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THE EFFECT OF COMPACTION
ON
PIPE-SOIL INTERACTION

Nuri Ener

Boğaziçi University

June, 1986

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ON
PIPE-SOIL INTERACTION

by

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PIPE-SOIL INTERACTION

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ABSTRACT

The friction forces between the pipe and the surrounding soil are required in pipeline design. Presently there is insufficient information available regarding pipe-soil interaction. This information is needed to determine the horizontal forces acting on the pipe when the pipe is expanded under the action of temperature and pressure differences.

Although there is available information on the static coefficient of friction for many materials, there is a lack of data on friction between soils and various coatings used in the pipeline industry. The effect of compaction is known very little on the pipe-soil interaction. In the past, coefficient of friction information was taken from the literature that was believed to have a similarity to the external pipe coating to soil interfare. With the development of tapes and plastic coatings and the increase use of these systems in the pipeline industry, a change from conventional coatings to tapes and plastic coatings would indicate a significiant change in the coefficient of friction design criteria.

An experimental model was prepared in the laboratory in order to determine the coefficient of friction and horizontal forces acting on the pipelines. Influences of the degree of compaction, soil density, water content, the size of pipe diameter and the use of different types of coatings were investigated in this laboratory test system.

ÖZET

Master tezi olarak hazırlanan bu çalışmada; serbest ve sıkıştırılmış zeminlerdeki boruların yatay doğrultudaki hareketlere karşı gelen kuvvetler incelenmiştir.

Günümüzde yaygınlaşan boru hatları üzerlerinde sıcaklıktan, basınçtan ve zemin hareketlerinden dolayı gerilmeler ve hareketler gözlenmektedir. Bu tezde boru üzerindeki kuvvetlerin azami değerleri basit bir sistem kullanılarak hesaplanmıştır.

Borularda korozyon etkisi de düşünülerek, borulara sarımlar da yapılmış ve yatay hareketler bu koşullar için de hesaplanmıştır.

Boru çaplarında, zeminin su muhtevasında ve zeminin sıkıştırılmasında yapılan değişikliklerin ve farklı sarım kullanılmasının sürtünme katsayısına olan etkileri incelenmiştir.

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LIST OF SYMBOLS

Symbol	Meaning
A	area of the pipe
A_s	surface area of the pipe
c	cohesion intercept
D	diameter of the pipe
F	friction force
G_s	specific gravity of the soil
H	height of soil from the center of the pipe
I_p	plasticity index of the soil
K_o	lateral pressure coefficient
L	length of the pipe
N	normal force
R	radius of the pipe
T	pull out force
V	volume of the container (or mold)
W	weight of the soil in the container (or mold)
W_p	weight ofthe pipe
ω	water content
ω_{omc}	optimum moisture content
L	liquid limit of the soil
p	plastic limit of the soil

LIST OF SYMBOLS (Cont'd)

α	angle from the vertical axes
γ	wet unit weight of the soil ($=\gamma_{wet}$)
γ_d	dry unit weight of the soil ($=\gamma\ /1+\omega$)
μ	coefficient of friction
Σ	summation
σ	normal stress
σ_a	vertical stress above the pipe
σ_b	vertical stress below the pipe
σ_H	horizontal stress
ζ	shear stress
ϕ	angle friction

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I. INTRODUCTION

World's present need for energy has led to the construction of a large network of pipelines. More oil, gas solid fluid can be transferred from the place of production to the place of consumption by the use of pipelines.

Different soil conditions create serious corrosion effects on pipes. Therefore some protection methods are needed for preventing the pipelines from corrosion effects. In the past stripping of the coating due to pipe-soil friction has been a problem which resulted in severe corrosion damages.

In pipeline design the frictional forces between the pipe and the surrounding soil are needed. Presently there is insufficient information available regarding pipe-soil interaction. This information is needed to determine the horizontal forces acting on the pipe when the pipe is expanded under the action of temperature and pressure differences.

In this study experimental model was prepared in the laboratory in order to determine the horizontal forces acting on the pipelines.

The aim of the study is to investigate the influence of the parameters of the degree of compaction, soil density, water content, pipe diameter and the use of coatings on the frictional forces.

A total of 248 tests were carried out for the determination of the effects of these parameters. Some useful and acceptable results were obtained during the tests.

The contents of the chapters are :

First chapter is a general introduction to the study. After the introduction, a literature review can be found in chapter two. General reviews of pipeline construction and the use of coatings are explained in this chapter.

In chapter three; analysis of pipe stress is given.

In chapter four; details of experimental set-up and materials are explained. This chapter is followed by chapter five, where the experimental procedure is presented.

The obtained results and a discussion are given in chapter six.

The study terminates with chapter seven where the conclusions take place.

II. LITERATURE SURVEY

2.1 GENERAL REVIEW OF PIPELINE CONSTRUCTION

Pipelines of the types used for gas lines, watermains,and the like have served to improve the standard of living of mankind since the down of civilization.

The efficiency of the pipeline was recognized and utilized very early in civilization. It is believed thatthe Chinese had piped water through bamboo lines about 5000 B.C and by 900 B.C. they were piping natural gas to brine evaporators.(Journal of the PIPELINE DIVISION. Proceedings of the American Society of Civil Engineers. January, 1959) Rome had a water system that handled 332 million gallons of water per day by about 200 B.C. Some of the pipes in the water system were made of lead. Bronze piping with silver faucets were found in the baths of Caracalla. From the standpoint of size and of engineering design, this piping system was not excelled for about 2000 years. The joints of pipe laid in the first underground system of iron pipe constructed in Paris in 1685. The joints were one meter long and coupled by bolted flanges. Part of this system is still in use today.

tried, tested and accepted for use on some pipelines. Coatings of asphalt and inert aggregates applied in thick coatings are used for special applications. Rubber, nylon and other plastic materials have been successfully combined with steels, and steel is being glass coated with bonds of high strengths. A wide range of dry plastic coatings and tapes are used on today's pipelines because of easier application to the pipelines.These materials simplify pipeline construction and give efficiency for corrosion control.

2.2.1. Coatings in Corrosion Protection

Steel pipelines are used for the transportation of gases, water, mineral oil, long-distance heating water and chemical products as well as for the hydroulic transportation of solid materials. In most cases the pipe material is unalloyed or low alloy steel. Stainless steels (high alloy steels) are used for special applications. Corrosion is seen on unalloyed or low-alloy steels.(Mannesmann-Röhrenwerke Catalogue)

Corrosion is the reactions of the material in question with chemical constituents of its environment. The changes resulting from these reactions are manifestations of corrosion. In the case of steel in water and humid soil, the corrosion manifestation is always the transformation of iron into corrosion products, mostly solid, called rust.

In case the construction element does no longer perform its task on if it may stop functioning within its projected service life, then there is damage. Generally corrosion damage may be taken to have occured, if the wall thickness falls to the of the specified minimum.

The maximum tolerable rate of corrosion of steel pipelines is 0.01 mm. per year. (Mannesmann-Röhrenwerke Catalogue) Corrosion rates drop in the course of time due to the formation of surface layers.

When the corrosion protection is correctly applied, it ensures the corrosion being less serious to a rate not exceeding the tolerable maximum. There is neither a technical necessity nor the possibility in common practice to achieve zero corrosion rate.

There are different methods of corrosion protection for underground pipelines that work in different ways. Which method should be applied mainly depends on the relevant conditions that may stimulate or mitigate corrosion.

2.2.2 Effectiveness of Coatings as a Means of Corrosion Control

First attempts to control pipeline corrosion relied on the use of coating materials. If the pipeline metal could be isolated from contact with the surrounding earth, no corrosion could occur. This concept is entirely reasonable and logical. A coating would be completely effective as a means of stopping corrosion if :

a) The coating material is an effective electrical insulator.

b) It can be applied with no breaks whatsoever and will remain so during the backfilling process. It must be mechanically as resistant as possible to minimize frequency and extent of mechanical damage, and

c) It constitutes an initially perfect film which will remain so with time. It must be stable for a long time in the ground. This is asking more than can be expected from presently available coatings which are in a price range making them economical for pipeline use.

Although coatings, by themselves, may not be the one perfect answer to corrosion control, they are an extremely effective weapon when properly used. A properly selected and applied coating will provide all the protection necessary on most of the pipeline surface to which it is applied. The protection should be better than 99 percent on a typical well-coated pipeline. (A.W.Peabody,1967)

2.2.3 Coating Application Procedures

Some of the more important application procedures influencing the quality of a completed pipeline coating include :

1) A Properly Cleaned Pipe Surface

All oil and grease must be removed by solvent cleaning. Sand, shot or grit abrasive cleaning will effectively remove all other material and leave the best surface for coating application. Pipelines coated "over the ditch" on job sites usually are surface prepared by line travelling cleaning machines using steel brushers and scrapers. These machines may remove all loose rust, dirt and some mill scale, but some tightly adherent material such as tight mill scale will not be removed. The brushes tend to burnish the steel surface rather than give it a "tooth" to help anchor coatings as is the case with abrasive cleaning. Such on-site compromise cleaning procedures are adequate if the brushes and scrapers on the cleaning are kept in good condition and in proper adjustment.

2) Careful Priming Techniques

Most coating materials used on pipelines require, or will perform better with, a primer of a material designed by the manufacturer to give the bets practicable bond between the pipeline metal and the coating. Conventional primers must be applied over a previously cleaned dry surface, so priming during rainy conditions obviously is wrong. It is important also, to avoid moisture from early morning dew, condensation under certain conditions of temperature and humidity, and (when coating under below freezing conditions) frozen moisture which may make the pipe appear dry. Some primers applied on such surfaces will lead to poor bonding of subsequently applied coatings with resulting poorer performance of the coating. (A.W. Peabody, 1967)

At modern, properly equipped coating plants, proper priming of clean dry pipe can readily be assured.

In recent years, centain synthetic primers have been developed for use with some types of coatings. Some of these primers tolerate slight moisture on the pipe and will give better priming and subsequent coating bond.

Certain pipeline priming materials have a limited effective life after application. Such primers tend to 90 "dead" if application of subsequent coats is delayed too long. Repriming is required then if adequate bond is to be attained. On the other hand, with most coating materials, it is just as important that the primer be dry before subsequent coatings are applied.

3) Proper Application of Coating Materials

Application of the coating material being used should be permitted only on clean, properly primed and dry pipe. With most materials, moisture on the pipe will prevent good bonding. In the case of hot-applied materials, moisture on the pipe surface can vaporize and cause voids in the coating film.

A coating system may consist of a single layer of protective material or may be built up of layers of insulating materials reinforcing wrappers and protective wrappers or shields.

4) Careful Materials Storage and Handling

Coating materials must be stored, prior to application under conditions that will ensure their remaining clean and dry. During application, particularly during over- the ditch coating work, care must be taken to handle them so that they will remain clean and dry. Foreign matter and dirt, as well as moisture, will reduce their effectiveness.

5) Handling, Placing and Backfilling

Under practical pipelining conditions, some damage can be expected. This damage should be limited as much as possible so maximum performance can be obtained from coating being used.

Assuming that all coating defects have been repaired before the pipeline is lowered into the ditch, the lowering-in must be done carefully using padded slings to handle the pipe. The pipeline ditch must have been graded previously and free from rock, other foreign matter and projections so that the coated surfaces will bear on a smooth bed. In rocky areas, it may be necessary to pad the ditch bottom with rock-free dirt or place dirt-filled burlap sacks at intervals along the ditch bottom as bearing points for the pipe.

Severe coating damage can be caused by careless backfilling operations when rocks and debris striking the line break the coating. Where backfill includes such materials, only dirt which is free of objects capable of damaging the coating should be allowed to strike the coated pipe directly. When a sufficient padding layer of this debris-free material has covered the pipe, general backfilling may be used to complete the trench filling operation.

6) Specifications

Such specifications are necessary to ensure that the materials being used are applied in a manner which will permit dedelopment of the best coating of which those materials are capable.

Areas to be covered by specifications should include the following :

a. Cleaning the pipe surface.
   The surface of the pipe must be technically free of dirt, oil, grease, welding beads and moisture and then it must be either sand-blasted or pickled.

b. Priming, if required

Primer ensures very effective temporary corrosion protection of the pipe surfaces and improves the peel strength of the coating material which is used.

c. The coating material thickness.

The minimum coating thickness is the minimum thickness of the polyethylene layer which must exist at every spot.

d. Specifications applicable to the particular materials to be used such as application temperature and thickness (for hot applied enamels), tension (for tapes or wrappers) and other items of a similar nature.

e. Handling requirements for coating materials such as storage provisions and maintenance of dry and clean conditions.

f. Inspection requirements

g. Procedure for repair of coating defects

h. Basis for rejection of unacceptable coating.

i. Requirements for handling and transporting the coated pipe.

j. Details of coating field joints when factory coated pipe is used.

k. Backfilling requirements.

2.2.4 Types of Coating Materials

Over the years since the start of large scale pipelining there have been, and continue to be, many developments in coating materials and protective coating systems. The objective is to find materials that will have the best possible electrical and mechanical strength, ease of application and stability in long term performance (all at a cost compatible with economical pipeline construction.)

1. Enamels. This term is usually applied to hot-applied coatings of coal tar or asphalt, both of which have been in use for many years, usually in combination with reinforcing and protective wrappers. Heating equipment is required. These materials are commonly used with coating machines which permit rapid and efficient application to pipe. Thickness for typical single layer application is usually in the order of 3/32 in (2.4 mm.) (A.W. Peabody, 1967)

2. Waxes. Hot applied coatings are produced using a base of microcrystalline wax. These coatings are generally similar in performance to the asphalt and coal far enamels. They are usually applied in thinner coats than the enamels and are used with wrappers for mechanical strength and improvement of electrical strength of the coating.

3. Mastics. This term is commonly used to refer to materials which are formulated with selected sands and other inert materials bound with an insulating compound which is commonly asphalt. These materials are applied hot and are normally thicker than other coatings in common use. Thicknesses of 1/2 to 5/8 - in (12.7 to 15.9 mm.) are typical. (A.W. Peabody, 1967)

4. Greases. Inhibited greases are used as a protective coating in some applications, particularly on distribution piping. The greases are applied usually by smearing on with the gloved hand. Although greases are sometimes used as the sole protec-

tion, they are more commonly used with a wrapper having a dielectric membrane,to give mechanical and electrical strength to the system.

5. Cold Applied Liquid Coatings. Coatings in this category include materials which are applied in a cold liquid form and solidify either by solvent evaporation or chemical cure. Evaporative setting coatings include solvent cut backs of coal tar and asphalt. The solvent evaporative coatings are combined with reinforcing wrapper materials and may be applied in more than one layer, with time for drying required between coats.

Chemically cured coatings include materials such as combinations of epoxy resins and coal tar or other chemical compounds of a similar nature. Such materials are normally received as two components, one of which is a chemical hardener. Once the two materials are mixed, they must be applied to the pipe promptly as the material will harden chemically within a limited period. The length of time will vary with the material being used and with temperature.

