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EVALUATION OF BOTTOM BREAKOUT REDUCTION METHODS

By

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13. ABSTRACT

Breakout forces present problems in making retrieval lifts by increasing the lift force requirement, creating a dynamic snap-load in the lifting line, and causing control difficulty during ascent. Three breakout reduction methods are tested using small submersible-sized objects. These methods are: (1) Mud Suction Tubes, (2) Water Flooding, and (3) Air Jetting. The results showed that all methods were effective at reducing the breakout force to less than 10% of the wet weight of the object. Diver handling techniques are evaluated and described. Also, a review of three methods which calculate breakout forces is presented.

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DD FORM 1 NOV 65 1473 (BACK)
(PAGE 2)

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CONTENTS

INTRODUCTION

As a postscript to a recently completed three-year analytical breakout study,[1, 2] the Supervisor of Salvage has sponsored work to carry the study of the breakout mechanism to a hardware stage. Deriving its goals from the LOSS (Large Object Salvage System) concept,[3] the objective of this project was to develop equipment and techniques for reducting breakout forces of submersible-sized embedded objects. This study is limited to vehicles like the ALVIN and Deep Quest, not full-sized submarines. All equipment is applicable to diver supported operations to 850 feet.

In marine salvage, a major problem occurs during the retrieval lift operation. Certain bottom sediments create a "mud suction" on the embedded object. This suction or breakout force, is the differential force between the total lift force required and the object weight in water. This suction force can be many times the weight of the submerged object. This force not only increases the lift force requirement, but once breakout is attained, a dynamic snap loading condition occurs in the lifting line. Snap loading is the impact condition which takes place when the cable becomes slack after the object breaks loose from the bottom. The net force in the lifting line is composed of the wet weight of the object plus the breakout force. If the object breaks out quickly, a transient condition exists in which the lift force exceeds the object's weight by the amount of the breakout force. The object is then accelerated upwards causing the line to slacken. As the object falls, the cable is subsequently subjected to severe impact stresses when it again becomes taut.

In an attempt to alleviate the breakout problem, three reduction concepts and their related equipment were proposed: (1) Mud Suction Tubes; (2) Water Flooding; and (3) Air Jetting. To evaluate these concepts, several field tests were conducted, and the test procedure is presented, including a description of the seafloor site, the test objects, and the lifting apparatus and instrumentation. The results of the tests for each breakout reduction method are discussed, and the interpretation of these results is listed.

A review of three methods developed at NCEL by Muga[1], Liu[2], and Lee[4] to predict breakout forces is presented in the Appendix. Each method description gives a brief background leading to the breakout force equation and an explanation is given for the breakout mechanism parameters and how their values are obtained. Following the explanation of terms are the calculations of the predicted breakout forces that should occur during the field tests if no reduction method were applied.

REDUCTION METHODS

Previous salvage operations have employed reduction methods by either rotating the embedded object or lifting one end first. Other concepts, such as vibration, water and air jetting, chemicals added to bottom sediment, were devised in the hopes that they might be more economical and efficient, and easier to deploy.

Three of these reduction methods, (1) Mud Suction Tubes, (2) Water Flooding, and (3) Air Jetting, were tested in Port Hueneme Harbor and their effectiveness was evaluated. The following description of each of the methods shows how the reduction is accomplished and lists the required equipment.

Mud Suction Tubes

Since breakout forces produce a subsurface low pressure cell beneath the embedded object, any means that relieves this pressure differential would reduce the breakout force. Dr. Liu of NCEL invented the Mud Suction Equalization Tube (MUSET) to accomplish this task. The mud suction tube penetrates the low pressure cell, allows water at ambient pressure near the bottom to be drawn down the tube, equalizing the pressure, and thereby reducing the breakout force (see Figure 1).

The tubes themselves are five-foot sections of one-inch pipe with one end capped. The one-third of the pipe nearest the capped end has many 1/8" diameter perforations, randomly spaced. The only accessory equipment that may be required is a short-handled five-pound sledge hammer for diver placement of the tubes by hand.

Water Flooding

In addition to equalizing the low pressure cell to ambient bottom pressure as a means of reducing breakout forces, any reduction in adhesion between the object surface and the soil would have the same effect. One way to reduce adhesion is to pump water beneath the object.

The equipment tested for water flooding is the same mud suction tubes which are described in the previous section. However, 3/4" to 1" diameter water hose is attached to the tubes, and water pressure from the surface forces the water into pockets beneath the object.

This action of water flooding should not be confused with water jetting, which employs a jet stream to displace bottom sediments. Therefore, water pressures should be limited to 50-75 psi over ambient bottom pressure and there should be many small holes to prevent a jetting nozzle effect. If water jetting occurs, the object will settle deeper into the sediment as soil particles are removed.

