4. Determination of a Lift

4.1. Historical Review

Appendices A through I disclose the diversity of lift requirements in the salvage operations of the last fifty years.

4.1.1. F-4 (1915)

As reported in Appendix A, this lift was 260 dead-weight tons. The hull was fully flooded as shown in the figure preceding the Appendices.

4.1.2. S-5 (1920)

S-5 surface displacement was 875 tons. Since the lift was unsuccessful, the amount of buoyancy remaining, upon completion of the rescue operation, was never determined. Appendix B gives more details on the salvage of S-5.

4.1.3. S-51 (1925)

This completely flooded hull was an 800-ton lift and since the hull had sunk 5 feet deep in clay (Appendix C), a 25 percent margin was added for breakout. It was anticipated that 350 tons of lift would be obtained by blowing tanks and compartments, and the balance of lift would be provided by eight 80-ton pontoons. Nine and one-half months later, many new lifting schemes had been devised. Hard work in sealing compartments and tanks resulted in gaining more than 350 tons; however, it was still necessary to provide eight 80-ton pontoons and two 60-ton pontoons.

The major factor in the decision to increase the pontoon lift force available was the uncertainty as to the movement of the center of gravity of the submarine and its contents as it assumed various angles during the lift.

4.1.4. S-4 (1927)

Salvage of S-4 (described in Appendix D) was accomplished satisfactorily after correct calculation of lift requirements. Divers entering the compartments verified that they were completely flooded. Hence, the weight to be lifted and its center of gravity were accurately known. Six 80-ton pontoons were successfully used to augment self-lift, and good control was maintained (see Appendix D). Experience gained in the successful lift of S-51 was put to good use.

4.1.5. USS SQUALUS (1939)

LCDR F.A. Tusler's report, a source of material for Appendix E, shows that the control requirements were initially underestimated. The submarine's weight and its center of gravity at the completion of the rescue operation were assumed to be fairly accurate based upon reports from the survivors. First calculations showed the need for seven pontoons: five 80-ton pontoons at the stern and two 80-ton pontoons at the bow with all main ballast tanks and fuel oil tanks blown empty with a very small margin. The first attempt to lift was made on 13 July 1939, and, as results proved, there were too few control pontoons (see Paragraph 5.2.3.). Again, valuable experience was gained, i.e., an adequate margin of control lift must be allowed for unknown conditions. Since the lift on 13 July fully illustrates the need for an adequate margin of lift control, a detailed discussion follows.

The external lift on 13 July used all of the lift which was available. Providing a greater margin of control would have required a delay in the operation until additional lifting wire could be manufactured. Calculations of the moments of the weight to be lifted and of the lifting forces indicated that one control pontoon at the bow would be sufficient. The loss of buoyancy when the pontoon reached the surface would slightly more than compensate for the gain in buoyancy of the main ballast tanks, i.e., the tanks would gain in buoyancy as the depth decreased and the ship leveled off. The calculations were accomplished using the following assumptions:

1. The stern was to be lifted first, and

2. The bow was assumed to leave the bottom at the instant the forwardmost ballast tank was blown to the level at which the air in the tank would expel the remaining water; the water was expelled by expanding air to the volume of the tank as the submarine rose to ride on the control pontoon. This was the most unfavorable condition, since it created the greatest excess buoyancy as the submarine was lifted.

Even though the predicted momentum of the ship might cause it to rise above the desired level, it was expected that partial reflooding of the main ballast tanks, as the ship took an up angle, would cause her to settle back in the forward slings with the forward control pontoon supporting some of the submarine's weight.

When the lift was made, the stern lifted as planned. The forward main ballast tanks were blown and the bow lifted, but failed to stop, until it penetrated the surface.

The submarine assumed an "up angle" of some 45 to 50 degrees throwing the major portion of the lift upon the after slings, parting one of them. The bow sling slipped loose and SQUALUS settled back to the bottom stern first. (See Figure E-1 in Appendix E.)

Later analysis of this first lift attempt revealed that the initial assumption of the location of the submarine's center of gravity was in error. Though correct at the time of the rescue operations, it did not represent the facts at the time of the first lift.

After salvage had been accomplished, it was discovered that a 1/4-inch gage line from No. 3 ballast tank had been burned through during the discharge of the after electrical storage battery. This was caused by a short circuit due to the water. As a result, air leaked from the tank into the flooded compartments and water was blown from these compartments through the induction line after the stern had been lifted and while the ship had a large down angle. The air bubble in these interconnected compartments became fairly large and traveled to the after torpedo room. Then, as the bow lifted, the bubble migrated forward which generated unforeseen excess buoyancy forward. This incident illustrates how a minor item of missing information on the condition of the ship can significantly affect the success of the salvage operation.

A successful lift from 240 feet was made on 12 August, 1939, using ten pontoons: three lift pontoons (Paragraph 5.2.3.), three control pontoons at the stern, and one lift pontoon with three control pontoons at the bow. A lift from 160 feet was also successful on 17 August using one less lift pontoon at the stern. During the last lift from a depth of 92 feet, a list resulted from static instability, causing air to spill from the main ballast tanks. As a result, SQUALUS, having already reached the surface, sank back to the bottom. A second attempt on the same day was successful, after the blowing sequence was modified to ensure that the bow pontoons would continue to be loaded, and provide static stability for the ship after they reached the surface.

4.1.6. THETIS (1939)

This salvage operation was conducted utilizing a merchant ship which had been specifically modified for the lifting phase. The operation took place in an area where the scope of tide was in excess of 20 feet. Utilizing the lift ship and tides, THETIS was lifted in four stages as the tide flooded and was grounded at high tide to prepare for the next lift.

the total deadweight of THETIS was about 1000 tons. (Appendix F describes the lift methods used.)

4.1.7. TRUCULENT (1950)

This salvage operation was conducted utilizing two large lift ships each having 600 tons lift capacity. The deadweight lift requirement was reduced from 950 tons to 800 tons by blowing dry the main ballast tanks. (Appendix G describes this salvage operation.)

4.1.8. German Submarine, HAI (1966)

On 15 September 1966, the German submarine HAI sank in the North Sea in 145 feet of water. Within a few days the hull was raised by MAGNUS III, a new sea-going crane possessing improved sea-keeping qualities. The salvage operation was hampered by 7-foot waves on the first day, but a 57-foot lift and a 130-mile tow to Helgoland at a speed of two knots was completed by 21 September. The lift requirement was estimated to be 210 tons. This compares to HAI's surface displacement of 250 tons.

4.2. Determining Deadweight and Center of Gravity

The first step in making a salvage plan is to determine the weight to be lifted as well as its center of gravity. When operating at sea, a submarine is kept in diving trim, that is, near neutral buoyancy when the main ballast tanks are flooded. Therefore, the weight to be lifted is:

1. The weight of the water that has entered the main compartments.
2. The water and oil tanks that are vented to the main compartment, or whose boundaries are not able to withstand the pressure in the adjacent compartments.