6. Tapes. In recent years, tape materials have been increasingly used as pipeline coatings. Tapes being used as a full coating system include plastic films, (such as polyethylene and polyvinylchloride) with a self-adhesive backing applied to primed pipe surface for best results, plastic films with butyl rubber backing applied to a primed surface and plastic films with various bituminous backings or combinations of bituminous material and chemical resins.

Tapes are usually thin film coatings and may range typically from about 0.25 mm. up to 0.625 or 0.75 mm. Tapes sometimes are given the additional protection by outer wrappers to protect them from mechanical damage by backfill.

An advantage of tape coating systems is that field application requires substantially less equipment and smaller crews than, for example, systems involving hot-applied materials. This can mean significiant saving in contract installation costs on pipeline projects.

In addition to complete coatings, tapes are used with other coatings as part of a system. This includes coating field joints in mill-coated pipe as well as various fittings and appurteances. Tapes consisting of bituminous material on a glass or fabric backing which may be softened and applied with a torch are used similarly.

7. Plastic Coatings. (Fusion Bonded) This category covers the application of recently-developed continuous plastic films as differentiated from plastics applied as tapes. Plastics may be applied by extrusion, fluidized bed processes or by other procedures which will apply and set the coating as a continuous film of uniform thickness. Some such plastic coatings require a primer while others use none.

Recently,techniques have been developed for applying a tough thin-film thermosetting plastic to large-diameter transmission pipelines. Film thickness may be in the order of only 0.20 to 0.25 mm. but the film is so tough it has excellent resistance to damage during handling and backfilling.

In contrast to the thermoplastics,thermosetting materials have the advantage of not softening as operating temperatures increase. Certain thermosetting materials can be operated at several hundred degrees °C without failure and without softening which permit distortion by soil action. This characteristic can be important for pipelines which must be operated at high temperature.

8. Wrappers . Wrappers are used to increase the mechanical or electrical strength of coatings and/or provide on outer barrier (i.e. rock shield) to help prevent damage by material in the backfill that otherwise could penetrate the coating and cause defects. These defects are called holidays in pipeline terminology. Wrappers used within coatings to improve mechanical strength include :

a) Asbestos felts similarly saturated
b) Rag felts similarly saturated
c) Glass felts, saturated
d) Glass fabrics, saturated

Products used as an outer wrap include :

a) Asbestos and rag felts as above
b) Glass felt outer wraps with a reflective surface
c) While asbestos felts.

9. Weighted Over-Coatings (Saddle Weights). Where pipelines are to be used under water or in a non-stable fill, they must have negative bouyancy to prevent their floating to the surface. The necessary weight is in some cases added in the form of cast iron or concrete weights attached to the pipeline at intervals. In other cases, additional weight is added in a continuous

over-coat of a heavy material applied over the basic corrosion-protective coating. Such weighted over-coats are commonly made of a dense concrete using a heavy aggregate such as, iron pyrites. These over-coats are commonly reinforced with wire mesh or a spirated-on wrap of wire. Thickness of the weighted coating is a function of the weight per linear meter needed to produce the desired degree of negative bouyancy.

A particular advantage of the continuous weighted over-coat is the mechanical protection that it gives to the corrosion-protective coating system underneath. This is a valuable feature when installing pipeline in swampy or submerged areas where locating and repairing coating defects can be accomplished only with great difficulty.

10. Concrete Coatings (Swamp Weights) Although not commonly used as a pipeline coating, suitably compounded concrete (or cement mortar) can protect steel against corrosion very effectively. When the concrete or mortar is cast directly on the bare steel, the steel assumes a strongly cathodic potential. Further, with good concrete, the steel polarizes to resist either current collection or current discharge.

Concrete has proved to be an excellent protective material on distribution piping, in limited applications on transmission lines and for shielded areas where cathodic protection cannot be used effectively. It is relatively expensive but results in a strong, long-lived coating for special applications.

2.2.5 Selecting the Coating to be Used

The coating selected for a specific application ideally should be that coating which will have the lowest applied cost per meter of pipe and still have the desirable characteristics of good electrical and mechanical strength and long term stability under the environmental conditions which obtain for the project. Here are some of the factors which must be considered (A.W.Peabody,1967)

1. Will the line be installed in a soil which is free of rock or other matter which can mechanically damage a coating or must protection be afforded against such damage?
2. Is the soil a type which will subject the coating to damaging soil stress?
3. Will all or part of the line be installed where not readily accessible (such as river crossings, swampland installations, submarine locations and other similar situations)?
4. Will the pipeline be operated at temperatures substantially above that of normal soil? If so, what is the maximum operating temperature?
5. If coating application is to be over-the-dicth, what are expected ambient temperatures during the coating and installation period?
6. Are there any other conditions pertaining to the pipeline environment that might affect the coating used?
7. Is there specific need for restricting cathodic protection current to be absolute minimum?

Each coating system considered should be evaluated carefully in terms of the preceeding items. All application and performance characteristics of each coating must be determined, particularly with respect to limitations beyond which good performance cannot be expected.

2.2.6 Nature and Effect of Coating Defects

The exposed steel comprising the less than one percent of total surface on a well coated pipeline usually will be under many small defects in the coating film. These effects are commonly called "holidays" and may result from :

1. Skips by the coating machine,
2. Pinholes in the coating film as applied,
3. Cracks from excessive mechanical or thermal stresses,
4. Scrapes or gouges caused during subsequent handling of the coated pipe.
5. Penetration by rocks, clods on debris in the backfill surrounding the pipe,
6. Distorting stresses exerted on the coating by certain soils having a very high shrinkage rate upon drying,
7. Penetration by growing roots,
8. Action of solvents in earth surrounding pipeline (such as from leaks on a products pipeline),
9. Action of bacteria in the soil surrounding the pipeline, (Some coating materials are relatively inert in this respect while others are sensitive to such damage),

10. Damage from subsequent construction on other facilities making it necessary to uncover the pipeline, and
11. Any other action which will serve to damage the coating film.

Some of this damage can be prevented by rigid application specifications followed implicitly, care in placing and backfilling coating methods can result in a completed coating which may contain so many defects that its performance will not live up tothe capability of the coating material used.

The ability of a coating to resist development of holidays after initial construction is governed basically by its characteristic behavior in the environment and proper application. Again, if a wise choise is not mode, rapid deterioration can result.

It may be well wondered why just a few pinholes could be of any particular consequence, particularly if better than ninety-nine percent of the pipeline is protected substantially against corrosion. It is a matter of concentration. Assume for the moment conditions which would be expected to favor the establishment of a small anodic area and a large anodic area-such as a pipeline river crossing (anodic) with the line buried in well aerated earth on either side (cathodic)-without a coating the entire pipe surface under the river could tend to discharge current (and corrode) with the current flowing through the earth to pipeline surfaces in the cathodic areas. Conversely, with the entire line coated, while the tendency for current to discharge at the rivercrossing still exits, harmful discharge can occur only at breaks in the coating. In this case less total current will be discharged than would have been the case with bare pipe, but the current that does flow will be concentrated at the small coating breaks and the current density may be substantially higher than would have been the case had the line been bare.

This means that first leaks can develop sooner on a coated pipeline than they would have on the same line left bare. With coatings, corrosion current will be greatly reduced and the total loss of metal will be much less than if the line had been bare.

III. PIPE STRESS ANALYSIS

3.1 DETERMINATION OF STRESSES ON STEEL PIPES

Stresses on steel pipes are due to internal gas or liquid pressure, external loads (dead weight, wind, wave, current, ice load, traffic load) and imposed, but restricted, deformations of the pipeline (due to temperature changes, platform displacements and settlements of the soil)

It is examined that the stresses on pipes created by external loads because of the weight of soil and the dead weight of steel pipe.

A major factor in the stress analysis of buried pipelines is the movement that pipe undergoes in the presence of temperature and pressure differentials during its life. This movement is highly dependent upon friction resistance of the soil.

Although there is available information on the static coefficient of friction for many materials,there is a lack of data on friction between soils and various coatings used in the pipe-line industry. Very little is known about the effect of compaction on pipe-soil interaction and consequently on the pipe-soil interface failure mechanism. In the past, friction coefficient information was extrapolated from data in the literature that was believed to have a similarity to the external pipe coating to soil interface. However, with the development of tapes and plastic coating systems and the increasing use of these systems in the pipeline industry, a change from a conventional coal-tar felt coating to tapes and plastic coatings would indicate a significiant change in the friction coefficient design criteria due to the extreme contrast in the surface texture of these materials. To evaluate the effect of surface texture on a pipeline system, test procedures were developed to determine the coefficient of friction under various soil conditions.

The theoretical longitudinal soil force acting on the pipe surface can be calculated conventionally from equation 1.

$$F = \mu \int_A p.\ dA \qquad (1)$$

where;

F = longitudinal soil friction force

μ = coefficient of friction

p = normal soil pressure acting on the pipe surface

dA = soil to pipe differential contact area.

$\int_A .p.dA$= total normal soil force on pipe surface.

If the weight of the pipe and contents are taken into account the soil force can be calculated from equation 2.

$$F = \mu (\int_A p.dA + \int_A w_p.dA) \qquad (2)$$

where ;

w_p = weight of the pipe and contents per unit area.

$\int_A w_p \cdot dA$ = total dead weight of the pipe.

Soil friction force is inversely proportional to the active length of the pipeline. Pipelines move as a result of temperature and pressure expansion. Therefore, the coefficient of friction becomes a major factor in pipeline stress design.

3.2 MODEL TEST SYSTEM

The simple model test system for investigating the soil friction force is given in Figure 1.

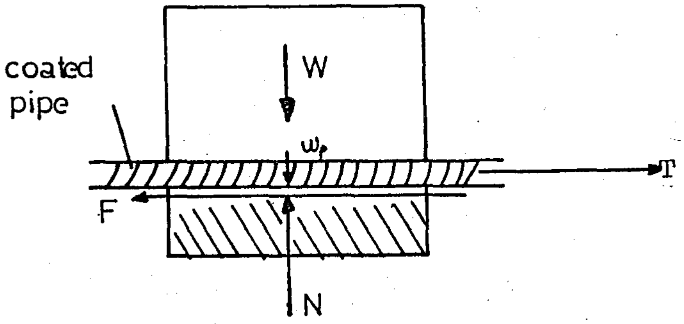


Figure 1. Simple Model Test System

where ;

T = pulling force of the system

W = weight of the soil above the soil

N = normal force acting on the pipe surface = $W+w_p$

The theoretical soil friction force acting on the surface of a coated pipe can be calculated from equation 3.

$$F = \mu \cdot N \tag{3}$$

and the coefficient of friction is

$$\mu = \frac{F}{N} \qquad (4)$$

3.3 STRESSES ON THE SURFACE OF THE PIPE

The side view of a pipe which is buried at a depth of H and has a diameter D is given in Figure 2.

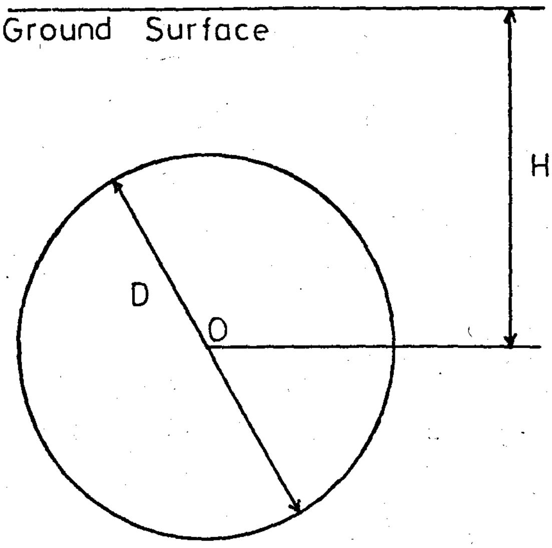


Figure 2. Side view of a buried pipe.

where

H = height of backfill

D = diameter of the pipe

The stresses on the horizontal on vertical tengential planes are given in Figure 3.

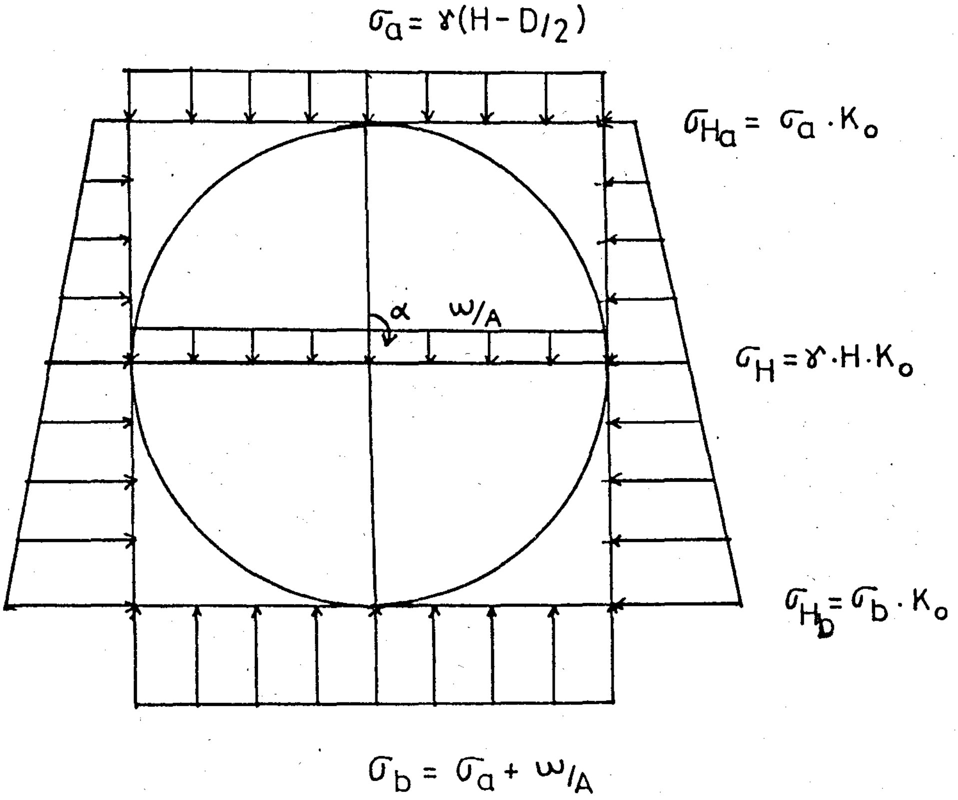


Figure 3. Stresses on the horizontal and vertical planes

Since the stresses on the pipe surface are symmetrical only half of the pipe can be considered. (Figure 4.)

