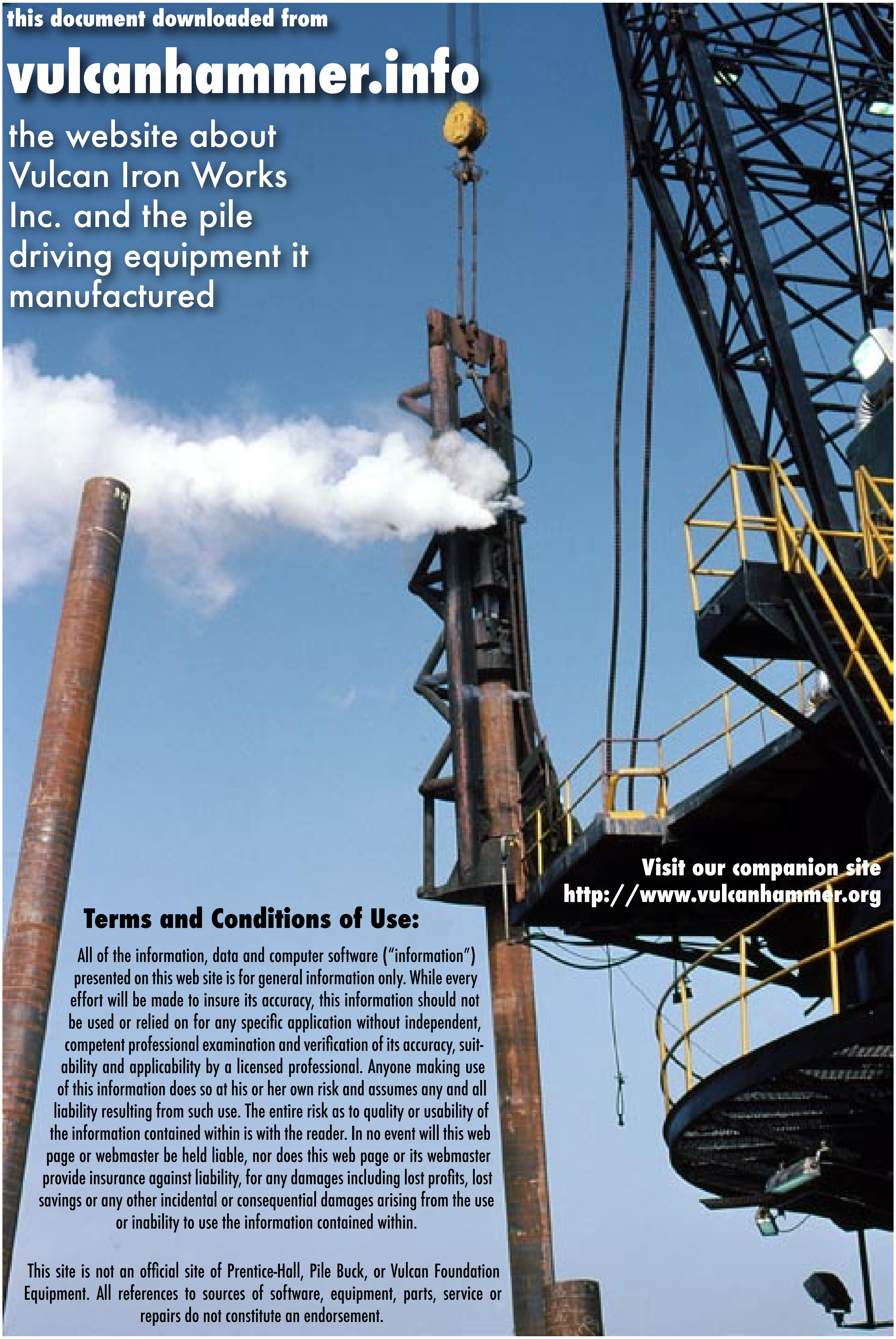

THE DESIGN CONCEPT AND DRIVING CAPACITY OF A 40 TON ABOVE/UNDER WATER HYDRAULIC HAMMER

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SUMMARY

As the exploration and exploitation of the world's offshore oil and gas reserves continues in both shallow and now deeper water; we believe that there will be an increase in demand for the driving of piles underwater for applications such as the driving of conductor tubes, pinning of templates, installation of single point moorings, floating breakwaters, buoyant bridges and tension leg platforms, etc.

This has led to the development of a hammer system suitable for all the above applications along with many other piling applications and that can be used for both above and below water operation. It is envisaged that the hammer will operate in both shallow and deep water environments up to depths of 300 metres.

The design concept and modular construction gives a completely flexible system capable of being tailored to suit a particular piling requirement.

This paper is in two parts: Part A discusses the development of the Hydraulic Hammer System and the need to prove its capability, reliability and durability. A rigorous programme of tests and trials were undertaken culminating in the testing of the 40 ton (H.A) piling hammer. This was carried out by driving a 1.22m diameter steel tube pile of 25mm wall thickness driven both above and eventually below water. The pile is closed ended and will be driven to refusal. This is taking place within a circular cofferdam 6.2m diameter, approximately 4.0m deep, through soil conditions consisting mainly of chalk with occasional flint layers.

The pile has been extensively monitored and analyses of the results are taking place.

Part B of the paper describes independent measurements made on the hammer and the upper portion of the pile, together with the results of associated analyses.