4.2.1. Computing the Lift Requirements

The lift requirements consist of these weights plus sufficient lift to initially break the submarine free from any bottom mud suction (breakout force) to which it may be subjected. An additional lift capability must be provided to control the submarine's attitude after it has broken free of the bottom, and to allow for the uncertainties that surround the submarine's actual state of flooding at the time of lift. (See Paragraph 4.1.5. SQUALUS.)

4.2.2. Gathering of Pertinent Data

The survivors of the crew may be able to furnish information concerning the amount of flooding and the status of bulkheads and external closures. The crews of S-5 and SQUALUS were able to give the Salvage Officer much of the required information. However, if such firsthand information cannot be obtained concerning the extent of flooded compartments, the compartment air salvage fittings may be used as described in the following paragraphs.

4.2.3. Use of Air Salvage Fittings

All U.S. submarines are provided with two air salvage fittings in each compartment: one leading to a point high in the compartment; the other to a low point. The high air salvage line is suitable for:

1. Supplying water and liquid food to entrapped personnel.
2. For supplying or exhausting air from the compartment.

The low salvage line may be used for supplying air or removing water from the compartment by pumping or blowing. A strainer protects this line against blockage by debris.

A hose from the salvage ship to the high salvage fitting on the submarine can reveal the extent of water in a compartment and the condition of the bulkhead closures. For example, by blowing air for a short time through the hose to clear it of water, and then securing the air, the pressure at the terminal of the salvage connection inside the ship may be determined via the manifold pressure gage. The first indication that the compartment is open to the sea is when the pressure in the compartment is the same as sea pressure at that depth. This may be further checked by attempting to vent down the compartment. If the pressure cannot be changed materially, then the compartment is certainly open to the sea. Accurate pressure readings in this manner must be through a hose that has had all water blown from it.

To determine whether or not the bulkheads are tight, compare the pressure in various watertight compartments and attempt to change the pressure in one compartment at a time. If they are not tight, rates of pressure change may give some clue as to whether there are large openings or only small leaks.

When changing the pressure in compartments, keep the pressure down to about 2/3 of the bulkhead design pressure, since these bulkheads are designed to permit a considerable amount of permanent distortion before failure. Connecting a differential pressure gage across the high and low salvage lines at the salvage manifold (Figure 4-1) and blowing the hoses clear of water will usually determine the height of the water above the end of the low salvage connection.
It should be noted that this method is applicable only at depths shallow enough to permit the hose to be subjected to the external pressure differential of water at depth, and one atmosphere inside the hose without collapsing.
It is also possible to determine whether or not the compartment is open to the sea. An accurate reading of the water level may be obtained by knowing:

1. The height and longitudinal and transverse positions of the low salvage connection.
2. The attitude of the ship.
3. The pressure differential.

The position of the salvage connection can be determined from the building or planning yard, or from a sister ship built at the same yard. The attitude of the ship can be determined by sending down open-ended air hoses to known points on the ship, blowing them clear of water, and observing the differential pressure. If possible, the differential pressure gage should be one with a full-scale reading of about 25 psi.

The volume of air as well as the amount of compartment water which is not open to the sea can be calculated with somewhat less accuracy by admitting air to the compartment from an air bank of known volume. This can be accomplished by using a hose attached to the high salvage connection and observing the pressures in the compartment and air bank before and after transferring the air. By delaying the second pressure observations for several hours until the air bank and compartment temperatures have returned to the ambient temperature, the accuracy of the observation will be improved. If several compartments are connected to each other, only the total volume of water in all the interconnected compartments can be determined using the above method.

It should be noted that internal pressure cannot be contained since hull closures such as hatches and air induction and exhaust valves are not able to maintain an internal pressure in excess of sea pressure in the submarine.

D_1 = WATER DEPTH OF HIGH SALVAGE DECK CONNECTION

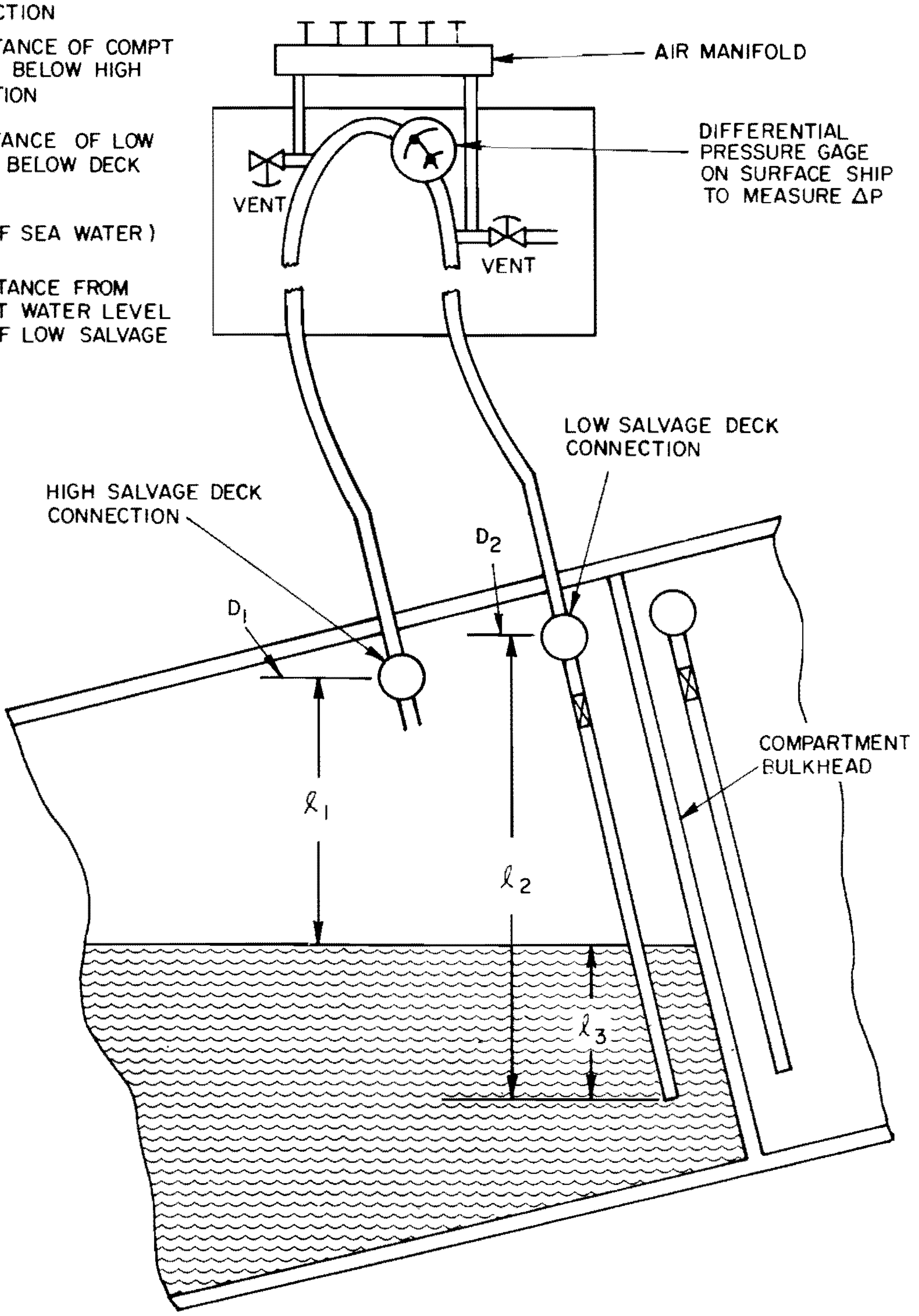
D_2 = WATER DEPTH OF LOW SALVAGE DEPTH CONNECTION