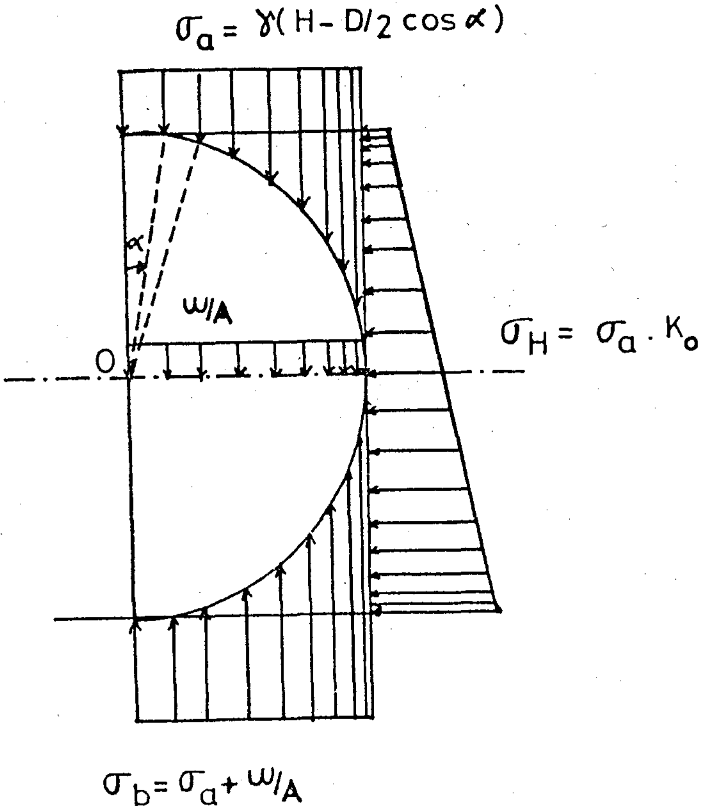


Figure 4. Stresses on the horizontal and vertical planes

ÜNİVERSİTESİ KÜTÜPHANESİ

where,

σ_a = vertical stress above the pipe

σ_H = horizontal stress

σ_b = vertical stress below pipe

γ = unit weight of soil

D = diameter of the pipe

H = height of soil from the center of the pipe

α = angle from the vertical axes, changes from 0° to 180° at clockwise direction.

A_s = surface area of the pipe

w_p = weight of the pipe

K_o = coefficient of earth at rest (lateral pressure)

$A = \frac{1}{2} A_s$

3.3.1 Stress above the pipe

Vertical stress imposing on pipes are created by the dead weight of soil above the pipes.

When the Figure 4. is considered, it is understood that the vertical stress above the pipe, σ_a, are given as,

$$\sigma_a = \gamma(H - D/2. \cos\alpha) \tag{5}$$

3.3.2. Stresses below pipe

Vertical stresses below the pipes are calculated by Equation 6.

$$\sigma b = \sigma_a + w_p/A \tag{6}$$

where,

wp/A is considered affecting at the lower half of the pipe.

Since the surface area, $A_s = \Pi DL$, A becomes, $A = \frac{1}{2} A_s$.

Then w_p/A becomes, $$w_p/A = \frac{2\, w_p}{\Pi DL} \tag{7}$$

where,

L = length of the pipe.

substituting Equation 5 and Equation 7 into Equation 6.

$$\sigma_b = \gamma(H - D/2 \cos\alpha) + \frac{2\,w_p}{\Pi DL} \qquad (8)$$

3.3.3 Horizontal Stress

Horizontal stresses exerted on the pipes can be computed from the vertical stresses by

$$\sigma_H = \sigma . K_o \qquad (9)$$

where,

σ = vertical stress

K_o = coefficient of earth pressure

The values of K_o for normally consolidated soils are given in Table 1.

Table 1. Earth Pressure Coefficients for Normally Consolidated Soils (Sowers, 1970)

Soil	K_o
Soft clay	0.6
Hard clay	0.5
Loose Send, gravel	0.6
Dense sand, gravel	0.4
Overconsolidated clay	0.6 to 1.0
Compacted, pirtially saturated clay	0.4 to 0.7

Substituting Equation 5 into Equation 8.

$$\sigma_H = \gamma(H - D/2 \cos\alpha) . K_o \qquad (10)$$

3.3.4 Radial Stresses

Radial stresses can be calculated in two cases

a. angle between 0^o to 90^o (above part of the pipe)

b. angle between 90^o to 180^o (below part of the pipe)

at clockwise direction.

Radial stresses at an angle from 0^o to 90^o are given by the relation,

$$\sigma R_a = \sigma_a . \cos\alpha \quad \sigma_H . \sin\alpha \qquad (11)$$

substituting Equations 5 and 10 into Equation 11.

$$\sigma R_a = \gamma(H-D/2 \cos\alpha) . \cos\alpha + \gamma(H-D/2 . \cos\alpha) . K_o . \sin\alpha \qquad (12)$$

Radial stress from 90^o to 180^o are given by the relation

$$\sigma R_b = \sigma_b . \cos\alpha + \sigma_H . \sin\alpha \qquad (13)$$

substituting Equations 8 and 10 into Equation 13.

$$\sigma R_b = \left[\gamma(H-D/2 \cos\alpha + \frac{2w_p}{\pi DL}\right] \cdot \cos\alpha + \gamma(H+D/2 \cos\alpha) . K_o . \sin\alpha \qquad (14)$$

Radial stresses are shown in Figure 5.

For loose case, earth pressure coefficient K_o was taken as 0.5 for 1/10 Proctor Energy case, K_o was taken as 1.0 and for 100/100 Proctor Energy case, K_o was taken as 2.0

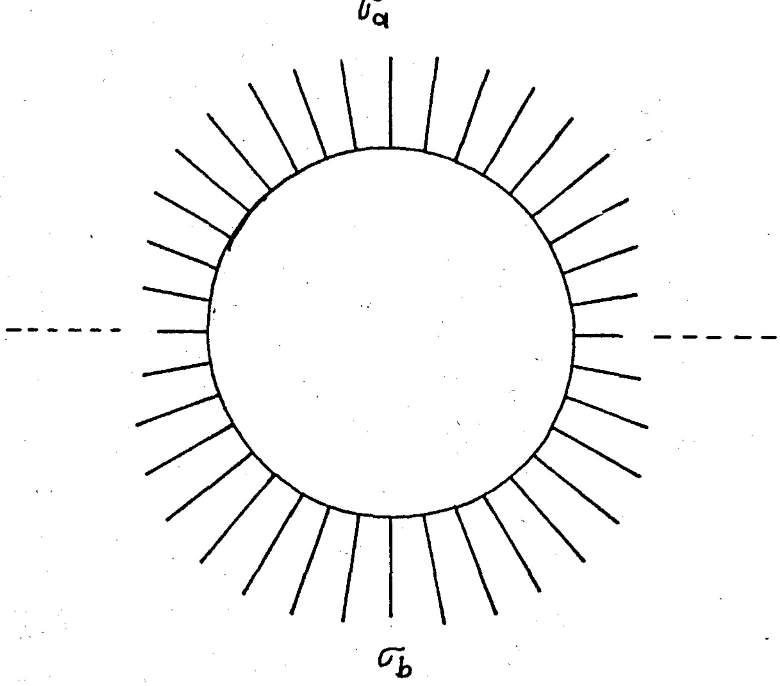


Figure 5. Radial Stress on pipe.

Radial force on a segment of the pipe is:

$$\text{Radial force} = \sigma_R \cdot A_R \tag{15}$$

A_R is the surface of the segment area that each radial stress acts. The total radial force is

$$\text{Total radial force} = \Sigma F_R = \Sigma(\sigma_R \cdot A_R) \tag{16}$$

Since A_R = Constant, then

$$\Sigma F_R = A_R\ (\Sigma\sigma_R) \tag{17}$$

Since the normal force equals to the total force (radially), it becomes:

$$N = \Sigma F_R$$

$$N = (\Sigma\sigma_R) \cdot A_R \tag{17}$$

Substituting Equation 17 into Equation 4, the coefficient of friction becomes:

$$\mu = \frac{F}{(\Sigma\sigma_R) \cdot A_R} \tag{18}$$

IV. EXPERIMENTAL SET-UP AND MATERIALS

4.1 SELECTION OF THE EXPERIMENTAL SYSTEM

The main purpose of the present study was to investigate the influence of soil density, water content, soil compaction degree and pipe diameter on the friction forces coefficient of friction values between the soil and the pipe surfaces. The influence of coatings which were wrapped around the pipe was also investigated. To achieve this an experimental system was prepared and the tests were carried out in the laboratory. The set-up is described in following parts.

4.2 EXPERIMENTAL SET-UP

The study consisted of the following parts :

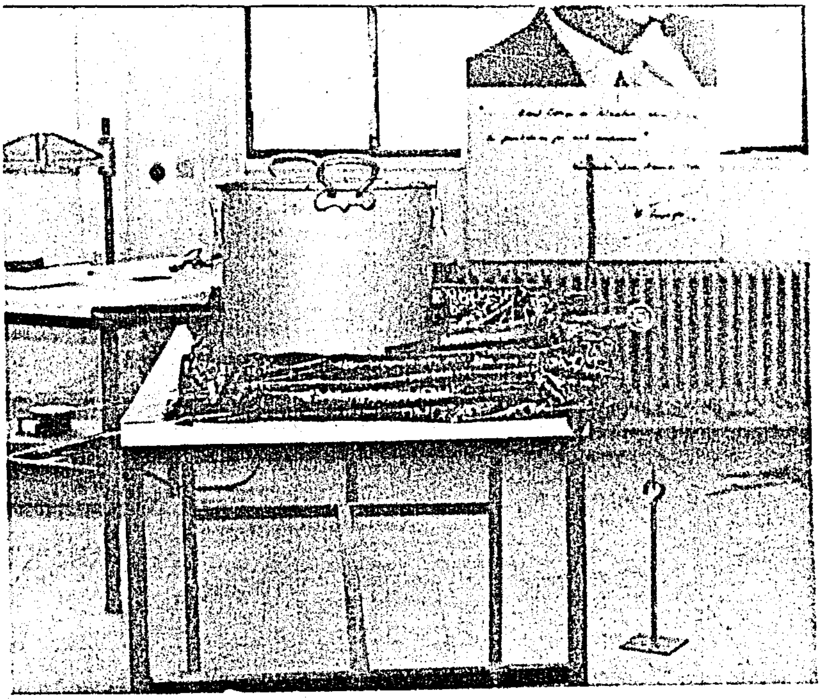
a. Container
b. Pulley system
c. Pipes
d. Hanging plates and weights
e. Dial gauges

The experimental equipment is depicted in Figure 6. in detail. Details of the different units are given in sections which follow.

4.2.1 Container

The container used in this study was made of alluminium. It was 0.37 m. in diameter, 0.35 m. in height and had an internal volume of 0.03763 m^3. (Figure 7)

Two holes which were 60 mm. in diameter and 95 mm. above the bottom were opened on the sides of the container. These holes were aligned on the longitudinal axes.



FGURE 6. Experimental Set-up

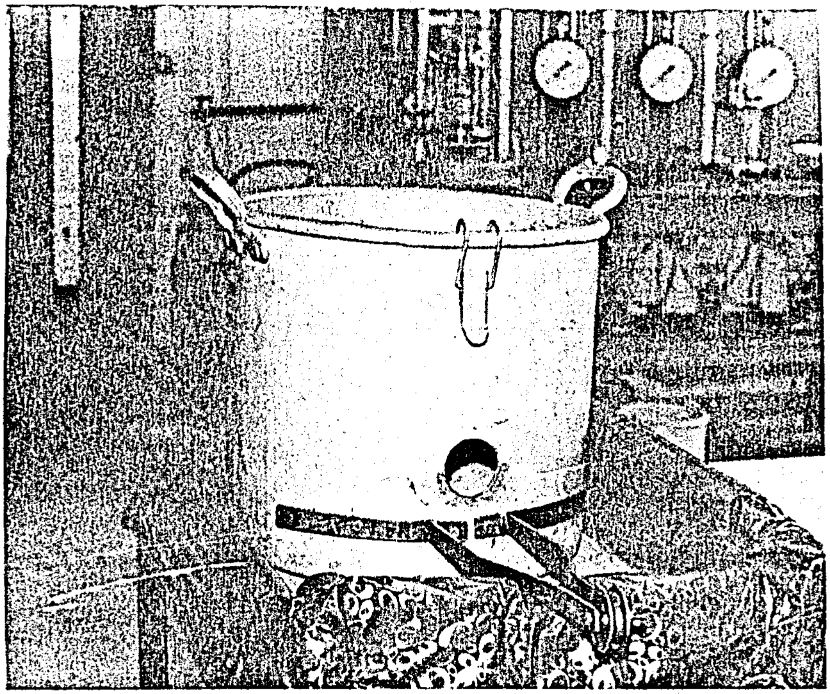


FIGURE 7. General view of the container

4.2.2 Pulley system

The purpose of the pulley system was to provide pulling the pipe with a known weight. The friction forces were minimized in pulley by usage of oil and grease. The pulley was placed 0.4 m. away from one of the container holes. It was attached to the container by steel rods. The top of the pulley and the centers of the two holes aligned with the longitudinal axis as shown Figure 8.

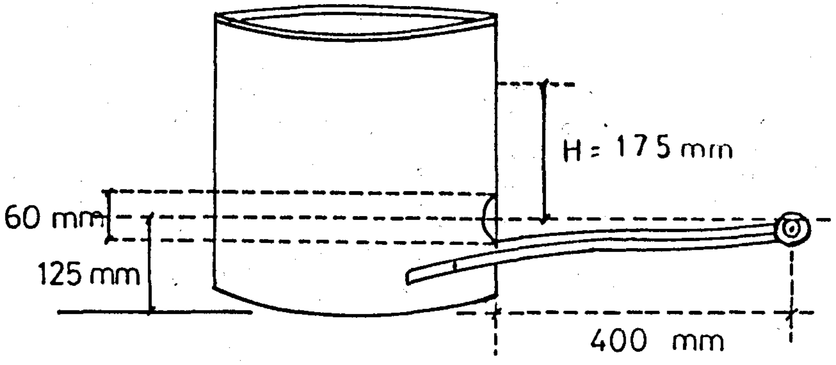


FIGURE 8. Pulley system.

4.2.3 Pipes

Two different size of pipes were used during the experiments. One of the pipes was 1.5 inches having an inside diameter of 42 mm and outside diameter Of 48.5 mm. The other one was 1.0 inch with an inside diameter of 27.5 mm. and outside diameter 34 mm.

When the pipes were coated by means of tapes the outside diameters of pipes were increased. Since 50 percent overlap was used and each layer was 0.75 mm in thickness, the outside diameters increased 3mm for both pipes. Therefore the outside diameter of 1.5 inche pipe become 51.5 mm and 1 inch was this included in the surface area calculation pipe 37mm. (Figure 9).

Pipe lengths were 0.6 to 0.7 m. and one of the ends was closed with steel sheets.

Sheets were 80 mm in width, 150 mm in length. Steel wires were connected to these closed ends. The steel wire was hanged over the pulley. Each wire was 0.8 m in length.