The instrumentation includes stress and acceleration measurements on the pile monitored, during above water driving. The results have been examined with particular reference to:-

1. The performance of the hammer under various modes of operation.

2. Supplementing the scant information currently available on the driving of Large Diameter Piles into chalk.

The hammer performance has been assessed by examination of stress time spectra and evaluation of total energy imparted to the pile. The results of wave equation and impedence type analyses have been used in conjunction with the measurements to establish appropriate values for such drivability parameters as quake and damping for chalk.

PART A

Introduction

From the early 1970's it was evident that the exploration and exploitation of oil and gas reserves was going to enter deeper and deeper water. It was, therefore, clear that an underwater piling hammer would help with the installation of driven piles into the sea bed, etc. This concept led to the design of a range of hydraulic piling hammers for use both above and below water to considerable depths. It was decided to develop a hammer on an interchangeable modular system. The major component of the total system being the hydraulic actuator which provides the lifting mechanism for the ram weight. The actuators are of various capacities, along with varying sizes of ram weights and guide cages for numerous piling applications.

The Hydraulic Actuator

The hydraulic actuator is shown in Fig. 1 and basically provides a cylinder with an extendable piston rod which lifts the various ram weights. Either side of the cylinder is the low pressure and high pressure accumulators, thus the piston is extended in the cylinder when hydraulic fluid flows under high pressure from the power source and the high pressure accumulator through ports into the cylinder. Towards the end of the stroke the fluid from the high pressure port is shut off and the velocity of the piston thus slows to an equilibrium position and then begins the downward stroke. When this occurs, oil from the cylinder is transferred from the full bore side of the cylinder to the other side of the piston head and also into the low pressure accumulator and return line to the power source and fluid pressure is again increased in the high pressure accumulator ready for the next stroke.

Tests were first carried out on a 5 ton capacity actuator to determine its efficiency by varying flow rates, accumulator precharge and back pressures. The actuator was used to lift a drop weight of approximately 2.5 tons and this was placed on a set of conventional piling leaders to drive a 0.457m diameter steel tube pile. In all, eighty tests were recorded and the actuator and hammer efficiency under free fall calculated at 89%. From these tests it was clearly evident that there would be no major problems involved in scaling up the 5 ton actuator to the 10 and 20 ton capacities envisaged.

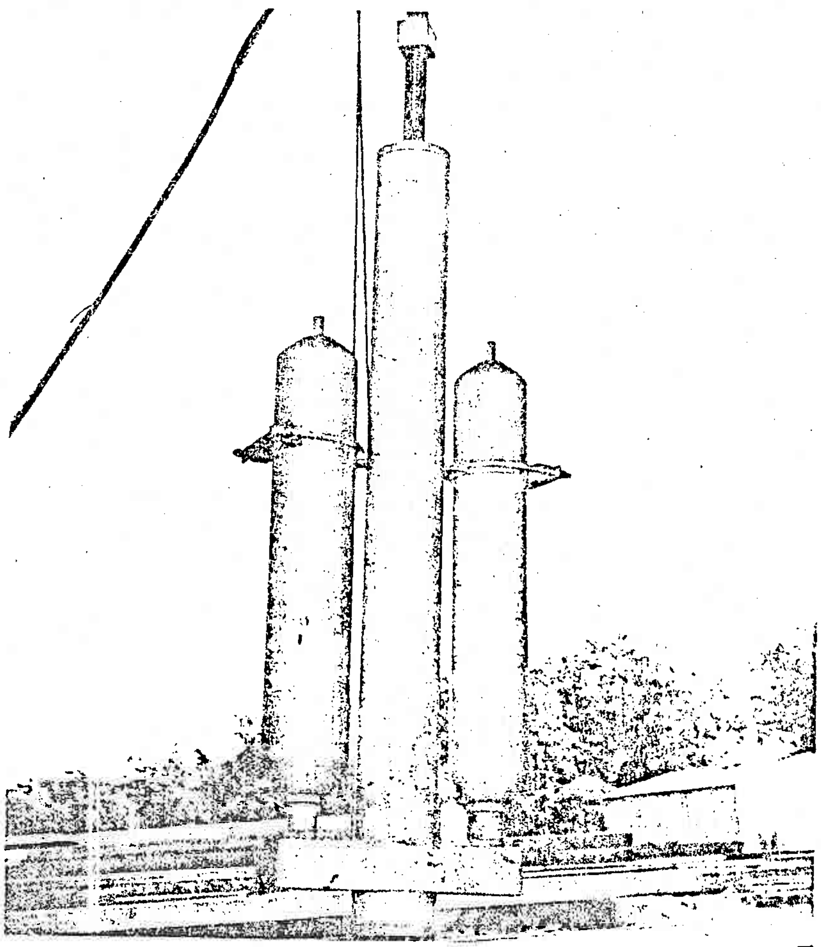


Fig. 1

Hydraulic Actuator

Efficiency Tests

A series of tests were undertaken to compare the efficiency of the hammer in water with that in air, and determine the best shape possible. Firstly, theoretical calculations were undertaken. An assessment of a piling hammer operating in air is very simple, the energy capacity available from the falling ram weight at impact being generally the criteria used and can be calculated by simple laws of motion. Experience has shown that frictional loss is minimal. However, in water other factors are involved and the initial series of tests were to primarily establish these factors, relevant to assessing the kinetic energy of a drop weight falling through water, which will allow the actual energy capacity of a hammer system to be predicted and also enable the design of hammer to be chosen that will minimise the effect of these factors.