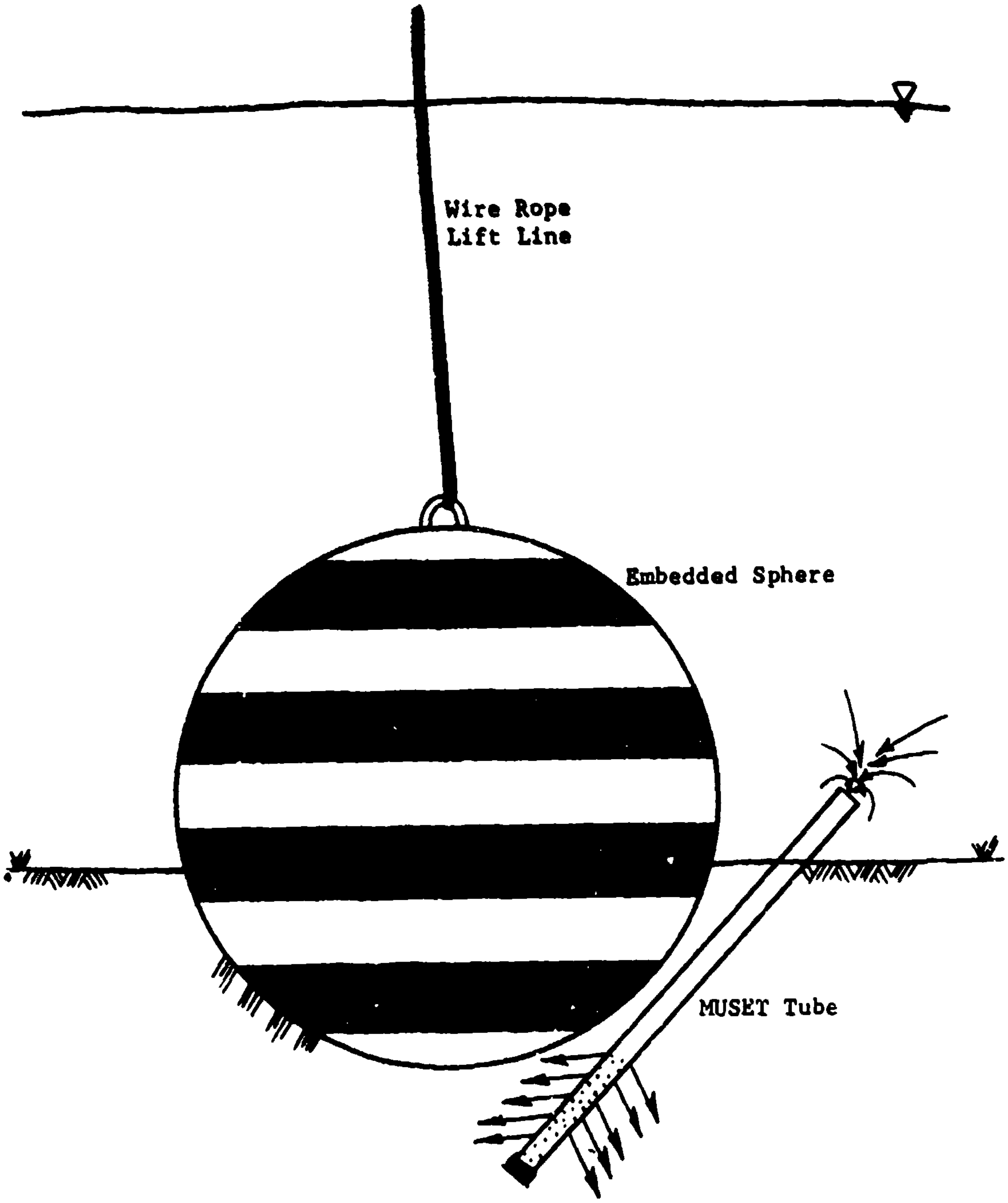

Figure 1. Placement of MUSET Tubes

Air Jetting

Another means of reducing adhesion between the object and sediment is jetting air beneath the object. This procedure depends on a layer of bubbles which flows under and around the embedded object, thus reducing the breakout force.

A topside air compressor provides the necessary pressure and quantity of air which flows through 5/8" air hose, attached to the MUSET tubes. The flow of air should be throttled to approximately 5 cfm per tube since additional quantities of air will simply create small "tunnels" of least resistance in the soil and bubble off to the surface. In addition, the "tunneling" effect undermines the object and allows it to settle deeper into the sediment. To prevent this settling from occurring, it is best to allow the lift force to reach the estimated wet weight of the object before the air is applied.

FIELD TESTS

A series of baseline tests was run to establish the amount of mud suction without employing any reduction methods. Then several pullout tests were performed to evaluate the effectiveness of each breakout reduction method. The details of the tests are given in the following description of the site location, test objects, lifting apparatus, and testing procedure.

Site Description

The site for the breakout tests was Port Hueneme Harbor in 30 feet of water. The bottom sediment at the proposed site was a sandy clay with a vane shear strength at a depth of one foot of 0.2 psi. Divers performed this test with a hand-held vane shear device. Considerable debris (e.g., steel plates, wire, coffee cups) had to be cleared away from the work area on the bottom. However, undetected rubble buried in the bottom could have affected the homogeneity of the bottom sediment and, consequently, reduced the holding strength of the soil.

Test Object Description

The test objects were of three basic shapes: (1) horizontal cylinder; (2) sphere; and (3) cube. The cylinder and sphere were steel pressure vessels filled with concrete, and the cube was a block of unreinforced concrete. The dimension and weight of each test object appear in Table 1.

Table 1. Description of Objects Used In Breakout Testing

OBJECT	DIMENSIONS	DRY WEIGHT	WET WEIGHT
Cylinder	Diameter = 2.5 ft. Length = 10 ft.	7860 lbs.	4770 lbs.
Sphere	Diameter = 4.8 ft.	8940 lbs.	5245 lbs.
Block	Side = 3.5 ft.	6080 lbs.	3320 lbs.

Lift Force Apparatus and Application

The lift apparatus was simply an 8.4 ton collapsible salvage pontoon with a dynamometer connected between the test object and the pontoon. The lifting configuration is shown in Figures 2 and 3.

A constant rate of lift force application was a desired control parameter. The salvage pontoon lift system was chosen because the air pumped into the pontoon could be throttled to any preset flowrate. The flowrate was established by throttling the air to give a constant rate of loading as indicated by the dynamometer and recorded on a strip-chart recorder. The rate of loading chosen for all breakout tests was set at 200 lb/min to give a reasonable breakout time of 15-30 minutes for the object being lifted. The time history of a typical lift appears in Figure 4, which clearly shows that the total lift force equals the sum of the breakout force and the wet weight of the object.

This lifting configuration and slow rate of loading reduces the possibility of snap loading. There is no wire rope in the lift system to become slack. The rate of loading allows the objects to "ease" out, not suddenly break loose.

Testing Procedure

Once the site had been cleared, the test objects were placed on the bottom and the initial embedment times and depths were recorded. The time that the embedded objects were on the bottom was varied from one to 48 hours.