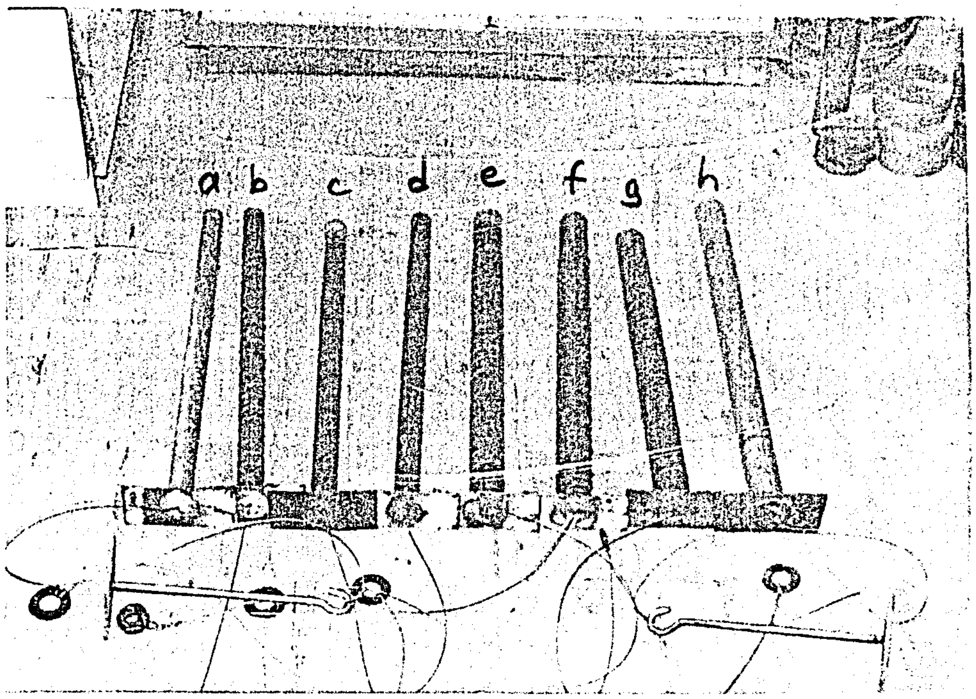


FIGURE 9 Pipes

(a-1 inch without coating b-1 inch coated with Densolen Tape S40, (DTS40) c-1 inch reserve coated DTS40, d-1 inch coated Densolen Tape R41(DTR41), e-1.5 inches coated DTS40, f-1.5 inches coated DTR41, g-1.5 inches reserve coted DTR41, h-1.5 inches without coating).

4.2.4 Hanging plates and the weights

Hanging plates were connected to the free ends of the steel wires. These plates were needed to place the weights. The used types of weights were 50,100,250,500 grams and 1,2,4,10 kilograms. Therefore the maximum measurement error was 50 grams.

4.2.5 Dial Gauges

Two dial gauges were used during the experimentation.The weighths corresponding to the initial and continuing movements were observed and noted by the use of dial gauges.

4.3 DESCRIPTION OF THE SOIL

The soil was taken from the the European Site of Fatih Bridge Construction area. The soil is light brown sandy and silty clay. (Soil classification and necessary experimental results are given in Appendix 1)

Liquid limit of the soil,	w_L	= 35.0 %
Plastic limit of the soil,	w_P	= 23.3 %
Plasticity Index	I_p	= 11.7 %
Specific gravity of, the soil,	G_s	= 2.74
Optimum moisture content	W_{omc}	= 16.5 %
Maximum dry density,	$\gamma_{dry\ max}$	= 17.9 kN/m^3
Percent clay value		4.58 %.

According to unified soil classification, the soil is CL "light brown sandy (and little gravelly) and silty clay".

According to AASHTO Soil Classification, the soil is A-6(5)

Typical gradation curve of the soil is shown in Figure 10.

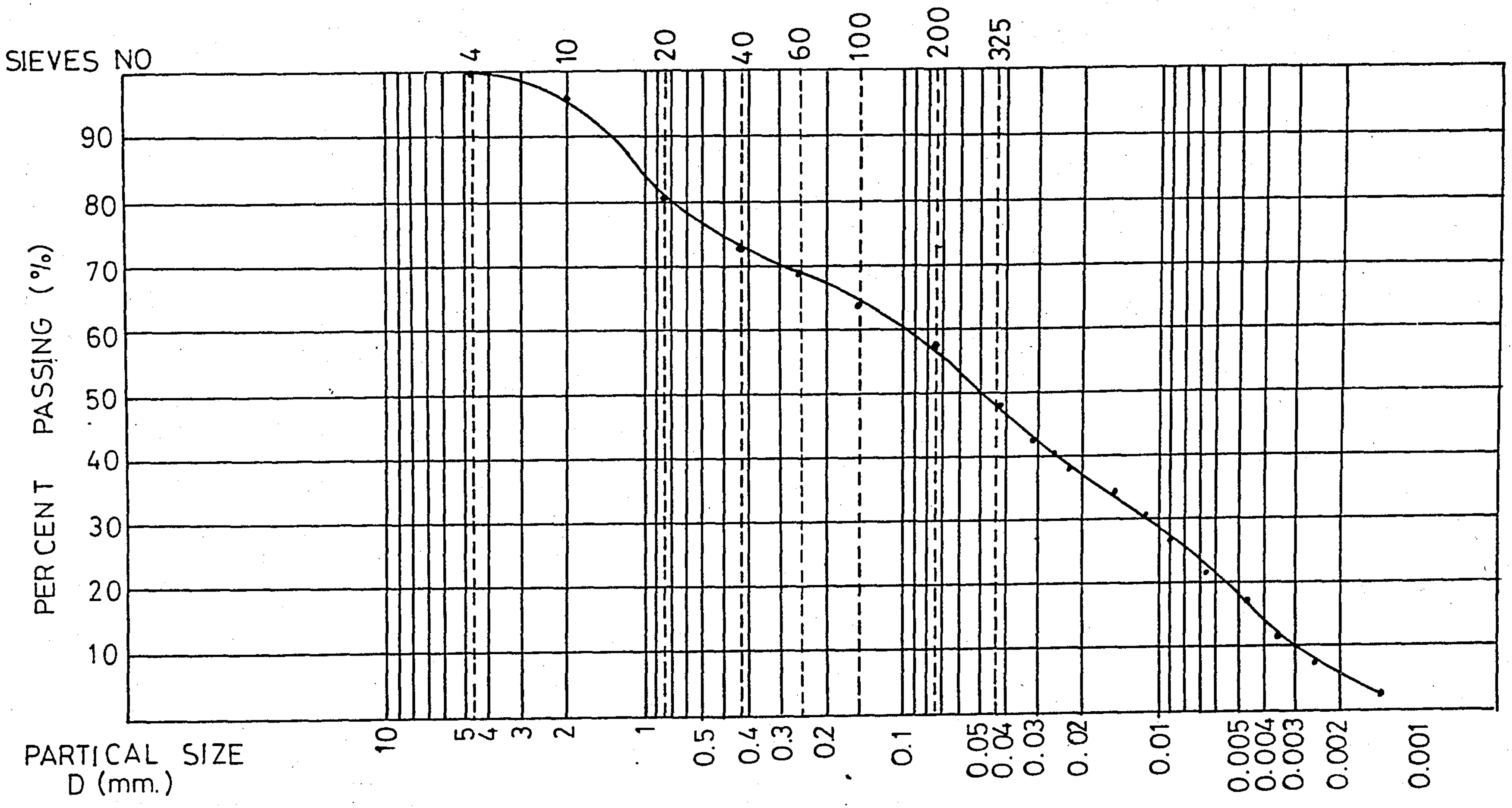


FIGURE 10. Typical Gradation Curve of the Soil.

V. EXPERIMENTAL PROCEDURE

5.1. OBJECTIVE OF THE STUDY

The aim of the study is to investigate the magnitude of the forces around the pipe due to horizontal motion of the buried pipelines and the effects of the soil compaction on those forces. The pipeline movements were simulated in a simple model shown in Figure 1 . A total of 248 tests were carried out.

The maximum motion which would take place due to temperature, pressure differences and soil movements were created by pulling the pipes through the soil using a pulley system.

The purpose of the test can be grouped in 3 categories :

1. to study the soil-pipe interaction,
2. to investigate the influence of the coatings which surrounded the pipes,
3. to investigate the influence of such parameters; as pipe diameter, water content, degree of compaction and soil density.

The procedure followed in this study can be summarized in two groups :

a. Preliminary work before starting the experiments.
b. Procedure followed during the experimentation.

5.2 PRELIMINARY WORK

5.2.1 Soil Preparation

Soil was prepared in three cases. This cases can be summarized as follows :

a. Loose soil condition
b. Soil compacted with 1/10 Proctor Energy
c. Soil compacted with 100/100 Proctor Energy

5.2.2 Pipe Preparation

Pipe types used were described in section 4.2.3. It was explained how to coat the pipes in Section 2.2.3. Coating procedure used in preparation of the pipes summarized below.

First of all, pipe surface was properly cleaned from oil and grease. Densolen primer HT was applied to the pipe surface and after waiting for 20 minutes the coating material was applied with 50 percent overlap. Densolen Tapes S40 and R41 were used as coating materials.

It was used two types of pipes and each consisted of four different configurations. In 1.0 inch pipes, one pipe was coated with Densolen Tape R41 (DTR41), the second one with Densolen Tape S40 (DT S40), the third one with reverse DTS40 and the last left bare.

In 1.5 inches pipe, first pipe was coated with DTS40, the second with DTR41, the third with reverse DTR41 and the last left bare.

The properties of the Densolen Tapes and Primer are given in Appendix II. and III.

5.3 EXPERIMENTAL WORK

The experiments were done with different water contents and corresponding unit weights of soil for eight pipes described in Section 4.1.2.

Friction forces were calculated in six categories and these categories are :

a. Loose soil at 6 percent water content (air dried water content)

b) Soil compacted with 1/10 Proctor Energy at 6.5 percent water content

c. Loose soil at 11.1 percent water content

d. Soil compacted with 1/10 Proctor Energy at 11.2 percent water content

e. Soil compacted with 1/10 Proctor Energy at 17.3 percent water content.

f. Soil compacted with 100/100 Proctor Energy at 17.7 percent water content.

5.3.1 Loose Soil Condition

The container was filled with the soil up to the bottom of the holes, then the pipe was placed through the holes. The wire which was connected to the closed end of the pipe was passed over the pulley and the hanging plate was hanged to the swinging end of the wire. After the placement of the pipe, the rest volume was filled with the soil. The loose soil layers were prepared by placing the soil inthe container with minimal levelling of the surface.

Two dial gauges were placed in front of the closed end of the pipe in order to see the displacements. Then weights were put on the hanging in order to pull the pipe through the soil and initial displacement was observed. When the initial displacement was seen, the corresponding weight was noted. After a while the movement stopped, then more weights were added. While the pipe was sliding completely through the soil, the corresponding weight was the needed value.

5.3.2 Compacted Soil Condition

The procedure is same as described in Section 4.2.1 except the compaction. The dense soil condition was obtained by dynamic compaction. Standard Proctor Energy was used for the compaction. The compaction was done in 6 layers each 50 mm. in thickness. It was done 428 blows per layer for 100/100 Proctor and 43 blows per layer for 1/10 Proctor.

Calculations of blow counts are given in Appendix IV.

VI. RESULTS AND DISCUSSIONS

6. RESULTS

6.1 Tables of Results

The data and results obtained inthis study can be separated into six categories.

a) Loose soil at 6 percent water content (air dried content)

b) Soil compacted with 1/10 Proctor Energy at 6.5 percent water content

c) Loose soil at 11.1 percent water content

d) Soil compacted with 1/10 Proctor Energy at 11.2 percent water content

e) Soil compacted with 1/10 Proctor Energy at 17.3 percent water content

f) Soil compacted with 100/100 Proctor Energy at 17.7 percent water content.

The pull out force results obtained in categories (a) and (b) are listed in Table 2. where,

Unit weight of loose soil was calculated by using a graduated tube and found to be 11 kN/m^3 at 6 percent water content.

Unit weight of dense soil (1/10 Proctor Energy) was calculated by using the sand cone method and found to be 12.6 kN/m^3

at 6.5 percent water-content.

The pull out force results of categories (c) and (d) are listed in Table 3. where

Unit weight of loose soil was calculated by using a graduated tube and found to 11.8 kN/m^3

Unit weight of dense soil was calculated by using the sand cone method and found to be 14 kN/m^3.

The pull out force results of categories (e) and (f) are listed in Table 4 where

Unit weights were calculated by using the sand cone method. Unit weight of soil with 1/10 Proctor Energy was found to be 15.3 kN/m^3

Unit weight of soil with 100/100 Proctor Energy was found to be 20.3 kN/m^3.

TABLE.2 Pull out Forces measured at w_L=6%, $w_{1/10}$ p = 6.5%. (air dried water content)

γ_{loose}=11 kN/m^3, w_{loose}=6%			1" PIPE				1 1/2" PIPE			
$\gamma_{1/10\ Proctor}$=12.6kN/m^3, $w_{1/10}$=6.5%			values are in grams			mean value	values are in grams			mean value
bare pipe	loose	initial	3450	3450	3500	3467	3700	3700	3600	3667
		continuing	3950	3950	4000	3967	4700	4700	4700	4700
	1/10 Proctor	initial	8450	8700	8600	8583	9200	9200	9200	9200
		continuing	9700	9700	9650	9683	10200	10200	10200	10200
coating no: R41	loose	initial	3450	3200	3250	3300	4800	5000	5000	4933
		continuing	6950	650	6750	6717	9800	10300	10100	10067
	1/10 Proctor	initial	18700	20700	19500	19633	34800	35800	34800	35133
		continuing	35700	36700	36000	36133	70800	70800	70800	70800
coating no : S40	loose	initial	3450	3450	3500	3467	4700	5000	4700	4800
		continuing	6700	6700	6700	6700	8450	8500	8350	8433
	1/10 Proctor	initial	27200	26200	27000	26800	34700	34700	34500	34633
		continuing	44700	44200	44000	44300	68700	68700	68500	68633
reserve coating no: R41	loose	initial	-	-	-	-	3700	3700	3600	3667
		continuing	-	-	-	-	7600	7500	7450	7517
	1/10Proctor	initial	-	-	-	-	14700	12700	13200	13533
		continuing	-	-	-	-	33700	32700	30700	32367
reverse coating no : S40	loose	initial	3250	3450	3450	3383	-	-	-	-
		continuing	5000	4950	5200	5050	-	-	-	-
	1/10Proctor	initial	17700	18700	18700	18367	-	-	-	-
		continuing	36700	38700	38200	37867	-	-	-	-