The theoretical approach has been concentrated on an idealised cylinder which is easier to evaluate. The variables under consideration were the drag coefficient, the physical proportions of the falling weight, the mass of water entrained with the falling weight together with external friction effects.

All these various factors were considered and finally by using a simple numerical technique whereby the motion of the body is advanced in increments, and considering a particular free-falling, unguided weight in water, the formula for the equation of equilibrium of motion becomes

[illegible] $$\text{MASS} - FT)\, g - 3.11 \times C_d \times \frac{(dy)^2}{(d\theta)} = 1.128 \times \text{MASS} \times \frac{(d^2y)}{(d\theta^2)}$$

where FT = External Friction Forces
C_d = Drag Coefficient
g = Gravity

Substitution of the values into the above equation then enables us to obtain a theoretical guide to the efficiencies of a falling weight through air or water.

To try and prove the above, model tests were undertaken with various shaped unguided weights which were allowed to fall from rest within an 800 gallon rectangular tank. The displacement of the falling weights and duration of fall from rest were monitored for three different shapes.

a) Cylindrical
b) Semi Elipsoid
c) Stepped

From the tests the comparison of the performance of differing shaped weights of the same mass and sectional area falling through water are summarised in Fig. 2. and indicate the difference in performance to be quite insignificant. This infers that the drag coefficient (Cd) itself does not play a major part in the performance of the falling weight. A further assumption was made that the falling body carries with it a volume of water no greater than the volume of the body.

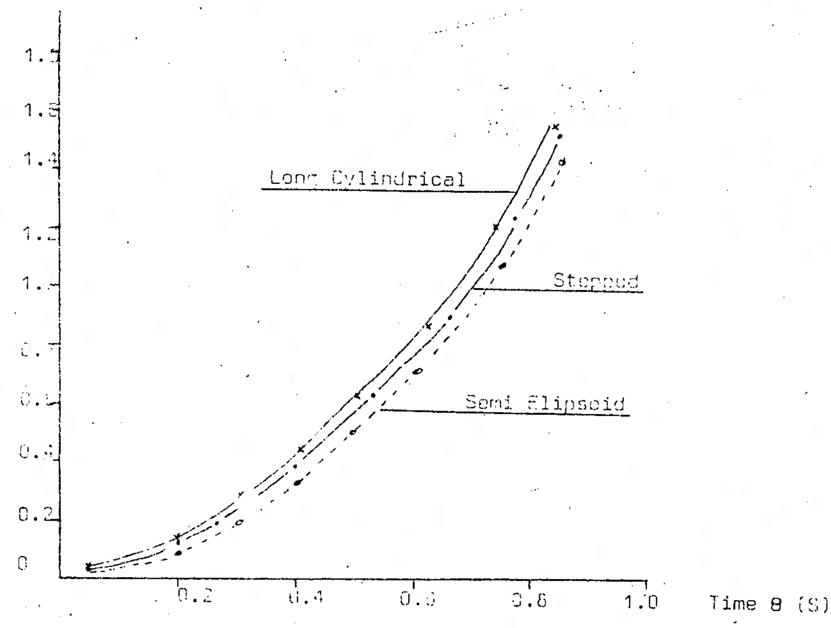


Fig. 2.

...ison of Different ...eights Falling ... in Water.

From all the results the following can be ascertained:-

a) The value of the external friction force (Ft) is evidently clearly contributory to the major deviance in the results expected, the solution worsening as the mass of the falling weight was reduced. This problem of the frictional forces resulted from the test arrangement used for these particular experiments. In the case of a full size piling hammer, neither the frictional forces acting on the falling weight, nor the forces retarding the weight, caused by back pressure in the hydraulic cylinders, should be ignored. The effect of the latter can be minimised by the choice of suitable hydraulic return hose, whereby fluid friction loss in the hose can be kept to a minimum. As the size and weights increase the performance should accurately reflect that which could be anticipated.

b) The value of drag coefficient (Cd) was found to have minimal effects on the shapes chosen.

c) It is noted that for the value of the effective mass (Me) no improvement resulted in the predicted performance if one considers that less water was entrained with the falling weight.

d) The relationship of length to diameter is critical and altering proportions caused performance variation.

In conclusion, whilst the actual results of the series of tests have been somewhat distorted by the scale of the models used, we have been able to recognise the major factors likely to effect performance of a weight falling in water. The next series of tests involve a full scale trial and should be able to confirm the conclusions without inherent distortions.

Testing of 9 Ton Drop Weight

As before in the model tests the procedure is to monitor the fall of the drop weight from rest with respect to a time base. The measurements of the slope of the curve of displacement against time provide us with the velocity of the falling weight of any particular point.

The tests were conducted with a 9 ton hammer operating in air and in water and subsequently repeated in order to check on the consistency of the results.

The tests were carried out within a water filled cofferdam. The cofferdam was formed from 50 sections of Larssen 2 sheet piles, each 10 metres long, pitched inside a template to form a circle. At the centre a 762mm diameter, 50 metre long, tubular pile, had already been driven, the base of a cofferdam was excavated to a depth of 1.5 metres below ground level.