Divers inserted all the tubes (MUSET, water and air) as close to the object as possible at a 45° angle, so that the tubes would extend under the test object. The tubes were spaced every two to three feet around the perimeter of the embedded object.

Diver handling presented no serious problem in any one of the reduction methods. The tubes were made relatively short to aid in diver handling but long enough to reach beneath a submersible-sized object. Hose entanglement can present a problem when using the water flooding and air jetting methods.

Safety features employed during the lift minimized the hazards encountered by divers. First, the lowering line connecting the object

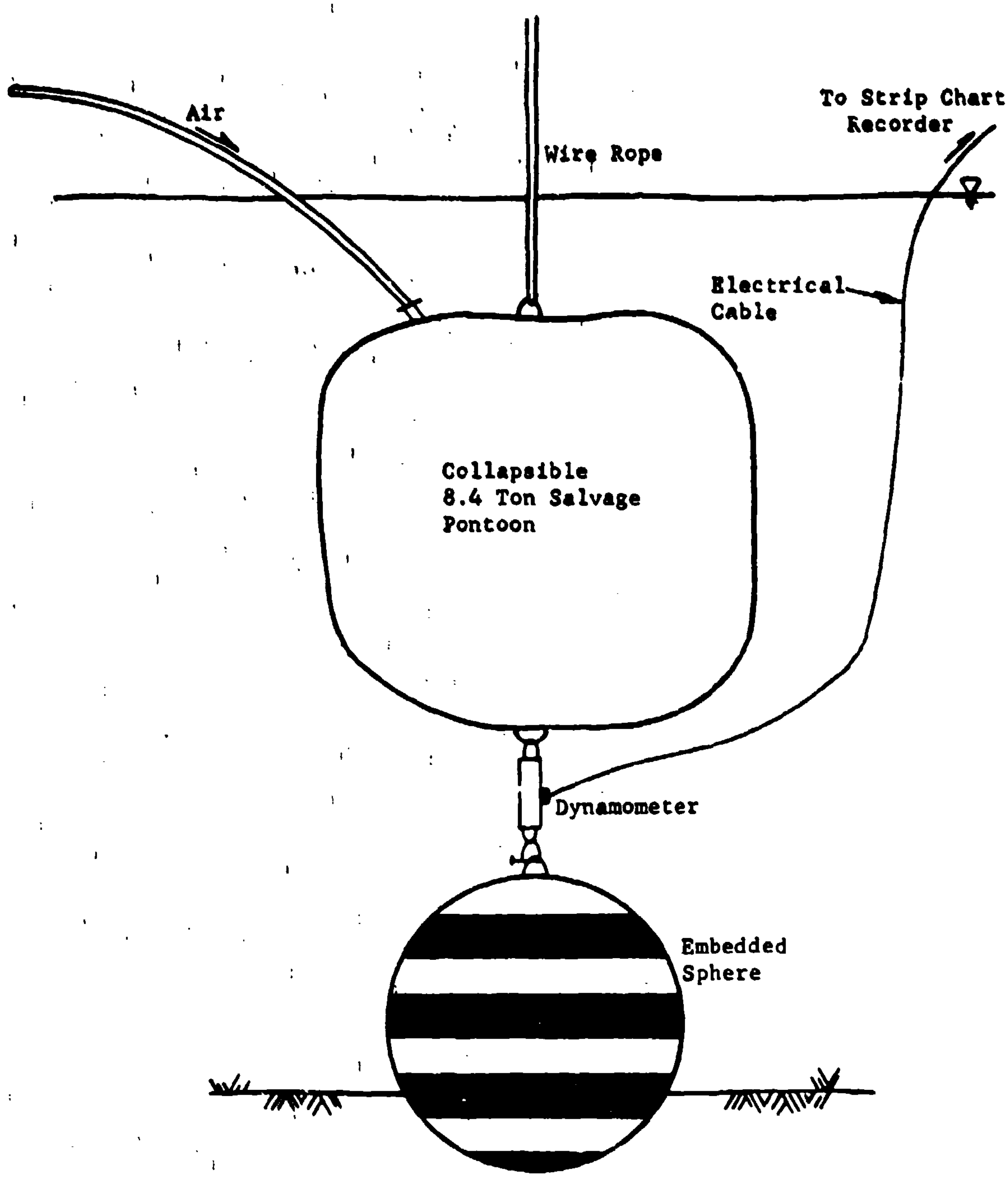

Figure 2. Lifting Apparatus Configuration

Figure 3. Breakout Lift Apparatus

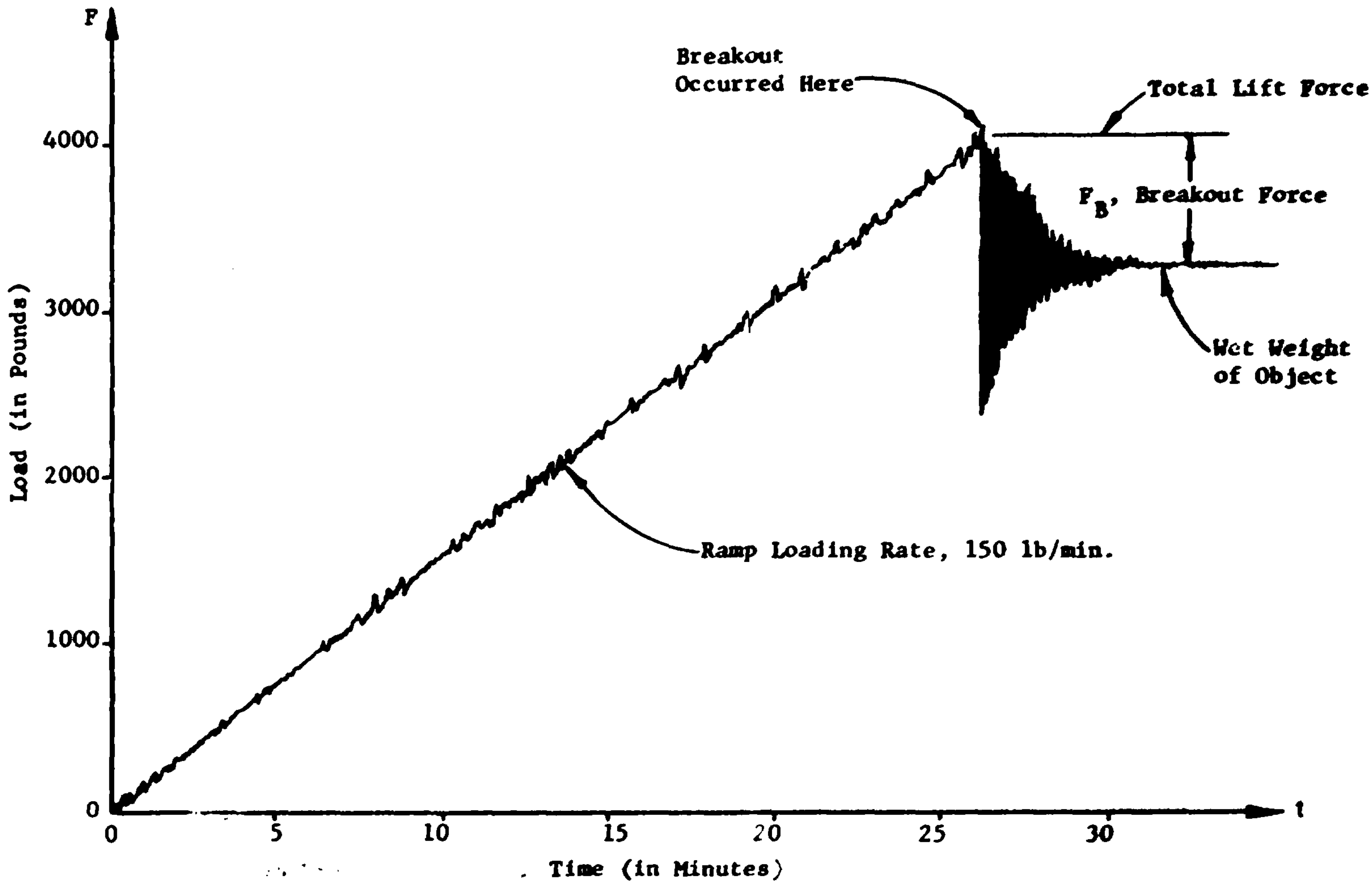

Figure 4. Typical Time History of Breakout Lift

with a dockside mobile crane remained attached throughout the lifts as a backup system for the pontoon. No divers were allowed in the water after lifting commenced. Once the pontoon broke the surface (see Figure 5), the air was shut off to prevent an explosive blast of air from hitting the diver as he disconnected the air hose from the inflated pontoon. Also, at this time the crane operator took in the slack of the lowering line to carry the load while the pontoon was deflated.

The lifting pontoon almost vented itself upon breaking the surface during lifts where a large breakout force occurred. If the pontoon had vented, the object would have sunk to the bottom. Lift control was not a problem as long as the breakout force was less than 20% of the wet weight of the embedded object.