TABLE.3 Pull out Forces Measured at w_L=11.1%, $w_{1/10p}$ = 11.2 %

γ_{loose}=11.8 kN/m^3;w_{loose}=11.1%			1" PIPE				1 1/2" PIPE			
$\gamma_{1/10\ Proctor}$=14 kN/m^3;$w_{1/10P}$=11.2%			values are in grams			mean value	values are in grams			mean value
bare pipe	loose	initial	2700	2700	2540	2617	3200	3200	3200	3200
		continuing	2900	2900	2900	2900	4250	4350	4300	4300
	1/10Proctor	initial	12700	12700	13200	12867	20450	20700	20600	20583
		continuing	13200	13200	13700	13367	20700	20950	20850	20833
coating no : R41	loose	initial	2700	2700	2700	2700	4500	4300	–	4400
		continuing	4650	4550	4600	4600	10550	10550	–	10550
	1/10Proctor	initial	20700	18700	18700	13967	28800	30800	–	29800
		continuing	39700	38700	36700	38367	74800	76800	–	75800
coating no : S40	loose	initial	2950	2950	2950	2950	4700	4900	–	4800
		continuing	5300	5400	5200	5300	8200	8400	–	8300
	1/10Proctor	initial	28700	30700	28700	29367	34700	32700	–	33700
		continuing	63700	62700	62700	63033	70700	68700	–	69700
reverse coating no : R41	loose	initial	–	–	–	–	3700	3700	–	3700
		continuing	–	–	–	–	5200	5200	–	5200
	1/10Proctor	initial	–	–	–	–	18700	16700	17200	17533
		continuing	–	–	–	–	36200	36200	35700	36033
reverse coating no : S40	loose	initial	2700	2700	2700	2700	–	–	–	–
		continuing	4200	4250	4300	4300	4250	–	–	–
	1/10Proctor	initial	28700	28700	28700	28700	–	–	–	–
		continuing	43700	44700	44700	44367	–	–	–	–

TABLE.4 Pull out Forces Measured at $w_{1/10}p=17.3\%$, $w_{100/100}p=17.7$ %
(nearly optimum water content)

$\gamma_{1/10}$Proctor=15.3kN/m^3, $w_{1/10}$p=17.3%			1" PIPE				1 1/2" PIPE			
$\gamma_{100/100}$Proctor=20.3kN/m^3, $w_{100/100}$ p.=17.7%			values are in grams			mean value	values are in grams			mean value
bare pipe	1/10Proctor	initial	15500	15650	-	15575	26200	25200	25700	25700
		continuing	15700	15900	-	15800	26700	25700	26200	26200
	100/100 Proctor	initial	*	*	*	*	*	*	*	*
		continuing	70000	78000	-	74000	104000	102000	-	103000
coating no : R41	1/10Proctor	initial	14700	14700	-	14700	26800	27800	-	27300
		continuing	18950	18700	-	18825	54800	54300	-	54550
	100/100 Proctor	initial	70000	74000	-	72000	140000	143000	-	141500
		continuing	78200	80000	-	79100	160000	168000	-	164000
coating no : S40	1/10Proctor	initial	20700	20300	-	20500	31700	30700	-	31200
		continuing	40700	3950	-	40100	48700	46700	-	47700
	100/100 Proctor	initial	108000	104000	-	106000	*	*	*	*
		continuing	128000	130000	-	129000	158000	162000	-	160000
reverse coating no: R41	1/10Proctor	initial	-	-	-	-	20700	21700	-	21200
		continuing	-	-	-	-	22700	22450	-	22575
	100/100 Proctor	initial	-	-	-	-	*	*	*	*
		continuing	-	-	-	-	126000	130000	-	128000
reverse coating no: S40	1/10Proctor	initial	20700	21700	-	21200	-	-	-	-
		continuing	29200	29700	-	29450	-	-	-	-
	100/100 Proctor	initial	88000	86000	-	87000	-	-	-	-
		continuing	108000	110000	-	109000	-	-	-	-

*It could not be measured

The averaged pull out force results given through Table 2-4 are summarized in Table 5 where all values are in grams. Averaged pull out forces are listed in Table 6 as in kN's.

It can be easily seen that the pull out forces created around the pipe surface decreases with the increase in water content in loose soil condition.When it was used 1/10 Proctor case the situation is the reverse of above. Pull out force values increase with the increase in water content up to the optimum moisture content, than there is observed decrease again in 1/10 Proctor.

It is seen that if the coated pipes are used in the experiments, there will be very difference in pull out forces between initial and the continuing movements. These differences are because of the overlaps of the coatings on the pipe.

Total radial stresses for each category were calculated by using Equations 12 and 14 and they are listed in Tables from 7 to 12.

$$\sigma_{Ra} = \gamma(H-D/2.\cos\alpha).\cos\alpha + \gamma(H-D/2.\cos\alpha).k_o.\sin\alpha \qquad (12)$$

$$\sigma_{R_b} = [\ \gamma(H-D/2\ \cos\alpha) + \frac{2w_p}{\pi DL}\ ]\ \cos\alpha + \gamma(H+D/2.\cos\alpha).k_o.\sin\alpha \qquad (14)$$

Since the stress are symmetrical with the vertical axes, the stresses were calculated from 0^o to 180^o (from vertical axis) at clockwise direction at every 10^o interval. Total stress were calculated by using the relation below.

$$\Sigma\sigma_R = \sigma_{\text{total stress}} = \sigma_o + 2.\sum_{k=1}^{17} \sigma_{10k} + \sigma_{180} \qquad (19)$$

While the diameter of the pipe increased, the total stress around the pipe decreased and this was observed in the given Tables 7 to 12. It was observed that the coating material increased the diameter of the pipe and the increase in the pipe diameter decreased the total stress.

Unit areas of 10° segments were calculated by equation below and listed in Table 13.

$$A_R = \frac{\pi DL}{36} \qquad (20)$$

Total Forces around the pipe were calculated by Equation 17 and listed in Table 14. The way of calculation of Normal Forces by integration is given in Appendix V.

$$N = \Sigma F_R = (\Sigma \sigma_R) . A_R \qquad (17)$$

Coefficient of friction values, μ's, were calculated by Equation 18. and listed in tables 15 and 16.

$$\mu = \frac{F}{(\Sigma \sigma_R) . A_R} = \frac{F}{N} \qquad (18)$$

Internal soil-pipe friction values, φ's, were calculated by the relation below and listed in Tables 17 and 18

$$\mu = \tan \phi$$

$$\phi = \tan^{-1} \qquad (21)$$

BLE.5 Pull out Forces (grams)

l out Forces,F		1" PIPE						1 1/2" PIPE					
t weight, γ		11 kN/m^3	12.6kN/m^3	11.8 kN/m^3	14 kN/m^3	15.3kN/m^3	20.3 kN/m^3	11 kN/m^3	12.6kN/m^3	11.8kN/m^3	14 kN/m^3	15.3kN/m^3	20.3kN/m^3
er content, ω		6 %	6.5 %	11.1 %	11.2 %	17.3 %	17.7 %	6 %	6.5 %	11.1 %	11.2 %	17.3 %	17.7 %
values are in grams		loose	1/10 Proctor	loose	1/10 Proctor	1/10 Proctor	100/100 Proctor	loose	1/10 Proctor	loose	1/10 Proctor	1/10 Proctor	100/100 Proctor
re pe	initial	3467	8563	2617	12868	12867	*	3667	9200	3200	20583	25700	*
	continuing	3967	9683	2900	13367	15800	74000	4700	10200	4300	20833	26200	103000
oating o:R41	initial	3300	19633	2700	19367	14700	72000	4933	35133	4400	29800	27300	141500
	continuing	6717	36133	4600	38367	18825	79100	10067	70800	10550	75800	54550	164000
oating o:S40	initial	3467	26800	2950	29367	20500	106000	4800	34633	4800	33700	31200	*
	continuing	6700	44300	5300	63033	40100	129000	8433	68633	8300	69700	47700	160000
everse oating o:R41	initial	-	-	-	-	-	-	3667	13533	3700	17533	21200	*
	continuing	-	-	-	-	-	-	7517	32367	200	36033	22575	128000
everse oating o:S40	initial	3383	18367	2700	28700	21200	87000	-	-	-	-	-	-
	continuing	5050	37867	4250	44367	29450	109000	-	-	-	-		-

could not be measured

TABLE 6 Pull out Forces (kN.)

Pull out Forces, F		1" PIPE						1 1/2" PIPE					
Unit weight, γ		11 kN/m^3	12.6kN/m^3	11.8kN/m^3	14kN/m^3	15.3kN/m^3	203kN/m^3	11 kN/m^3	126kN/m^3	118kN/m^3	14 kN/m^3	153kN/m^3	203kN/m^3
Water content, ω		6 %	6.5 %	11.1 %	11.2 %	17.3 %	17.7 %	6 %	6.5 %	11.1 %	11.2 %	17.3 %	17.7 %
All values are in kN		loose	1/10 Proctor	loose	1/10 Proctor	1/10 Proctor	100/100 Proctor	loose	1/10 Proctor	loose	1/10 Proctor	1/10 Proctor	100/100 Proctor
bare pipe	initial	0.034	0.084	0.026	0.126	0.153	*	0.36	0.090	0.031	0.202	0.252	*
	continuing	0.039	0.095	0.028	0.131	0.155	0.726	0.046	0.100	0.042	0.204	0.257	1.010
coating no:R41	initial	0.032	0.193	0.027	0.190	0.144	0.706	0.048	0.345	0.043	0.292	0.268	1.388
	continuing	0.066	0.354	0.045	0.376	0.185	0.0776	0.099	0.695	0.104	0.774	0.535	1.609
coating no:S40	initial	0.034	0.263	0.029	0.288	0.201	1.040	0.047	0.340	0.047	0.331	0.306	*
	continuing	0.066	0.435	0.052	0.618	0.393	1.266	0.083	0.673	0.081	0.684	0.468	1.570
reverse coating no:R41	initial	-	-	-	-	-	-	0.036	0.133	0.036	0.172	0.208	*
	continuing	-	-	-	-	-	-	0.074	0.318	0.051	0.353	0.222	1.256
reverse coating no:S40	initial	0.033	0.180	0.027	0.282	0.208	0.853	-	-	-	-	-	-
	continuing	0.050	0.371	0.042	0.435	0.289	1.069	-	-	-	-	-	-

*It could not be measured

TABLE.7 Radial Stresses around the pipe (kN/m^2)

	loose	loose	loose	loose
unit weight γ, (kN/m^3)	11	11	11	11
diameter,m	0.0340	0.0485	0.0370	0.0515
type α	without coating	without coating	with coating	with coating
0	1.738	1.658	1.722	1.642
10	1.866	1.781	1.848	1.764
20	1.943	1.860	1.926	1.842
30	1.968	1.891	1.952	1.875
40	1.938	1.871	1.924	1.857
50	1.851	1.799	1.841	1.788
60	1.709	1.672	1.701	1.664
70	1.511	1.489	1.506	1.484
80	1.261	1.251	1.259	1.249
90	0.963	0.963	0.963	0.963
100	1.383	1.375	1.381	1.376
110	1.749	1.729	1.743	1.729
120	2.050	2.013	2.040	2.012
130	2.279	2.221	2.263	2.217
140	2.429	2.349	2.498	2.342
150	2.500	2.398	2.474	2.388
160	2.493	2.371	2.463	2.357
170	2.411	2.273	2.377	2.256
180	2.259	2.111	2.223	2.092
Total Stress	68.605	66.381	68.083	66.060

TABLE.8 Radial Stresses around the pipe (kN/m^2)

Dense	1/10 Proctor	1/10Proctor	1/10Proctor	1/10Proctor
UnitWeight γ, (kN/m^3)	12.6	12.6	12.6	12.6
Diameter(m)	0.0340	0.0485	0.370	0.0515
type α^o	without coating	without coating	with coating	with coating
0	1.991	1.900	1.972	1.881
10	2.310	2.206	2.288	2.184
20	2.568	2.458	2.545	2.435
30	2.759	2.651	2.736	2.628
40	2.875	2.777	2.855	2.756
50	2.912	2.830	2.895	2.813
60	2.866	2.803	2.853	2.790
70	2.732	2.692	2.724	2.684
80	2.511	2.493	2.508	2.489
90	2.205	2.205	2.205	2.205
100	2.675	2.676	2.674	2.678
110	3.048	3.043	3.045	3.047
120	3.312	3.294	3.306	3.297
130	3.459	3.421	3.447	3.422
140	3.486	3.424	3.469	3.421
150	3.396	3.307	3.373	3.300
160	3.196	3.080	3.167	3.067
170	2.897	2.756	2.862	2.739
180	2.512	2.352	2.474	2.331
Total Stress	102.917	100.484	102.350	100.122

TABLE.9 Radial Stresses around the pipe (kN/m^2)

	loose	loose	loose	loose
Unit Weight γ, (kN/m^3)	11.8	11.8	11.8	11.8
diameter,m	0.0340	0.0485	0.0370	0.0515
type α^o	without coating	without coating	with coating	with coating
0	1.864	1.779	1.847	1.761
10	2.001	2.911	1.983	1.892
20	2.084	1.995	2.066	1.976
30	2.111	2.028	2.094	2.011
40	2.078	2.007	2.064	2.992
50	1.986	1.930	1.974	1.918
60	1.833	1.793	1.825	1.785
70	1.621	1.597	1.616	1.592
80	1.352	1.342	1.350	1.340
90	1.033	1.033	1.033	1.033
100	1.477	1.470	1.475	1.470
110	1.864	1.844	1.858	1.844
120	1.281	2.143	2.170	2.142
130	2.420	2.361	2.404	2.357
140	2.577	2.495	2.556	2.487
150	2.649	2.544	2.623	2.533
160	2.639	2.512	2.607	2.480
170	2.549	2.405	2.514	2.388
180	2.386	2.231	2.349	2.212
Total Stress	73.160	70.830	72.620	70.489

TABLE 10. Radial Stresses around the pipe (kN/m^2)

dense	1/10Proctor	1/10Proctor	1/10Proctor	1/10Proctor
unit weight γ,kN/m^3	14	14	14	14
diameter,m	0.340	0.0485	0.0370	0.0515
type / α^o	without coating	without coating	with coating	with coating
0	2.212	2.111	2.191	2.090
10	2.567	2.451	2.543	2.427
20	2.854	2.731	2.828	2.706
30	3.065	2.945	3.040	2.920
40	3.195	3.085	3.172	3.063
50	3.236	3.144	3.217	3.125
60	3.184	3.115	3.170	3.101
70	3.036	2.991	3.027	2.982
80	2.790	2.770	2.786	2.766
90	2.450	2.450	2.450	2.450
100	2.962	2.965	2.962	2.967
110	3.367	3.364	3.365	3.368
120	3.651	3.635	3.645	3.638
130	3.806	3.769	3.795	3.770
140	3.828	3.766	3.812	3.763
150	3.723	3.631	3.699	3.623
160	3.496	3.375	3.466	3.361
170	3.161	3.013	3.126	2.994
180	2.733	2.563	2.693	2.540
Total Stress	113.697	111.074	113.090	110.678

TABLE 11. Radial Stress around the pipe (kN/m^2)

dense	1/10Proctor	1/10Proctor	1/10Proctor	1/10Proctor
unit weight γ,kN/m^3	15.3	15.3	15.3	15.3
diameter,m	0.0340	0.0485	0.0370	0.0515
type α °	without coating	without coating	with coating	with coating
0	2.417	2.306	2.394	2.284
10	2.805	2.678	2.779	2.652
20	3.119	2.985	3.091	2.957
30	3.350	3.219	3.323	3.191
40	3.491	3.372	3.467	3.347
50	3.537	3.436	3.516	3.415
60	3.480	3.404	3.464	3.388
70	3.318	3.269	3.308	3.259
80	3.049	3.027	3.045	3.023
90	2.678	2.678	2.678	2.678
100	3.229	3.233	3.229	3.236
110	3.663	3.662	3.661	3.666
120	3.966	3.952	3.960	3.955
130	4.128	4.092	4.117	4.093
140	4.147	4.084	4.130	4.080
150	4.027	3.932	4.002	3.923
160	3.776	3.649	3.774	3.634
170	3.407	3.251	3.370	3.231
180	2.939	2.759	2.896	2.734
Total Stress	123.696	120.911	123.064	120.474

TABLE 12. Radial Stresses around the pipe (kN/m^2)

dense	100/100 Proctor	100/100 Proctor	100/100 Proctor	100/100 Proctor
unit weight γ, kN/m^3	20.3	20.3	20.3	20.3
diameter, m	0.340	0.0485	0.0370	0.0515
type α°	without coating	without coating	with coating	with coating
0	3.207	3.060	3.177	3.030
10	2.480	4.087	4.240	4.047
20	5.242	5.017	5.195	4.971
30	6.071	5.834	6.022	5.784
40	6.746	6.515	6.698	6.467
50	7.244	7.038	7.201	6.995
60	7.544	7.380	7.510	7.346
70	7.629	7.518	7.606	7.494
80	7.486	7.431	7.474	7.419
90	7.105	7.105	7.105	7.105
100	7.812	7.846	7.818	7.855
110	8.251	8.305	8.261	8.321
120	8.403	8.459	8.412	8.477
130	8.259	8.298	8.263	8.315
140	7.825	7.831	7.822	7.842
150	7.121	7.078	7.107	7.080
160	6.175	6.075	6.150	6.066
170	5.029	4.679	4.991	4.848
180	3.729	3.513	3.679	3.480
Total Stress	243.380	239.945	242.606	239.374

TABLE 13. Type of coatings, diameters, surface and unit areas of the pipes.