ℓ_1 = VERTICAL DISTANCE OF COMPT WATER LEVEL BELOW HIGH DECK CONNECTION

ℓ_2 = VERTICAL DISTANCE OF LOW PIPE BOTTOM BELOW DECK CONNECTION

$\Delta P = \ell_3$ (IN FEET OF SEA WATER)

ℓ_3 = VERTICAL DISTANCE FROM COMPARTMENT WATER LEVEL TO BOTTOM OF LOW SALVAGE PIPE



DETERMINATION OF COMPARTMENT CONDITION AND EXTENT OF FLOODING.

FIGURE 4-1

However, by building up the internal pressure to somewhat below that of sea pressure at the depth of the compartment, the water can be pumped out through the low salvage connection by means of a pump on the salvage vessel.

4.3. Types of Lift

The types of lift available from which the Salvage Officer can develop his plan include:

1. Surface Lift (see Chapter 7)
   a. Lift ship (ARS, ATS)
   b. Non-self-propelled barges (YMLC)
   c. Floating cranes
2. Pontoons
   a. Rigid (see Chapter 5)
      (1) Lift
      (2) Control
   b. Collapsible (see Chapter 7)
3. Self-Lift (see Chapter 6)
   a. Main ballast tanks
   b. Fuel tanks (on diesel-driven submarines)
   c. Reduction of level of water in main compartments
   d. Variable ballast tanks

The advantages and limitations of the three types of surface lift are discussed in Chapter 7. Chapter 5 describes the operation of rigid pontoons. Experience gained in the Chesapeake Bay salvage of U-1105, as reported in Reference 6, reveals a degree of unreliability in the collapsible pontoons of the late 1940's and 1950's. These rubber fabric pontoons appear to have been vulnerable to punctures and to seams bursting when used in the vicinity of heavy salvage equipment and wrecks.

4.4. Developing the Lift Plan

As previously mentioned, an operational submarine is normally kept in diving trim, and as a result, is in neutral buoyancy when the main ballast tanks are flooded. Therefore, the weight to be lifted is the weight of all the water that has entered the main compartments, and those water and oil tanks whose interior boundaries are not able to withstand the pressure in adjacent compartments.

To these weights must be added the forces required to break the submarine free of the suction effect of the bottom with a margin suitable for the existing conditions.

The steps leading to a firm lift plan are:

1. Determine, as accurately as possible, the water level in each compartment. Consider means of securing dry compartments against slow flooding, such as mechanically clamping openings or reducing the pressure differential by pressurizing compartments with compressed air. If this latter method is used, the Salvage Officer must ensure that the differential pressure across watertight bulkheads does not exceed 2/3 of the bulkhead design pressure. He must also be aware of the possibility of loosing a major closure device since submarine closures seat with sea pressure. Air pressure, coupled with a sudden change in submarine depth, will produce a differential pressure opposite to that for which closures are designed.

2. Calculate the weight and center of gravity of the water in each compartment.

3. Estimate breakout force and its center of gravity. Consider this as a weight to be lifted.

4. Establish margins and their centers of gravity for steps 2 and 3. These margins, when added to the weights and breakout force, will give the largest lift that can reasonably be expected. The amount of the margins depends on:

   a. The Salvage Officer's level of confidence in the data which formed the basis of the calculations.

   b. His knowledge of the bottom conditions.

5. Decide which end will be lifted first and the height of the lift. This decision may be affected by the slope of the keel in way of the slings, or by the ease of guarding against slippage of the slings in one or the other direction. If any free surface is present in the ship or its tanks, it must be compensated for by the lift control devices used.

6. Decide the probable position of the bottom reaction point at the end to be lifted last.

7. Calculate moments of weights and breakout force (allowing for uncertainties which exist) about this bottom reaction point.

The sum of these weights and moments must be within the lift capability of the lift system.

8. Estimate the weight of water that can be removed from each ballast tank, its center of gravity, and its moment about the bottom reaction point.

9. Subtract these tank and compartment buoyancies, and their moments from the total weight to be lifted and its moment. The result is the smallest amount of external lift that must be provided and its moment.

10. Decide on possible methods of attaching increments of external lift, points of attachment, and the maximum amount of lift that can be applied to each attachment.

11. Using the method of trial and error, assign lifting forces to the attachment points and calculate their moments about the pivot point. Add the increments of external lift and their moments, starting at the end to be lifted first, until the lifting moments are greater than the moment obtained in step 9. When this amount of lift force is applied, the first end should rise. The lift system at this time will be supporting the raised end of the submarine and will be less than the maximum lift force prior to breakout by at least the amount of breakout force which was required.

12. Assuming that the first end has been raised the desired distance by the action of step 11, recalculate the weights and centers of gravity of the water in the compartments and tanks about the bottom reaction point. Summarize the weights and moments without any breakout force.

<u>CAUTION</u>: It is not possible to ascertain exactly how much applied moment is needed to break out and lift the end to be raised first. It is therefore wise to assume that the tank, or compartment supplying the largest increment of buoyancy, has been blown down to that point at which the air in the tank is sufficient to expel all remaining water by expansion as the submarine is lifted. As previously noted, this will define the maximum amount of compensation for excess buoyancy. To ensure that no greater excess buoyancy is created, dewater tanks and compartments one at a time.

13. Establish lift control requirements. Compensation for excess buoyancy is accomplished by reducing the lifting force. If the lift control mechanism is by means of pontoons, the reduction in lift force is achieved by providing an adequate number of control pontoons.

When these reach the surface, their buoyancy will be reduced by the amount needed to establish equilibrium. A considerable lift force should still be required of the control pontoons even after the first end reaches equilibrium. If the lift force requirement for the control pontoons approaches zero, the ship will probably continue to rise out of control.