DISCUSSION OF TEST RESULTS

The results of the breakout tests are shown in Tables 2 and 3.

Table 2. Breakout Tests
Without Application of Any Reduction Method

TEST NO.	EMBEDMENT DEPTH (IN)	EMBEDMENT TIME (HR)	BREAKOUT FORCE (LB)	BREAKOUT RATIO*	DURATION OF LIFT (MIN)
Cylinder					
C-1	6	24.5	300	1.06	20
C-2	9	2.5	180	1.04	21
C-3	10	1.3	250	1.05	22
C-4	12	42.7	190	1.04	30
Sphere					
S-1	18	23.2	1705	1.32	28
S-2	12	22.5	315	1.06	22
S-3	20	1.2	665	1.24	29
S-4	16	43.3	395	1.07	23
Block					
B-1	9	24.2	1280	1.39	20
B-2	3	19.5	1660	1.50	21
B-3	6	3.0	280	1.08	16
B-4	6	43.5	600	1.18	19

* Breakout ratio is the dimensionless quantity, $\frac{\text{Lift Force.}}{\text{Object Wet Weight}}$

Table 3. Breakout Tests Using Reduction Methods

TEST NO.	REDUCTION METHOD	EMBEDMENT DEPTH (IN)	EMBEDMENT TIME (HR)	BREAKOUT FORCE (LB)	BREAKOUT RATIO*	DURATION OF LIFT (MIN)
Cylinder						
C-1	MUSET	6	2.5	40	1.01	29
C-2	MUSET	12	19.5	230	1.05	29
C-3	Water Flooding	9	4.2	80	1.02	25
C-4	Air Jetting	8	23.8	180	1.04	30
Sphere						
S-1	MUSET	20	5.0	65	1.01	32
S-2	MUSET	9	18.5	305	1.06	27
S-3	Closed MUSET	18	2.4	205	1.04	27
S-4	Water Flooding	18	1.7	95	1.02	25
S-5	Air Jetting	15	0.8	355	1.07	37
Block						
B-1	MUSET	14	4.5	140	1.04	20
B-2	MUSET	9	20.0	505	1.15	20
B-3	Water Flooding	6	3.5	330	1.10	19
B-4	Air Jetting	11	22.0	150	1.04	23

*Breakout ratio is the dimensionless quantity, $\frac{\text{Lift Force}}{\text{Object Wet Weight}}$.

Figure 5. Lift Pontoon Breaking Surface

The first table gives the test data without the aid of any reduction methods. The second table compares the three breakout reduction methods, identified in column two.