As anticipated from early experiments, the results obtained in the case of this full size test were quite encouraging when compared with those anticipated by the theoretical analysis. This is mainly accounted for by the frictional losses being much smaller in proportion to the size of the falling mass than in the earlier model tests. At the typical rated stroke of 1.37 metres the following performance data is extracted.

	VELOCITY M/S	
	AIR	WATER
Theoretical	5.18	4.42
Experimental	5.16	4.30
% Error	1%	2.8%

The reduced impact energy is given by:-

$\frac{4.3^2}{5.16^2}$ which equals 69% for the same mass of falling weight.

If the mass of falling weight is increased to utilise the same available energy from the hydraulic cylinders then increased mass equals $\frac{7.83}{6.89}$ which equals 1.146 x Mass.

The reduced impact energy becomes 69% x 1.146 and is, therefore, 79% efficient below water.

The results obtained indicate that in general the shorter cylindrical shaped drop weights give suitable efficiencies both above and below water.

Investigation Of The Use of Water As a Drive Cushion

From the previous experiments, we can be reasonably certain of the velocity of a body falling through water. This enables us to assess the kinetic energy of that body at a point where its motion is arrested by impacting on a face. At impact, particularly in water, we are unsure as to the efficiency with which the kinetic energy is transmitted through to the pile in the form of impact energy. It is, however, desirable to afford some protection to both the falling drop weight and the top of the pile from excessive impact forces.

Conventionally in air this is done by transmitting the impact forces from the hammer to the pile by a resilient material, such as timber or coiled wire rope. Alternatively in sophisticated hammers the drop weight impacts onto the elements supported by hydraulic oil under gas pressure.

When a hammer operates submerged we suspect the efficiency by which the kinetic energy of the hammer is dissipated into the pile is impared by the rate in which the water contained between the closing impact faces can be displaced radially to the surrounding water.

Our next set of experiments were set to assess the degree to which this water film influences the build up of the impact forces in the pile and to set out to optimise this, by varying the geometry of the impacting faces, to render the need for a resilient material to protect the hammer and pile from excessive impact forces unnecessary.

As with the earlier test to ascertain the best shape of the ram weight, we firstly examined the behaviour of small scale models and extended the experience gained to full scale tests involving the 9 ton hammer, impacting on the pile already described. The model tests were aimed at observing the effect of three variables on the impact stresses by a weight falling onto a surface whilst underwater:-

a) The effect of the impact velocity by varying the height from which the weight has fallen.

b) Variations in the geometry of the falling weight.

c) Variations in the geometry of the impacting surfaces.

Some of the results obtained can be seen in Fig. 3.

Conclusions

The results of the tests show clearly that the standard drive cap would be unsuitable for use underwater where water would be present between the impacting faces, the degree of attenuation of the peak forces being unacceptable. If one considers the results of the tests conducted with the special form drive cap, then in terms of maximising the peak stress, then design tested, provides us with the best results we could expect, but at the same time the rate of increase of stress on the pile has been effectively reduced whereby the risk of damage to the pile head and the chassis of the hammer is minimal.

Generally, it is suggested that the hammer will operate satisfactorily underwater without the need for an air bell providing the marginal reduction in impact performance of . 25% is acceptable. If this is not the case then the stroke of the hammer could be increased to increase the impact velocity and/or mass of the drop weight increased to increase the kinetic energy at impact, and also utilising more fully the available horsepower.

The benefit of using the water film as a cushion, however, must not be forgotten, particularly when compared with the complexity of the construction of other hydraulic underwater hammers, or the tediousness of replacing timber cushions, used in conventional above water steam hammers driving through the follower system.

All the tests proved that with the special drive cap most piles could be effectively driven underwater. As all the previous tests and experiments proved successful and effective it was decided to continue with the development programme.

