $\beta = \beta e$ rest on the bed surface.

4. THE MAGNITUDE AND THE POINT OF APPLICATION OF THE EARTH RESISTANCE

Starting from the values Kh, Kv, α, β, hc which can be measured during tests the values E, T and zc can be determined by applying

the four equilibrium equations of the shank and the head when $\beta < \beta e$
or by applying
the three equilibrium equations of the total anchor when $\beta = \beta e$.

4.1. THE EARTH RESISTANCE DURING THE CROWN SLIDING-TIPPING MOVEMENT

During the crown Sliding-Tipping movement is $\beta < \beta e$; $Pb > 0$; $Lb > 0$; $Pd > 0$ and $Ld > 0$.
Unknown are nine values, the forces Pb; Lb; Pd; Ld; E and T and the distances zc, bb and kd and there are only four equilibrium equations. Therefore these unknown values can not be determined starting from the results of tests related to this movement.
During this movement applies:

$$E = (Kh-Lb-Ld)\sin\alpha-(Ga-Pb-Pd-Kv)\cos\alpha \quad (101)$$
$$T = (Kh-Lb-Ld)\cos\alpha+(Ga-Pb-Pd-Lv)\sin\alpha \quad (102)$$

$$Kh.l.\sin(\alpha-\beta) = Lb\{l.\sin(\alpha-\beta)+bb\} + \{(1-\lambda l)Gs-Pb-Kv\}l.\cos(\alpha-\beta) \quad (103)$$

and

$$(Kh-Lb).p.\sin\alpha-(Gs+\lambda p.Gc-Pb-Kv).p.\cos\alpha + Pd\{(p+a)\cos\alpha+kd.\sin\alpha\}-Ld\{(p+a)\sin\alpha-kd.\cos\alpha\} + zc\{(Ld+Lb-Kh)\sin\alpha+(Ga-Kv-Pd-Pb)\cos\alpha\} = 0 \quad (104)$$

4.2. THE EARTH RESISTANCE DURING THE ROTATING-TIPPING MOVEMENT

During the Rotating-Tipping movement $Pb > 0$; $Lb > 0$; $\beta < \beta e$ and $Pd = Ld = 0$.
Unknown are six values, the forces Pb, Lb, E and T and the distances bb and zc.
Only four equilibrium equations are available. Therefore the unknown values can not be determined exactly starting from the results of tests related to this movement.

Useful approximately values can be derived assuming $bb = bsh$ and $Lb = \rho.Pb$.
Then the moment equation of the shank about A indicates:

$$Pb = \frac{Kh.l.\sin(\alpha-\beta)-\{(1-\lambda l)Gs-Kv\}.l.\cos(\alpha-\beta)}{\rho\{l.\sin(\alpha-\beta)+bsh\}-l.\cos(\alpha-\beta)}$$

Further $E = (Kh-Lb)\sin\alpha-(Ga-Pb-Kv)\cos\alpha$ ....(105)

$T = (Kh-Lb)\cos\alpha+(Ga-Pb-Kv)\sin\alpha$ ....(106)

4.3. THE EARTH RESISTANCE DURING THE CROWN SLIDING-WHIPPING MOVEMENT

During the crown Sliding-Whipping movement $Pd > 0$; $Ld > 0$; $\beta < \beta e$ and $Pb = Lb = 0$.

Unknown are six values, the forces Pd, Ld, E and T and the distances kd and zc. Only four equilibrium equations are available. Therefore the unknown values can not be determined starting from the results of tests related to this movement.

A rough estimate with regard to the values Pd, Ld and kd may not be made because the crown rises and pushes up a mould of bed material.

4.4. THE EARTH RESISTANCE DURING THE ROTATING-SWINGING MOVEMENT

During the Rotating-Swinging movement $Pb = Lb = Pd = Ld = 0$ and $\beta < \beta e$.

Unknown are only three values, the forces E and T and the distance zc and there are four equilibrium equations available. Starting from the results of tests related to this movement the unknown values and the actual value of angle β can exactly be determined.
From the equilibrium equations can be derived:

$$E = Kh.\sin\alpha-(Ga-Kv)\cos\alpha \quad \text{......(107)}$$

$$T = Kh.\cos\alpha+(Ga-Kv)\sin\alpha \quad \text{......(108)}$$

$$\mathrm{tg}(\alpha-\beta) = \{(1-\lambda l)Gs-Kv\}/Kh \quad \text{......(109)}$$

$$zc = p(Kh.\mathrm{tg}\alpha-Gs-\lambda p.Gc+Kv)/(Kh.\mathrm{tg}\alpha-Ga+Kv).$$

4.5. THE EARTH RESISTANCE DURING THE CROWN SLIDING-TILTING MOVEMENT

During the crown Sliding-Tilting movement $\beta = \beta e$; $Pb = Lb = 0$; $Pd > 0$ and $Ld > 0$.

Unknown are six values, the forces Pd, Ld, E and T and the distances kd and zc. Only three equilibrium equations can be derived. Therefore the unknown values can not be determined starting from the results of tests related to this movement.

4.6. THE EARTH RESISTANCE DURING THE ROTATING-TILTING MOVEMENT

During the Rotating-Tilting movement $\beta = \beta e$; $Pb = Lb = Pd = Ld = 0$.

The three unknown values E, T and zc can be determined starting form the results of tests related to this movement using the three available equilibrium equations.
During this movement the equations (107...108) apply. Further the equilibrium equations indicate:

$$\{(Ga-Kv)\cos\alpha-Kh.\sin\alpha\}\ zc =$$
$$= Kh\{p.\sin\alpha-l.\sin(\alpha-\beta e)\}+Kv\{p.\cos\alpha-l.\cos(\alpha-\beta e)\} +$$
$$+ Gs.\{(1-\lambda l)l.\cos(\alpha-\beta e)-p.\cos\alpha\}-Gc.\lambda p.p.\cos\alpha.$$

4.7. THE EARTH RESISTANCE DURING THE STRETCHED-PENETRATING MOVEMENT

During the Streched-Penetrating movement $\beta = \beta e$; $Pd = Ld = 0$; $Pb > 0$ and $Lb > 0$.

The unknown values *Pb*, *Lb*, *E*, *T*, *zc* and *bb* can not be determined with the three available equilibrium equations.
A symplification as made in paragraph 4.2 may not be introduced here because the shank end can penetrate the bed substantially.

The equilibrium equations indicate: $E = (Kh-Lb)\sin\alpha-(Ga-Pb-Kv)\cos\alpha$,
$T = (Kh-Lb)\cos\alpha+(Ga-Pb-Kv)\sin\alpha$.

4.8. THE STARTING POSITION

Dragged by the chainpull, an anchor sliding with crown and fluke points over the bed, starts penetration when the contact pressure between points and bed exceeds the earth resistance of the bed surface.
In this position, figure 47, usually the chainpull will be horizontal and will be too small to lift the shank. $Kv = 0$.

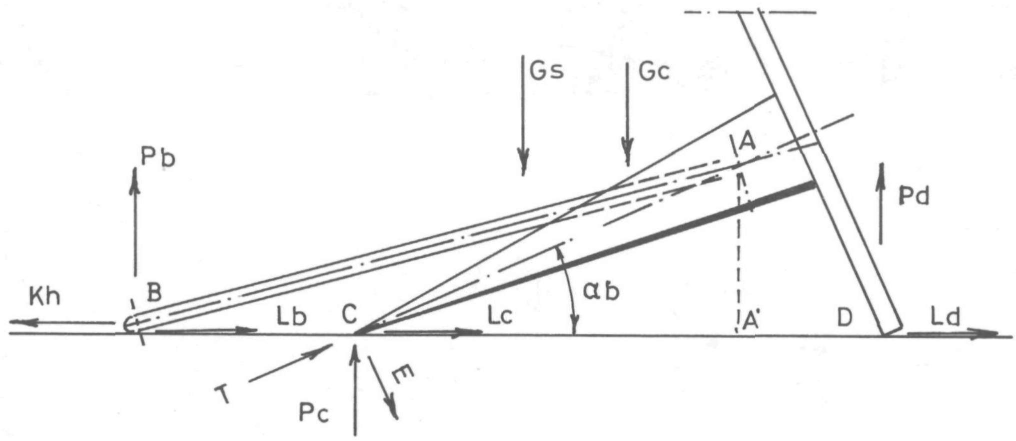


Fig. 47. The starting position

In this position the equations (101, 102, 103 and 104) of the crown Sliding-Tipping movement apply.
Substituting $zc = 0$, $Lb = Pb.\rho b$ and $Ld = Pd.\rho d$ the unknown forces *Pb*, *Lb*, *Pd*, *Ld*, *E*, *T* and ***Kh*** can be calculated assuming the points rest on the bed in a similar way as the crown extremity *D* and the shank end *B*, so that may be assumed $Lc = \rho c.Pc$. Thus $Pc = T.\sin\alpha-E.\cos\alpha$ and $Lc = E\sin\alpha+T\cos\alpha$.

To realise a sufficient pressure of the points on the bed, *Pc*, there must be a substantial distance between *A'* and *D*.
Also it is favourable when the point of application of the weight of the head *Gc* lies between *B* and *A*, thus $\lambda p < 1$.

The weight of a stock forms an important portion of the total weight of the head.
Therefore to increase the starting pressure of the points on the bed the stock of a stocked anchor is commonly situated at the hinge point *A*.

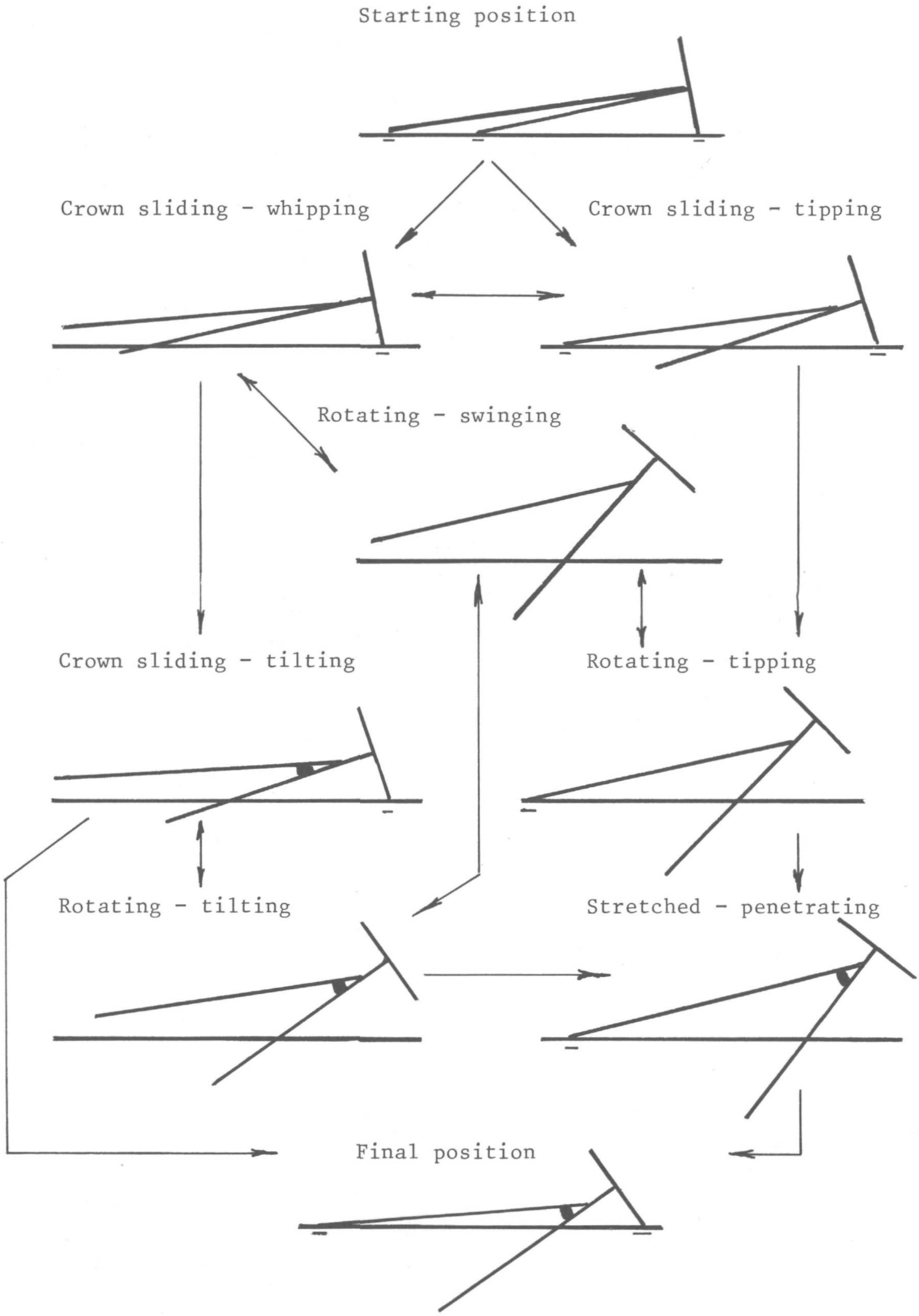


Fig. 48. The succession of penetrating movements.

4.9. THE SUCCESSION OF THE MOVEMENTS

Figure 48 indicates the succession of the penetrating movements. What happens depends principally on the development of the earth resistance forces of the bed during the movements.

During dragging tests usually the transition from a Sliding into a Rotating movement can be observed [27]. The crown is lifted from the bed and the flukes do not penetrate deeper, because the bed material ahead the anchor is lifted upwards, distorting the planar surface of the bed.
This can be explained as follows. The values E and T depend mainly on the position of the anchor in the bed, which can be determined with hc and α.
Assuming α constant E and T increase with hc.
Assuming hc constant T and E increase with α.
During the crown Sliding movements the earth resistance values E and T in each position determine principally the holding pull, but during the rotating movement the value of the chainpull and the actual value of T depend mainly on E.

Starting from the formulas regarding the rotating movements, assuming $Kv = 0$, (107...108) can be derived:

$$Kh = \frac{E}{\sin\alpha} + \frac{Ga}{\mathrm{tg}\alpha}$$

$$T = \frac{E}{\mathrm{tg}\alpha} + \frac{Ga}{\sin\alpha}$$

and from (105...106):

$$Kh = \frac{E}{\sin\alpha} + \frac{(Ga-Pb)}{\mathrm{tg}\alpha} + Lb$$

$$T = \frac{E}{\mathrm{tg}\alpha} + \frac{(Ga-Pb)}{\sin\alpha} .$$

During the Rotating movement E and α are increasing. Therefore the formulas related to Kh indicate a small increasing influence of E and a decreasing influence of α. This means, as observed during tests, the chainpull increases less or decreases during a Rotating movement.
The formulas related to the actual T value indicate also that T increases only slightly or decreases during a rotating movement. But the resistance of the bed in the direction of T increases with α. Therefore usually an anchor will not penetrate deeper during a rotating movement.

Contrary to the Sliding and Rotating movements α decreases during the Stretched Penetrating movement increasing hc directly. Therefore the character of this movement is completely different from the other movements.

Penetrates an anchor substantially deeper after a Rotating movement, the same penetration depth and related holding pull will be reached when the anchor starts penetration on the bed with the shank in its extreme position, $\beta = \beta e$.
In this case model tests can be made with simplified anchor models with the shank fixed to the crown.

When after a Rotating movement an anchor does not penetrate deeper, usually after a start on the bed with the shank in its extreme position, a smaller depth of penetration and a smaller related holding pull will be reached.
This is caused by the greater α and related E and T values during the Stretched movement with respect to the smaller α and related E and T values during the Sliding movements.
For these anchors a properly working hinge is of very great value.

4.10. THE INFLUENCE OF A STOCK

When a stock of a penetrating anchor touches the bed, usually a transition from the Sliding into a Rotating movement will arise due to the increased earth resistance. The anchor will not penetrate deeper. Therefore the holding pull can be reduced substantially by adding a stock to an anchor model.
When a stock is situated too near to the points, the penetrating flukes will rotate upwards about the stock driven by the weight of the crown and shank. Thus the anchor will bear out of the bed. To prevent these prematurely Rotating movements the stock may not be situated too far before the hinge point A.

4.11. THE DRAGGING MOVEMENT

After the Stretched-Penetrating movement an anchor further digs in or starts continuous dragging. During this Dragging movement the bed material slides upwards over flukes and crown, rising the mould before the anchor.
Usually soon the mould supporting the shank, introduces an upward movement of the anchor and forces the anchor out of the bed. Under these circumstances many stockless anchor types lose their stability and tend to roll out of the bed. Stocked anchors usually remain stable. Only a relatively low holding power, from one up to seven times the weight of the anchor, will be attained. Therefore, to develop a high holding pull an anchor must dig in completely.

5. CONCLUSIONS

- The penetrating movements of an anchor and the related holding pull depends on the anchor dimensions, the bed material and sometimes on the position from which an anchor starts, resting on the bed, the penetrating movements.

- The addition of a stock reduces the depth an anchor will penetrate, decreases the attained holding pull but prevents an anchor tends to roll out of the bed.

- A penetrating movement of the flukes starts only when the pressure on the bed, due to the chainpull, the anchor weight and earth resistance acting at the crown extremities, exceeds the earth resistance of the bed.
  Therefore the weight distribution, the position of the hinge point, crown extremities and stock determine to a large extent wether an anchor penetrates easily or not at all.