A modification of the MUSET method to determine how well the tubes operated was performed. This test (S-3 of Table 3) was conducted by capping the open ends of the MUSET tubes so that water could not flow down the tubes and relieve the low-pressure area beneath the sphere. However, there was no appreciable difference in the results. This lack of disparity can be explained by the creation of "shafts" by the tubes as they were being placed. These small "tunnel shafts", larger than the MUSET tubes themselves, allowed water to flow along the outside of the tubes and beneath the object, which reduced the suction, even with caps on the MUSET tubes.

There is no significant correlation between embedment depth or time and the breakout force. Of course, this lack of correlation is to be expected since there are many variables which influence the breakout mechanism. Other than embedment depth and time, bottom soil conditions, object shape parameters and loading applications also have an effect on the resulting breakout force.

Since all three of the breakout reduction methods worked equally well, the determination of their effectiveness lies in the comparison between using and not using the reduction methods. For each object shape, the averages of the breakout ratios of Tables 2 and 3 are compared in Table 4 with the predicted breakout ratios calculated in the Appendix. The breakout ratio is the total lift force divided by the object wet weight (e.g., b.r. = 1.00, no breakout force; b.r. = 1.20, 20% of object wet weight is breakout force).

Table 4. Breakout Ratio Comparisons

OBJECT SHAPE	MUGA'S METHOD	LIU'S METHOD	LEE'S METHOD	WITHOUT REDUCTION	USING REDUCTION METHOD
Cylinder	1.34	1.19	1.38	1.05	1.03
Sphere	1.35	1.14	1.20	1.17	1.04
Block	1.43	1.13	1.22	1.29	1.08

It can be seen that by using a reduction method there is a significant drop in the breakout force of the sphere and block of 77% and 72%, respectively. However, the cylinder shows only a 40% decrease in the breakout force. This difference is probably the result of the lifting straps binding on the rounded ends of the cylinder during the lift. As the wire rope became taut, it rotated the cylinder; thus, an unwanted reduction method was being applied on each cylinder test.

In comparing the "Without Reduction" column with the prediction methods from the Appendix, Liu's method is good for the sphere but deviates over 50% from the baseline tests for the block and cylinder. On the other hand, Muga's method does not predict the baseline test results well for any one of the three object shapes. Lee's method comes closest to predicting the breakout forces. His calculation differed significantly from the cylinder, but that data point is of questionable value, as explained in the preceding paragraph.

CONCLUSIONS

1. Use of these breakout reduction methods will reduce the total lift force requirements by approximately 15% and will virtually eliminate the snap loading condition.
2. All breakout reduction methods tested were equally effective at reducing the breakout force by approximately 75%.
3. The selection of the type of breakout reduction method depends on the salvage operation, equipment available, bottom soil conditions, and diver capability.
4. Retrievable lifts do not require breakout reduction for control where the predicted breakout ratio is less than 1.20.

RECOMMENDATIONS

Should operational requirements indicate that additional research is required, the following work is recommended:

1. Further study should be done on one of the more exotic but promising breakout reduction concepts: vibration, electrolysis, chemical, as well as two common practices, rotating the object or lifting it by one end first.
2. Additional evaluation should be conducted in other representative bottom sediments.

REFERENCES

1. Naval Civil Engineering Laboratory, Technical Report R-591, Ocean Bottom Breakout Forces by Bruce J. Muga, June 1968.

2. Naval Civil Engineering Laboratory, Technical Report R-635, Ocean Sediment Holding Strength Against Breakout of Embedded Objects by C. L. Liu, August 1969.

3. Deep Submergence Systems Program, Large Object Salvage System - Technical Development Plan, Report No.46-17, Washington, D.C, April 1966.

4. Naval Civil Engineering Laboratory, Technical Report R-755, Unaided Breakout of Partially Embedded Objects from Cohesive Seafloor Soils by Homa J. Lee, February 1972.

Appendix

BREAKOUT FORCE PREDICTION

by K. D. Vaudrey and H. J. Lee

A brief summary of three analytical methods which have been developed at NCEL to predict breakout forces is presented. Following the methods are the calculations giving the predicted values for the Port Hueneme Harbor breakout tests.

Muga's Method

In his report Muga developed an analytical method of predicting strains, stresses, and displacements in an elastic, perfectly plastic medium subjected to loads applied to arbitrary boundary conditions. This numerical method used a lumped parameter model of the material and a computerized iterative approach to obtain predictions of the breakout forces.

However, a need often arises to quickly estimate the breakout force once a few in-situ field tests have been made. In this case, Muga established the following empirical formula from field tests to describe the breakout force for seafloor soil:

$$F = Q\, A_{max}\, q_d\, e^{-R(t-t_o)} \qquad \text{(A-1)}$$

where

F = breakout force (pounds)

Q = constant

A_{max} = horizontal projection of the maximum contact area (in^2)

q_d = average supporting pressure provided by the soil to maintain the embedded object in static equilibrium (psi)

R = slope of the "failure line" when $\log(F/\underline{C}A)$ is plotted versus time, t

t = time allowed for breakout (min)

t_o = reference time (min)

A = horizontal projection of the contact area (in^2)

$\underline{C}$ = effective average cohesion along the failure surface at the instant of breakout (psi)

The values for the quantities Q, q_d, R, and t_o can be found from a few in-situ soil tests. The value for A_{max} can be found from the size and shape of the object and the depth of embedment. It is advantageous to apply the lifting force as slowly as possible, since as t becomes larger, the breakout force gets smaller.

The Muga report includes data from breakout tests with specimens conducted in San Francisco Bay. These tests were used to determine values for the constants in Equation (A-1), which now reads as:

$$F = 0.20 A_{max} q_d e^{-0.0054(t-260)} \quad \text{(A-2)}$$

where

$Q = 0.20$

$R = 0.0054$

$t_o = 260$

These parameter values are meant to be used only for seafloor sites that have soil characteristics similar to San Francisco Bay. These numeric values are shown here to give an order of magnitude to these constants for fine grain sediments.