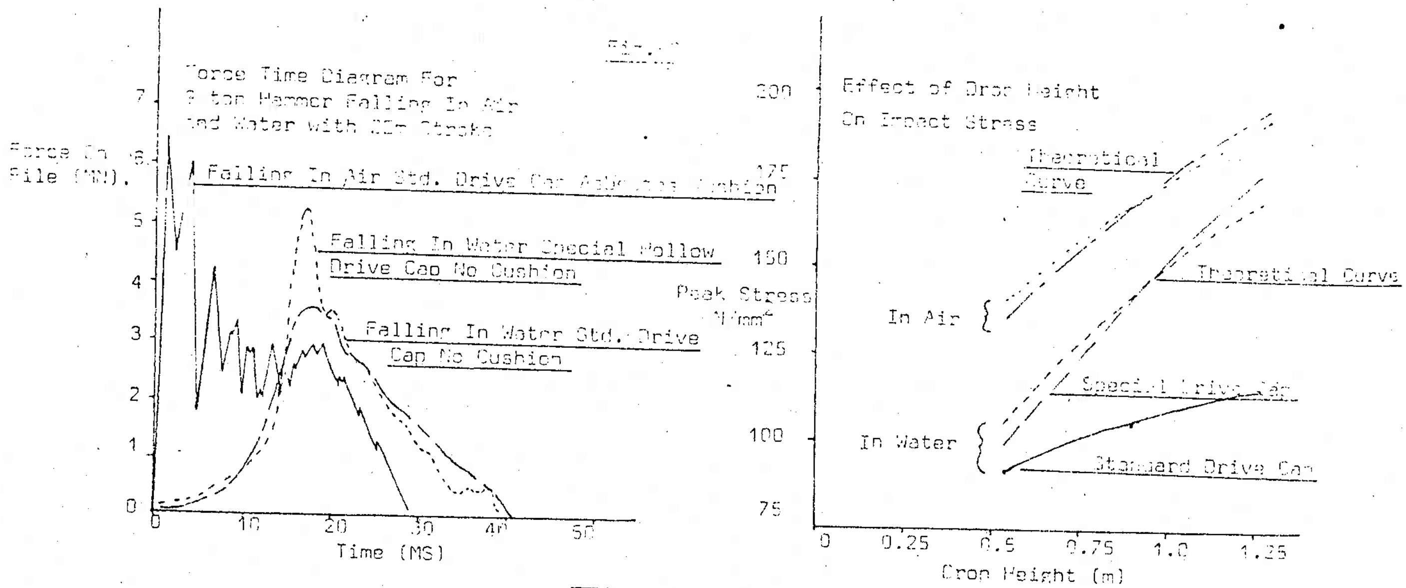
Underwater Trials

After completion of the land based trials it was decided to take the 10 ton ram weight hammer offshore to drive a pile on to the sea bed. The trials took place at Loch Linnhe, Scotland, in approximately 120 metres of water.

The pile used in this instance was for consideration of pontoon stability, only 10 metre overall length x 762mm diameter, but the duration of driving was intended to be extended by a flange 2 metres from the top of the pile, being arrested by the pile guide, which has a much greater area in contact with the bed of the lake.

The hammer size used was the 10 ton version which was fully instrumented. The depth of water in which the pile and hammer were placed was measured by using the pneumatic athometer method.

The pile frame, winches, power pack and hammer were all stored upon a specially designed barge, as can be seen in Fig. 4. The pile and pile template were lowered down guide wires to the sea bed and then the hammer was guided down the same wires and interlocked with the top of the pile.



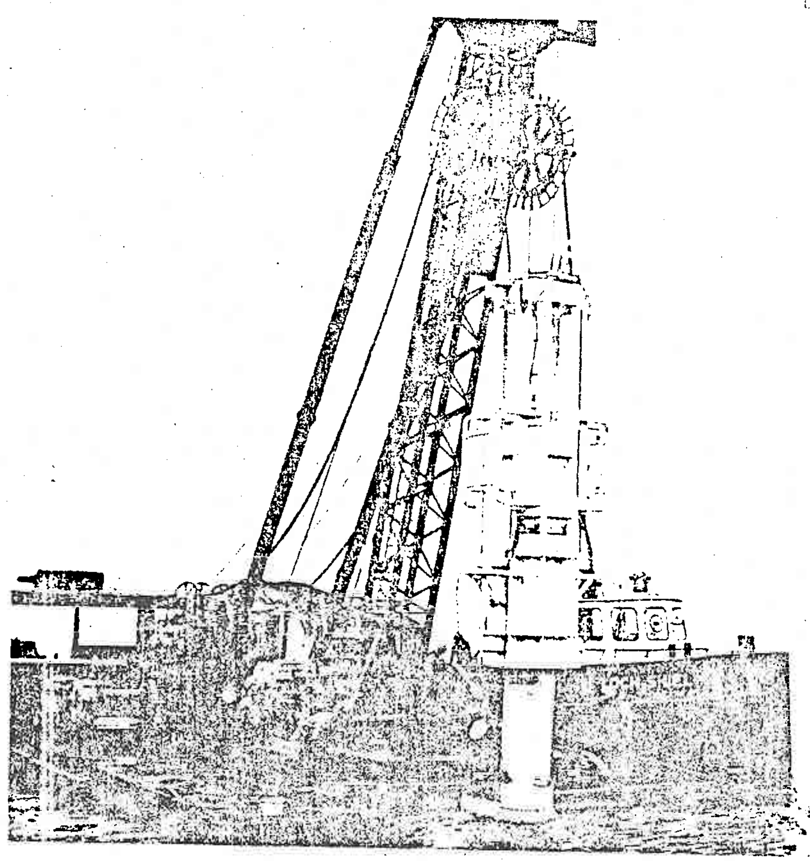


Fig. 4.

Barge and 10 Ton Hammer System Used for Underwater Trials at Loch Linnhe.

A camera observed the approach of the hammer to the pile and the picture was simultaneously relayed to a monitor on the barge so that the operator could fully negotiate the seating of the pile in the cone.

The drive cap resting on the pile was indicated by the first proximity switch on the control panel lighting up.

The whole system is controlled by a remote electric hydraulic system which allows for both manual and single blow operation and for an automatic sequence. This enables the stroke to be varied from 0.3 metres to 1.5 metres during operation and allows for the blow count to be varied to suit individual circumstances.

The height of stroke and blow count will be indicated at the surface at all times and the velocity at impact was recorded on the oscillascope and provision is made to indicate the penetration per number of blows with the manometer system.

Although the verticality of the pile at Loch Linnhe was checked by a signal from an inclinometer which was situated at the top of the hammer, the extra weight on the pile when the hammer interlocked caused the pile to be pushed 4.6 metres into the bed of the lake. The pile was then given several blows with the hammer and was quickly driven to the remaining pile test length, until the flange met the pile guide.