- When an anchor drags continuously with crown and shank above the surface of the bed, the attained holding pull depends mainly on the weight of the mould of bed material risen ahead of the anchor. Therefore the holding pull in relation to the anchor weight remains only small.

CHAPTER 7

ANCHORS DIGGING IN AND HOLDING IN A SOFT PLANAR BED

1. INTRODUCTION

Following the analysis of the phenomena with regard to anchors penetrating and holding on a soft planar sea bed, it follows that the phenomena relating to anchors digging-in and holding in a soft planar sea bed has to be investigated. Starting from the model situation as represented in figure 49, this differs from the preceeding model situation of an anchor penetrating an impervious bed, in that the crown and the shank penetrate into the bed.

2. THE FORCES ACTING ON THE ANCHOR

The earth resistance forces are acting on shank and head. The forces acting on the head can be resolved in the same directions and components as indicated in chapter 6, paragraph 2, with regard to the penetrating flukes.
The forces acting on the shank can be resolved in a force *Ts* coinciding with centre-line *AB* and a force *Es*, perpendicular to *AB* with a distance *zs* from its point of application on line *BA* from *B*.

Usually the point of application of force *E* acting on the flukes lies between *C* and *A*. Therefore the shank will remain in its extreme position with $\beta = \beta e$.
The distances from the bed surface to the points of application are denoted with *hzc* and *hzs*.

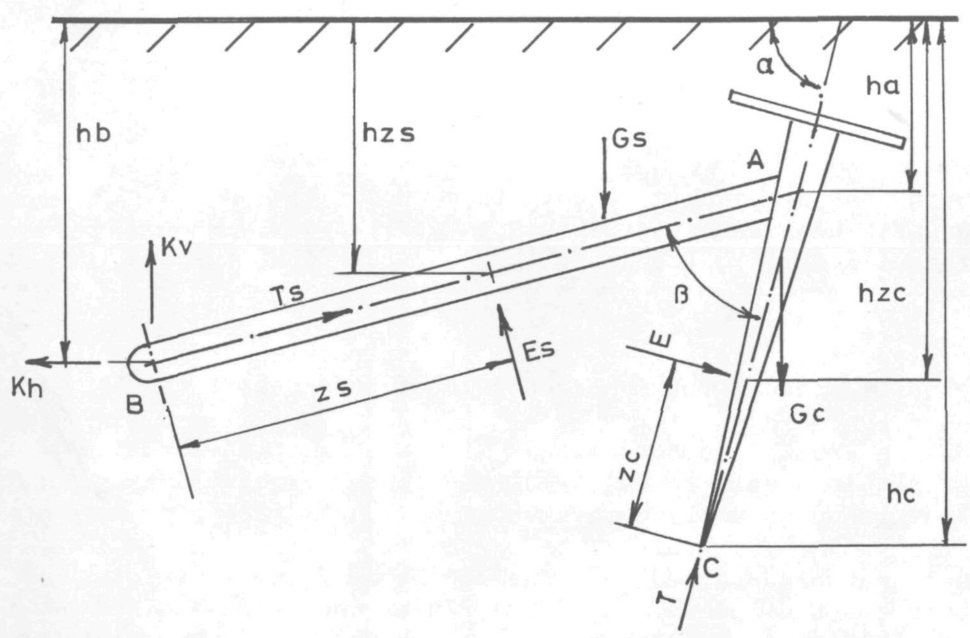


Fig. 49. Loads and forces acting on an embedded anchor.

3. THE EQUILIBRIUM EQUATIONS AND COMPLEMENTARY ASSUMPTIONS

In this case only three equilibrium equations can be derived:

$$Kh = Ts.\cos(\alpha-\beta e)-Es.\sin(\alpha-\beta e)+E\sin\alpha+T\cos\alpha \quad \ldots\ldots(111)$$

$$Ga = Ts.\sin(\alpha-\beta e)+Es.\cos(\alpha-\beta e)-E\cos\alpha+T\sin\alpha+Kv \quad \ldots\ldots(112)$$

and

$$Kh.zs.\sin(\alpha-\beta e)+Kv.zs.\cos(\alpha-\beta e)+Gs.(\lambda l.l-zs).\cos(\alpha-\beta e) + Gc\{(l-zs)\cos(\alpha-\beta e)-p(1-\lambda p)\cos\alpha\}-T(l-zs)\sin\beta e + E\{(l-zs)\cos\beta e-p+zc\} = 0 \quad \ldots\ldots(113)$$

During dragging tests the position of the anchor with regard to the surface of the bed and the *Kh* and *Kv* values can be measured. Unknown are *E*, *T*, *Es*, *Ts*, *zs* and *zc*, values which can not be determined with only three equilibrium equations.

To make it possible to calculate indicative values related to these earth resistance forces some complementary assumptions have to be made.

During dragging tests, when an anchor digs in,the bed material around and above the anchor is moving intensively and shows some similarity with fluid movement. Therefore is assumed the earth pressure acting on the shank and head are proportional to the distance from the surface of the bed.
Further is assumed this indicative earth pressure acts on the sectional area of the shank through centre-line *AB* and on the sectional area of the head through centre-line *BC*.

Due to these assumptions the distance from the points of application of the forces *E* and *Es* to the points the centre-lines intersect the planar bed surface will be: *I*/*M* and *Is*/*Ms*. *I* and *Is* the moments of inertia of the areas of the head and the shank about the intersecting lines of the sectional planes and the bed surface and *M* and *Ms* the moments of the areas about the intersecting lines.
Thus

$$zc = \frac{hc}{\sin\alpha} - \frac{I}{M} \quad \ldots\ldots(114)$$

and

$$zs = \frac{hb}{\sin(\alpha-\beta)} - \frac{Is}{Ms} \quad \ldots\ldots(115)$$

This means that during the dragging movement of an anchor the points of application of the earth resistance forces change and that only when $\alpha = 0$ the point of application of force *E* coincides with the centroid of the area of the section of the head.

When α decreases the point of application moves in a direction from *C* to *A* and can sometimes move past point *A*, when the centroid of the area of the head lies also past *A*.
This consequence of the assumption corresponds with the fact that sometimes after an anchor has dug in deeply the value of α becomes negative and the anchor rises out of the bed without a rolling movement.

During dragging tests can be observed that during the dragging movement there is a loss of contact between the undersides of the flukes and crown and the bed material. Therefore with regard to anchors with sharp pointed fluke points and sides and with a streamlined crown construction can be assumed $T = \rho E$.
Starting from these assumptions indicative *E*, *T*, *Es* and *Ts* values can be calculated.
To analyse the character and usefulness of the indicative values some anchor dragging tests with model anchors were conducted.

CHAPTER 8

EXPLORATORY ANCHOR EXPERIMENTS

1. INTRODUCTION

To determine the indicative forces some experiments were carried out at the Laboratory of Shipbuilding at the Delft University of Technology.
The experiments included:

- the influence of the width and height of a model anchor-testing tank upon the results of tests related to dragging pull and
- the influence of the dragging speed of model anchors on test.
  Further, dragging tests on model anchors were conducted to determine the indicative forces of single-fluke and twin-fluke model anchors; and to investigate the mutual influence between shank and flukes.

2. THE ANCHOR TANK

To carry out anchor dragging tests, a steel-framed tank with an inside length of 2.0 meters, a maximum width between the sides and an inside height of 0.6 meters was constructed. The bottom and the ends were made of wood, and the removable transparent front and rear portions were made of "Trovidur" with a thickness of 10 mm. The width between the sides can be altered by changing the transparent portions into alternate slots of the tank bottom and ends. Figure 50.

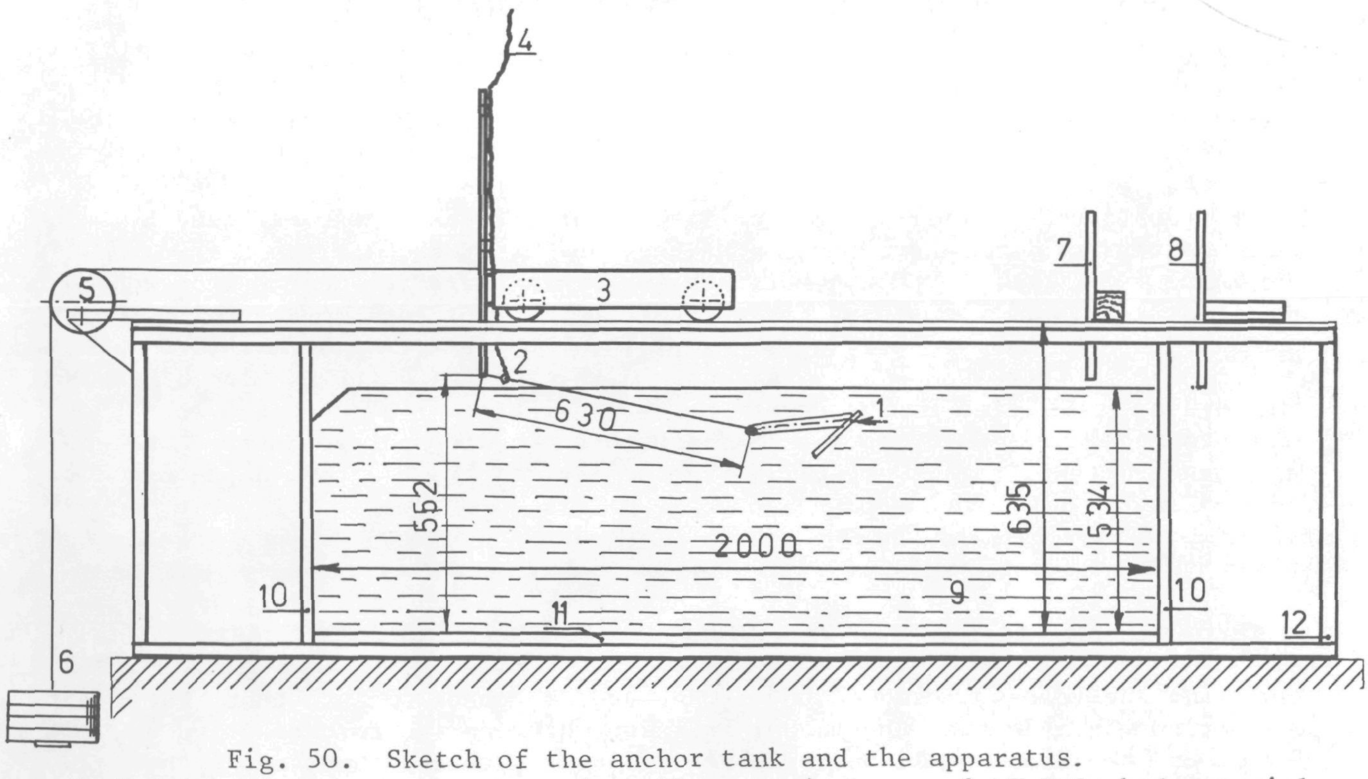


Fig. 50. Sketch of the anchor tank and the apparatus.

1. Model anchor
2. Straingauge dynamometer
3. Carriage
4. Vertical connection with electrical equipment
5. Pulley or winch
6. Weights
7. Sliding scale
8. Level planer
9. P.V.C. bed material
10. Wooden ends
11. Wooden bottom
12. Steel frame

3. THE MATERIAL OF THE MODEL ANCHORS AND THE TEST BED

Up to the time of writing steel or bronze model anchors are usually tested in tanks filled with sand, clay or shingle; sometimes dry and sometimes flooded. After each test the tank has to be drained and the bed to be restorted to its original condition by levelling and compacting (by vibration), whereupon the tank can again be flooded. Looking for a simpler solution, a method of dry testing with results comparable with the usually submerged tests was found by introducing a synthetic ideal "soil", P.V.C. with an average grain diameter of about one mm.

Resistance forces depend on the anchor dimensions; the unit weight of the submerged bed material; the internal friction coefficient of the bed and the friction coefficient between bed and anchor, assuming an ideal soil.
If the ratio between the submerged unit weight of the bed and the unit mass of the submerged anchor remains constant, and both unit weights are chosen with a specific smaller factor, the measured forces will be factorially smaller if both friction coefficients can be kept equal to the basic flooded situation.
The submerged unit weight of sand is about 1.0 . . . 1.1 kg/dm^3 and its angle of internal friction is about 30^o . . . 35^o.

Using P.V.C. granular material, with a unit mass of 0.58 kg/dm^3, and an internal friction of 35^o, a model anchor material with a unit mass about 0.58 x (7.8-1.0)/1.1 = 3.6 kg/dm^3 is indicated. Using aluminium model anchors with some steel parts, the needed average unit weight can be realised. The friction angle between aluminium and P.V.C. appears to be about 25^o. The model anchors, manufactured for the following dragging tests, were made of aluminium, with an average unit mass of 2.7 kg/dm^3. Therefore, the bed represented during the tests with these anchors is of a heavy nature with a unit mass submerged of 0.58 x 6.8/2.7 = 1.46 kg/dm^3. Therefore, to determine the comparable dragging pull of submerged, steel model anchors of the same size, the measured dragging forces have to be multiplied by a factor of 1.46/0.58 = 2.52.

During the first tests, the bed material was packed by mechanical vibration of the tank frame and the sides similar to that of the steel anchor tank at the "Admiralty Experiment Works" at Haslar and the tank of the "Laboratoire de Mécanique des fluides de la faculté des Sciences" at Strasbourg [23 and 25].
Verifying tests with a penetrometer indicated great differences in density after vibration. Therefore an approximate constant density was realised by continuously removing and refilling of the tank after each test.
The being impervious P.V.C. to moisture, the relative small unit weight and small total weight of the bed, together with the light tank construction (and the avoidance of heavy vibrating machinery near the electronic measuring equipment), appeared to be advantageous. During the tests the packing of the bed was regularly verified with a penetrometer consisting of a one-meter long polished steel bar, Ø 12 mm, top-loaded with two additional weights of one kg. This penetrometer, total weight 2.90 kg, penetrated the bed to a depth of 200 ± 5 mm.

4. THE MODEL ANCHORS

Analysing the forces acting on the flukes and the shank of an anchor, the silent assumption was made that the mutual influence between the forces acting on the flukes and the shank would be neglected. To verify this assumption, eight fixed-fluke anchors were manufactured (see figure 51, 52 and 53).
Four single-fluke anchors, numbered 1 to 4 and four twin-fluke anchors, numbered 5 ... 8, all having approximately the same fluke area, the same shank, crown wings, βe value and main dimensions.

The fluke area of the single-fluke anchors is 80.5 cm^2, that of the twin-fluke anchors 86.3 cm^2. The distance from the points to the centre of gravity of the fluke surface is 6.94 cm. To analyse the unknown influence relating to the sectional shape of the fluke points, sides and of the shank undersides and their mutual influence the anchors 1 and 5 were made with rectangular-shaped points, sides and shank undersides; 2 and 6 with rectangular points, sides and bevelled shank undersides; 3 and 7 with bevelled points and sides and rectangular shaped shank undersides; the anchors 4 and 8 with bevelled points, sides and shank undersides. The weights of the anchors are respectively 146, 145, 138, 136 grams for the single-fluke anchors and 153, 147, 141, 136 grams for the twin-fluke anchors. Due to the production tolerances βe has been made $34^{\circ} \pm 1.8^{\circ}$. Cross-sections of the rectangular and the bevelled-shaped sides, points and shank undersides are indicated in figure 51.

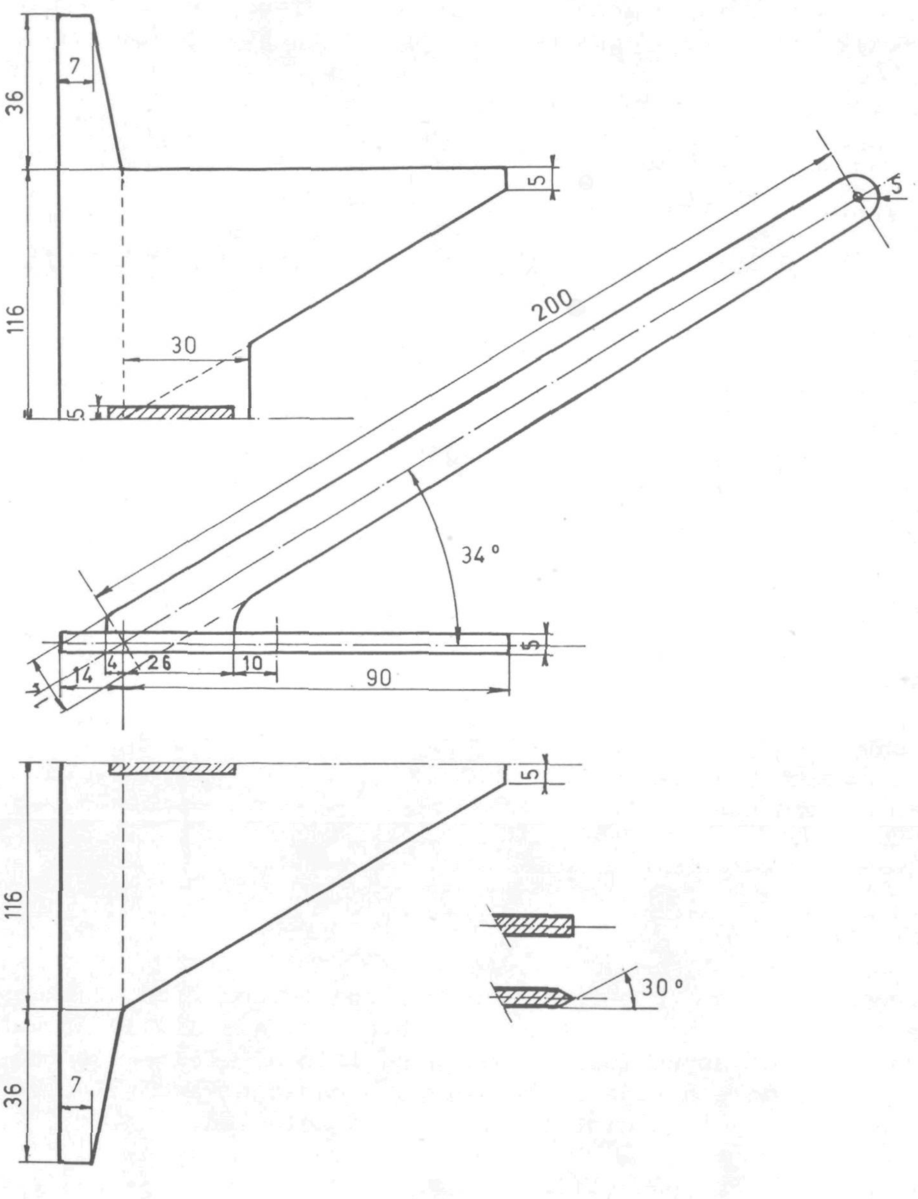


Fig. 51. Main dimensions model anchors.