PIPE	1"	1 1/2"	1"	1 1/2"
type of coating	bare pipe	bare pipe	coating Denso S40,R41	coating Denso S40,R41
outside diameter,m.	0.0340	0.0485	0.0370	0.0515
surface area,m^2	0.0395	0.0564	0.0430	0.0600
unit area,m^2	0.0011	0.0016	0.0012	0.0017

TABLE 14. Total Forces around the pipe

Pipe	1"	$1^{1/2}$"	1"	$1^{1/2}$"
All values are in kN	without coating	without coating	with coating	with coating
Loose $\gamma=11$ kN/m^3	0.075	0.104	0.082	0.110
1/10Proctor $\gamma=12.6$kN/m^3	0.113	0.157	0.112	0.116
Loose $\gamma=11.8$kN/m^3	0.080	0.111	0.087	0.117
1/10Proctor $\gamma=14$ kN/m^3	0.125	0.174	0.135	0.184
1/10Proctor $\gamma=15.3$kN/m^3	0.136	0.189	0.147	0.200
100/100 Proctor $\gamma=20.3$kN/m^3	0.264	0.372	0.286	0.394

TABLE.15 Coefficient of Friction Values, μ

Coefficient of friction Values, μ		1" PIPE							$1^{1/2}$" PIPE						
Unit Weight, γ (kN/m^3)		11	12.6	11.8	14	15.3	20.3	20.3	11	12.6	11.8	14	15.3	20.3	20.3
Water Content, %		6	6.5	11.1	11.2	17.3	17.7	17.7	6	6.5	11.1	11.2	17.3	17.7	17.7
earth pressure coef. K_o		0.5	1.0	0.5	1.0	1.0	2.0	3.0	0.5	1.0	0.5	1.0	1.0	2.0	3.0
		loose	1/10Pr.	loose	1/10Pr.	1/10Pr.	100/100 Proc.		loose	1/10Pr.	loose	1/10Pr.	1/10Pr.	100/100 Proc.	
Bare Pipe	initial	0.453	0.743	0.325	1.008	1.125	*	*	0.346	0.573	0.279	1.161	1.333	*	*
	continuing	0.520	0.841	0.350	1.048	1.140	2.750	2.039	0.442	0.637	0.378	1.172	1.360	2.715	2.008
Coating NO:R 41	initial	0.390	1.582	0.310	1.407	0.980	2.469	1.824	0.436	2.078	0.368	1.587	1.340	1.523	2.604
	continuing	0.805	2.902	0.517	2.785	1.259	2.713	2.005	0.900	4.187	0.889	4.043	2.675	4.084	3.019
Coating NO:S40	initial	0.415	2.156	0.333	2.133	1.367	3.636	2.687	0.427	2.048	0.402	1.899	1.530	*	*
	continuing	0.805	3.566	0.598	4.578	2.673	4.427	3.271	0.755	4.054	0.692	3.717	2.340	3.985	2.946
Reverse coating NO:R41	initial	–	–	–	–	–	–	–	0.327	0.801	0.308	0.935	1.040	*	*
	continuing	–	–	–	–	–	–	–	0.673	1.916	0.436	1.918	1.110	3.188	2.356
Reverse coating NO:S40	initial	0.402	1.475	0.310	2.089	1.415	2.983	2.204	–	–	–	–	–	–	–
	continuing	0.610	3.041	0.483	3.222	1.966	3.738	2.762	–	–	–	–	–	–	–

*It could not be measured

TABLE 16 Coefficient of Friction Values, μ (initial)

Coefficient of friction Values, μ		1" PIPE							$1^{1/2}$" PIPE						
Unit Weight, γ (kN/m³)		11	12.6	11.8	14	15.3	20.3	20.3	11	12.6	11.8	14	15.3	20.3	20.3
Water Content, μ %		6	6.5	11.1	11.2	17.3	17.7	17.7	6	6.5	11.1	11.2	17.3	17.7	17.7
earth pressure coef. K_o		0.5	1.0	0.5	1.0	1.0	2.0	3.0	0.5	1.0	0.5	1.0	1.0	2.0	3.0
		loose	1/10Pr	loose	1/10Pr.	1/10Pr.	100/100 Proc.		loose	1/10Pr.	loose	1/10Pr.	1/10Pr	100/100 Proc.	
Bare Pipe	initial	0.453	0.743	0.325	1.008	1.125	*	*	0.346	0.573	0.279	1.161	1.333	*	*
Coating No:R41	initial	0.390	1.582	0.310	1.407	0.980	2.469	1.824	0.436	2.078	0.368	1.587	1.340	1.523	2.604
Coating No:S40	initial	0.415	2.156	0.333	2.133	1.367	3.636	2.687	0.427	2.048	0.402	1.899	1.530	*	*
Reverse coating No:R41	initial	-	-	-	-	-	-	-	0.327	0.801	0.308	0.935	1.040	*	*
Reverse Coating No:S40	initial	0.402	1.475	0.310	2.089	1.415	2.983	2.204	-	-	-	-	-	-	-

*It could not be measured

TABLE 17. Angles of Pipe-soil Friction, ϕ

Pipe-soil Friction angles, ϕ		1" PIPE							$1^{1/2}$" PIPE						
Unit Weight, γ (kN/m^3)		11	12.6	11.8	14	15.3	20.3	20.3	11	12.6	11.8	14	15.3	20.3	20.3
Water Content, %		6	6.5	11.1	11.2	17.3	17.7	17.7	6	6.5	11.1	11.2	17.3	17.7	17.7
earth pressure coef. K_o		0.5	1.0	0.5	1.0	1.0	2.0	3. 0	0.5	1.0	0.5	1.0	1.0	2.0	3.0
		loose	1/10Pr.	loose	1/10Pr.	1/10Pr	100/100 Proc.		loose	1/10Pr.	loose	1/10Pr.	1/10Pr	100/100 Proc.	
Bare Pipe	initial	24.4	36.6	18.0	45.2	48.4	*	*	19.1	29.8	15.6	49.3	53.1	*	*
	continuing	27.5	40.1	19.3	46.3	48.7	70.0	63.9	23.8	32.5	20.7	49.5	53.7	69.8	63.5
Coating NO:R41	initial	21.3	57.7	17.2	54.6	44.4	67.9	61.3	23.6	63.4	20.2	57.8	53.3	74.2	69.0
	continuing	38.8	71.0	27.3	70.2	51.5	69.0	63.5	42.0	76.6	41.6	76.1	69.5	76.2	71.7
Coating NO:S40	initial	22.5	65.1	18.4	64.9	53.8	74.6	69.6	23.1	64.0	21.9	60.9	56.8	*	*
	continuing	38.8	74.3	30.9	77.7	69.5	71.3	73.0	37.1	76.1	34.7	74.9	66.9	75.9	71.2
Reverse coating NO:R41	initial	-	-	-	-	-	-	-	18.1	38.7	17.1	43.1	46.1	*	*
	continuing	-	-	-	-	-	-	-	33.9	62.4	23.6	62.5	48.0	72.6	67.0
Reverse coating No:S40	initial	21.9	55.9	17.2	64.4	54.7	71.5	65.6	-	-	-	-	-	-	-
	continuing	31.4	71.8	25.8	72.8	63.0	75.0	70.1	-	-	-	-	-	-	-

*It could not be measured

TABLE 18 Angles of Pipe-soil Friction, ϕ

Pipe-soil Friction angles, ϕ		1" PIPE							$1^{1/2}$" PIPE						
Unit weight, γ (kN/m^3)		11	12.6	11.8	14	15.3	20.3	20.3	11	12.6	11.8	14	15.3	20.3	20.3
Water Content, %		6	6.5	11.1	11.2	17.3	17.7	17.7	6	6.5	11.1	11.2	17.3	17.7	17.7
earth pressure coef. K_o		0.5	1.0	0.5	1.0	1.0	2.0	3.0	0.5	1.0	0.5	1.0	1.0	2.0	3.0
		loose	1/10Pr.	loose	1/10Pr.	1/10Pr.	100/100	Proc.	loose	1/10Pr.	loose	1/10 Pr.	1/10Pr	100/100	Proc.
Bare Pipe	initial	24	37	18	45	48	*	*	19	30	16	49	53	*	*
Coating No:R41	initial	21	58	17	55	44	68	61	24	64	20	58	53	74	69
Coating No:S40	initial	23	65	18	65	54	75	70	23	64	22	61	57	*	*
Reverse coating No:R41	initial	-	-	-	-	-	-	-	18	39	17	43	46	*	*
Reverse coating No:S40	initial	22	56	17	64	55	72	66	-	-	-	-	-	-	-

*It could not be measured

6.1.2 Graphical Representation of the Results

6.1.2.1 Pull out Forces

Pull out force values of Table 6. corresponding unit weight and water content values are drawn in Figures from 11 to 26. Since the increase in water content caused increase in unit weight, the discussions were made for only one parameter (unit weight), but Figures were drawn both of them. (unit weight and water content.)

1.0 inch Pipe

a. Pipe without coating (bare pipe)

Pull out forces corresponding unit weight and watercontent values are shown in Figures 11 and 12.

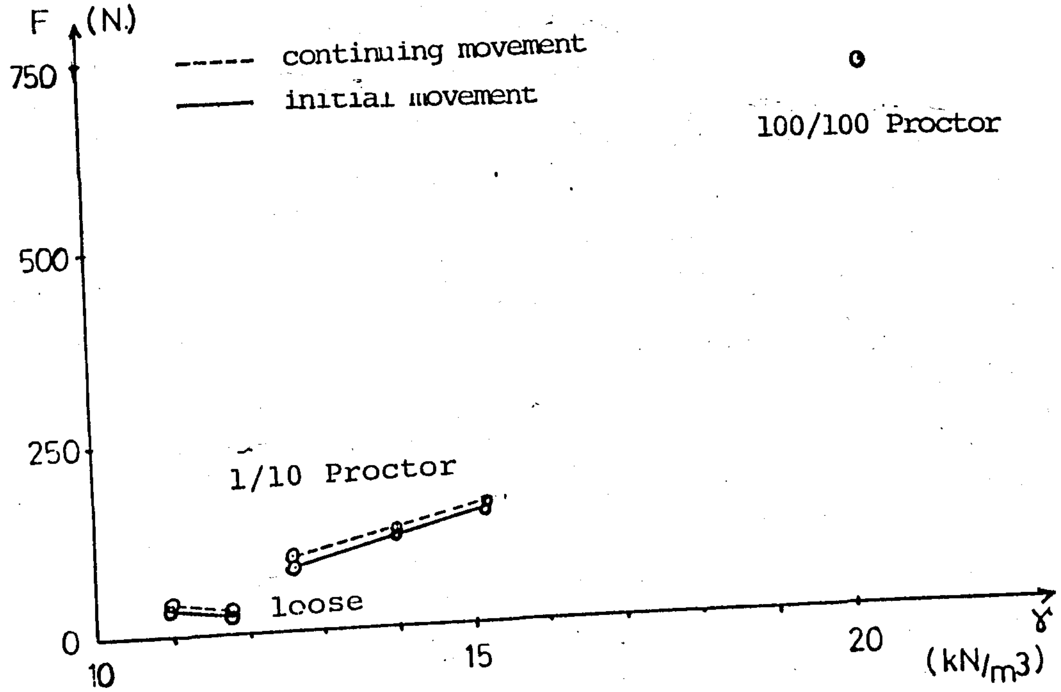


FIGURE 11. Pull out Force vs. unit weight (1.0 inch bare pipe)

In soil condition; an increase in unit weight caused a decrease in pull out force. This phenomena can be explained as follows :

Since the water content of the soil increased, the soil particles behaved as lubricated therefore reduced the pull out force.

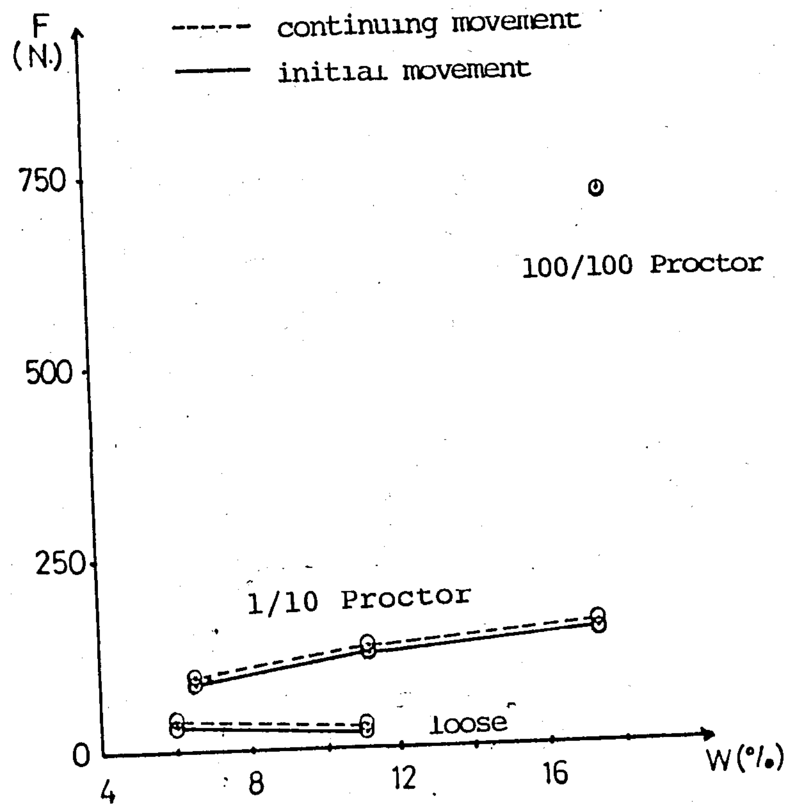


FIGURE 12. Pull out Force vs. water content

(1.0 inch bare pipe)

In 1/10 Proctor condition; an increase in unit weight caused an increase in pull out force because of the over consolidation. When 100/100 Proctor was made the pull out force increased six times of the averaged pull out force at Proctor value.

b. with coating no : DT R41

Pull out forces corresponding unit weight and water values are shown in Figures 13 and 14.