Hard driving conditions could now be attained. However, the operations had to be curtailed as the pile and pile guide tilted to such an angle that driving was no longer possible. The hammer system spent a total of 14 hours in sea water and no ingress of water was noted within the hydraulic actuators at the end of this period.

Although the tests were unable to continue, enough information had been gained to indicate that the total package hammer and in particular the hydraulic cylinders would operate sufficiently well in a reasonable depth of water, and it was envisaged that no problems would occur at even greater depths.

From the successful underwater trials, it was decided to link up 20 ton actuators with a 40 ton ram weight and guides and also manufacture a drive cap and cushion, etc.

40 Ton Ram Weight Hammer

At our original test site within the cofferdam it was decided to ascertain the overall capability, reliability and durability of the 40 ton hammer system by driving a 1.22m closed ended steel tube pile into material mainly consisting of soft to hard chalk. The sections of pile driven are between 4.0m and 5.0m long, and are extended by welded joints.

The hammer is shown in Fig. 5 and the driving record Fig. 6. At present the pile has reached a depth of 45.36m and as yet, refusal conditions have not been reached, but this is expected shortly. The hammer has performed approximately 14000 blows on the pile at various stroke heights. Generally at the commencement of each driving period we have attempted to use a longer stroke, hence reaching high energy at the start of the drive. This has caused a "set up" effect to appear on the driving record. Monitoring of the pile has continued throughout the driving period, and some of these results are discussed in Part B of this paper. At present over 8 hours driving has taken place and the 2 No. 20 ton actuators being used have presented no problems. They were removed and examined after approximately 8000 blows and showed no sign of wear. After further driving of the pile, using the full stroke of 1.37m at refusal conditions, we will then be aware of the hammer capabilities above water. It is envisaged that after completion of the above water trials, the cofferdam will be flooded to try to attain underwater driving conditions. Further monitoring of the pile and hammer will then take place.

PART B

The installation, by driving of a 1.22m diameter pile to a depth of about 50m completely in chalk presents a unique opportunity to examine the response of chalk to driving action. Piles of such size are rarely driven onshore although they are common place on offshore structures.

In order to examine independently the performance of the BSP 40 ton hammer whilst at the same time gaining valuable data on piling in chalk, Fugro Limited offered to make measurements on the test pile. The measurements were secondary to BSP International Foundations main aim of installing a pile which would provide a realistic test bed for their hammers. Measurements were only made at one depth of penetration but further measurements are planned.