5. EXPERIMENT APPARATUS

On the upper surface of the tank steel-frame rails were mounted, on which a towing carriage with a vertical, adjustable towing arm was placed.
One side of a straingauge dynamometer was connected with a 2,0 mm steel wire to the towing arm and on the other side, with a long steel wire to the anchor shank. During all tests, the distance between the towing arm and the anchor shank was a constant 630 mm (figure 50). The carriage was hauled by means of a wire, passing round a guide pulley, and driven by weights or directly with a hauling winch, situated at the end of the tank. At the points B, D, D', and D'', of figure 52, thin threads were connected, each thread with an indication point at a fixed distance from the connection point. The position of the anchor (below the bed surface), could be observed and determined, after pulling the threads vertically by hand; measuring the vertical position of the indication points (in relation to the bed surface), with the help of an over-the-rails sliding measuring scale. An accurate relationship between the surfaces level of the bed and the measurement of the anchor position was realised by sliding the level planer over the rails. The indications of the straingauge dynamometer are measured with a Peekel straingauge instrument (581 DNH) and recorded with a Kipp & Zonen (BD9) recorder. The speed of the winch can be continuously controlled by varying the voltage of the Delta Elektronika Power Supply (DO50-10) of the D.C. Shunt Winch motor.

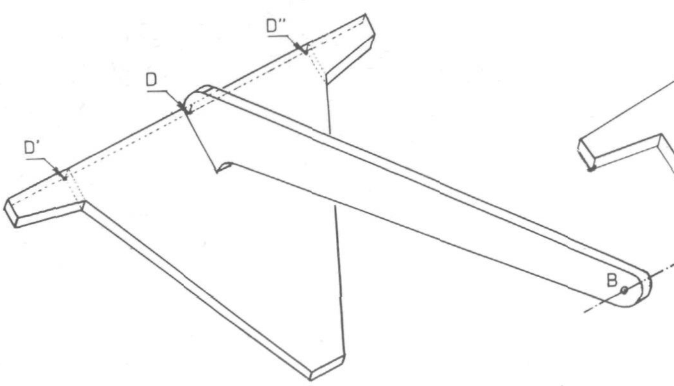


Fig. 52. Single-fluke model anchors. Number 1...4.

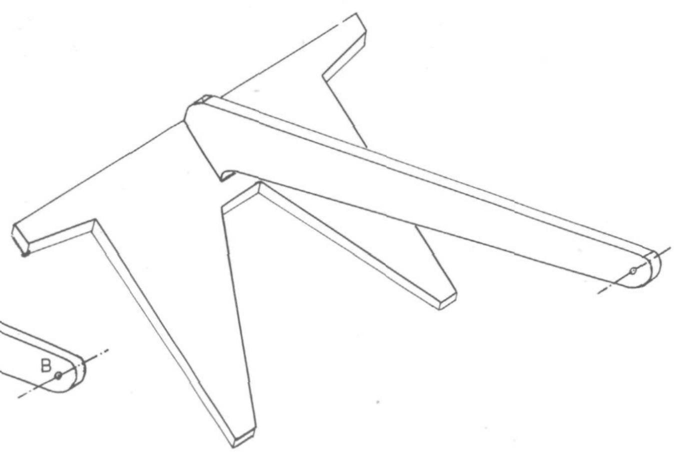


Fig. 53. Twin-fluke model anchors. Number 5...8.

6. EXPERIMENT PROCEDURES

The influence of the earth resistance on the anchor wire (running over a long distance through the bed), presents problems and is disadvantageous to experiments if the anchor wire is held horizontal. To reduce the earth resistance influence on the anchor wire, a constant and relatively short distance between towing point and shank was selected.

Therefore during the penetration of the anchor, the scope angle ϕ increased. All anchors were tested with the carriage driven by the weights and also driven by the winch. Driven by the weights, at each step a weight of 100 grams was added, introducing an additional penetration of the anchor and movement of the carriage. With the zero method, the dragging pull in the anchor wire between carriage and shank was measured when the carriage had stopped. Driven by the winch, the carriage was stopped each 100 mm to determine the dragging pull with the deflection of the recorder. During each stop, the position of the anchor in the bed and the height of the mound before the anchor above the bed level was measured with the help of the auxiliary wires and the sliding measuring scale. With the assistance of a computer programme and the computer of the University, the positions of the anchor in relation to the bed surface, and the vertical and horizontal components of the dragging forces was determined.

7. PRELIMINARY EXPERIMENTS

Initially all anchors were dragged in the tank along a distance of 1.12 m, without auxiliary measurement wires. The recorded dragging pull (figure 54), indicated the greatest dragging pull for anchor 4. *sw* is the distance the anchor dragged. Assuming that the anchor with the greatest dragging pull causes the greatest deformations of the bed, anchor 4 was selected for all further preliminary experiments.

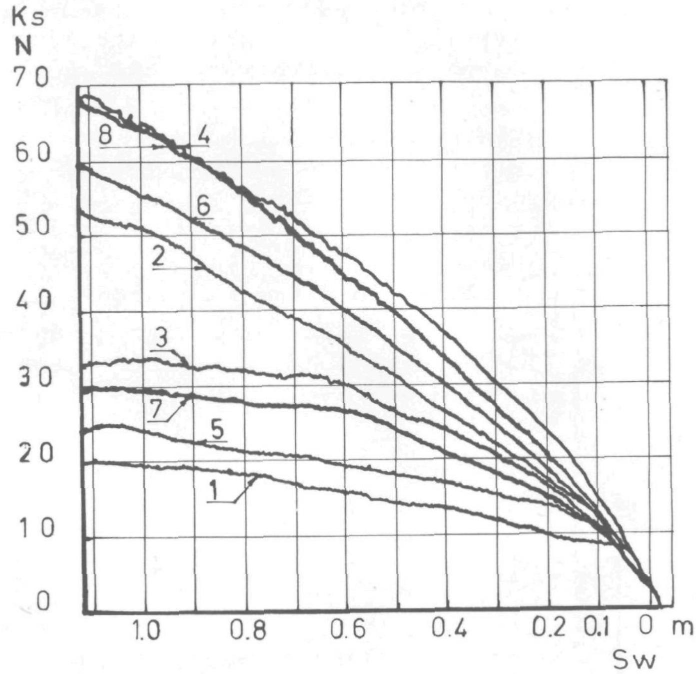


Fig. 54. Recorded dragging pull dependent on the distance the anchors dragged.

7.1. INFLUENCE OF STARTING POSITION

To investigate the influence of the starting position of an anchor, anchor 4 was towed a constant distance of 1.12 m starting in different positions.
Amongst other attitudes, the anchor was posed with the shank horizontal (with its upper side levelled with the bed surface), and with the points of the flukes and the end of the shank touching the bed.
The obtained recordings indicated only slight differences directly after commencement. At the end of the distance, the measured dragging force differed only from 69*N* to 70*N*. Therefore it was concluded that the influence of the starting position, dragging over a length greater than five times the length of the shank is negligible. To obtain during all further experiments a realistic starting position, the anchors were placed on the bed unloaded, in order that initial penetration was by anchor weight only.

7.2. INFLUENCE OF TANK SIDES AND TANK BOTTOM

The dragging anchor compresses the bed material to a great extent before and around the anchor, introducing consolidation. Where the influenced soil meets walls and bottom, additional consolidation will be introduced (caused by the greater stiffness of the material of the tank sides and bottom).
This additional consolidation effect can influence the measurements directly, but also indirectly, by introducing anchor instability when the anchor moves a small distance outside the area of the middle path of the tank. To reduce the influence of the sides, a smooth synthetic material with good elasticity was selected. The bottom has been made of a 25 mm thick very rigid supported plank. To verify the influence of the tank sides, two additional wooden sides were situated in the slots with bed material on both sides, with consecutively

distances between them of 580, 450 and 300 mm. Dragging anchor number 4 between the sides situated at a distance of 300 mm, the maximum measured dragging pull remained about 69*N*; but the course of the recorded curve of the dragging pull had changed. With distances of 450 and 580 mm between the sides, the curves and the maximum dragging pull appeared to be equal to the curves without additional inserts. Next, an additional wooden bottom was placed in the tank (in three different positions), reducing the height of the bed successively to 179, 234 and 314 mm. With the bottom in the first position, a very deformed dragging curve was measured because the anchor points touched the bottom planking.
In both the other cases no differences in relation to the situation without additional bottoms could be observed in the course of the curves.
The influence of sides and bottom in a tank with cross-section of 0.3 x 0.24 will be small. Hence the influence in the 0.6 x 0.6 meter tank will be negligible. The influence of the winch end of the tank could sometimes be observed. To reduce that influence a slope was made over about 0.1 m as indicated in figure 50.

7.3. INFLUENCE OF THE DRAGGING SPEED

The dragging speed during preliminary tests was about 0.1 m/min. To verify the additional influence of the dragging speed, anchor 4 was tested from speeds of 0.063 m/min up to 0.21 m/min, over a constant distance of 1.145 m. The measured values 73.2*N* $\pm$ 2.5% appeared to be independent of speed. Therefore the influence of testing speeds between 0.06 and 0.2 m/min can be considered as negligible.

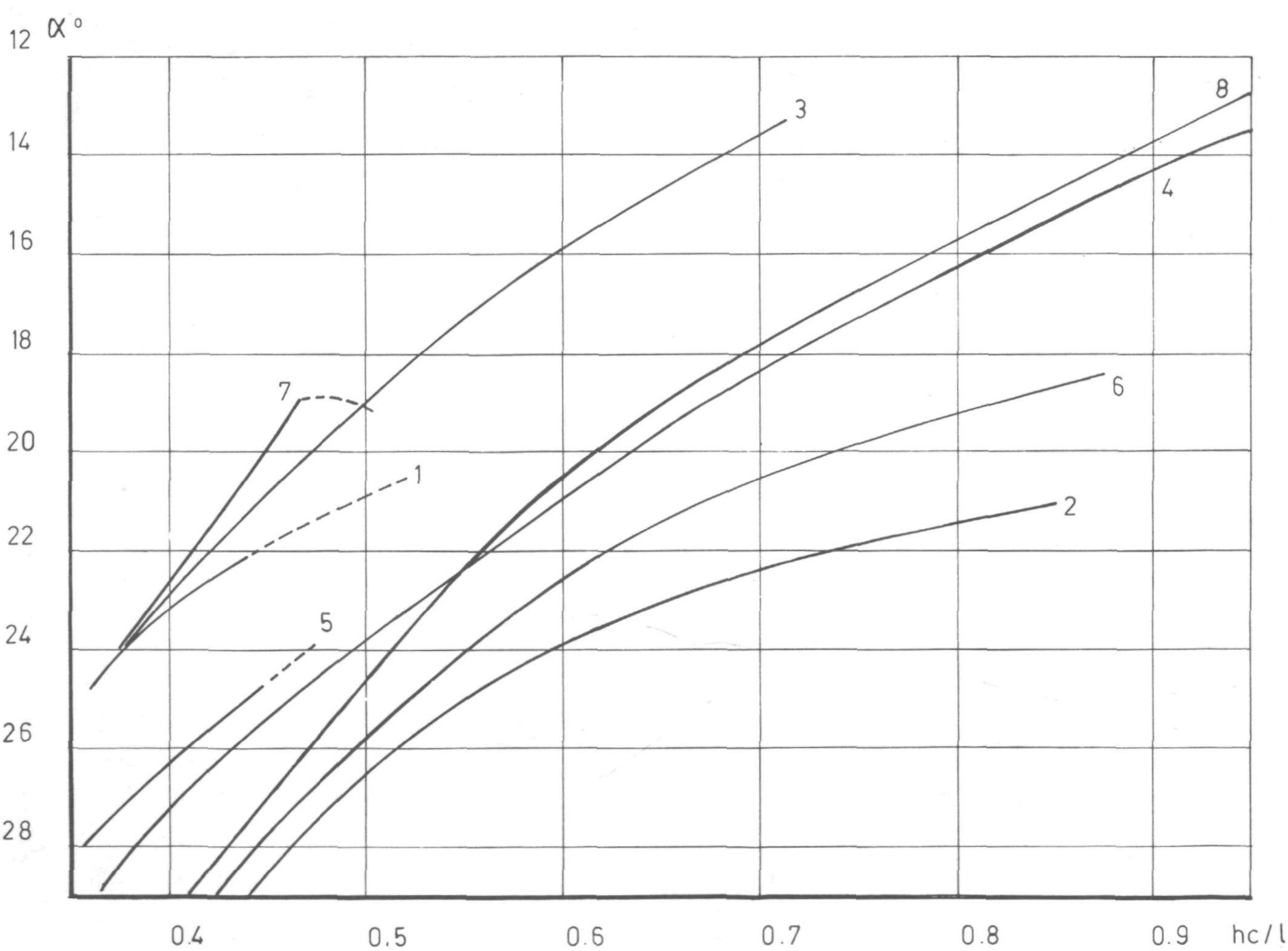


Fig. 55. The fluke angle dependent on the depth of penetration.

The test speed of 0.1 m/min is small, considering this speed is only a half of the shank length per minute. During all further tests with the winch a speed of 0.092 m/min was maintained. Increasing the dragging speed by hand an increase of the recorded dragging pull could be observed. This increase appears due to the greater acceleration and therefore resistance of the disturbed mass of the soil, forward of the moving embedded anchor.

8. DRAGGING TESTS

Dragging the model anchors, the results of tests where carriage was driven by increments of weight appeared to be most accurate. Using the winch, at the moment winching ceases, the recorded dragging pull decreases immediately, due to the elasticity of the total system (wires, carriage, anchor and soil), and due to the consolidation of the compressed part of the bed, before the anchor.
The anchor moves and settles so that the measured anchor position (after stopping), deviates from the position with the recorded dragging pull.
In the measured position, the unloaded anchor will rest with the backside of the flukes on the bed. Driven by the weight, during measuring the dragging pull can be maintained and so the compressed situation of the bed and the related position of the anchor.

8.1. INSTABILITY OF THE ANCHORS 1, 5 and 7

Observing the movement of the anchors during dragging with the help of four auxiliary threads, the anchors 1, 5 and 7 appeared to be unstable.
Rolling of the anchors 1 and 5 could be observed after the anchors had penetrated the bed to a depth of $hc/l = 0.44$, following dragging over a distance of $2.5l$. At a depth of $0.47l$, anchor 7 started rolling after dragging over a distance of only $1.6l$. It appeared very difficult to obtain reliable test results of these anchors, especially of anchor 5, because a slight difference in density of the soil introduced an advanced start of the rolling movement.

8.2. THE RESULTS OF THE DRAGGING TESTS

The results of the dragging tests, are indicated in the figures 55 ... 58.
Only the auxiliary threads in B and D were used, to reduce the additional resistance of the threads as far as possible. The relation between the depth of penetration hc/l and the inclination angle α is indicated in figure 55.
It is remarkable that the α values of the anchors 1, 3, 5 and 7 (anchors with a rectangular shank), are greater than the values of the anchors with a bevelled shank underneath 2, 4, 6 and 8.

8.2.1. THE DEPTH OF PENETRATION

Figure 56 indicates the relation between the distance the anchor drags (sw), and the depth the anchor penetrated into the bed. Comparing figure 56 with figure 54, it is obvious that anchors which penetrate deeper (dragging over a specific distance), develop a greater dragging pull. Therefore observing the penetrating movement of anchors during dragging, a provisional opinion regarding the holding capability can be derived.

8.2.2. THE HEIGHT OF THE MOUND

The height to the top of the mound above the level of the bed, hs, is indicated in figure 57 dependent on hc/l. It appears that the maximum height of the mound is proportional to the degree of instability of the anchors 1, 5 and 7.
It appeared that during these tests the start of a rolling movement of the anchor can be deduced from the development of an asymmetrical formed mound.