Liu's Method

In his report[2] which concluded three years of breakout force research for the Supervisor of Salvage, Liu developed a dimensionless correlation between breakout force and time.

$$\frac{F_m}{F_r} = C_1\left(\frac{t}{T_{in}}\right)^{-C_2} \text{ for } 10^{-3} < t/T_{in} < 10 \quad \text{(A-3)}$$

where

F_m = mean value of estimated breakout force (lb)

F_r = static soil resistance (lb)

t = time allowed for breakout (min)

T_{in} = time of object embedment (min)

C_1, C_2 = constants

This correlation was determined from results of field tests conducted in the Gulf of Mexico and verified by laboratory model experiments. It must be pointed out that this equation is valid for seafloor soil similar to the site off the Louisiana Coast. Values for constants C_1 and C_2 are presented here to show their relative order of magnitude:

$$C_1 = 1.5; \qquad C_2 = 0.07 \tag{A-4}$$

The net breakout force F is considered to be a random variable, and a probabilistic relationship of the ratio F/F_m gives the limits for both necessary conditions: (1) breakout will occur at $F/F_m > 2.1$, and (2) breakout will not occur at $F/F_m < 0.42$. Again, these values are the result of field data of only one area of the Mississippi Delta. Using the basic Equation (A-3), the values for the constants, C_1 and C_2, and the necessary condition for breakout to occur, a more useful equation can be written to estimate the required breakout.

$$\frac{F}{F_r} = 3.15 \left(\frac{t}{T_{in}}\right)^{-0.07} \tag{A-5}$$

The probability of successful breakout using Equation (A-5) is 1.0.

The breakout time is very sensitive to changes in the breakout force. From this relationship and the uncertainties common to all soil mechanics problems, it is almost impossible to predict the breakout time with any degree of accuracy. Fortunately, it is not necessary to pinpoint the breakout time in most cases, but merely specify a maximum allowable breakout time as governed by rescue missions or poor weather environment. Therefore, it is desirable to minimize the time required for breakout to occur.

Lee's Method

In his report[4] Lee developed empirical relations for predicting the forces required to dislodge partially embedded objects immediately and the times required for breakout if forces less than these immediate breakout forces were applied. These relations were based on the NCEL San Francisco Bay and Gulf of Mexico field tests and a series of laboratory model tests performed during FY 1971.

Lee presented the following empirical equation for predicting the immediate breakout force:

$$\frac{F_{Ib}}{F_q} \text{ or } \frac{F_{Ib}}{F_q'} = 1.0 - 0.97e^{-2.75\left(\frac{D}{B}\right)} \tag{A-6}$$

where

F_{Ib} = portion of immediate breakout force carried by the soil

= $F_{\ell Ib} - W_b + W_s$

$F_{\ell Ib}$ = line force required for immediate breakout

W_b = weight of object in water

W_s = buoyant weight of soil displaced by object

F_q = downward force carried by soil prior to application of breakout force

= $W_b - W_s$

F_q' = bearing capacity force soil is capable of maintaining

$$F_q' = 6AS\left(1 + 0.2\frac{D}{B}\right)\left(1 + 0.2\frac{B}{L}\right) \qquad \text{(A-7)}$$

A = cross sectional area of object at soil-water interface

S = undrained shear strength of soil averaged over the sediment depth range, 0 to D + B

D = object embedment depth

$= \frac{V_s}{A}$

V_s = volume of object below soil-water interface

B = object width at soil-water interface

L = object length at soil-water interface

The decision as to whether to use F_q or F_q' rests upon the way in which the object became embedded. If the object was placed slowly (placement velocity less than 2 ft/sec) and the relative embedment depth (D/B) is greater than 0.25, then F_{Ib} may be estimated using F_q. Otherwise, F_{Ib} must be estimated using F_q'.

For cases in which a line force less than $F_{\ell Ib}$ is applied, Lee suggests the following empirical equation for predicting the time at which breakout will occur:

$$\log_{10} \frac{F_b}{F_{Ib}} = -.193\ (\log_{10} T - 3.84) \qquad \text{(A-8)}$$

where

F_b = portion of line force carried by soil

$= F_{\ell b} - W_b + W_s$

$F_{\ell b}$ = line force

F_{Ib} = predicted immediate breakout force obtained from Equation A-6.

T = normalized breakout time

$$T = \frac{pt_b}{D^2}\left(\frac{B}{D}\right)^2 \qquad \text{(A-9)}$$

t_b = time required for breakout after force application

$p = F_b/A$

Foot, minute, and pound units must be used in the estimate of breakout time.

Because of the amount of data scatter involved in his empirical correlation, Lee suggests a factor of safety of 1.5 on the immediate breakout force estimate and 2.0 on the breakout time estimate.

Breakout Force Calculations

The methods by Muga, Liu, and Lee are used to compute the predicted breakout forces on the three test objects of the harbor tests. The assumptions made in these calculations are based on the soil characteristics of Port Hueneme Harbor and the test object shapes. The time of embedment and time allowed for breakout are assumed to be constants.

Muga's Method

(1) Cylinder (2.5' D x 10'):

$x = \sqrt{225 - 36}$

$x = 13.75$

$B = 2x = 27.50''$

$L = 10' = 120''$

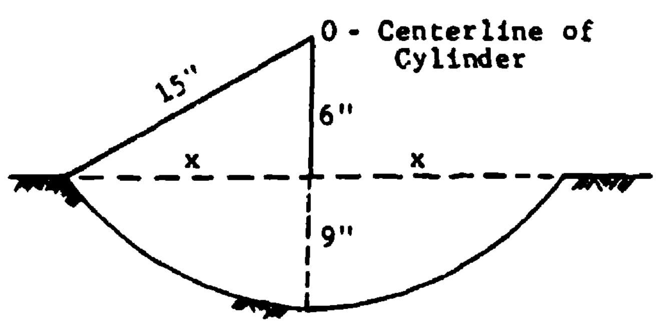

Figure A-1. Geometry of Embedded Cylinder

Assume - Embedment depth = 9 in.

q_u = 0.2 psi

t = 25 min.