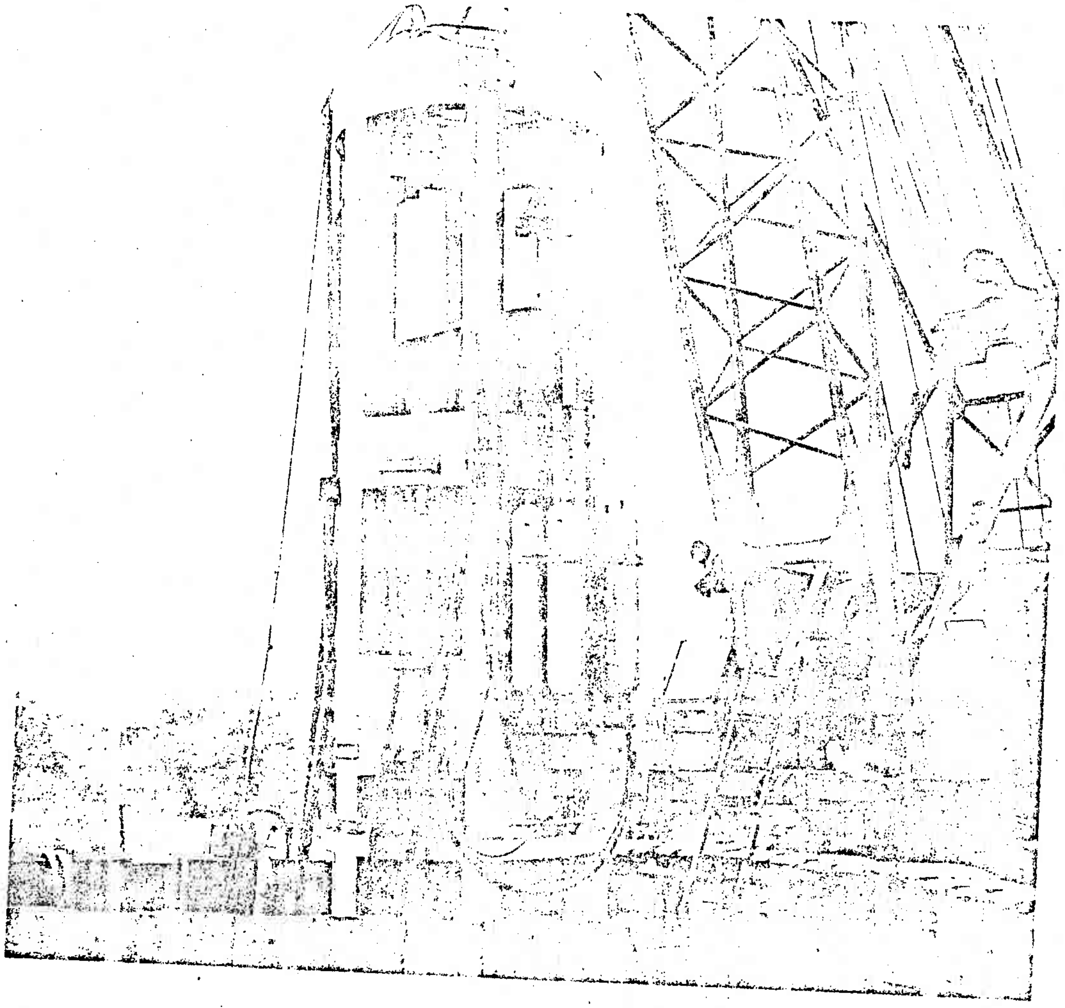
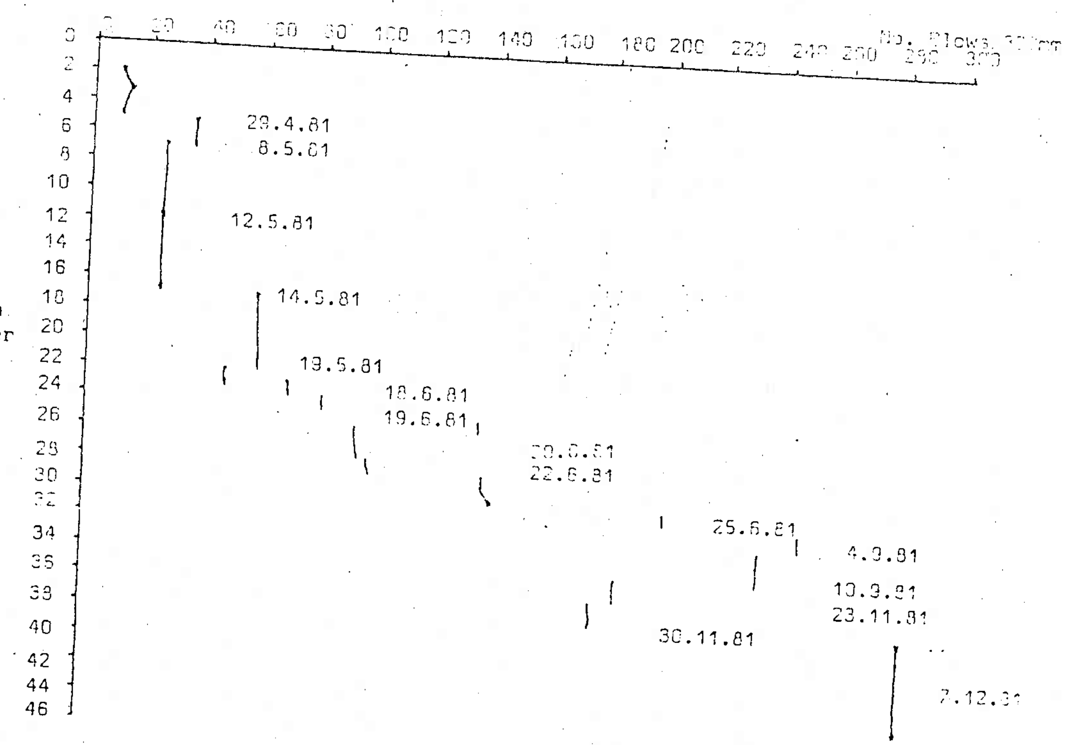


Fig. 5

40 Ton Hydraulic Hammer Driving 1.22m Tube Pile Within Cofferdam

Fig. 6



Depth (m)

Driving Record For 1.22m Pile Driven With 40 Ton Hydraulic Hammer

easuring Techniques

Strain and acceleration measurements were made on the outer surface of the pile at a vel three pile diameters below the driven head. Use was made of bolt-on transducers obtained Pile Dynamics Inc. These sensors were mounted in pairs diagonally opposite each other. view of the slight rake of the pile the appropriate diagonal to minimize the effects of nding was selected.

The sensors were connected to a Fugro designed signal conditions which, in addition to roviding the excitation voltage, permits signal amplication averaging of signals and tegration. The amplified signals were fed directly into a seven track FM recorder. Two annels of recorded signal were simultaneously examined on a digital oscilloscope.

est Sequence

At the time of making the measurements the pile had penetrated 31m below the ground level within the caisson. At this stage the sensors were about 2.5m above ground level, the total stick up being about 6m.

The 40 ton hammer was fitted with a 200mm elm cushion on end grain. Driving was carried t at various set stroke lengths during which time the sensors were continuously monitored. e to the nature of the test programme no measurements were possible immediately before and after a significant break in driving.

alyses

Typical records for hammer strokes of 0.68m, 0.84m and 1.02m have been examined in etail. The analogue records were digitized and stored as computer data files. Using an pproach akin to that described by Dolwin and Poskitt (Ref.1) an attempt was made to establish n acceptable mathematical model of the driving. In their paper Dolwin and Poskitt describe imilar independent measurements made on the same pile and the same hammer, but using a ngossi cushion.

The elm cushion fitted during the tests described here proved considerably softer than gossi which influenced both the magnitude of the initial peak force in the pile and the rise to this peak. As a consequence the measured peak acceleration and stress were influenced he arrival of reflections from the upper levels of the chalk. Any model set up to describe is part of the blow had therefore to include this soil influence.

Preliminary analyses indicated that the soil damping and quake parameters normally used Fugro were inappropriate for this site. Use was made of the side and end quake and damping lues established by Dolwin and Poskitt. The period of interest for assessing hammer rformance (the first 6 milliseconds) is relatively insensitive to these values.