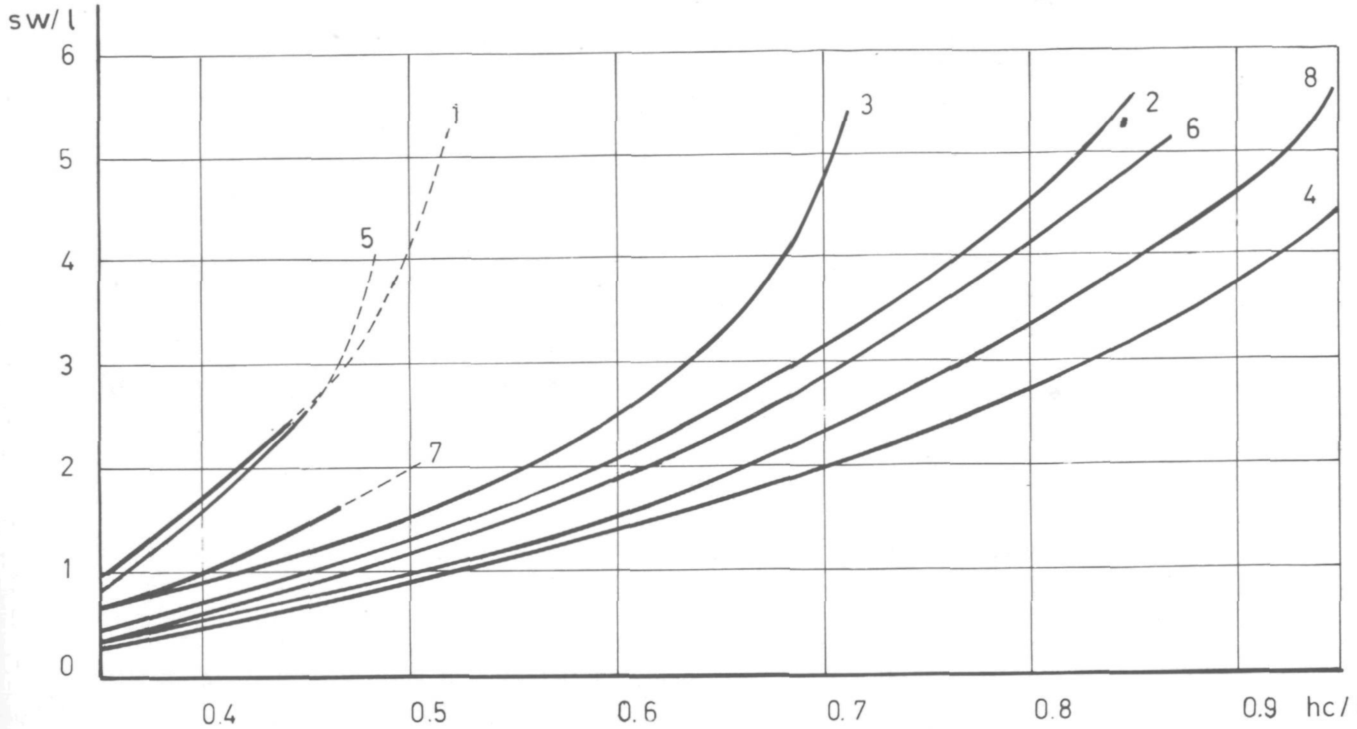


Fig. 56. The distance the anchors dragged dependent on the depth of penetration.

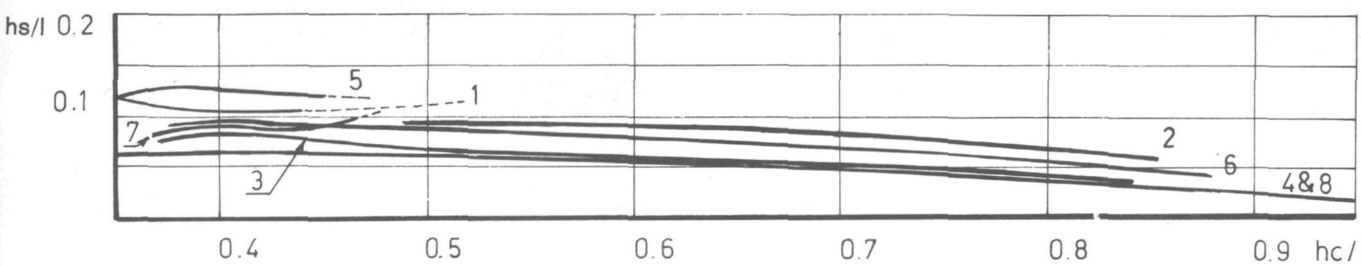


Fig. 57. The height of the mound dependent on the depth of penetration.

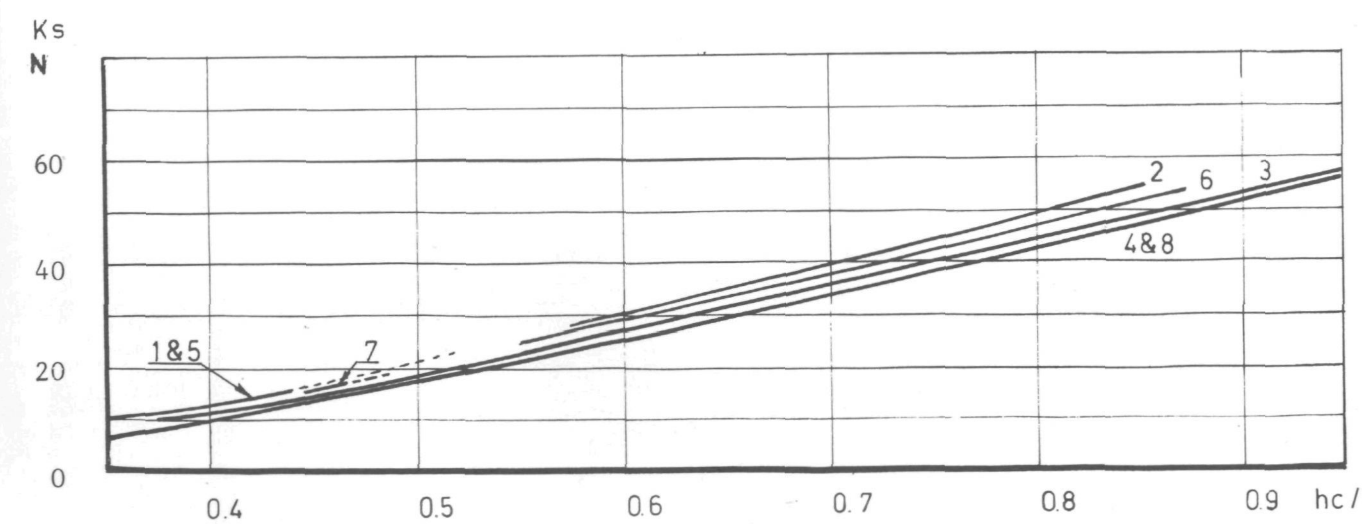


Fig. 58. The dragging pull dependent on the depth of penetration.

8.2.3. THE DRAGGING FORCE

In figure 58, the value *Ks* is indicated dependent on the depth of penetration. *Ks* appears to be about proportional to hc/l. The course of the curves indicates the anchors with the highest mound develop at first the greatest dragging pull. Penetrating deeper, the influence of the mound decreases as can be expected.

8.2.4. BREAKING-OUT TESTS

Several times during the dragging tests the breaking-out forces were measured by lifting the carriage with the anchor wire, so measuring vertically with the dynamometer, above shank-point . The ratio of the breaking-out forces and the dragging pull in the position the anchor was broken-out appeared to be for the anchors 1...4, 0.22 up to 0.25 and for the anchors 5...8, 0.30 up to 0.35. The breaking-out forces of the twin-fluke anchors is probably greater than the breaking-out forces of the single-fluke anchors, due to the greater distance of the fluke surfaces of the twin-fluke anchors to the shank.

8.2.5. INSTABILITY

By changing the length of the anchor wire and the height of the attachement of the anchor wire to the towing arm of the carriage, it was attempted to stabilize the movement of the unstable anchors 1, 5 and 7, but each time the anchors had penetrated the bed to hc/l = 0.4...0.5 rolling recommenced. The stable anchors remained stable.

9. CONCLUSIONS

- The height and the shape of the mound indicate anchor instability.
- Therefore it is preferable to measure the position of anchor and cable and the form of the mound during dragging tests.
- Bevelling of the underside of the shank and bevelling of the fluke points and sides increase stability and the holding capacilities of anchors.
- Stability of single-fluke model anchors appears to be greater than that of twin-fluke model anchors.
- Bevelling of the shank underside increases the inclination angle of the flukes in the holding position. Bevelling the fluke sides and points decreases the inclination angle of the flukes in the holding position.
- Regarding a specific anchor, anchor chain and bed, primarily the depth of penetration and secondly the inclination angle of the flukes, determine the dragging pull of an anchor.
- The depth of penetration can attain values greater than the length of the shank.

CHAPTER 9

DISCUSSION AND EVALUATION OF THE TEST RESULTS

1. INTRODUCTION

With respect to the holding pull of anchors there is a contradiction between the "Approximate law" of "de Parsons", and "Herreshoff" [20] and the formula of "Leahy and Farrin" [21].

Mr. de Parsons indicates "the holding powers of different sized anchors are proportional to the surface of their flukes multiplied by the square of the distance they are buried in", thus proportional to a moment of inertia.
But "Leahy and Farrin" concluded "the moment about the bed surface of the vertical projected fluke area can be used to compare the holding power of different anchors", thus a moment of area.

As Rear Admiral Land stated in his reply [15], "that the holding power of an anchor should depend upon a linear dimension, cubed (a volume)", which is reflected in the moment.

2. THE DRAGGING PULL IN RELATION TO THE MOMENT AND THE MOMENT OF INERTIA OF THE VERTICAL ANCHOR PROJECTION

Denoting the moment and the moment of inertia of the vertical anchor projection about the bed surface with Mv and Iv, the values Kh/Mv and $l.Kh/Iv$ have been calculated and indicated in the figures 59 and 60. To compare Kh the value Iv/l is chosen instead of Iv because the holding pull depends on a volume of disturbed and deformed bed material.

The values Mv and Iv were calculated including the moments of the shank because during the tests angle $\alpha-\beta e$ remained negative.
Therefore,

$$Mv = M\sin^2\alpha + Ms.\sin^2(\alpha-\beta e) \qquad (116)$$

$$Iv = I\sin^3\alpha - Is.\sin^3(\alpha-\beta e) \qquad (117)$$

The values Kh/Mv are increasing with hc/l, the values $l.Kh/Iv$ are decreasing and become about constant with respect to the anchors 3, 4, 7 and 8, anchors with bevelled fluke sides and points, as most anchor types have.

Obviously, when an anchor digs in the horizontal component of the dragging pull becomes proportional to the moment of inertia of the vertical anchor projection. Due to the relatively small values of the scope angle ϕ between the towing wire and a horizontal line through B, the values of Ks are slight greater than the values of Kh. Therefore may be stated, as indicated already by "Herreshoff" and "de Parsons", the holding pull related to situations with a small value of the scope angle is about proportional to the moment of inertia when a stable anchor digs in deeply.

"Leahy and Farrin" tested geometrically similar anchors. Therefore their statements have to be considered in relation to anchors of an anchor series.

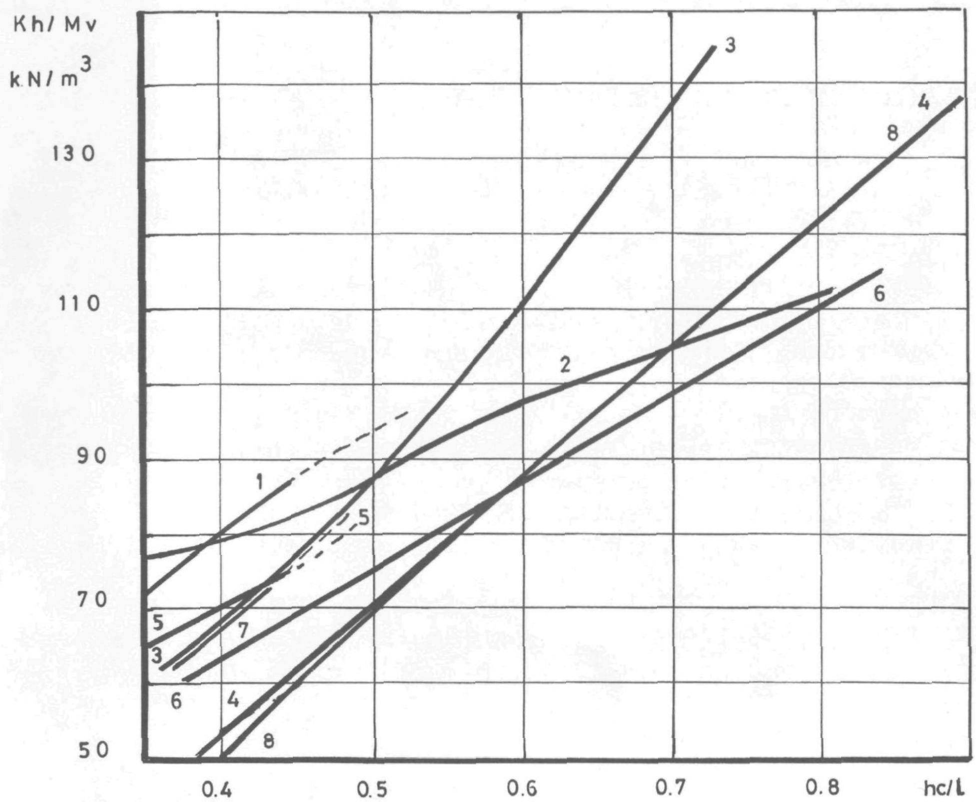


Fig. 59. The ratio *Kh/Mv* depending on the depth of penetration *hc/l*.

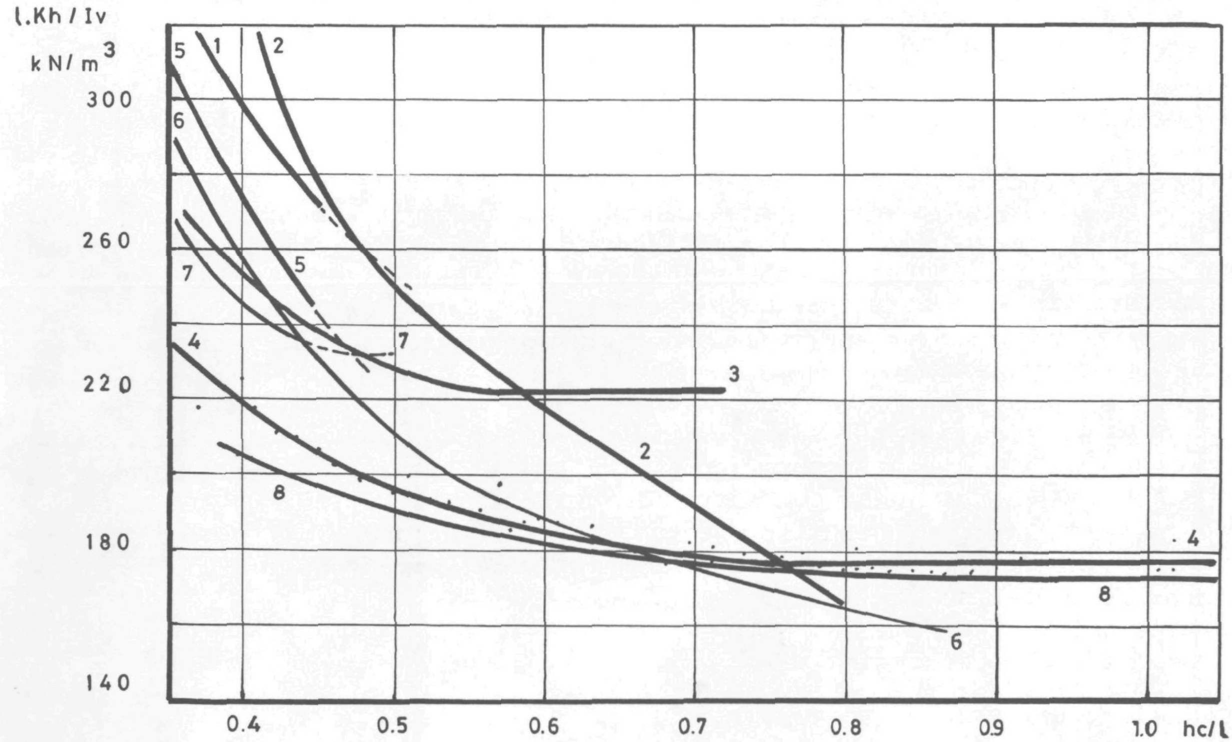


Fig. 60. The ratio *l.Kh/Iv* depending on the depth of penetration *hc/l*.

To give an impression of the accuracy of the test results in respect to the derived curves in figure 60 the calculated values regarding anchor 4 differing from the curve are indicated with dots.