In loose condition; an increase in unit weight and moisture content caused a decrease in pull out force.

In 1/10 Proctor condition; an increase in unit weight caused first a slight increase then a large decrease in pull out force. Since the optimum moistures were passed at the third values of 1/10 Proctors, the pull out forces decreased at the third points for all coated pipes.

The slight increase in pull out force is because of the lusterness and the suitability to 1.0 inch pipe of the Tape R41.

The pull out force increased three times of 1/10 Proctor value, when 100/100 proctor was made.

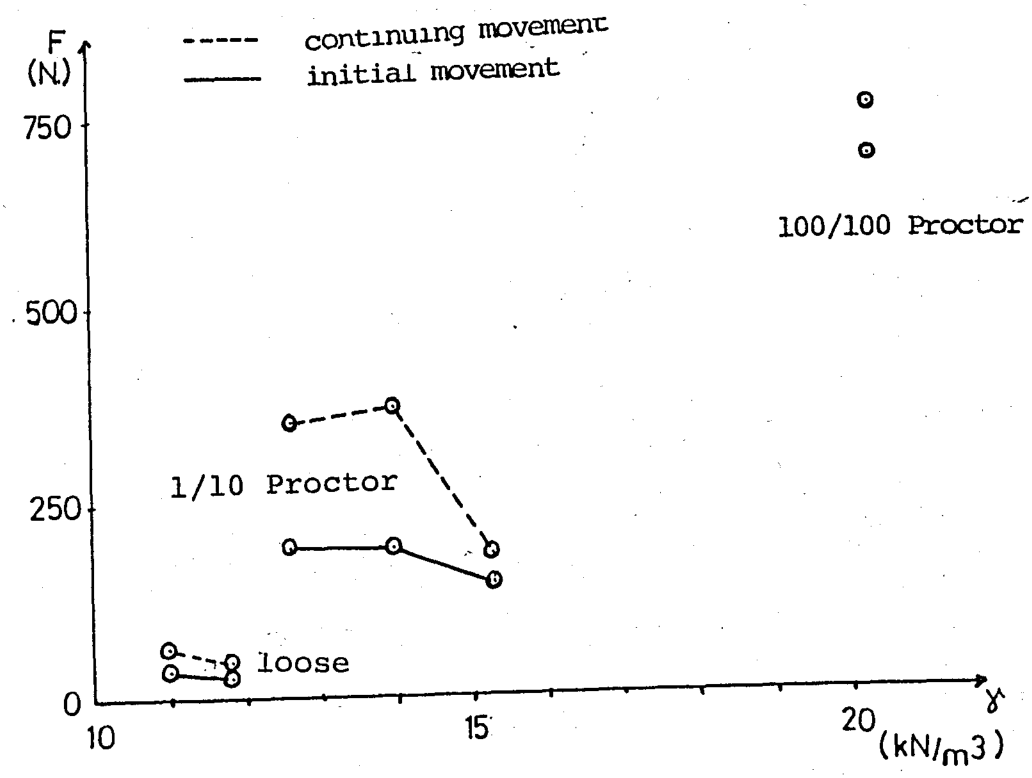


FIGURE 13. Pull out Force vs. unit weight
(1.0 inch coated with DT R41)

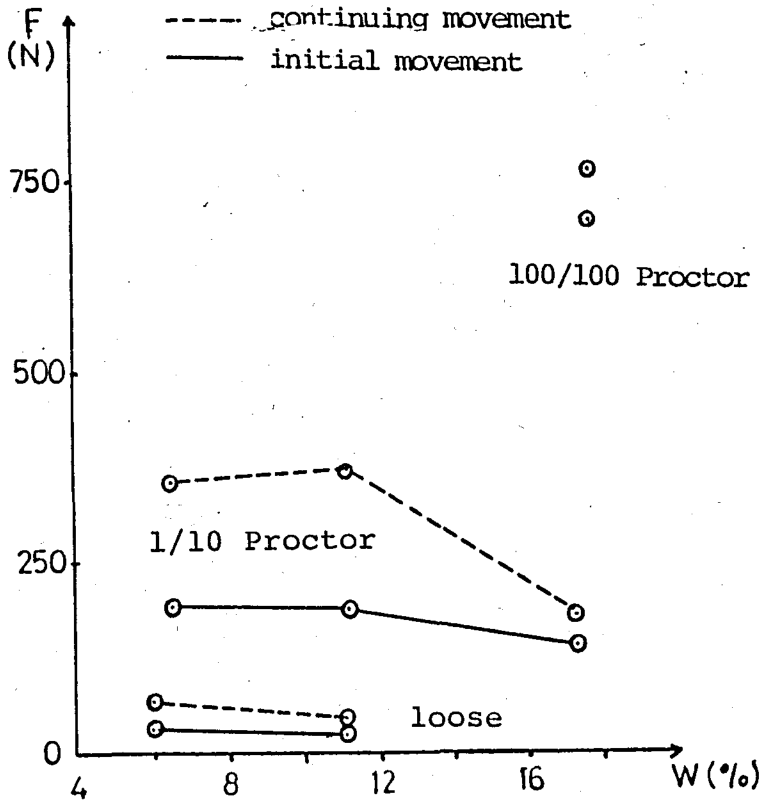


FIGURE 14. Pull out Force vs. water content
(1.0 inch coated with DT R41)

c. with coating no : DT S40

Pull out forces corresponding unit weight and water content values are shown in Figures 15 and 16.

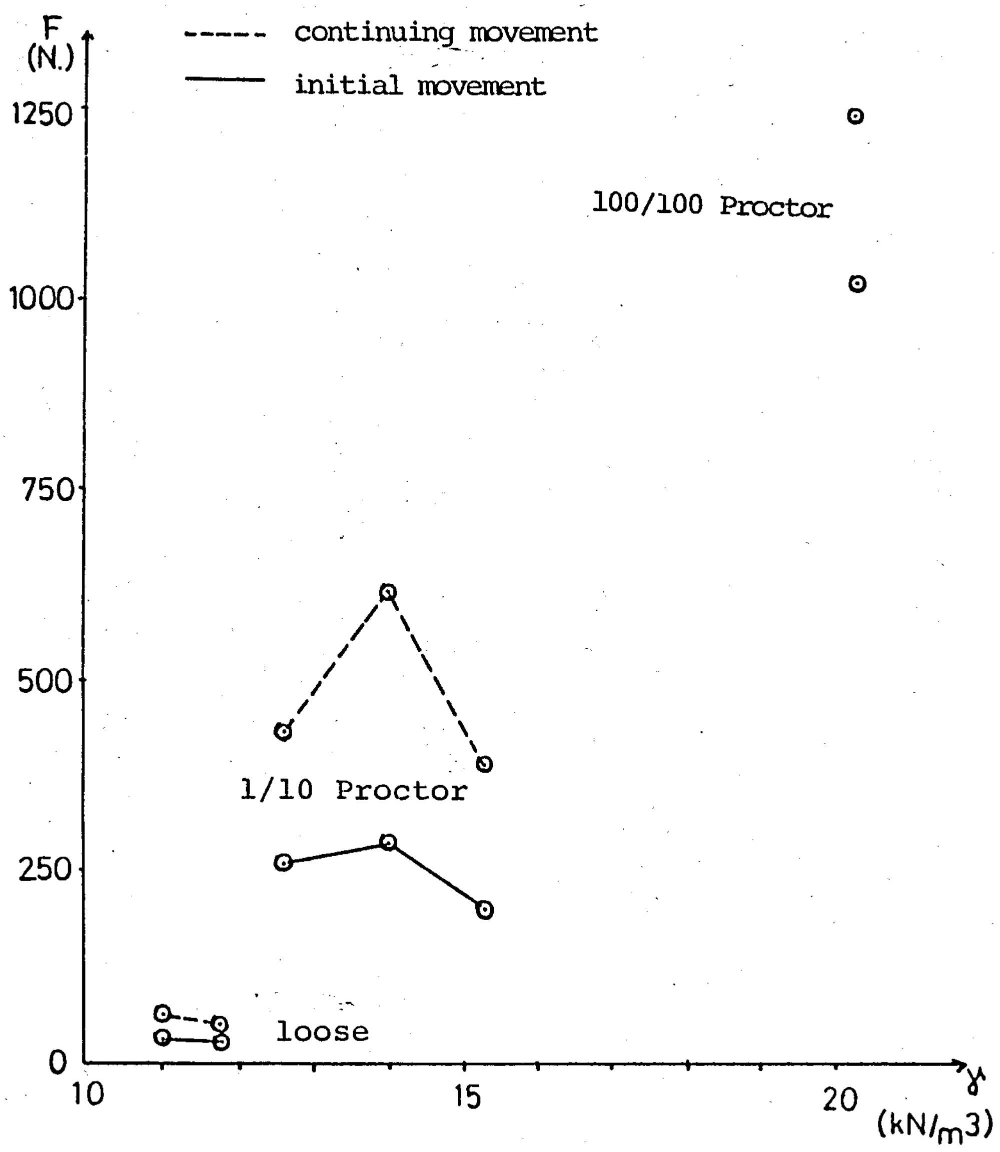


FIGURE 15. Pull out Force vs.unit weight
(1.0 inch coated with DT S40)

In loose condition; a decrease in pull out force was observed.

In 1/10 Proctor condition; first a large increase and than a large decrease where observed. DT S40 is less luster than DT R41 therefore more force is necessary to pull the pipe.

The pull out force increased three times of 1/10 Proctor value 100/100 Proctor was made.

d. with reserve coating no:RDT S40

Pull out forces corresponding unit weight and water content values are shown in Figures 17. and 18.

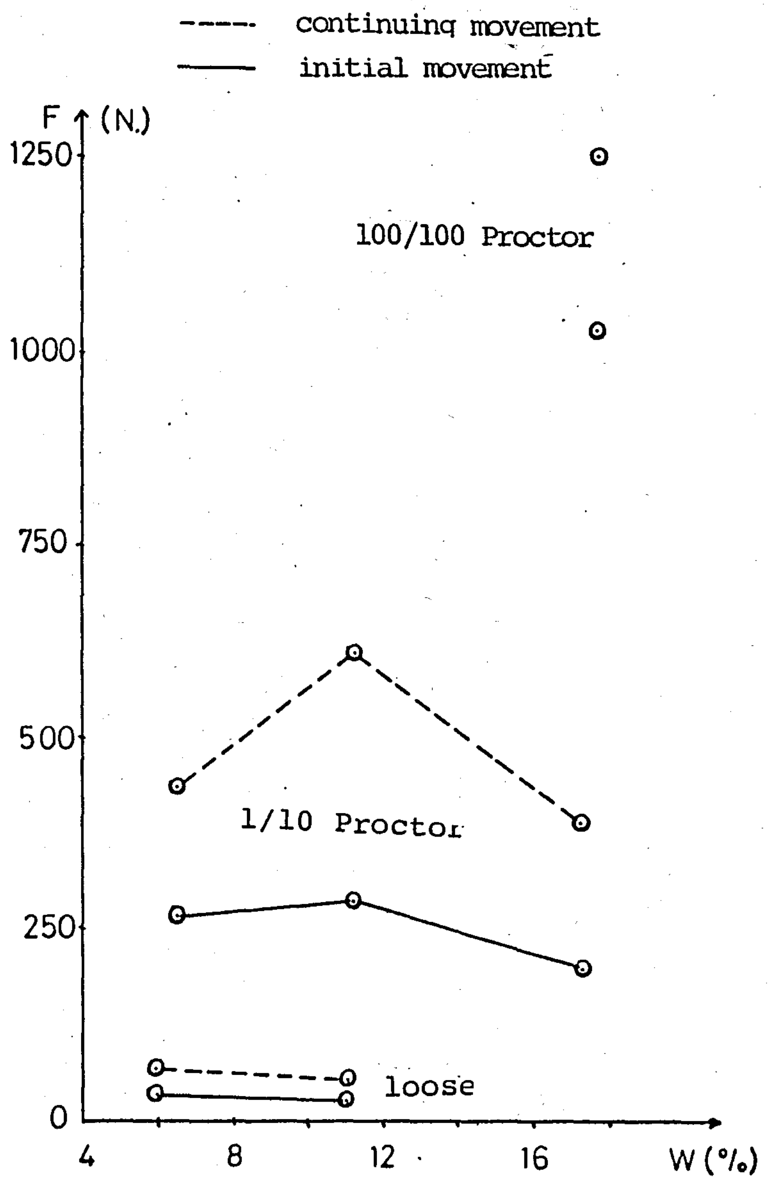


FIGURE 16. Pull out Force vs. water content

(1.0 inch coated with DT S40)