14. Next, consider the end remaining on the bottom. Using the weights obtained in step 12, calculate the moments of those weights about the point at which the surface control pontoons are attached to the submarine.

15. Apply increments of buoyancy in succession, starting from the lower end, until the lifting force moment is equal to the weight moment, plus any allowance for uncertainty. By this time, the lower end should rise.

16. Assuming that the end to be raised last has reached the desired depth, recalculate the weights and moment of the water in the ship and in the tanks. As in step 12, assume that the lower end of the submarine left the bottom at the most unfavorable time and that excess buoyancy will be created as the ship rises. The lift force must be decreased with control pontoons as in step 13. At this time, the applied lift will equal the negative buoyancy of the submarine. When either end of the submarine is raised, the control pontoons at that end must always be required to provide some finite lift force after equilibrium is established. If the lift force requirements for the control pontoons diminish to zero, attitude control of the submarine will be lost as in the 13 July 1939 lift of SQUALUS. (See Appendix E.)

If lift ships are available, they must be used for controlling the lift of each end. In such a case, the lifting takes place more slowly and the lift applied by the surface lift ships must be such that a condition of equilibrium exists at all times, especially at the time of breakout when there may be a sudden and large reduction in the amount of lift required.

Satisfactory solutions in the foregoing steps constitute the preliminary lift plan. In this discussion, it has been assumed that the ship will be lifted by an amount less than the depth of the water, as the control is more critical in this case.

4.5. Self-Lift vs. External Lift

In deciding between self-lift and external lift, the Salvage Officer is guided by the size and number of external lifting devices available, the amount of work and time required to attach them, and the amount of work and time required to create self-lift. Generally, large amounts of self-lift can be created by dewatering the main ballast tanks and they are often easily obtained.

Often the submarine will be deficient in transverse static stability. This may not be apparent before the submarine arrives at the surface because an external lift applied by an increment of buoyancy, which is attached to the submarine above its center of gravity, will improve static stability. On 13 September 1939, SQUALUS was raised to the surface on two occasions. During the first lift, the second (bow) end to be raised arrived at the surface, and the expansion of air and free surface effects made the bow so light that no lift was required from the bow pontoons.

The ship, even with the stern pontoons at the surface, was unstable and heeled over sufficiently to spill air from the main ballast tanks and allow them to reflood until the stern sank. The bow was then lowered to the bottom by venting the ballast tanks. The submarine was rolled upright by partially blowing the ballast tanks on the low side and was raised again, this time successfully with no heeling.

No change was made in the SQUALUS lift scheme for this last lift except to alter the sequence in which the tanks were blown. This time the tanks were blown in a sequence such that the bow would leave the bottom when one tank was almost completely empty and the buoyancy gained during the ascent would be minimized. The bow pontoons were thus fairly well loaded after they reached the surface, and in this condition, would contribute to the static stability of the ship by an amount which made the ship remain upright after she reached the surface.

This instance also illustrates the fact that whenever an entire submarine, or even just one end, is lifted from the bottom, knowledge of the lifting forces and moments greatly improves the knowledge of the weight and center of gravity of the water in the ship. The submarine can be effectively weighed by observing the draft of pontoons on the surface and calculating their actual lift at the time.

Since a submarine on the bottom has no waterplane, the longitudinal $\overline{GM}$ cannot be greater than the vertical distance between the center of gravity and the center of buoyancy.

This figure is reduced by the effect of any free surface in the compartments or tanks; thus, the longitudinal $\overline{GM}$ may safely be considered either insignificant or negative. The attitude of the ship is therefore controlled by the balance between the lifting forces and the weight of the ship and their moments. As the ship is being raised, expansion of the entrapped air bubble in compartments open to the sea may blow water from the compartments and cause a reduction in the weight to be lifted. The moment of the reduction will depend on the depth of the water and on the distance the ship is lifted.

If a free surface exists in any tank or compartment, there will be a change in the center of gravity of the water in way of the free surface. This change will depend not on the depth, but on the angle through which the ship rotates and the length of the space possessing the free surface. It may be large if bulkhead doors are open and the free surface extends over more than one compartment.

In this chapter, the effect of the expansion of an entrapped air bubble and the effect of a free surface were estimated in steps 12 and 16 of section 4.4. The calculation of weights and moments made in those steps must take into account the changes in weights and moments which have been discussed in this section.

4.6. Calculating the Flooded Weight

In calculating the weight of water in any compartment, it is necessary to apply a permeability factor to the gross volume of the compartment. This factor will differ for each compartment of each class of submarine. The floodable volume of each compartment may be obtained from the shipyard that prepared the working plans of the ship.

For a survey of the situation, and to arrive at a tentative plan of salvage, permeability factors of 0.85 for machinery spaces and 0.92 for living spaces are sufficiently accurate, but for a final salvage plan, the actual factors should be obtained and used.

4.7. Bottom Breakout Force

The deadweight of the submarine must be overcome with lifting forces - buoyant or mechanical - to lift the sunken submarine from the bottom; often, additional force is required to break the bottom mud suction. Salvors have encountered bottom suction forces in operations of years past; some insight into this force can be obtained by review of available reports.

The available literature does not address itself to the specific problem of freeing objects from the ocean bottom; mention of the problem is, however, made, but no numerical evaluation of the force is indicated. Following is a brief review of several salvage operations with apparent bottom suction (breakout) considerations:

SÖDRA SVERIGE

The SÖDRA SVERIGE, a cargo-passenger steamship with an 800-ton displacement, sank in the Baltic Sea in 1895 in a depth of 185 feet. The ship came to rest at a sharp angle from the vertical and during the course of a year sank about 10 feet into the clay bottom. Calculations indicated that the ship had a submerged weight of 600 tons and that a force of 960 tons would be sufficient to break it loose from the bottom. Sixteen wooden pontoons, each having a lifting force of 60 tons, were attached to the ship and pumped out. This was sufficient to righten the ship and raise it off the bottom.

LIBERTÉ

The French battleship LIBERTÉ, with an 8,000-ton displacement, sank in the harbor at Toulon in 1911. The salvage effort extended over a period of 14 years. During the long period of submergence, the wreck settled into the mud and Crapaud (1925) reports that "a considerable part of the task of the salvors consisted in breaking this contact and freeing the hulk so that it could be lifted and towed away." No information was given to permit an estimation of the breakout force.

S-51

The S-51 was a 1,230-ton submarine which sank in 1925 approximately 14 miles east of Block Island. The depth at the site was 132 feet and the submerged weight was estimated to be 1,000 tons. The boat came to rest on a clay bottom with an 11-degree port list.