3. ANCHOR SERIES

The ratio of the main dimensions of an anchor to the reference length, the length of the shank l, is reasonably constant for all anchors of an anchor series. Anchor series such as the Hall, the Gruson, the Pool and the Delta among many others. As reference length, preference to the shank length l is given because this length, the distance between the centre line of the hole of the anchor shackle and the centre line the crown and flukes rotate about, is a well defined distance which can be determined easily to most of the movable-fluke anchors and also to anchors which do not have a hinge-pin construction. The weight of anchors of most series is proportional to l^3 so that $Ga = ag.l^3$ assuming ag to be a constant.
For instance, the ratios relating to the main dimensions and the value of ag for the undermentioned anchor series are approximately

Series	ag kg /m^3	p/l	a/l	k/l	t/l	βe
Hall	179	0.500		0.176	0.25	45^o
Gruson	295	0.555	0.16	0.155	0.295	45^o
Inglefield	175	0.527	0.132		0.264	45^o
Stokes	180	0.57	0.16	0.16		40^o
Spek	300	0.555	0.167	0.18	0.278	40^o
Normal Pool	268	0.654		0.205	0.428	42^o

The constant ratio of anchor dimensions to l in relation to the constant ratio of the anchor weight to l^3 simplifies the anchor movement and holding problems, because of the friction- and holding forces, the earth resistance forces of non-cohesive soils and the forces due to the anchor weight of anchors of a series, will have in the first instance values with a constant ratio to l^3.
Forces due to, and influenced by, the cohesion and adhesion of a soil will have an additional term with a constant ratio to l^2. A dragging force acting on an anchor of a series can be expressed in the general form $Fg = af.l^3 + ac.l^2$...(118) expressing with the first term the volumentrical influences of the anchor and the affected part of the soil in combination with the unit weight of anchor and soil, and with the second term, the influences of the anchor areas and the areas of the rupture surfaces through the soil, in combination with adhesion and cohesion. Drafting the formulas in this general form, the behaviour of all anchors of a series can be analysed by comparing the values of af and ac, and with respect to a specific bed.

Holding in a non-cohesive and adhesive bed $Fg = af.l^3$...... ......(119) applies. In the same relative position to the bed surface, α and hc/l being equally, the value af will be equal for all anchors of a series.
Holding in a cohesive and adhesive bed the values of af and ac will be different for each anchor of the series holding in the same relative position to the bed surface.

4. THE FORMULA OF "LEAHY" AND "FARRIN"

In the same relative position of the bed surface, (hc/l and α), the dragging pull in relation to l^3, will be equal for all geometrically similar anchors of a series.

For each different position one particular af value applies to all anchors. Therefore with respect to the maximum holding pull in a particular bed, in the first instance one specific af value, denoted with afh applies.
The maximum holding pull Fh will be

$$Fh = afh \times l^3 \qquad \text{......(120)}$$

"Leahy and Farrin" indicated "that the holding power of an anchor should depend upon a linear dimension cubed, a volume, which is reflected in the moment". Their formula

$$P = K.A.^{1.53} \qquad \text{......(121)}$$

where P holding power, A area of the flukes and K a constant depending upon anchors of a series and a specific type of bottom, corresponds with their statement [21]. Their value $A^{1.53}$ represents also a specific length to the third power. By introducing the moment of the projected fluke area they related the third power of this length to the depth of penetration times the vertical projected fluke area, assuming a horizontal direction of the shank.
Their formula applies in the first instance to the anchors of a series in a specific bed because all anchors attain the same relative depth of penetration, hc/l, holding the maximum pull.

Holding the maximum pull, even the situations related to unstable anchors of a series will be similar.
With respect to non-cohesive and non-adhesive soils, the coefficients afh or K determined in relation to a specific hc/l and α value, will apply to all anchors of a given series, because of volumetric-unit weight, terms related to l^3 govern in the first instance all movements, situations and forces. With respect to adhesive and cohesive soils, the coefficients related to a specific hc/l and α value will probably be different for each anchor in a series due to the terms l^2 and l^3 governing the movements, situations and forces of an anchor dragging in a cohesive and adhesive bed. Only the results of many dragging tests with model and full-scale anchors (tests which are very difficult to execute), can give further indications of a relationship between the size of an anchor from a given series, the position of the anchor and the coefficients, af and ac.
Therefore the formula of "Leahy" and "Farrin" is too simple to be applied with respect to adhesive and cohesive beds.

5. THE CONTRADISTINCTION

In an ideal soil the holding pull of the anchors of a series depends on the moment of an area if the formula of "Leahy" and "Farrin" may be applied.
But the holding pull depends on a moment of inertia, if the approximate law holds good.

Figure 59 indicates the value of Kh/Mv increases with hc/l. Therefore the formula of "Leahy" and "Farrin" may not be applied introducing Mv and thus introducing the influence of the shank and angle α.
In their paper [21] in figure 12 their calculation of the moment, Mlf, is indicated.

Due to their assumed horizontal direction of the shank the moment is:

$$Mlf = A.\sin\beta e.hzc \qquad \text{......(122)}$$

a constant area times a distance related to the depth of penetration.
In figure 61 the ratios Kh/Mlf are indicated with respect to the model anchors.

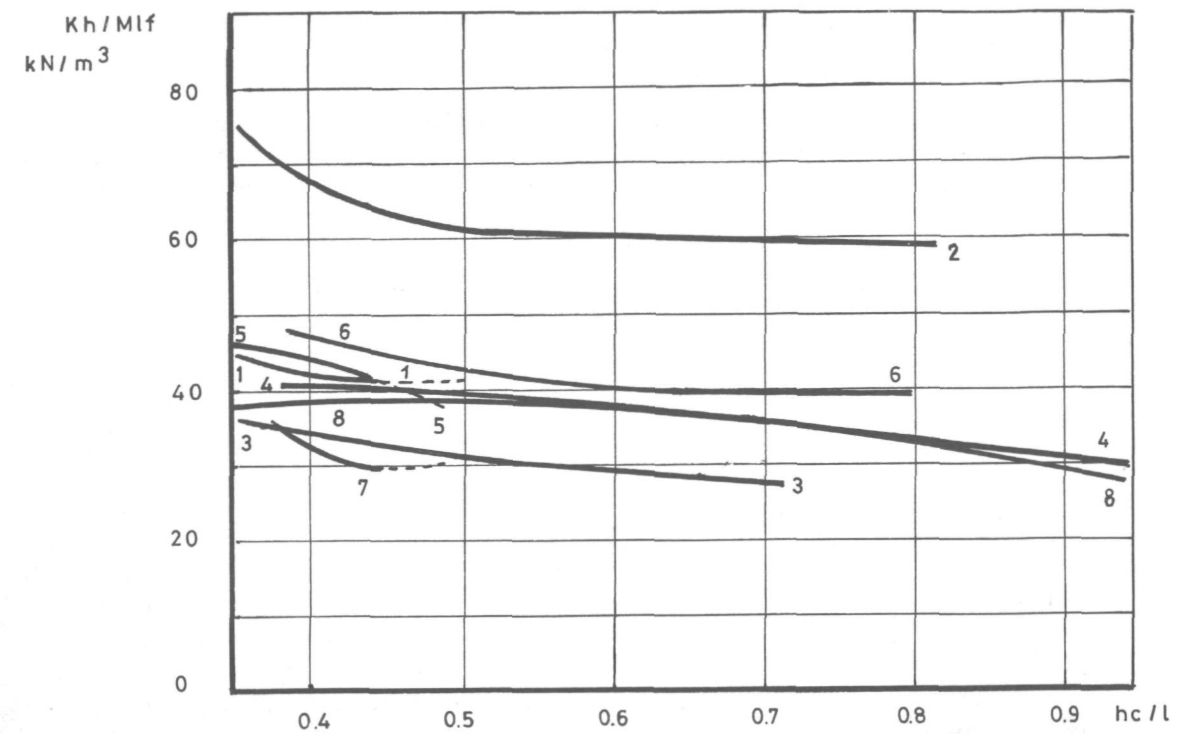


Fig. 61. The ratio *Kh/Mlf* dependent in the depth of penetration *hc/l*.

Concerning the unstable anchors 1, 5 and 7 and the anchors 2 and 6 the formula of "Leahy and Farrin" and thus the general formula (118) applies.
Penetrating deeper, the value *Kh/Mlf* of the anchors 3, 4 and 8 decreases and probably also the value *Kh/Mlf* of the anchors 2 and 6.

"Leahy" and "Farrin" tested U.S. Navy standard stockless anchors which attained holding pulls equal to 5...7 times their weights and therefore will not have deeply penetrated the bed.
The curves in figure 61 are about constant between 0.4 and 0.7 *hc/l*.
Therefore the formula of "Leahy" and "Farrin" applies to holding pulls of 10...35*N* or 6...25 times the weight of the model anchors.
Thus can be concluded the formula of "Leahy" and "Farrin" may be applied with respect to ordinary anchor types and high holding power anchors up to a depth of penetration of about 0.7 *hc/l*, holding an ideal bed.

Then the maximum holding pull of stable anchors of a series depends on the fluke area and the depth of penetration. Penetrating deeper into an ideal bed the Approximate Law will apply and therefore the maximum holding pull of stable anchors of a series will be dependent on the fluke area, the depth of penetration and the relative depth of penetration.

When an anchor digs in first the mould is formed. The soil is disturbed from the points up to the surface of the bed and moves intensively. Digging in deeper, the mould disappears and the surface of the bed is only lifted over a large area above and ahead of the anchor.
Therefore it is comprehensible that two different formulas have to be applied with respect to the holding pull of a digging in anchor.

6. THE PROPOSAL OF MR. P. BRUCE

A further distinction of anchors in three instead of two classes, a first class of ordinary anchors, a second class of anchors which have at least twice the holding ability of an ordinary anchor of the same weight and a third class of extra high holding power and stable anchors which have at least 4 or 5 times the holding ability of an ordinary anchor, as suggested by Mr. P. Bruce, seems reasonable and desirable [28].

Denoting the ratio of the maximum holding pull and the anchor weight with V, $V = Fh/Ga$.
The V values of the anchors holding in a sand bed will be about

Class	V	hc/l
Ordinary	4....6	< 0,4
High holding power	6...20	< 0,7
Stable, extra high holding power	> 20	> 0,7

The first class regards the anchors which penetrate only with the flukes into the bed, as indicated in chapter 6.
The second class concerns anchors which dig in so deeply that the formula of "Leahy" and "Farrin" may be applied with respect to the digging in movement and formula (119) to compare the maximum holding pull of anchors of a series.
The third class regards anchors which dig in so deeply that the Approximate Law may be applied to determinate the dragging pull during the digging in movement and formula (119) to compare the maximum holding pull of anchors of a series.
The anchors of this class will always be stable.

7. INSTABILITY

It appears difficult to predict wether an anchor is stable or not.
Only by bevelling the points and sides of anchor 1, or by bevelling the shank underside, leads to the stable anchors 2 and 3.
As the curves related to the height of the mound, figure 57, indicate unstable anchors disturb the bed surface greatest, rising the highest mounds.
The start of the rolling movement of an instable anchor could be determined during the dragging tests observing the mounds. When a mound became asymmetrically the anchor started rolling.

Perhaps an anchor acts in a stable manner when the crown extremities remain outside the soil mass disturbed by the flukes. When the crown wings enter the moving current of bed material, disturbed by the flukes, a small difference in density starts rolling, so the anchor turns to one side, rolls further and leaves the bed with the flukes uppermost.

8. THE DEPTH OF PENETRATION

The "Approximate Law", the formula in general forms (119) and the formula of "Leahy and Farrin" expresses the holding pull dependent on constants which first have to be determined by testing anchors or anchor models.
The constants have to be determined directly related to the maximum holding pull, or with regard to some positions of an anchor when it is digging into the soil.

But after the determination of the value of the ratio the problem remains to what Iv value, to what depth the anchor will penetrate into the bed to hold its maximum pull. To analyse the influences determining the depth an anchor digs into a bed, the model situation indicated in chapter 7 has to be developed further.

9. CONCLUSIONS

- Digging into a cohesive and adhesive soil the behaviour of each anchor out of a series will be different.

- The Approximate Law of "de Parsons" and "Herreshoff" and the formula of "Leahy and Farrin" offer an indication of the dragging pull, each during a part of the digging in movement.
  The formula holds good between a depth of penetration hc/l = 0,4 and 0,7.
  The law holds good when the depth of penetration $hc/l > 0,7$.
  They can only be applied as a scaling law for shallow-digging in anchors and for deeply embedded anchors holding in an ideal soil.

- Anchor behaviour in adhesive and cohesive beds can only be determined by careful testing.

- The proposal of Mr.P.Bruce to distinguish three instead of two anchor classes, deserves approval.

CHAPTER 10

THE HOLDING PULL IN AN IDEAL BED

1. INTRODUCTION

To analyse the influences determining the maximum holding pull, the model situation indicated in chapter 7 can be completed introducing the results of the tests regarding the deeply digging in anchor models 4 and 8.

2. EARTH RESISTANCE FACTORS AND THE SHANK RESISTANCE ANGLE

In connection with the assumptions made in chapter 7 the earth resistance forces E and Es can be indicated as:

$$E = \rho e.g.fqc.M.\sin\alpha \quad \ldots\ldots(123)$$

$$Es = \rho e.g.fqs.Ms.\sin(\beta e-\alpha) \quad \ldots\ldots(124)$$

assuming $\beta e-\alpha > 0$.
ρe the unit mass of the bed material, fqs and fqc are unknown factors and g the acceleration due to gravity.
The forces E and Es are assumed to be equal to the weight of the bed above the cross-sectional areas times a factor.

Starting from the equations (111...113) and introducing a value of ρ = tangent 25°, the coefficient of friction between P.V.C. and aluminium, the values E, Es, T and Ts and value ρs, $\rho s = Ts/Es$ were calculated with respect to the test results of the anchors 4 and 8. The value ρs, includes the influence of friction between the bed and the shank and the direct earth resistance of the bed acting for the greatest portion at the underside of the shank.
With the formulas (123) and (124) the values fc and fs

$$fc = fqc \times l/hzc \quad \ldots\ldots(125)$$

and

$$fs = fzs \times l/hzs \quad \ldots\ldots(126)$$

are calculated.
Both values are earth resistance factors dependent on the depth of penetration.

The fc values and also the angle $\phi s = arc.$tangent ρs are indicated in the figures 62 and 63.
It appears that the fc values become about constant when $hc/l > 0.7$.

Substituting $fqc = fc.hzc/l$ in formula (123) and $fqs = fs.hzs/l$ in formula (124) E and Es become:

$$E = \rho e.g.fc.I\sin^2\alpha/l \quad \ldots\ldots(127)$$

$$Es = \rho e.g.fs.Is.\sin^2(\alpha-\beta e)/l \quad \ldots\ldots(128)$$

with fc about constant.
Plotting the value fs, it appeared that also the values of fs become about constant when an anchor digs in deeper than $hc/l > 0.9$.
Besides the values ϕs the auxiliary angle $\phi a = 90^{\circ}+\alpha-\beta-\rho$ ......(129) is indicated, a value that estimates ϕs suitable. This angle ϕa is equal to the angle between the horizontal direction, (the main direction of the movement of a dragging anchor) and a line perpendicular to the shank centre line AB minus the friction angle between soil and anchor material.

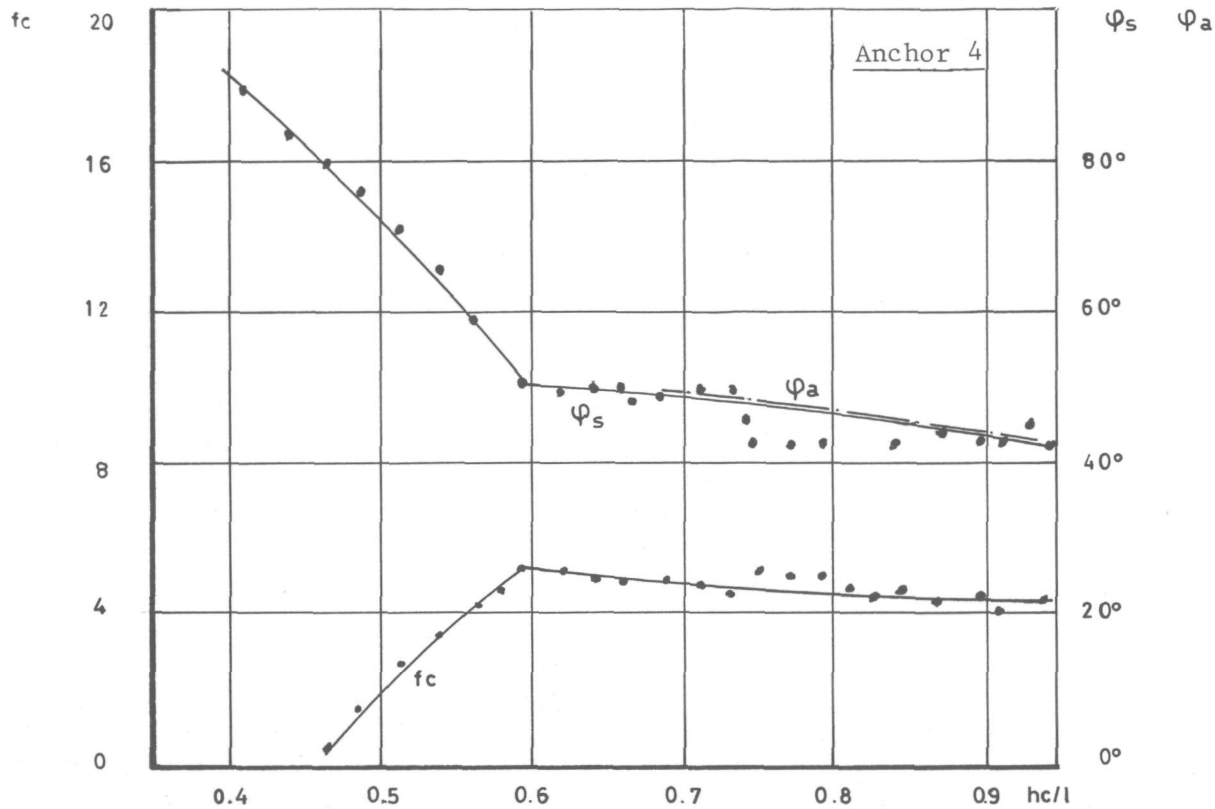


Fig. 62. The values *fc* and *ϕs* dependent on the depth of penetration.