First, the maximum horizontal contact area is calculated:

$$A_{max} = (2)\ (13.75)\ (10)\ (12) = 3300\ in^2 \qquad (A\text{-}6)$$

$$q_d = 2.85\ (1 + B/L)\ q_u = 2.85\ (1.23)\ 0.2 = 0.7\ psi \qquad (A\text{-}6a)$$

Using Equation (2),

$$F_B = F = 0.20\ A_{max} q_d e^{-0.0054(t-260)} \qquad (A\text{-}7)$$

$$F_B = 0.20\ (3300)\ (0.7) e^{-0.0054(-235)}$$

$$F_B = 1640\ lb. \qquad (A\text{-}8)$$

From Table 1 the cylinder wet weight is 4770 pounds; then the total applied lift force should be

$$F_c = 4770 + 1640$$

$$= 6410\ lb. \qquad (A\text{-}9)$$

with a breakout force of 1.34.

(2) Sphere (4.8' D):

$$x = (28.8)^2 - (10.8)^2$$

$$= 830 - 117$$

$$= 26.7\ in.$$

$$B = 2x = 53.4''$$

$$L = B = 53.4''$$

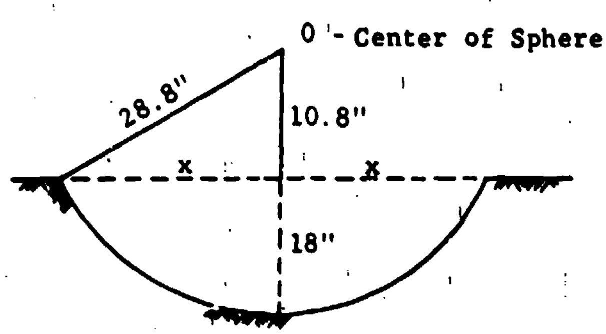

Figure A-2. Geometry of embedded sphere

Assume - Average embedment depth = 18 in.

q_u = 0.2 psi

t = 25 min.

The maximum projected contact area is found to be

$$A_{max} = \pi x^2 = \pi (26.7)^2$$

$$= 2240 \text{ in}^2 \quad \text{(A-10)}$$

and from Equation (A-6a)

$$q_d = 2.85 (1 + 1)0.2$$

$$= 1.14 \text{ psi} \quad \text{(A-10a)}$$

Again using Equation (A-2),

$$F_B = F = (0.2) (2240) (1.14)e^{-0.0054 (-235)}$$

$$= 1825 \text{ lb.} \quad \text{(A-11)}$$

Since the wet weight of the sphere is 5245 pounds, the total lift force required is

$$F_s = 5245 + 1825$$

$$= 7070 \text{ lb} \quad \text{(A-12)}$$

with a breakout ratio of 1.35.

(3) Block (3.5'):

The values for q_u and t are assumed to be the same as those for both the cylinder and sphere. The contact area becomes

$$A_{max} = (3.5)^2 (144)$$

$$= 1765 \text{ in}^2 \quad \text{(A-13)}$$

and B = L = 3.5'

Thus, q_d has the same value as calculated in Equation (A-10a).

Then the breakout force F_B is calculated:

$$F_B = F = (0.2)(1765)(1.14)e^{-0.0054(-235)}$$

$$= 1440 \text{ lb.} \qquad \text{(A-14)}$$

Then,

$$F_L = 3320 + 1440$$

$$= 4760 \text{ lb} \qquad \text{(A-15)}$$

with a breakout ratio of 1.43.

Liu's Method

(1) Cylinder:

With the same assumptions used in the previous breakout calculations, the average cohesion $\bar{c}$ can be determined

$$\bar{c} = \frac{q_u}{2} = 0.1 \text{ psi} \qquad \text{(A-16)}$$

also, $A_x = A_{max} = 3300 \text{ in}^2$ (A-6)

where A_x = base surface area of the failure prism

The side surface area A_s can be calculated:

$$A_s = (4.5)(2)(120 + 27.5)$$

$$= 1325 \text{ in}^2 \qquad \text{(A-17)}$$

Then the soil resistance is found from Liu's report.

$$F_r = \bar{c}\,(A_s + A_x) \qquad \text{(A-18)}$$

$$F_r = 0.1\ (4625)$$

$$= 463 \text{ lb} \qquad \text{(A-19)}$$

Substituting Equation (A-4) into (A-3) yields

$$\frac{F_m}{F_r} = 1.5\left(\frac{t}{T_{in}}\right)^{-0.07} \qquad \text{(A-20)}$$

Use 1080 min. for the time of embedment T_{in}, and calculate F_m.

$$F_m = 463\ (1.5)\left(\frac{25}{1080}\right)^{-0.07} \tag{A-21}$$
$$= 905\ \text{lb}$$

Then the lift force is

$$F_C = 4770 + 905 = 5675\ \text{lb} \tag{A-22}$$

With a breakout ratio of 1.19.

(2) Sphere:

Using the following assumed and calculated values for the necessary parameters, determine the soil resistance and then the mean breakout force from Equation (A-15).

Average embedment depth = 18 in

t = 25 min

T_{in} = 150 min

$\bar{c}$ = 0.1 psi

$$A_x = A_{max} = 2240\ \text{in}^2 \tag{A-10}$$

$$A_s = 2\ \pi\ (26.7)(9) = 1510\ \text{in}^2 \tag{A-23}$$

The soil resistance becomes

$$F_r = 0.1\ (2240 + 1510)$$
$$= 375\ \text{lb} \tag{A-24}$$

and the mean breakout force is

$$F_m = 1.5\ (375)\left(\frac{25}{1350}\right)^{-0.07}$$
$$= 742\ \text{lb} \tag{A-25}$$

Therefore,

$$F_s = 5245 + 742 = 5987\ \text{lb} \tag{A-26}$$

with a breakout ratio of 1.14.