Ellsberg (1927) estimated that the breakout force was about 8,000 tons, "a force so large we could never hope to overcome it by direct lift." His plan, which was executed successfully, was to "break the suction by letting water in between hull and clay in two ways - first, by rolling the boat to starboard, and second, by lifting her one end (stern) first."

S-4

The S-4 was an 830-ton submarine which sank in 1927 in 102 feet of water off Provincetown. It was initially and intermittently buried in a very permeable mud to a depth of 7 or 8 feet. The S-4, whose submerged weight amounted to 722 tons, was raised by lifting the stern first. Saunders (1929) states that "the bottom had an upper layer of very soft slit or mud not more than one foot deep. Underneath this, the bottom was more soft than hard, of a decidedly sand character, mixed with minute shells. The texture of the bottom was sufficiently coarse to permit the passage of water through it...yet sufficiently firm to hold its position when excavating tunnels underneath the vessel. Due to the permeable characteristic of the bottom, it is estimated that the so-called 'suction effect' on the S-4 was practically nil." As a matter of fact, there are no indications that breakout was a problem.

USS SQUALUS

The salvage of the USS SQUALUS is perhaps the most widely reported and documented of all submarine salvage operations. The USS SQUALUS, which sank in 1939 about 5 miles south of the Isles of Shoals off Portsmouth Harbor, was a 1,450-displacement boat having a submerged weight of 1,100 tons. The boat came to rest with a 10-degree-up angle in 240 feet of water on a mud bottom in which the stern was buried up to the superstructure deck. The entire operation consisted of five separate attempted lifts, three of which were from a mud bottom. Only the first lift is pertinent to this report. No estimate of the breakout force is reported; however, in a review of the events describing the unsuccessful lift of 13 July, Tusler (1940) indicates that the "unknown amount of mud suction tending to hold the bow down" was one of the main factors contributing to the failure. Previous to the attempted lift, Tusler states that "the bow had sunk down an unknown amount into the soft mud of the bottom, but due to the shape of the bow, it was thought that the mud suction would be relatively insignificant." In any event during each attempted lift, the USS SQUALUS was raised by lifting one end first.

USS LAFAYETTE (ex SS NORMANDIE)

The SS NORMANDIE was a 65,000-ton passenger vessel which sank in 49 feet of water adjacent to Pier 88, New York City Harbor. The submerged weight was estimated to be 50,000 tons. The vessel came to rest lying on one side in an organic river mud which was about 25 feet thick and which was underlain by a gray organic silty clay having a compressive strength of from 0.3 to 0.6 ton/ft^2. (This operation is of interest since it appears to have been the first time the principles of soil mechanics were considered in a salvage operation of this type).

It was anticipated that breaking contact between the ship's hull and the mud would be a serious problem. Accordingly, in addition to pumping out some 15,000 tons of mud which had entered the hull through the cargo doors and portholes, numerous porthole patches were fitted with pipes through which water and compressed air could be jetted to disintegrate the mud. The flotation of the vessel was preceded by a rotation or turning operation. Masters (1954) notes that during the rotation operation, the air and water jets were set to work, although the vessel did not stick as expected.

PHOENIXES

The PHOENIXES were 200-foot-long floating caisons of reinforced concrete which were to be sunk in a line off the Normandy beaches to provide a breakwater during the European invasion. Each unit was 60 feet wide, 60 feet high, and displaced 6,000 tons. They were divided into watertight compartments and fitted with valves for controllable flooding. Approximately 100 of these PHOENIXES were purposely sunk in staging areas off the south coast of England prior to invasion. The first attempt to refloat a PHOENIX by pumping failed. It was determined that the mud bottom suction was holding the PHOENIX down. The traditional method of breaking this contact is to apply buoyancy to one end and to use the ship as a lever. In this manner the contact is broken along the bottom, eventually freeing the vessel from the mud. However, in the case of the PHOENIXES there was not enough time to allow this system to work, because the rising tides would submerge the pump platforms before the lever action could be made effective. A second alternative is to jet air or water underneath the sunken vessel to partially reduce the contact and lessen the holding force. In the case of the PHOENIXES, compressed air was employed (all pumps were being used to empty the flooded compartments) to reduce the holding force to allow the excess buoyancy to float the PHOENIXES.

In addition to the case histories cited above, there are many other records of maritime salvage operations in which a ship has been raised from a mud bottom under very unfavorable circumstances. The background provided herein is not intended to be an all-inclusive treatment of salvage. Only those cases in which the breakout force was alluded to in the published literature were selected. It is worthy of note, however, that the published record (Bowman, 1964) of the salvage of the entire German High Seas Fleet, which was scuttled at Scapa Flow, does not mention that breakout was a problem. Further, the U.S. NAVY's experience with the ex-German submarine 1105 did not disclose the breakout problem, although the tests were carried out with the submarine eventually lying on a mud bottom.

NOTE: A comprehensive study on bottom breakout forces has been conducted by the Naval Civil Engineering Laboratory, Port Hueneme, California. The Technical Report R-591 of June 1968, titled "Ocean Bottom Breakout Forces" is the source of much material presented here. The R-591 report should be consulted for additional information.

4.7.1. Theoretical Considerations of Bottom Breakout Forces

Classical theory of soil mechanics and foundation engineering assumes that stress conditions alone determine the state of failure of a material, irrespective of the load duration and stress history of the specific soil/module situation. Field experimentation, theoretical analysis, and empirical data indicate that time is a necessary and real function deserving due consideration in the definitive breakout equation; the load duration, as applied to the breakout problem, is a major factor.

In the classical theories, one or two of such material parameters as yield stress, Young's modulus, or Poisson's ratio are sufficient to describe the behavior of an isotropic material; such simplifications are inadequate to predict breakout behavior.

Highly complex theories are rarely applicable in soil engineering problems; the advent of modern computers does not alter this premise. Theoretical calculation of soil engineering problems, and specifically those of breakout forces, is complexed by factors of unknown patterns of nonhomogeneity of soils in the particular application and the inability of mathematical models to deal with unknown parameters.

4.7.2. Mathematical Definition of Bottom Breakout Forces

Beginning with a very simple formulation of the mechanics of bottom breakout, the following equation may be expressed:

$$F = KCA \qquad \text{(Equation 1)}$$

where

- F = breakout force
- C = cohesion, or alternatively a measure of the vane shear strength
- A = horizontal projection of the contact area
- K = constant which is a function of object size, object shape, time duration of applied force, rate force is applied, soil sensitivity, and the elapsed time which the object has been in place after the initial disturbance. Soil sensitivity may be defined as the ratio of cohesion of undisturbed soil to cohesion of disturbed soil at constant water content.