Wave equation anaylses were made for a wide range of cushion stiffness, cushion estitution hammer efficiency and soil resistance distributions. A manual optimization process s used to obtain the best fit between predicted and measured stress and acceleration profiles r the 1.02m stroke blow. The values established for these parameters for the fit shown on igs. 7 and 8 were:

Cushion Stiffness	1250 kN/mm
Cushion Restitution	0.3
Hammer Efficiency	65%

Soil resistance - triangular distribution of side friction totalling 3000 kN with dditional 4000 kN applied to the pile tip.

It should be noted that the efficiency quoted represents the fraction of the total ergy available at ram impact from a free fall through the full stroke of 1.37m. Since the troke for this blow was constrained to be 1.02m the "effective" hammer efficiency amounts to [illegible].7%.

The parameters established above were then used for a range of hammer efficiency values o obtain best fit solutions for the measurements made for the 0.68m and 0.84m stroke blows. e 'best' solutions were obtained at overall hammer efficiency values of 54% and 44% spectively which represent 'effective' efficiency values of [illegible].3% and [illegible].1%.

The measurements thus indicate very consistent and highly efficient hammer performance e range of stroke lengths monitored.

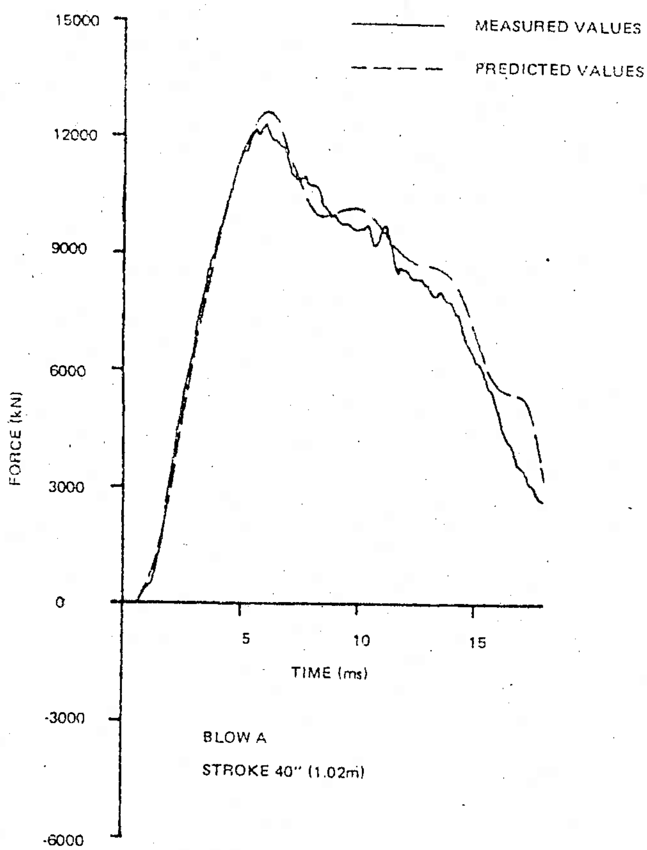


FIG 7

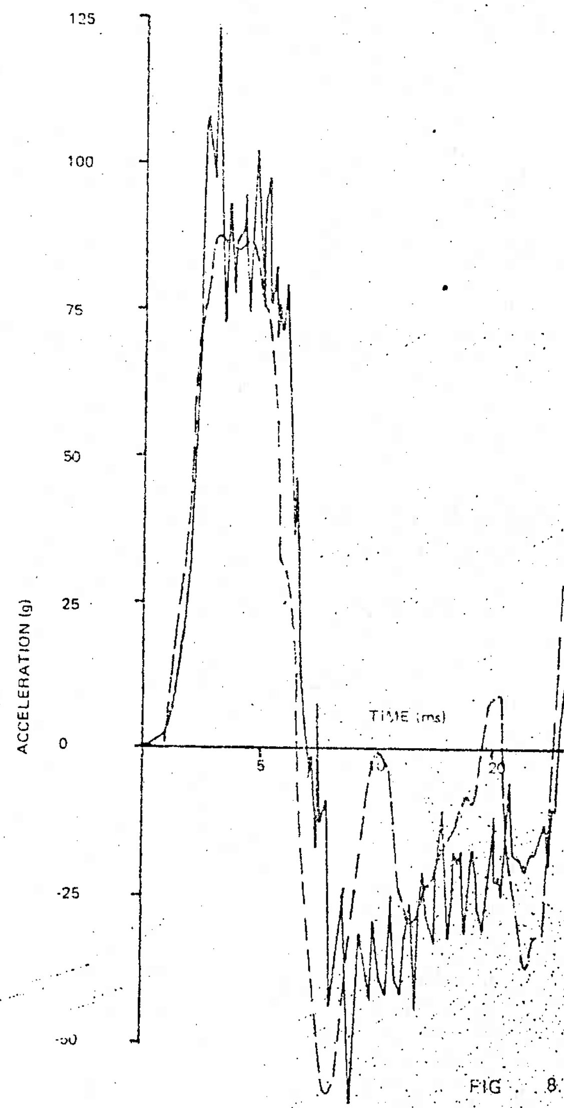


FIG 8

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Acknowledgements

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