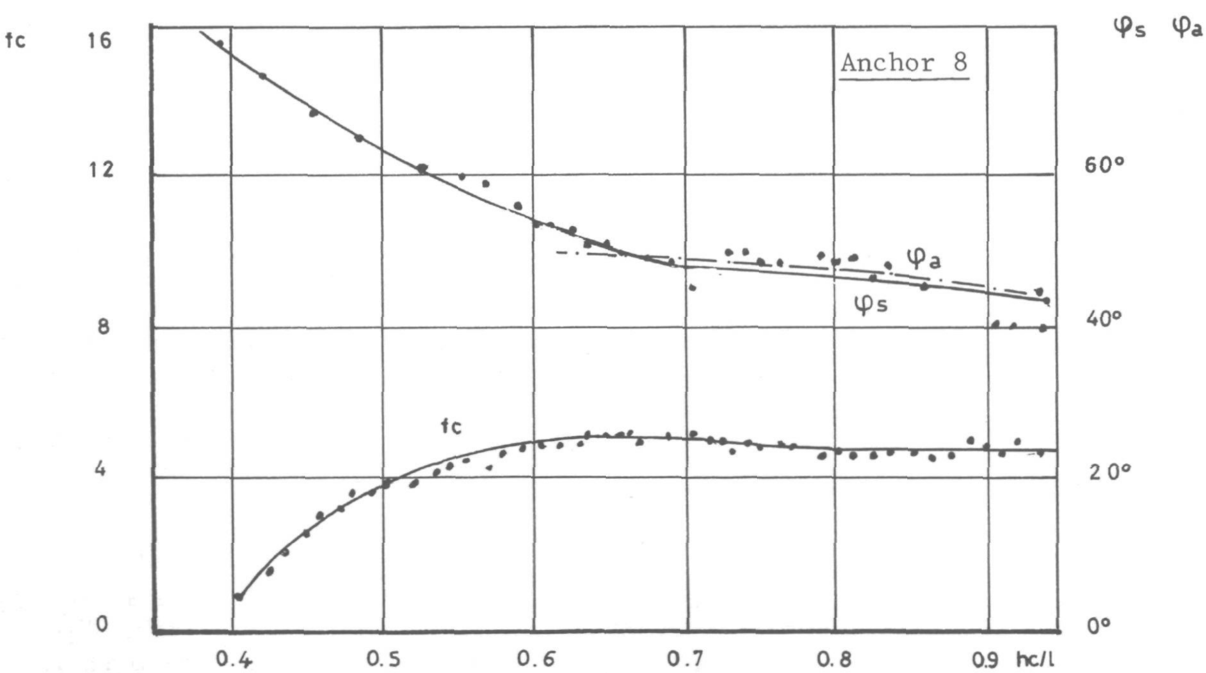


Fig. 63. The values *fc* and *ϕs* dependent on the depth of penetration.

3. THE APPROPRIATE MODEL SITUATION

Substituting $T = \rho E$, $Ts = \rho s.Es$ and $\varepsilon s = \beta e - \alpha$ the formulas (111) and (112) indicate:

$$Kh = E(\sin\alpha + \rho.\cos\alpha) + Es.(\sin\varepsilon s + \rho s.\cos\varepsilon s) \quad \ldots\ldots(130)$$

$$Kv = Ga + E(\cos\alpha - \rho.\sin\alpha) - Es.(\cos\varepsilon s - \rho s.\sin\varepsilon s) \quad \ldots\ldots(131)$$

The moment equation about point B indicates:

$$Es.zs = Gs.\lambda s.l.\cos\varepsilon + Gc.\{l.\cos\varepsilon s - p(1-\lambda p)\cos\alpha\} + E(l.\cos\beta e - p + zc - \rho.l.\sin\beta e) \quad \ldots\ldots(132)$$

Assuming the value fc is constant and $\phi s = \phi a$, determining E and ρs, the values Es, Kh and Kv can be estimated depending on hc and α for each anchor position. The about constant value of fs may not be used due to the assumption of zs, formula (115), and equation (132).
With these formulas the behaviour of deeply-embedded anchors holding in an ideal soil can be analysed.

4. THE INFLUENCE OF THE DEPTH OF PENETRATION

Burying itself deeply when an anchor drags the influence of its weight may be neglected. At a great depth the values zc and zs become about constant and equal to the distances to the centroids of the areas, $zc \approx zca$ and $zs \approx zsa$.
This means that Es becomes proportional to E due to formula (132), $Es = fe.E$, fe a constant factor.
The value of I is:

$$I = Ic + A\left(\frac{hc}{\sin\alpha} - zca\right)^2 \quad \ldots\ldots(133)$$

Ic the moment of inertia of the head about the centroid and A the area of the head. The relatively small values Ic and zca may be neglected when an anchor is deeply buried. Thus:

$$I \approx A\,\frac{hc^2}{\sin^2\alpha}\,.$$

This means, substituting I and Es,

$$Kh \approx \rho e.g\,.fc.A.\,\frac{hc^2}{l}\left[\sin\alpha + \rho.\cos\alpha + fe\{\sin(\beta e - \alpha) + \rho s\cos(\beta e - \alpha)\}\right] \quad ..(134)$$

Thus the horizontal component of the holding pull becomes proportional to the area of the flukes and crown A, to the square of the depth of penetration hc^2 and to the unit mass of the bed ρe.
Kh will always be positive because the scope angle at B will be positive due to the earth resistance acting at the chain or anchor rope, thus $\beta e - \alpha$ remains positive.
When the scope angle remains constant an anchor can hold any desired holding pull by penetrating the bed deeper.

5. THE INFLUENCE OF THE SCOPE ANGLE

Eliminating E and neglecting the influences of the anchor weight from the formulas (130) and (131) can be derived:

$$\text{tangent } \phi = Kv/Kh = \frac{\cos\alpha - \rho.\sin\alpha - fe(\cos\varepsilon s - \rho s.\sin\varepsilon s)}{\sin\alpha + \rho.\cos\alpha + fe(\sin\varepsilon s + \rho s.\cos\varepsilon s)} \quad \ldots\ldots\ldots(135)$$

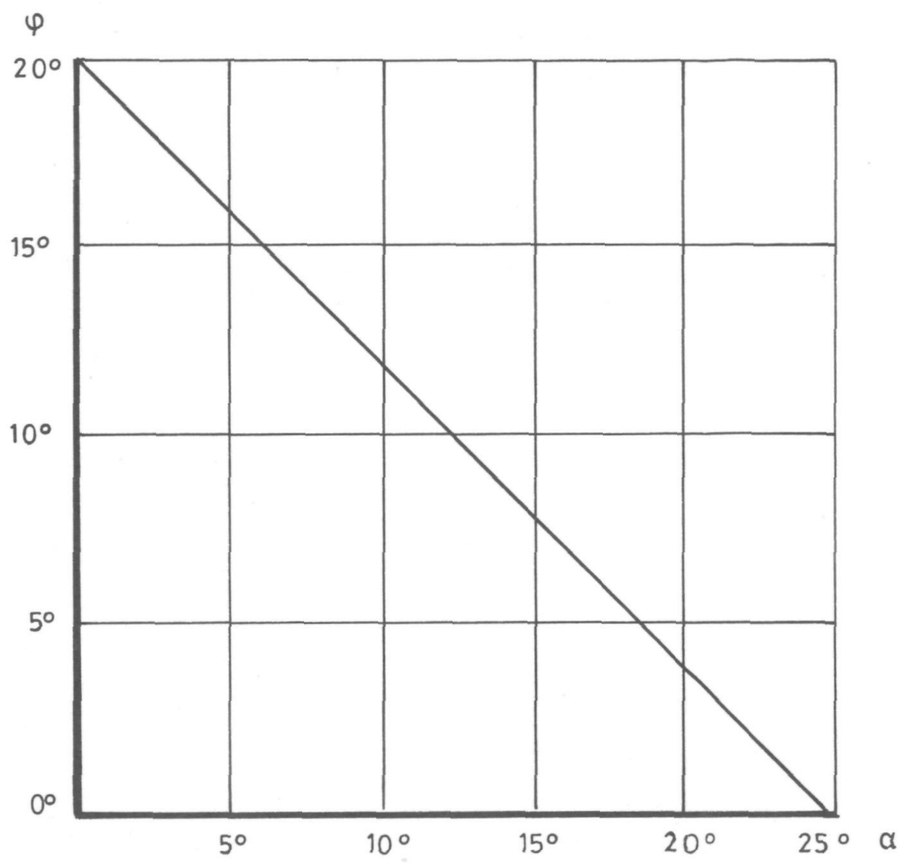


Fig. 64. The scope angle ϕ dependent on the inclination angle of the flukes α.

Thus angle ϕ appears to be independent of the depth of penetration h_c.

$\phi = 0$ when $\cos\alpha - \rho . \sin\alpha = fe\{\cos(\beta e - \alpha) - \rho s . \sin(\beta e - \alpha)\}$...... ......(136)

ϕ depends only on the variable inclination angle of the flukes α and the constant fluke angle βe.
An anchor rises in the bed when the scope angle increases above a maximum possible value which can be calculated by varying α in formula (135).
In figure 64 the value of ϕ dependent on α is shown with respect to the model anchor 4.

6. THE DECISIVE INFLUENCE OF THE EARTH RESISTANCE ACTING ON THE CHAIN OR ANCHOR ROPE

When an anchor digs in deeply the scope angle at B increases, even when the chain or rope is led horizontally upon the bed surface. The earth resistance acting at the underside of the penetrating chain or rope induces a scope angle at the shank end B.
When the maximum scope angle ϕ is reached stable anchors do not penetrate deeper but start dragging at constant depth with a constant holding pull, the maximum holding pull. Therefore the maximum holding pull attained depends on the size of the chain or cable the anchor is connected to. The maximum holding pull of an anchor connected to a chain will be less than the maximum holding pull of an anchor connected to an anchor rope because the earth resistance acting at the chain will be greater and also the related scope angle will be greater at the

same depth of penetration. An anchor fixed to a rope will start continuous dragging at a greater depth and will therefore attain a greater pull.

7. THE STABLE MODEL ANCHORS 2, 3 AND 6

In the figures 65 and 66 the calculated *fc* and ϕs values of the anchors 2, 3 and 6 dependent on the depth of penetration hc/l are shown.
The different *fc* values and the ϕs values indicate that the soil ahead between the fluke and shank form partly a whole with the anchors and cause a different situation with respect to the movement of the soil ahead of the anchors, over the flukes and passing the shanks.

Therefore the assumed distribution of the earth pressure and the consequent situation of the point of application of the forces *E* and *Es* do not apply, due to the hampering of bed material between the rectangular shaped shank undersides and the flukes and the additional disturbing influences of the rectangular shaped fluke points and sides.

Comparing the values of anchor two and six it seems that the movement of bed material across the space between both flukes of anchor six causes a comparable situation with the movement of the soil around the anchors four and eight.

The cross-section of the shank influences the position of the dragging anchor in the bed. The α values of anchors with a rectangular-shaped underside of the shank are greater than the α values of anchors with a bevelled-shank underside. Resultant greater *I* values cause the low *fc* values with regard to the anchors four and eight.
The curves create the impression some values become constant, but this can only be checked by testing the model anchors in a substantially extended tank.

8. ACCURACY AND SENSITIVITY

The calculated values of *fc* and ϕs lie near the drawn curves with a spread of about 5% at the beginning of the curves, during penetration increasing further up to about 10%. Sometimes greater fluctuations were observed. There must be a very great sensitivity between the measured values and the calculated factors *fc* and ϕs.
Increasing the measured dragging pull by 10%, for anchor 4 in the position hb = 118 mm and hd = 184 mm, *fc* increases by 9% and ϕs remaines about constant. In this position of anchor 4, with $\alpha = 14.1^o$ and $hc/l = 1.03$ this influence of *Ks* was too small to explain the observed deviations. The vertical position of the points *B* and *D* were measured by means of the auxiliary threads with an accuracy of $\pm$ 1 mm. A parallel deviation of 1 mm of the anchor in the indicated position, means a difference of 0.5% of *hc*, 2,6% of *fc* and about 1,2% of ϕs. This influence appeared also too small to explain the observed deviations.

Therefore, the influence of a measurement with point *B* one mm too high and point *D* one mm too low, or reverse, were calculated. This means a deviation of *hc* of the order of 0.0007%, of α 0.56^o, of *fc* 9,8 % and of ϕs 5,1%.
This indicated clearly the great influence of α on the calculated values. Penetrating deeper near the equilibrium position of the anchor the moments acting on the anchor decrease but the moments necessary to change α increases. This combined with the decreasing accuracy of the measurements with thin threads, when the anchor penetrates deeper, gives the explanation of the

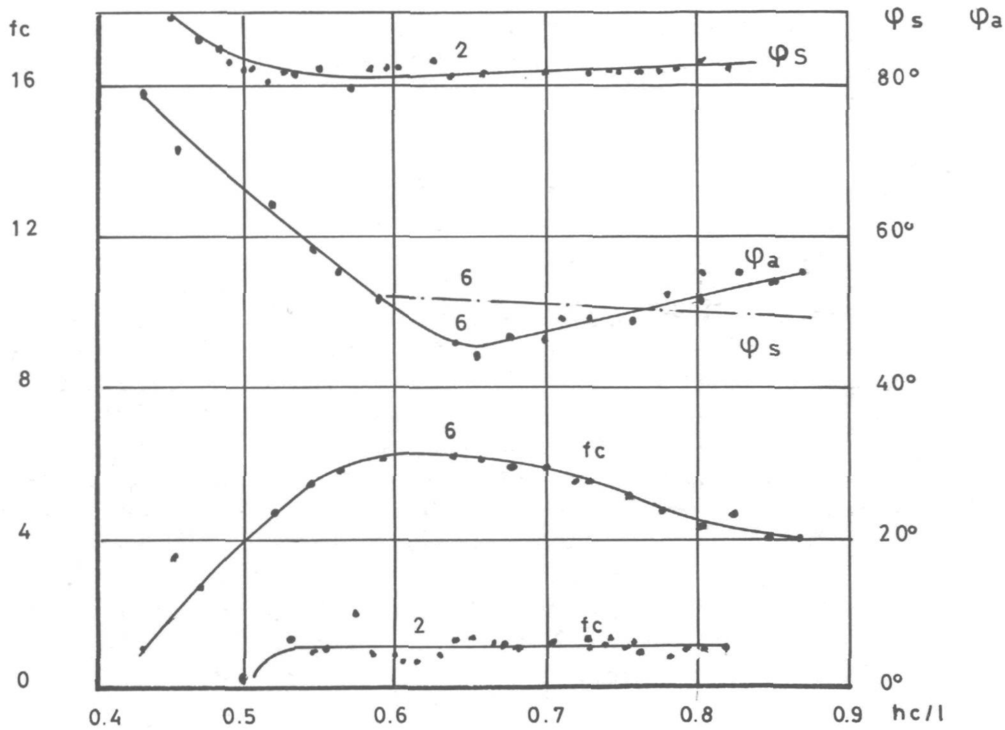


Fig. 65. The values *fc* and ϕs dependent on the depth of penetration, *hc*/*l* regarding the anchors 2 and 6.

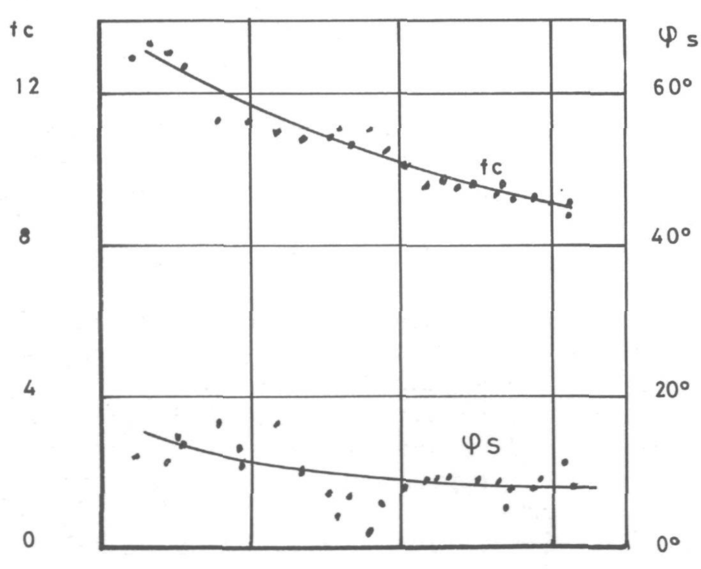


Fig. 66. The values *fc* and ϕs dependent on the depth of penetration *hc*/*l* regarding anchor 3.

increased spreading of the results during penetration and the great deviations sometimes observed at the end of the tests.

9. TWIN-SHANK ANCHORS

By introducing two shanks, the earth resistance of the shank at least is doubled. The penetration depth of the anchor will be less and therefore the dragging pull resultant.

10. ANCHORS IN TANDEM

Anchoring with two anchors behind one other, with the last anchor connected with a wire or chain to the first, offers a dragging pull slightly more than that anticipated for one anchor. This is caused by the lifting influence of the additional connection (between the anchors) on the first anchor, due to the chainpull of the last anchor and the vertical components of the earth resistance acting on the additional connection. When this connection is fixed to the crown of the first anchor, α remains about constant and the anchor does not penetrate the bed sufficiently. Even when the additional connection is fixed to the shank near the shackle, anchor rotating and penetrating is hampered. Therefore, when a high value of the dragging pull is urgently needed it is better to connect the additional chain or wire a greater distance prior to the shackle of the first anchor, accepting the increased risk of fouling. But better it is to use a greater anchor instead of two anchors.