Thus, we may write

$$\frac{F}{CA} = k$$

or

$$\log \frac{F}{CA} = \log k \qquad \text{(Equation 2)}$$

Letting C and k take on slightly different meanings, we may write

$$\frac{F}{\underline{C}A} = Qe^{-R(t-t_o)} \qquad \text{(Equation 3)}$$

where

- $\underline{C}$ = effective average cohesion along the failure surface at the instant of breakout
- Q = constant
- R = slope of the "failure line" when log $(F/\underline{C}\ A)$ is plotted versus time, t
- t = time allowed for breakout, or alternatively the elapsed time during which the breakout force is applied
- t_o = reference time in minutes

The constants Q and R are functions of the load duration or strain rate. In Equation 3, when $t = \infty$, the force required for breakout is a minimum. Conversely, as t is allowed to approach zero, that is, as the time allowed for breakout becomes increasingly short, the force requirement reaches a maximum constant value.

The quantity $\underline{C}$ requires some comment since it is also a time-dependent function which is related to the soil sensitivity. It may be estimated by an equation of the type:

$$\underline{C} = \frac{C}{s} + \left(C - \frac{C}{s}\right)\left[1 - e^{-bt/(t-t_1)}\right] \qquad \text{(Equation 4)}$$

where

- s = degree of soil sensitivity
- b = numerical constant used to force $\underline{C} = C$ for very large t, in keeping with our knowledge of thixotropic material behavior
- t_1 = reference time related to the thixotropic behavior of a material in regaining a stated percentage of its strength after initial disturbance

To illustrate that Equation 4 is approximately correct, we note that:

(1)

for $t = 0$, then $\underline{C} = C/s$,

(2)

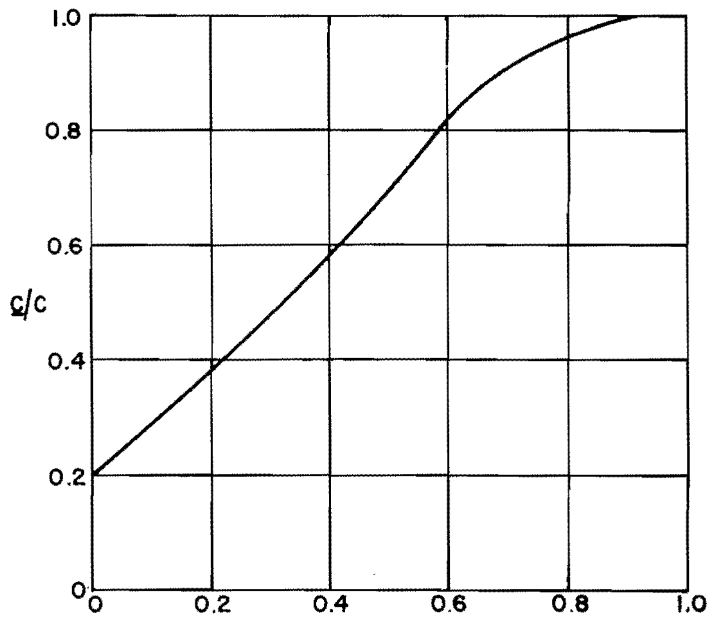
for $t = t_1$, $\underline{C} = C$, and

(3)

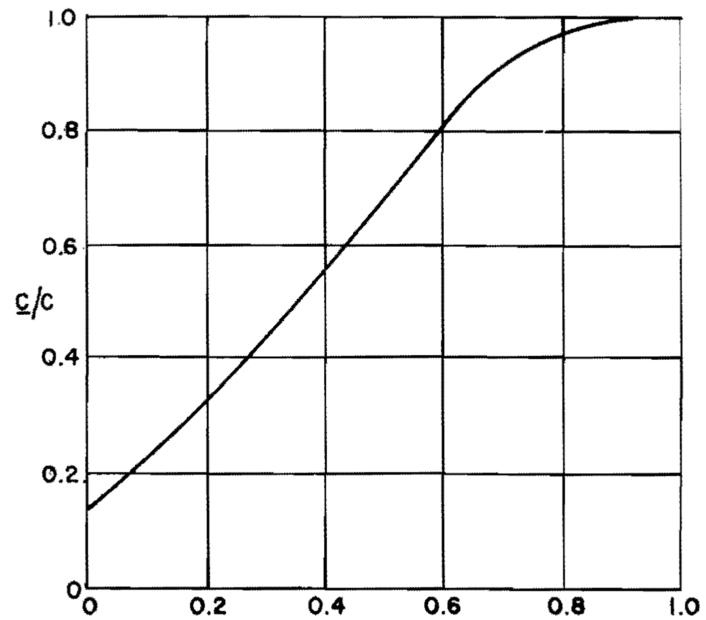
for very large t,

$\underline{C} = C$ even for relatively small values of b.

Dimensionless graphs of Equation 4 are shown in Figures 4-2 and 4-3 for values of $b = 1.0$ and $s = 5.0$ and 8.0, respectively. Experimental information on the validity of Equation 4 seems to be nonexistent. In addition, the reference time t_1 seems to be highly variable, being very short (that is, on the order of minutes) for such thixotropic materials as drilling muds and perhaps very long (that is, measured by geologic time) for many deep marine sediments.



DIMENSIONLESS GRAPH OF EQUATION 4
FOR b = 1.0, s = 5.0.
FIGURE 4-2



DIMENSIONLESS GRAPH OF EQUATION 4
FOR b = 1.0, s = 8.0.
FIGURE 4-3

On the basis of experimental test results we may estimate s, C, t_1, t_o, and the constants Q and R, and then compute the force F required to extract the specimen as a function of time, t. For example:

$$F = \underline{C}AQe^{-R(t-t_o)} \qquad \text{(Equation 5)}$$

or for maximum C

$$F = CAQe^{-R(t-t_o)} \qquad \text{(Equation 6)}$$

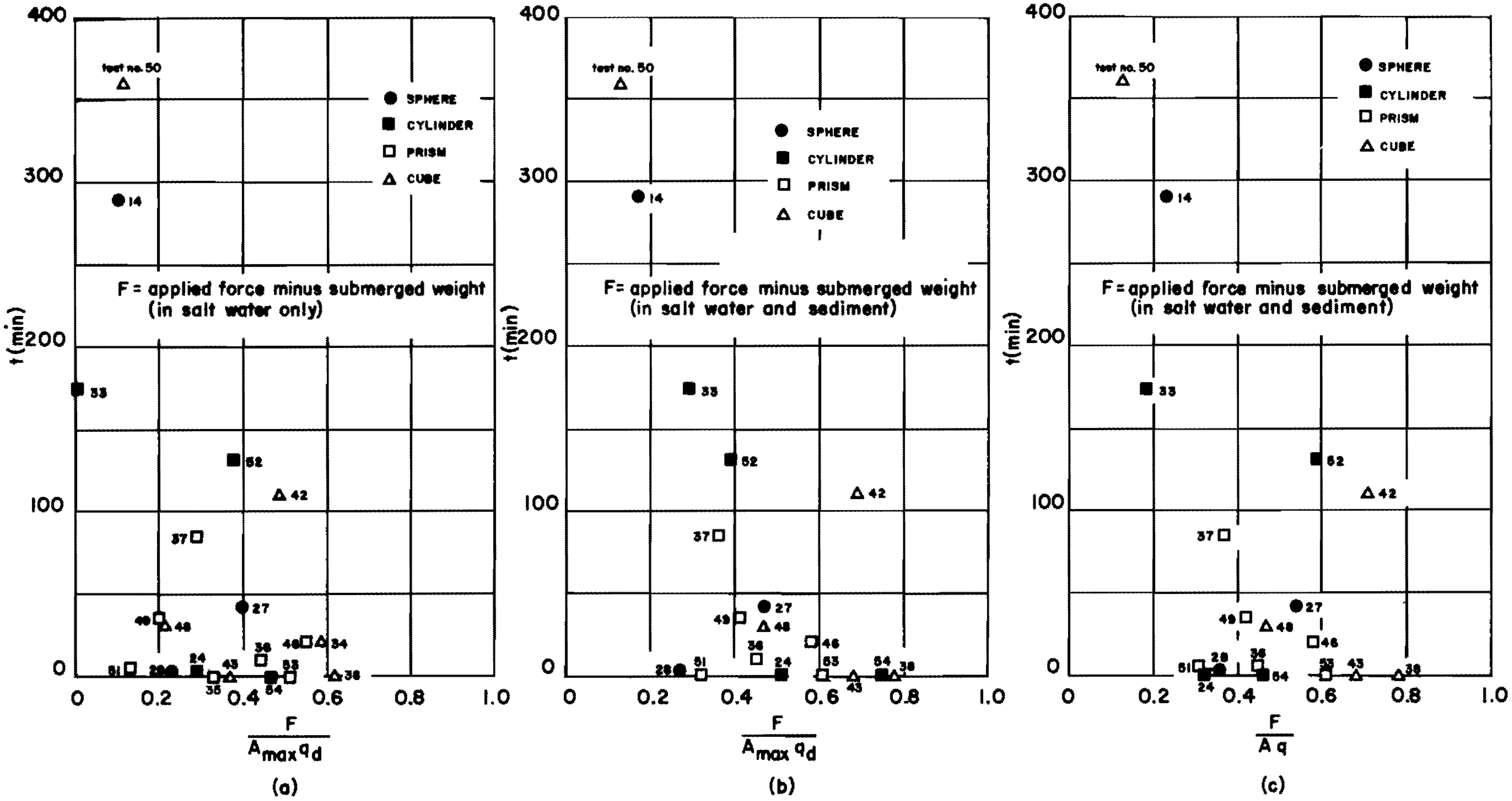
<u>NOTE:</u> It is to be emphasized that the reference times are those determined from large-scale field tests.

The foregoing illustrates how the field data may be analyzed and used for predicting breakout, assuming that scale effect is negligible. In connection with the data reduction, it was found that the cohesion, C, as obtained by vane shear tests, showed marked variability. Thus, as an alternative measure of the sediment strength, it was expedient to use the quantity q_d, which is defined as the average supporting pressure provided by the soil to maintain the embedded object in static equilibrium, in all of the data reduction since it exhibited very consistent trends. In a sense this is fortunate since the problem then becomes completely determinate, being no longer dependent on external measurements. (A summary of field data is presented in graphical form in Figures 4-4 and 4-5.)

Figures 4-5a, 4-5b, and 4-5c are semilogarithmic graphs of the data appearing in Figures 4-4a, 4-4b, and 4-4c respectively. The elapsed time over which the maximum force was applied appears as the ordinate in all figures.
In Figures 4-4a and 4-4b, the abscissa is the dimensionless quantity, $F/A_{max}\ q_d$); in Figure 4-4c, the abscissa is F/Aq_d). In Figures 4-4b, 4-4c, 4-5b, and 4-5c, the force F represents the net breakout force, which is the applied force minus the submerged weight of the object, not only that portion submerged in salt water, but also that portion of the object embedded in the bottom sediment.

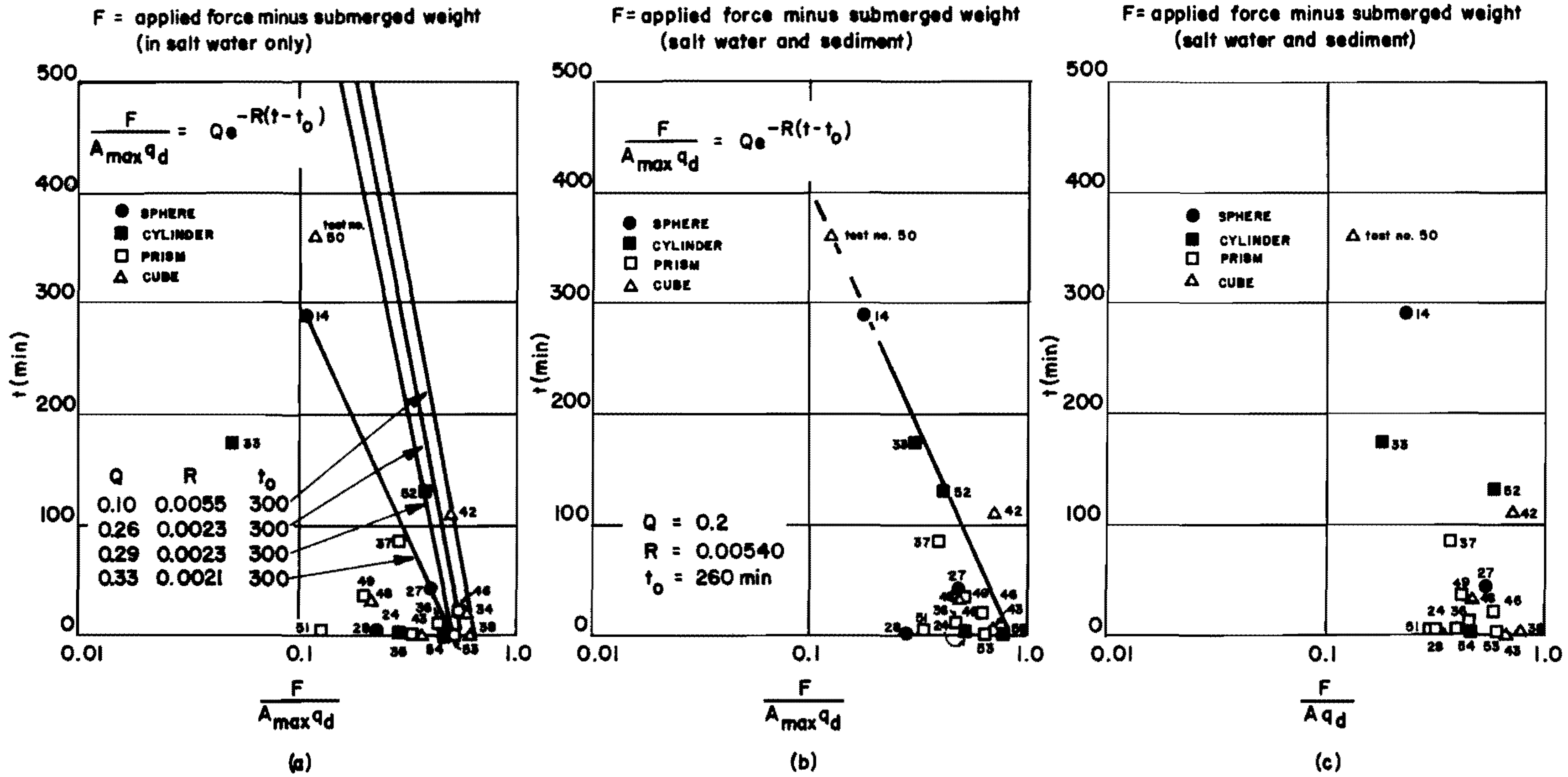
Figure 4-5a indicates some of the trends in selected data from field tests. The coefficients Q, R, and t_o used in Equation 5 are also shown on the figure. Although the data are extremely limited, the figure indicates that the forces required to extract the cube and the prism are higher than those for the cylinder and sphere. This seems to be in agreement with previous field experience.