(3) Block:

All of the constants used in the previous breakout prediction for the sphere are valid now except that the average embedment depth is 6 in. Thus, the two surface areas of the failure prism are

$$A_x = A_{max} = 1765 \text{ in}^2 \qquad \text{(A-13)}$$

$$A_s = 4(3)(42)$$

$$= 504 \text{ in}^2 \qquad \text{(A-27)}$$

Then the soil resistance is calculated,

$$F_r = 0.1\ (1765 + 504)$$

$$= 227 \text{ lb} \qquad \text{(A-28)}$$

and the breakout and corresponding lift forces becom

$$F_m = (227)(1.5)\left(\frac{25}{1350}\right)^{-0.07}$$

$$= 450 \text{ lb} \qquad \text{(A-29)}$$

and $F_L = 3320 + 450$

$$= 3770 \text{ lb} \qquad \text{(A-30)}$$

with a breakout ratio of 1.12.

<u>Lee's Method</u>

(1) Cylinder (2.5' D x 10'):

$$B = 27.5 \text{ in} = 2.29 \text{ ft}$$

$$L = 10 \text{ ft}$$

$$A = 22.9 \text{ ft}^2$$

$$V_s = 12.4 \text{ ft}^3$$

$$D = \frac{V_s}{A} \approx .542$$

$$\frac{D}{B} \approx .24$$

Therefore, F'_q must be used in the calculations.

$$F'_q = 6AS(1 + 0.2\,\frac{D}{B})\,(1 + 0.2\,\frac{B}{L}) \qquad \text{(A-31)}$$

Assume $S = 0.2$ psi $= 28.8$ psf

$$F'_q = (6)\,(22.9)\,(28.8)\,(1 + 0.048)\,(1 + 0.046)$$

$$= 4338 \text{ lb}$$

$$\frac{F_{Ib}}{F'_q} = 1.0 - 0.97e^{-2.75\,(\frac{D}{B})} \qquad \text{(A-32)}$$

$$= 1.0 - 0.97e^{-2.75(.24)}$$

$$= .55$$

$$F_{Ib} = 2169 \text{ lb.}$$

The mode of loading during this test series was to increase the line force gradually from zero until breakout occurred. Therefore, during most of this loading period the line force was less than the object weight in water. Only during approximately the last five minutes of each test was any upward force actually being carried by the soil. According to Lee's criterion this is immediate breakout, and the predicted breakout line force is $F_{\ell Ib}$ where $F_{\ell Ib} = F_{Ib} + W_b - W_s$.

Assuming a soil buoyant unit weight of 30 pcf,

$$W_s = 30\,V_s = 372 \text{ lb} \qquad \text{(A-33)}$$

$$W_b = 4770 \text{ lb}$$

$$F_{\ell Ib} = 2169 + 4770 - 372$$

$$= 6567 \qquad \text{(A-34)}$$

b.r. = 1.38.

(2) Sphere (4.8'D):

B = 53.4" = 4.4'

L = B = 4.4'

$$A = 15.29 \text{ ft}^2$$

$$V_s = 13.43 \text{ ft}^3$$

$$D = \frac{V_s}{A} = .88 \text{ ft}$$

$$\frac{D}{B} = 0.2$$

Therefore, F_q' must be used in calculations

$$F_q' = 6AS\ (1 + 0.2\ \frac{D}{B})\ (1 + 0.2\ \frac{B}{L}) \quad \text{(A-35)}$$

Assuming $S = 28.8$ psf again

$$F_q' = 3297 \text{ lb}$$

$$\frac{F_{Ib}}{F_q'} = 1 - 0.97e^{-2.75(\frac{D}{B})} \quad \text{(A-36)}$$

$$= .44$$

$$F_{Ib} = 1452 \text{ lb}$$

$$W_s = 30(13.43)$$

$$= 403 \text{ lb} \quad \text{(A-37)}$$

$$F_{\ell Ib} = 5245 + 1452 - 403$$

$$= 6294 \text{ lb} \quad \text{(A-38)}$$

b.r. = 1.20.

(3) Block

$$B = 3.5 \text{ ft}$$

$$L = B = 3.5 \text{ ft}$$

$$A = (3.5)^2 = 12.25 \text{ ft}^2$$

$$D = 0.5 \text{ ft}$$

$$\frac{D}{B} = .143$$

Therefore, F_q' must be used in calculations

$$F_q' = 6AS\ (1 + 0.2\ \frac{D}{B})\ (1 + 0.2\ \frac{B}{L}) \qquad \text{(A-39)}$$

Assuming S = 28.8 psf

$$F_q' = 2611 \text{ lb}$$

$$\frac{F_{Ib}}{F_q'} = 1 - 0.97e^{-2.75(\frac{D}{B})} \qquad \text{(A-40)}$$

$$= .343$$

$$F_{Ib} = 896 \text{ lb}$$

$$W_s = 30(0.5)\ (12.25)$$

$$= 183 \text{ lb} \qquad \text{(A-41)}$$

$$F_{\ell Ib} = 3320 + 896 - 183$$

$$= 4033 \text{ lb} \qquad \text{(A-42)}$$

b.r. = 1.[illegible]

These calcu[illegible] been summarized in Table A-1 for each object shape an[illegible] breakout prediction theories.

Table A-1. Comparison of Three Breakout Force Prediction Methods

OBJECT SHAPE	OBJECT WET WEIGHT (lb)	MUGA's METHOD			LIU's METHOD			LEE's METHOD		
		Break-out Force (lb)	Lift Force (lb)	Break-out Ratio	Break-out Force (lb)	Lift Force (lb)	Break-out Ratio	Break-out Force (lb)	Lift Force (lb)	Break-out Ratio
Cylinder	4770	1640	6410	1.34	905	5675	1.19	1797	6567	1.38
Sphere	5245	1825	7070	1.35	742	5987	1.14	1049	6294	1.20
Block	3320	1440	4760	1.43	450	3770	1.13	713	4033	1.22