11. THE MAXIMUM HOLDING PULL AND CHARACTERISTIC RATIOS

Most of the publications regarding anchor dragging tests indicate the maximum recorded pull in the anchor wire as holding pull, holding force or holding power. This pull is regarded in relation to the anchor weight and expressed in the holding force/weight ratio V. Commercially, this ratio is intensively used to recommend specific anchor models. But considering in some anchor models there are cavities, (cavities sometimes filled with concrete or sand),the question arises is the pull/weight ratio representative. When the anchor shackle remains above the bed, the dragging force depends on the anchor, the bed and the length and weight of the chain determining with the depth of water the scope angle ϕ. By observing the shank, can be verified that the anchor is stable.

The maximum dragging pull, in a stable anchor position (a position with the symmetrical plane of the anchor vertical), can be regarded as a holding pull related to the bed, the scope angle and the anchor model and weight. Therefore the holding pull/weight ratio referring to an also-indicated type of bed and scope angle is valuable. Also the distance the anchor dragged to realize the holding pull, swh, is essential in relation to the anchor dimensions. Further is important the area A of the crown and flukes in relation to the holding pull. Comparing the holding abilities of different anchor models, the square root of A, la is more representative as a specific length than the shank length. Therefore the holding abilities of different anchors can be compared with the help of a "compression ratio" Vc, $Ks/(\rho e.g.A.la) = Vc$ and a "soil disturbing ratio" Vd, $Ks/(\rho e.g.A.swh) = Vd$ substituting for Ks the value of the holding pull.

When the anchor digs in, the idea that holding pull is maximum dragging pull becomes problematical, because the recorded maximum dragging force depends on the anchor; the bed; the chain length; the dimensions and weight of the chain; the depth of water and the dimensions and weight of the anchor shackle.
The influence of the chain can be regulated by standardising the chain cable during tests, the grade U2 chain cable required in the Rules and a chain length/depth ratio for instance equal to 10. There remains the problem of the scope angle.

The scope angle the chain acts on the head in the bed cannot easily be determined due to the complex relation existing between the depth of penetration of the shank head; the length of cable penetrating the bed; the chainpull; the earth resistance acting on the chain and the scope angle of the chain above the bed near the bed surface.

Therefore the relationship between scope angle at the shank head and the maximum dragging pull cannot be determined easily during full-scale anchor tests. Even when the chain cable is led horizontally over the bed, the scope angle of the chainpull, acting at the shank head will be positive.
At this moment, the matter of the term "holding pull" of embedded anchors looks better when is indicated with "holding pull", the maximum dragging pull; when this dragging pull is measured in a stable position of the anchor, embedded in a specific well-known bed, with a part of the chain following horizontally the bed surface and if the chain dimensions agree with the indicated grade U2 chain cable, in relation to the anchor weight required in the rules. That the anchor is in a stable position can be determined by observing the mound.
When due to elaborate measurements, the scope angle at the shank can be determined, the indication of the maximum, measured dragging pull as "holding pull" related to the value of the scope angle and the type of bed, will be more favourable.

Considering figure 54, it appears the highest holding pull can be expected by anchors where the dragging pull (in relation to the distance the anchor is dragged) increases fastest. The value dKs/dsw gives an indication regarding the holding ability of an anchor. Therefore different anchor models can be compared by viewing this differential after dragging over the distances la and $2.la$.

12. DEPTH OF PENETRATION

For rough calculations, it has been the practice at Felixtowe to assume the depth of penetration to be equal to the perpendicular distance from the shank centre line, to the point of the fluke of a single-fluke anchor or, to the line through the points of the flukes of a twin-fluke anchor [21]. Dragging anchor 4 over a distance of $5.5l$ proved a penetration depth of $hc/l = 1$. The scope angle in this position was about 11^{0}. Therefore a greater depth of penetration can be expected when the anchor cable is led horizontally over the bed surface.

13. CONCLUSIONS

- A change in the direction of the chainpull (due to the earth resistance acting on the chain or rope), has a great influence on the pull when the anchor starts dragging, consequently on the maximum dragging pull.
  Therefore, the relationship between anchor dimensions to the dimensions of the anchor cable, influences the value of the maximum dragging pull, the measured holding pull.

- The main factors determining the holding pull and the holding position of an embedded anchor are: the anchor dimensions, weight and shape; the nature of the bed the anchor is holding in; the direction the chainpull is acting at the shackle end of the shank and therefore the length, weight and dimensions of the anchor chain and the depth of water.

- Following the area and shape of flukes and crown, the shank dimensions and shape determine the holding ability of an anchor.

- The unknown factor fc and angle ϕs can only be determined by means of the results of anchor dragging tests.

earth resistance factor

angle earth resistance on shank.

C H A P T E R 11

THE RELATIONSHIP OF MODEL TESTS TO FULL SCALE TEST RESULTS

1. INTRODUCTION

Testing full scale anchors at sea is difficult and expensive. The question rises does the combination of model testing (to derive the unknown factors), with estimation of the holding pulls (assisted by newly-developed anchor-dragging, simulation programmes) offer a representative and applicable alternative.
It is obvious that the indicated method of testing gives an excellent visual display of the stability of the anchor models, applying to full-scale anchors acting in a non-cohesive and non-adhesive bed.

The factors derived are related to volumetric influences and apply therefore only to non-cohesive and non-adhesive beds. Wether the factors unchanged can be used with a computer programme, introducing adhesion and cohesion is doubtful. Only by difficult and expensive tests of model and full-scale anchors in adhesive and cohesive beds, can such indications be given.
To verify the above-indicated method, some additional computer calculations and simulations were made with newly-developed programmes regarding the model anchor tests and full-scale anchor tests.

2. SIMULATION OF BEHAVIOUR OF TWO FULL-SCALE TESTED ANCHORS

In February 1973 the "DELTA dienst" of "Rijkswaterstaat" tested in the "Westgat" of the Oosterschelde a 1084 kg "Delta" anchor, l 2.65 m, A 1.4 m^2 and a 950 kg "Stevin" anchor, l 1.717 m, A 1.9 m^2.
Both anchors were dragged at a depth of 4,5 m, with a 85 m long Ø 32 mm wire, in a bed of very fine sand, ρe submerged 0.5 kg/dm^3. The internal friction of the bed was about 40°. The friction angle between the bed and the painted anchors can be assumed to be about 27°.

After a drag of 12.0 m the "Delta" anchor attained a dragging pull of 230 kN, and the "Stevin" anchor after a drag of 12.25 m 320 kN, see figure 67.
During the tests the scope angle near the bed surface remained about 4°.

The shape of model anchor 4 is about similar to the "Delta" anchor.
Therefore introducing ρe = 0.5 kg/dm^3, fc = 4.4 and $\phi s = \phi a$ and starting from the model situation developed in chapter 10,the holding pull was calculated relative to hc, α and ϕ. The results are summarized in figure 68.
The actual value of ϕ at the shank end will have been greater than 4°.
Therefore the figure indicates a calculated depth of penetration between 3.3 and 3.5 meters or hc/l between 1.25 and 1.35.

The shape of model anchor 2 looks like a "Stevin" anchor. Therefore introducing fc = 4.4 and ϕs = 8° the holding pull was calculated and indicated in figure 69.
The calculated depth lies between 2.65 and 2.75 meters or hc/l between 1.55 and 1.6.

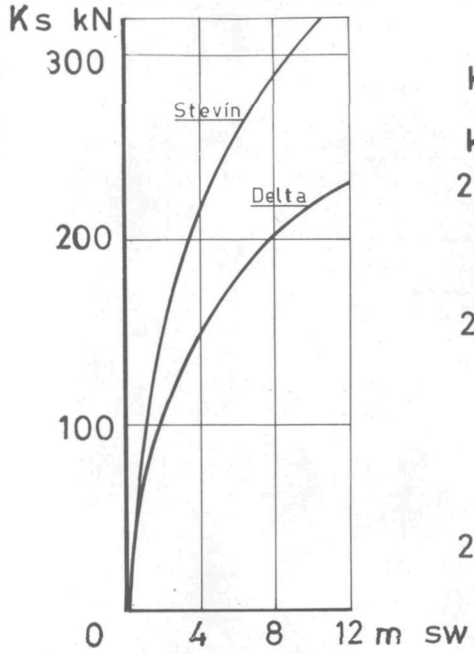


Fig. 67. Full-scale test results of a "DELTA" and a "STEVIN" anchor. The recorded dragging pull dependent on the distance the anchor dragged.

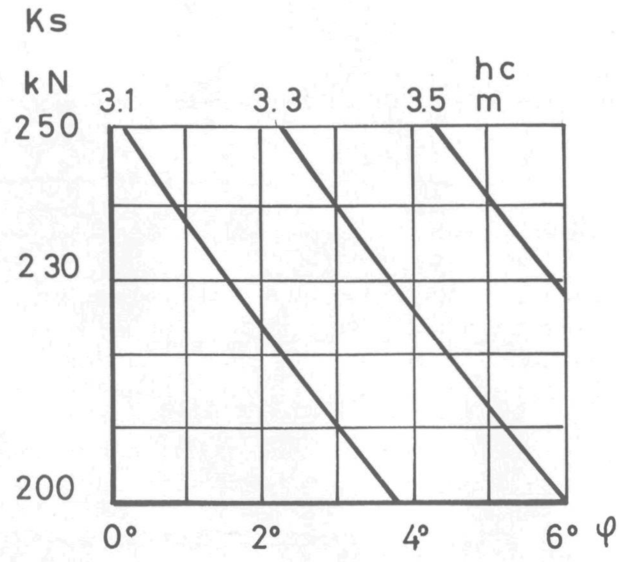


Fig. 68. The calculated holding pull of a "Delta" anchor.

The calculated depths of penetration relate to a soil with an angle of internal friction of 35°. However the internal friction of the bed was about 40° and this difference can not be corrected in the developed model situation.
The influence of this difference can only be determined during full scale anchor tests measuring the holding pull dependent on the position of the anchor to the bed surface.
Due to the greater actual angle of the internal friction we may expect the true depth of penetration will have been less than the values the calculations indicated.

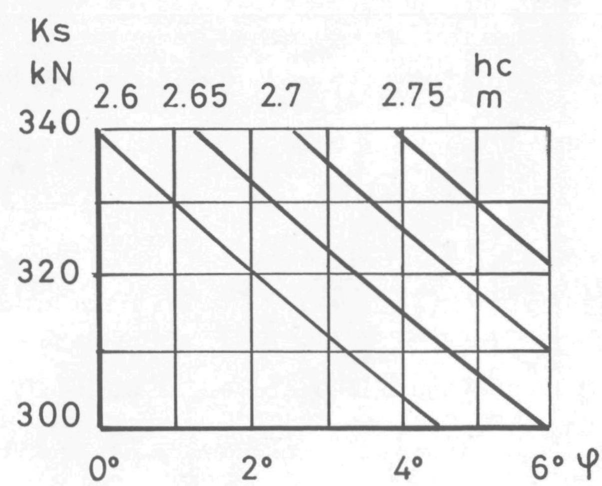


Fig. 69. The calculated holding pull of a "Stevin" anchor.

3. RELATIONSHIP BETWEEN THE MAXIMUM HOLDING PULL DURING MODEL TESTS AND FULL SCALE TESTS

The results of some model tests are indicated in figure 70.

Type	Model weight gram	Model material	l mm	Theoretical weight aluminium anchor models gram	Ks N	V
Delta	160	brass	125	45	10	22.1
	1030	"	265	430	84	19.5
Danforth	980	steel	210	361	40	11.1
	441	aluminium	216	393	44	11.2

Fig. 70. Test results regarding tests with model anchors

In February 1973 during the full-scale test the V value of the "Delta" anchor was 21.2 and of a 900 kg "Danforth" anchor was 14.6.

There is a difference between the V values of the model "Delta" anchors because there were some differences with respect to the extended crown parts of the models.
The model tests with the similar "Danforth" models indicate the influence of the anchor weight and the friction between anchor and bed is small.
The V values of the models are smaller than the values measured during the full-scale tests at the "Westgat".

Therefore it may be expected that the results of model tests,tested as indicated in figure 50 with a diameter of the connection wire to the model of 2 mm will indicate a lower V value than full-scale tests in the "Westgat" with a scope angle of 4^o near the bed surface and a Ø 32 mm towing wire.

4. THE DEPTH OF PENETRATION

The strength of an anchor determines the ultimate holding power and therefore the maximum depth an anchor may be dragged into a bed. Proofloads up to 20 times the anchor weight have to be applied to small anchors but the proof-loads on a 10,000 kg anchor is only ten times its weight.
Mr. Buckle indicates [28] a 30.000 lbs anchor has been dragged with a pull up to sixteen times its weight.

During the tests in the "Westgat" 1000 kg anchors held 23...32 times their weight. Therefore V values about 30 may be expected sometimes with respect to anchors with a weight up to 5000 kg. They will penetrate the bed in the "Westgat" about 1.5 times its shank lengths. This means that heavy loaded 5000 kg anchors, digging in deeply, will reach depth about 5.5 meters in a sand bed.

The penetration depth of larger stocked anchors, commonly used offshore, will be less due to the influence of the stock. The depths new anchor models will penetrate increase continuously due to the increasing holding pull required offshore.

5. CONCLUSIONS

- Starting from the factors determined with model tests,the results of full-scale anchor tests can be analysed.

- A useful correlation between full-scale and model test results may be expected.

- Full-scale and model testing is necessary to determine the influences of different kinds of bed on the holding power of an anchor.

- To realise a further development of anchor holding theory during full-scale tests the scope angles and the positions of an anchor with regard to the bed surface have to be determined in relation to the holding pull.

- Stable stockless anchors can penetrate some beds deeper than the length of their shank.

A C K N O W L E D G E M E N T S

The author is indebted to Prof.Ir.J.Gerritsma for permission to use the facilities of the Shipbuilding Laboratory and gratefully acknowledges the assistance of those members of his staff who have built the tank and anchor models and who provided the measuring equipment.

He also wishes to thank Mr.P.Willis who corrected the english texts and Mrs.M.E.Dalhuijsen - de Boer who typed this thesis carefully.

LIST OF SYMBOLS

A	Sectional area of the head.
Ad	Available dynamic energy at the final position.
Ak	Energy, provided by the horizontal chainpull *Khc*.
Ap	Potential energy absorbed by the shank.
E	Component of the earth resistance acting on the head perpendicular to line *CA*.
Es	Component of the earth resistance acting on the shank perpendicular to line *BA*.
Et	Earth resistance force acting on the head.
Fc	Total of the friction forces, acting at the fluke points in a direction parallel to the hinge axis.
Fc',*Fc"*	Friction forces acting at the fluke points,components of *Fc*.
Fg	Holding force.
Fh	Maximum value of the holding force.
G	Moving portion of thw anchor weight.
Ga	Weight of the anchor.
Gc	Weight of the head.
Gn	Portion of the weight acting at the hinge point.
Gr	Portion of the weight acting at the end of the shank.
Gs	Weight of the shank.
Gp	Static portion of the anchor weight.
I	Moment of inertia of the area of the section of the head about the the intersecting line of the sectional plane and the bed surface.
Is	Moment of inertia of the area of the section of the shank about the the intersecting line of the sectional plane and the bed surface.
Iv	Moment of inertia of the vertical anchor projection about the bed surface.
Ic	Moment of inertia of the sectional plane of the head about its centroid.
K	Constant depending on the holding pull and the fluke area.
Kh	Horizontal component of the chainpull.
Khc	Constant maximum value of the horizontal chainpull.
Khp	Anchor proofload.
Ki	Component of the chainpull parallel to the plane the anchor rests on.
Kp	Component of the chainpull perpendicular to the plane the anchor rests on.
Ks	Chainpull.
Kv	Vertical component of the chainpull.

Lb Resistance acting at the end of the shank in the plane the anchor rests on or plane *Qi* in a direction parallel to the projection of the shank on the plane the anchor rests on or on plane *Qi*.

Lb',Lb" Reaction forces acting at the end of the stock in the plane the anchor rests on or in plane *Qi* in a direction parallel to the projection of the shank on the plane the anchor rests on or on plane *Qi*.

Lc Total reaction of the resistance acting at the points of the flukes in the plane the anchor rests on or in plane *Qi* parallel to the projection of the shank on the plane the anchor rests on or on plane *Qi*.

Lc',Lc" Reaction forces acting at the points of the flukes in the plane the anchor rests on or in plane *Qi* in a direction parallel to the projection of the shank on the plane the anchor rests on or on plane *Qi*.

Ld Reaction force acting at the extremities of the crown in the plane the anchor rests on and in the direction of the projection of the shank.

M Moment of the area of the section of the head about the intersecting line of the sectional plane and the bed surface.

Mbc Moment about a line in the plane the anchor rests on, through the end of the stock and the point of a fluke the anchor rotates about.

Mlf Moment of the vertical anchorhead projection about the bed surface, assuming $\alpha = \beta e$.

Ms Moment of the area of the section of the shank about the intersecting line of the sectional plane and the bed surface.

Mv Moment of the vertical anchor projection about the bed surface.

Nc Holding force in the fluke point, parallel to the bed the anchor rests on and normal to the intersection of the uneven area and the plane the anchor rests on.

P The holding pull.