Figure 4-5b exhibits the clearest consistent relationships for all of the included data.



DATA SELECTED FROM FIELD BREAKOUT EXPERIMENTS.

FIGURE 4-4



DATA SELECTED FROM FIELD BREAKOUT EXPERIMENTS
PLOTTED ON SEMILOGARITHMIC GRAPHS.
FIGURE 4-5

That is, the trends shown in Figure 4-5a for the various shaped objects appear to be almost entirely obscured when the numerator in the abscissa is reduced by an amount equal to the submerged weight of the volume of sediment displaced by the embedded object. From these data, the equation for computing breakout has been determined to be:

$$F = 0.20\, q_d\, A_{max}\, e^{-0.00540(t-260)} \quad \text{(Equation 7)}$$

where

A_{max} = horizontal projection of the maximum contact area

for $t = 0$, Equation 7 reduces to

$$F = 0.81\, q_d\, A_{max} \quad \text{(Equation 8)}$$

for $t = 260$ minutes, the breakout force requirement becomes

$$F = 0.20\, q_d\, A_{max} \quad \text{(Equation 9)}$$

CAUTION: It is to be emphasized that relationships such as appear in Figures 4-5a, 4-5b, and 4-5c, of which Equation 7 is typical, are based on only one type of sediment (that is, that found in San Francisco Bay) and one size of test objects, all of which were similar both from characteristic length and bearing load.

4.7.3. Determination of Bottom Breakout Forces

The theoretical procedure considers neither the effects of remolding or the increase in strength due to consolidation. In the San Francisco Bay tests (upon which the empirical constants were determined), the maximum bearing loads were very high; much higher than the capacity of the soil near the surface to support such loads. Thus, the soil in the immediate vicinity of the test object was disturbed and remolded to a considerable degree. Moreover, the object penetrated a certain distance until the bearing loads were reduced to a level within the capability of the soil to support the imposed loads. There is a natural increase in strength with depth due primarily to an increase in bulk density and a decrease in water content. However, the strength of the soil is also affected by the presence of the object in two opposing ways. One, referred to previously, is the reduction in strength due to remolding. The other is the gain in strength due to consolidation. Both effects occur on vastly different time scales.

The loss in strength due to remolding takes place instantaneously, whereas the gain in strength due to consolidation is a long-term process depending initially to a large extent on the permeability of the soil. It seems likely that for a given object two worst situations are possible:

1. The shallow-penetration case, occurs when the soil has a high shear strength which is almost but not quite matched by the imposed bearing loads. This ensures a close bonding of the object skin surface to the sedimentary layer without inducing a strength reduction in the soil.

2. The deep-penetration case, occurs when penetration has been so deep that the volume of displaced soil becomes sufficiently large so as to completely dominate the breakout process.

The latter situation is not to be confused with the volume of material lying between the failure surface and the object boundary, which is a function of the gross dimensions of the object. We are concerned here with a given geometry.

In the theoretical approach, the computational scheme permits loads of any magnitude to be applied to any or all mass points. Again, in the cited example, equal loads were applied to the mass points located on the boundary geometry. Thus, unequal relative movement between the mass points on the boundary are permitted, whereas in fact, such unequal movements are realized only for flexible membranes.

It is difficult, at best, to calculate the effective value of bottom breakout forces by use of theoretical analysis; the use of empirical data to formulate a field-value equation to describe breakout is equally limited. Studies, to date, offer information and data so that a summation of pertinent facts can be made; some are:

1. A numerical method of predicting strains, stresses, and displacements in an elastic - perfectly plastic medium subject to loads applied to an arbitrary boundary geometry was found to be useful in developing a theoretical prediction of breakout forces.

2. A complicated computer program, which uses a lumped parameter model of the material and an iterative technique to obtain solutions, was found to be an integral part of the theoretical procedure. The program requires use of a high-speed large-memory-capacity computer. The programs used in computer study of breakout can be found in Appendixes C - to G, of "Ocean Bottom Breakout Forces." R-591. NCEL.

3. The computational procedure traces the development of the stress and displacement fields in an elastic - perfectly plastic material under conditions of plane strain, with specified boundary conditions and force-controlled loading.

4. Results yielded by the computational procedure were found to be verified by separate photoelastic studies, at least within the elastic range.

5. Data from breakout tests with large specimens in San Francisco Bay were found to develop the following empirical formula:

$$F = 0.20\,A_{max}\,q_d\,e^{-0.00540(t-260)} \qquad \text{(Equation 10)}$$

The geometry of the breakout object seemed to have relatively little effect on the breakout force.

6. The ocean bottom breakout force of an object of simple geometry can be estimated by means of an analytical method that uses numerical calculation by high-speed computers. The method takes into account the plastic behavior of soil beyond the elastic strain range.

7. The following empirical formula may be used to describe the breakout force for an ocean bottom soil:

$$F = Q\,A_{max}\,q_d\,e^{-R(t-t_o)} \qquad \text{(Equation 11)}$$

When a computer is not available, the empirical formula should be used to determine the breakout force. The constants Q, R, and t_o can be derived from a limited number of in-situ field test data.

NOTE: Technical Report R-635, "Ocean Sediment Holding Strength against breakout of Embedded Objects" published by the US Naval Civil Engineering Laboratory presents additional test data and theoretical solution to the bottom breakout problem.