Pb Reaction force acting at the end of the shank perpendicular to the plane the anchor rests on or to plane *Qi*.

Pb',Pb" Reaction forces acting at the ends of the stock perpendicular to the plane the anchor rests on or to plane *Qi*

Pc Total reaction acting at the fluke points perpendicular to the plane the anchor rests on or to plane *Qi*.

Pc',Pc" Reaction forces acting at the fluke points perpendicular to the plane the anchor rests on or to plane *Qi*.

Pd Reaction force acting at the extremities of the crown perpendicular to the plane the anchor rests on or to plane *Qi*.

Qh Horizontal plane.
Qi Auxiliary plane or inclined plane the anchor rests on.

T Component of the earth resistance force *Et* acting in the direction of line *CA*.
Ts Component of the earth resistance force acting on the shank in the direction of centre line *BA*.

V Ratio of the holding pull divided by the weight of an anchor.
Vs Compression ratio $Ks/(\rho e.g.A.la)$.
Vd Soil disturbing ratio $Ks/(\rho e.g.A.swh)$.

Wc Holdingforce acting at the point of the fluke parallel to the plane the anchor rests on and tangential to the intersection of the uneven area and the plane the anchor rests on.

a Distance of the projection in the symmetrical plane between the flukes of the extremeties of the crown to the hinge point.
*a*1,*a*2, *a*3 and *a* 4. Auxiliary values regarding shank-stocked anchors.
ac Constant regarding adhesion and cohesion in the general formula related to the holding pull of an anchor.
af Constant regarding friction and unit weight in the general formula related to the holding pull of an anchor.
afh Value of *af* related to the maximum holding pull.
ag Constant regarding the weight of an anchor of a series.

bb Distance from point B to the point of application of the earth resistance forces acting at the end of the shank.
bsh Diameter of the curved side of the shank end.

d Diameter of the chain.
dAa Energy available for acceleration
dAp Potential energy absorbed
dAk Energy provided by *Khc*

during the rotation of the anchor over a small angle $d\alpha$.

fc and *fqc* Earth resistance factors regarding force *E*.

fe Constant related to the ratio between the earth resistance forces *Es* and *E*.

fs and *fqs* Earth resistance factors regarding force *Es*.

g Acceleration due to gravity.

hb The distance from the centre of the pinhole *B* to its projection in the bottom plane or in the auxiliary plane *Qi*.

hbd Value of *hb* when the head lifts off the bed and the Swinging movement commences.

hbdt Maximum value of *hbd* and *hbt*.

hbt Value of *hb* at the transition between the Swinging and Tilting movement.

hbm Value of *hb* at the transition between the Whipping and the Tilting movement.

hbx Maximum value of *hb* , reached during the movements.

hc Distance between the points of the flukes to the surface of the bed.

hzc Distance from the point of application of the earth resistance force *E* to the surface of the bed.

hzs Distance from the point of application of the earth resistance force *Es* to the surface of the bed.

hs Height of the top of the mound above the level of the bed.

k Distance of the extremities of the crown to the symmetrical plane through the flukes.

kd Distance from the point of application of the earth resistance forces acting on the extremities of the crown to the symmetrical plane through the flukes.

l Length of the shank.

la The value of the square root of the sectional head area *A* .

ld Distance between the point *B* at the end of the shank and the stock.

p Distance from the points of the flukes to the extended hinge axis.

q Auxiliary value, equal to the length of the shank, minus the length of the projection of the fluke arm and the fluke to the shank.

ra Half the length of a stock, situated near the crown.
rb Half the length of a stock, situated near the end of the shank.
rd Difference between *ra* and *t*, or half the length of a stock.
re Auxiliary value regarding a crown-stocked anchor.
rg The distance between point *C* and the centre of gravity *CG*.
rm Radius of the circular curved arms of a Common anchor.

sw Distance an anchor drags.
swh The distance an anchor drags until the maximum holding pull is attained.
sz Distance from a line through *C* perpendicular to plane *Qi* or to the plane the anchor rests on to point *CG* .
szd Value of *sz* when the head lifts off the bed and the Swinging movement commences.
szm Value of *sz* at the transition between the Whipping and the Tilting movement.
szt Value of *sz* at the transition between the Swinging and the Tilting movement.

t Half of the distance between the points of the flukes.

v1,v2,vo,va,vb,vd and *vk* Auxiliary values regarding crown stocked anchors.

w Horizontal distance from the projection of the pinhole centre in the plane the anchor rests on, or plane *Qi* ,to the projection of the points of the flukes in the vertical symmetrical plane.
wb Value of *w* with the head and the shank resting on the bed.
wd Value of *w* when the head lifts off the bed and the swinging movement commences.
we Value of *w* in the final situation.
wm Value of *w* at the transition between the Whipping and Tilting movement.
wx Value of *w* at the moment *hb* is equal to *hbx* .

z The distance the fluke points penetrate into the bed.
zc Distance from the point of application of the earthresistance force *E* to point *C* .
zca Distance from the centroid of the sectional area of the head to the fluke points.
zs Distance from the point of application of the earth resistance force *Es* acting on the shank to point *B* .
zsa Distance from the centroid of the sectional area of the shank to point *B*.

α	Inclination angle of the flukes.
αb	Value of α when head and shank rest on the bed.
αe	Value of α in the final situation.
αf	Auxiliary angle between the bed and the centre line of a fluke perpendicular to the stock, measured in a plane through the centre line perpendicular to the stock.
αg	Angle between the centreline of the flukes and the line between the centre of gravity *CG* and point *C* .
αt	Value of α at the transition between the Swinging and the Tilting movement.
αx	Value of α when *hb* is maximum during the Swinging movement.

β	Fluke angle.
βb	Value of β when the head and the shank rest on the bed.
βd	Value of β when the head lifts off the bed and the Swinging movement commences.
βe	Maximum value of the fluke angle.

γ	The yaw angle, angle between the projection of the shank to plane *Qi* and the intersecting line of plane*Qi* or a horizontal plane.
γb	The angle between a horizontal line of the plane the anchor rests on and the line through the holding fluke point and the stock end where the anchor rests on.
γc	Angle between the projection of the shank, to the plane the anchor rests on and the line between the end of the shank and the point of the holding fluke.
γd	Angle between the projection of the shank, to the plane the anchor rests on and the line between the end of the shank and the end of the stock that rests on the bed.
γh	Angle between the projection of the shank to the plane the anchor rests on and the intersection of a horizontal plane with the same plane.
γi	Auxiliary angle regarding the direction of the chainpull and the plane through the holding fluke point and the stock in the Tilted holding position.
γn	Angle between the projection of the shank, to the plane the anchor rests on and the line through the holding fluke point, parallel to the bed and normal to the intersection of the uneven area and the plane the anchor rests on.
γo	Angle between the direction of the chainpull component, parallel to the plane the anchor rests on and the projection of the shank to this plane.
γq	Angle between the projection of the shank, to the plane the anchor rests on and the line through the holding fluke point and the resting end of the stock.

δ	The roll angle, the angle between the auxiliary plane *Qi* and a horizontal plane.
δf	Angle between the plane the anchor rests on and the centre line of a fluke, perpendicular to the stock and measured in a plane through the centre line perpendicular to the stock.

ε	Inclination angle of the shank to the bed.
εo	Auxiliary angle between a line thro-gh the fluke point and the end of the stock the anchor rests on and the plane through the shank perpendicular to the same plane.
εs	$\varepsilon s=\beta e-\alpha$
λ	Weight distribution factor related to the moving weight portion.
λp	Factor related to the point of application of the weight of the head.
λs	Factor related to the point of application of the weight of the shank.
ρ	Coefficient of friction between anchor and bed.
ρb	Coefficient of friction between the end of the shank,or the stock, situated at the end of the shank, and the bed.
ρc	Coefficient of friction between the points of the flukes and the bed.
ρd	Coefficient of friction between the extremities of the crown and the bed.
ρe	Unit mass of the bed material.
ρs	Coefficient related to the earth resistance acting on the shank and equal to the ratio Ts/Es.
ψ	Inclination angle of the stock to the bed, measured in a plane through the stock and perpendicular to the shank.
ψt	Particular value of ψ at the transition from the arm rolling movement of a "Common " anchor with circular curved arms.
ω	Auxiliary angle regarding the point of a "Common" anchor, with circular curved arms, where the arm rests on the bed.
ωe	Particular value of ω when the arm rests with a point adjacent to the point of the fluke on the bed.
ϕ	Angle the holding force Ks makes with a horizontal plane.
ϕa	Auxiliary angle related to ϕs .
ϕs	Angle related to the earth resistance acting on the shank.
ϕb	Angle of internal friction of the bed material.

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SAMENVATTING

In dit proefschrift wordt ingegaan op het gedrag van ankers waarbij rekening wordt gehouden met de bodemomstandigheden.Hierbij kunnen afhankelijk van de aard van de bodem, de stand van het bodemoppervlak en de bewegingen van het anker een aantal gevallen onderscheiden worden.

Wanneer een anker houvast vindt op een ondoordringbare bodem kan het gedrag aan de hand van theoretische beschouwingen bepaald worden. Wanneer een anker geheel of gedeeltelijk in de bodem dringt kan het gedrag verklaard of voorspeld worden door de resultaten van theoretische beschouwingen te vergelijken met de resultaten van sleepproeven met ankers en modelankers.

- Houvast vindend op een horizontale ondoordringbare bodem blijken ankers enkele bewegingen te kunnen maken welke het verliezen van houvast kunnen inleiden.
- Bij een zijdelings hellende stand van een stokloosanker rustend op een hellende ondoordringbare bodem neemt de zijdelingse stabiliteit evenredig toe met de afstand tussen de punten. Maar wanneer slechts één punt houvast vindt neemt daarbij eveneens evenredig de kans op zijdelings wegglijden toe. De stabilizerende invloed van een stok aangebracht aan het kettingeinde van de schacht blijkt gering te zijn.
- Klassieke stokankers blijken in onbelaste toestand meestal met de handen omhoog gericht op een horizontale bodem te rusten. Slechts nadat het schip het anker omgetrokken heeft kan één hand in de bodem dringen. Daarentegen nemen de oude houten Romeinse lodenstokankers onder water van zelf in onbelaste toestand een stand aan waarbij één hand, schuin naar beneden gericht, op de bodem rust.
- Wanneer een anker houvast vindt in een zachte bodem dient onderscheid gemaakt te worden tussen bewegingen waarbij de handen slechts gedeeltelijk in de bodem dringen en bewegingen waarbij de handen en ook de kroon en de schacht ingegraven raken. Welke bewegingstoestanden optreden hangt af van het type anker en van de bodemgesteldheid.

Wanneer de handen gedeeltelijk in de bodem dringen kunnen zeven onderling verschillende bewegingen optreden. Gedurende slechts twee van deze bewegingen kunnen aan de hand van de resultaten van sleep-

proeven de bodem weerstandskrachten bepaald worden.
Wanneer een anker zich geheel ingraaft kan slechts de grootte en richting van één ,op het gehele anker werkende, weerstandskracht bepaald worden. Door enkele aanvullende vooronderstellingen aan te nemen wordt het echter mogelijk indicatieve weerstandswaarden betreffende de schacht en de ankerkop te berekenen. Om deze waarden nader te bepalen en om de invloed van de vorm van een ingravend anker op de bodemweerstand te onderzoeken zijn een aantal sleepproeven met modelankers genomen. Daartoe werden uit aluminium vervaardigde modelankers gesleept in een uit polyvinylchloride korrels bestaand bed. Aan de hand van een aantal inleidende proefnemingen werd de bruikbaarheid van de proefopstelling ten aanzien van de afmetingen van de tank en de nauwkeurigheid van de meetresultaten gecontroleerd. Vervolgens werden acht modelankers beproefd ter bepaling van de invloed van enkele uitvoeringsvormen van de ankerhanden en de onderzijde van de schacht.
Aan de hand van de beproevingsresultaten kon vastgesteld worden dat onderscheid tussen ingravende en zeer diep ingravende ankertypen gemaakt dient te worden. De door "Leahy" and "Farrin" gevonden formule blijkt toegepast te kunnen worden ter vergelijking van de houdkrachten van ankertypen welke tijdens het slepen niet al te diep in een"ideale"bodem ingraven. De door "Herreshoff" en "de Parsons" geformuleerde "Approximate Law" betreffende de verhouding van de houdkrachten van verschillende ankertypen geldt slechts voor ankers die tijdens het slepen in een "ideale" bodem zeer diep ingegraven raken.
Door de door "Leahy"en "Farrin" en door"Herreshoff" en "de Parsons" aangegeven modelsituatie aan te vullen wordt het mogelijk de houdkracht van een anker afhankelijk van de stand van het anker in de bodem en van twee indicatieve factoren te bepalen.
Gelijkvormige ankers blijken gelijkvormige bewegingspatronen te doorlopen bij het ingraven in een "ideale" bodem. Daarbij is de verhouding tussen de houdkracht en het ankergewicht gelijk voor alle ankers behorend tot een gelijkvormige serie voor elke afzonderlijke tussenstand en daarmede ook gelijk voor de stand waarbij de maximale waarde van de houdkracht optreedt. Daarentegen blijkt het gedrag van gelijkvormige ankers welke in een cohesieve en adhesieve bodem ingraven onderling te verschillen.

Naast de weerstandskrachten welke de bodem direct op een ingravend anker uitoefent blijkt ook de bodemweerstand van de ankerdraad indirect het krachtenspel op het anker en daardoor ook de waarde van de maximaal optredende houdkracht te beinvloeden.
Gebruik makend van de met de modelproeven gevonden factoren betreffende de vormgeving van de ankerhanden en de schacht konden de resultaten van door "Rijkswaterstaat" uitgevoerde sleepproeven geanalyseerd worden.
Daarnaast blijkt de mogelijkheid aanwezig te zijn het gedrag van een anker tijdens sleepproeven in een "ideale" bodem aan de hand van de resultaten van modelproeven globaal te voorspellen.

CURRICULUM VITAE

THE AUTHOR OF THIS THESIS WAS BORN IN 1930, IN UTRECHT, HOLLAND. IN JANUARI 1954 HE PASSED THE MECHANICAL ENGINEER'S EXAMINATIONS OF THE DELFT UNIVERSITY OF TECHNOLOGY "CUM LAUDE".
LATER HE FOLLOWED AN INDUSTRIAL CAREER IN THE FIELD OF DESIGN AND COST-ESTIMTING OF HARBOUR AND DECKCRANES, DECKMACHINERY, GEARING, OFF-SHORE GIANT CRANES, VESSELS AND EQUIPMENT. IN 1970 HE WAS APPOINTED SENIOR SCIENTIFIC STAFF MEMBER OF THE DEPARTMENT OF NAVAL ARCHITECTURE AT THE DELFT UNIVERSITY OF TECHNOLOGY.

STELLINGEN

I

De oude Romeinse stokankers werden met een loden stok uitgerust om op de zee- of rivierbodem het anker uit zich zelf een goede stand voor het vinden van houvast te laten aannemen.

II

De handen van stokankers dienen puntvormig te zijn en dienen de houdkracht door elke punt afzonderlijk te kunnen opnemen.

III

Na zijdelings omgekanteld te zijn dient een stokloosanker met scharnierende armen en handen door te rollen naar een stand waarbij de kroon en de beide ankerpunten op de bodem komen te rusten.

IV

Naarmate een anker zich dieper ingraaft neemt de invloed van de op de ankerdraad of -ketting werkende bodemweerstand op de maximaal optredende houdkracht toe. De opgenomen houdkracht zal het grootst zijn wanneer een anker aan een ankerdraad in plaats van aan een ankerketting bevestigd wordt.

V

De verticale kracht nodig voor het uitbreken van een ingegraven anker is nagenoeg rechtevenredig met de maximale waarde van de door dat anker opgenomen houdkracht.

VI

Door de punten en zijden van de ankerhanden en de onderzijde van van de schacht af te schuinen vergroot men de stabiliteit en de maximale waarde van de houdkracht van een ingravend anker.

VII

Tijdens ankerproeven dient men de bewegingen van een anker ten opzichte van het bodemoppervlak te volgen en vast te leggen.

K.J.Saurwalt
Delft, 12 juni 1975

VIII

Aan de hand van resultaten van proeven met schaalmodellen en van simulatieberekeningen kan het gedrag van een anker ingravend in een "ideale bodem" geanalyseerd en voorspeld worden.

IX

Het is onmogelijk de goede eigenschappen van de vele reeds bekende ankertypen in één nieuw type te verenigen. Daarom dient een schip zonodig met ankers van een verschillend type te worden uitgerust.

X

Het tempo van de toename van de gemiddelde grootte van alle op de wereld in aanbouw zijnde schepen neemt sedert het begin van het jaar 1973 af.

XI

De toename van de produktiecapaciteit van de wereld-scheepsnieuwbouw komt voornamelijk tot stand door een evenredige vergroting van het aantal producerende eenheden.

XII

Een ondernemer dient er voor te waken dat planningsgegevens niet gebruikt worden voor het verbergen van eigen falen achter de tekortkomingen van derden.

XIII

Verkoopactiviteiten en het voeren van acquisitie dienen niet tot de hoofdtaken van werfdirecteuren gerekend te worden.

XIV

Door naast de gangbare notatie ook met verschillende kleurindicaties rond de tonen toonsverhogingen en -verlagingen aan te geven vergemakkelijkt men het lezen van muziekschrift.

XV

Zelfs zes ankers vermogen niets wanneer de HERE het schip niet beschermt.