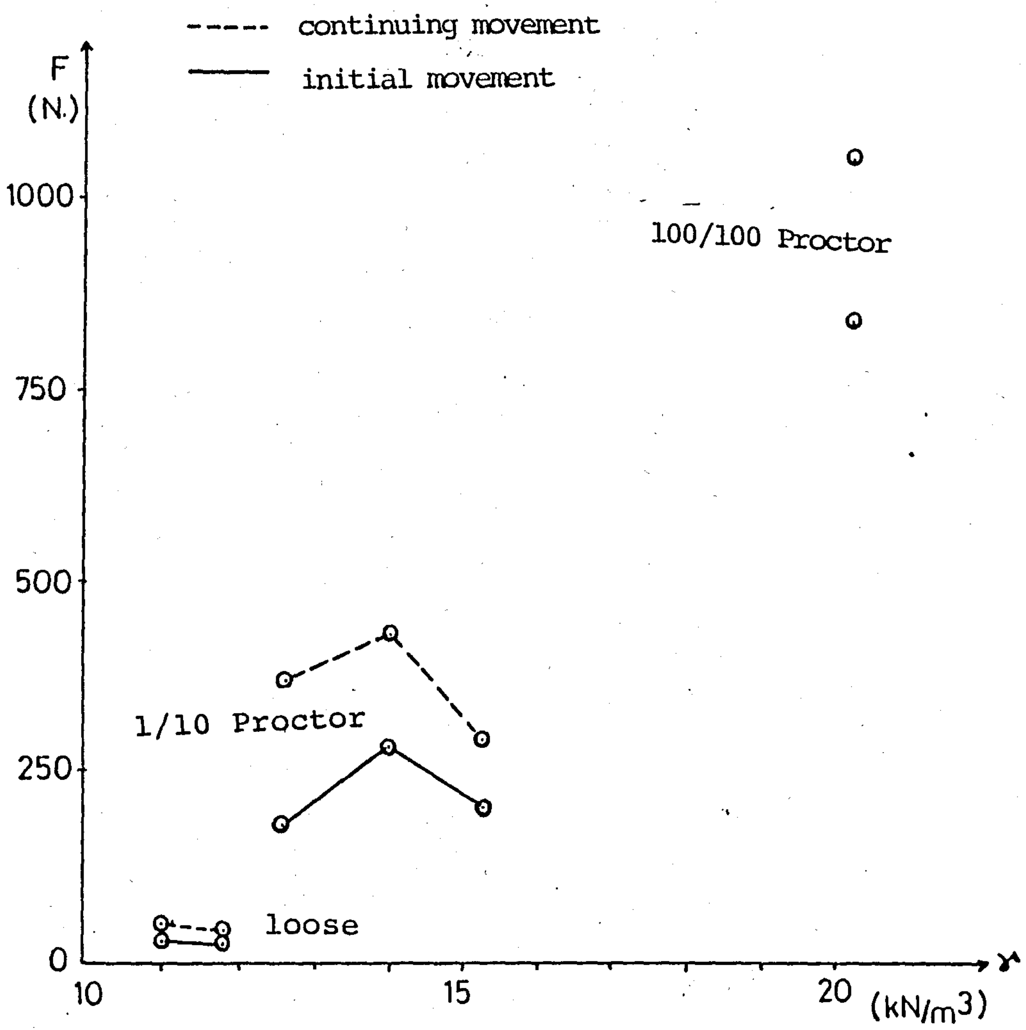


FIGURE 17. Pull out Force vs. unit weight (1.0 inch coated with RDTS40)

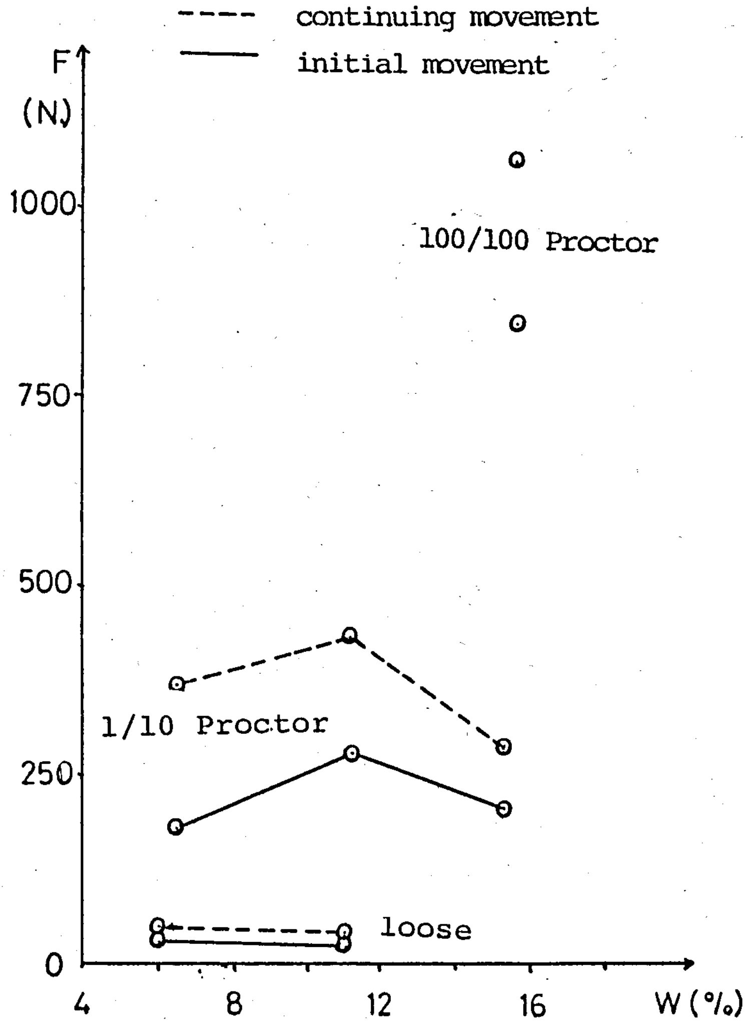


FIGURE 18. Pull out Force vs. water content (1.0 inch coated with RDTS40)

Pull out force values of RDTS40 showed the some properties of DTS40 but the values were smaller than DT S40.

1.5 inches Pipe.

Pipe without coating

a) Pipe without coating (bare pipe)

Pull out forces corresponding unit weight and water content values are shown in Figures 19 and 20.

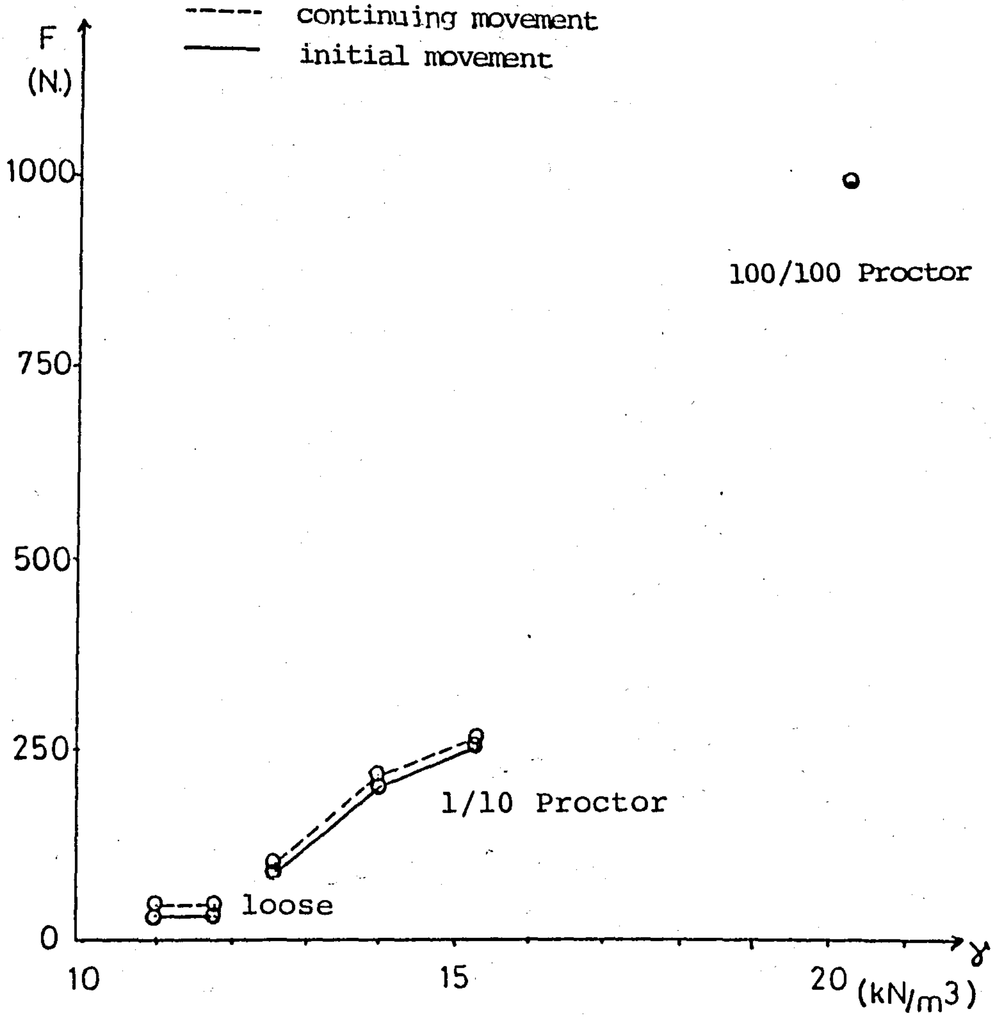


FIGURE 19. Pull out Force vs. unit weight (1.5 inches bare pipe)

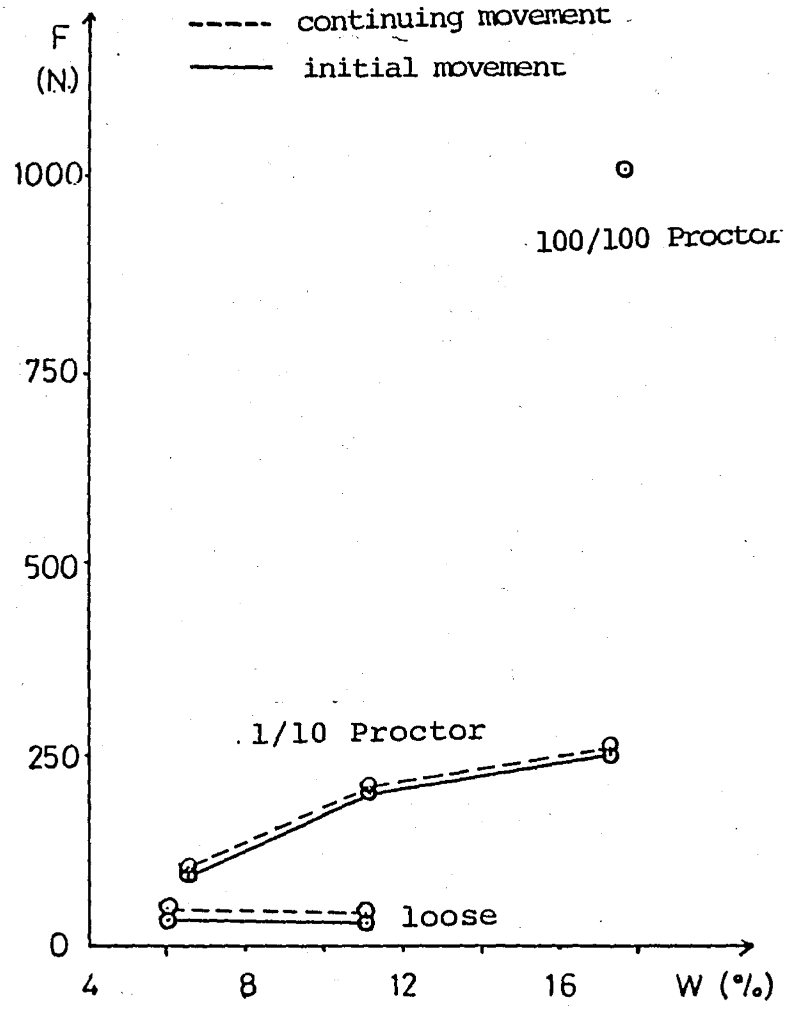


FIGURE 20 Pull out Force vs. water content

(1.5 inches bare pipe)

b. with coating no : DT R41

Pull out forces corresponding weight and water content values are shown in Figures 21 and 22.

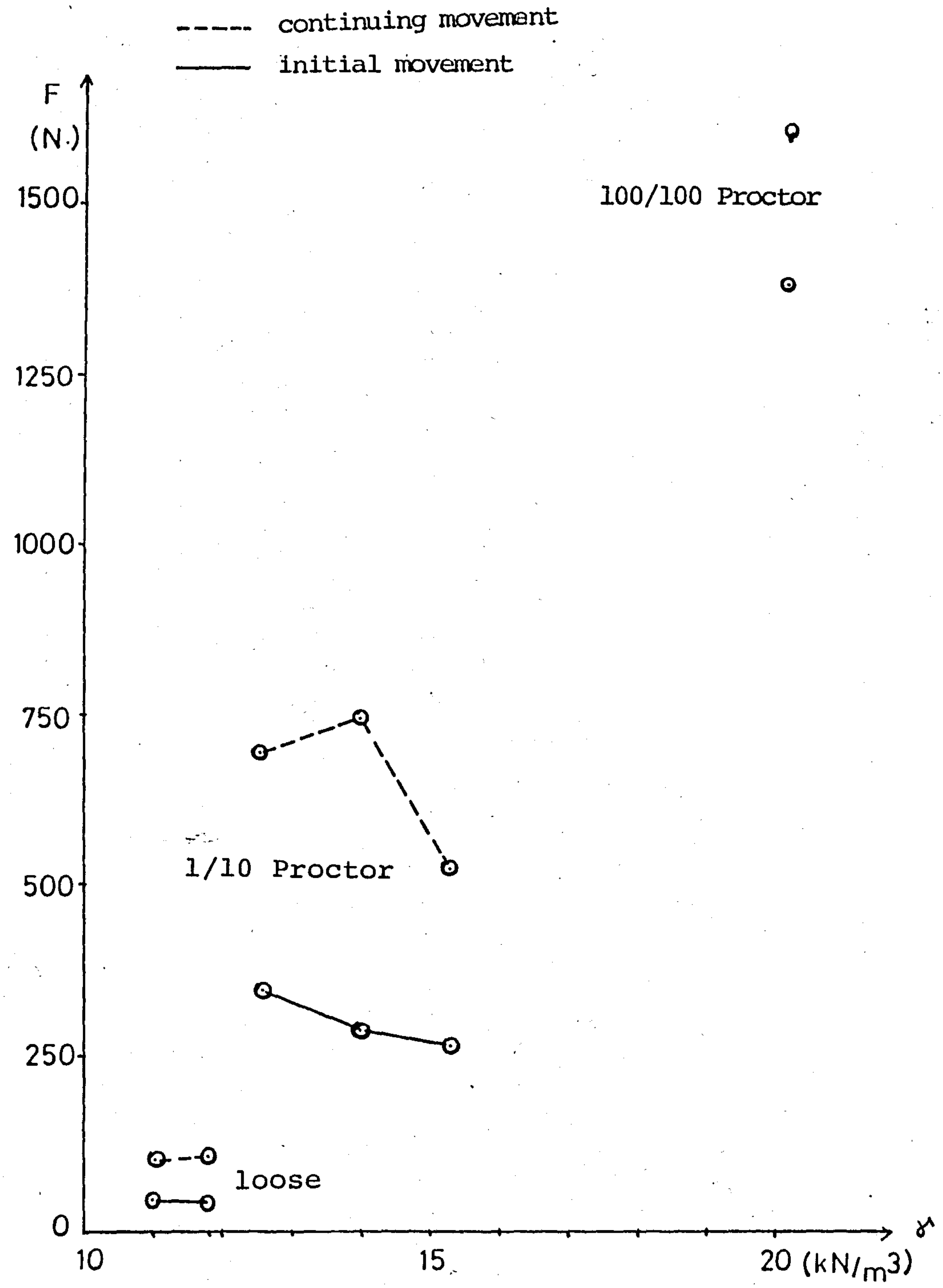


FIGURE 21. Pull out Force vs. unit weight

(1.5 inches coated with DTR41)

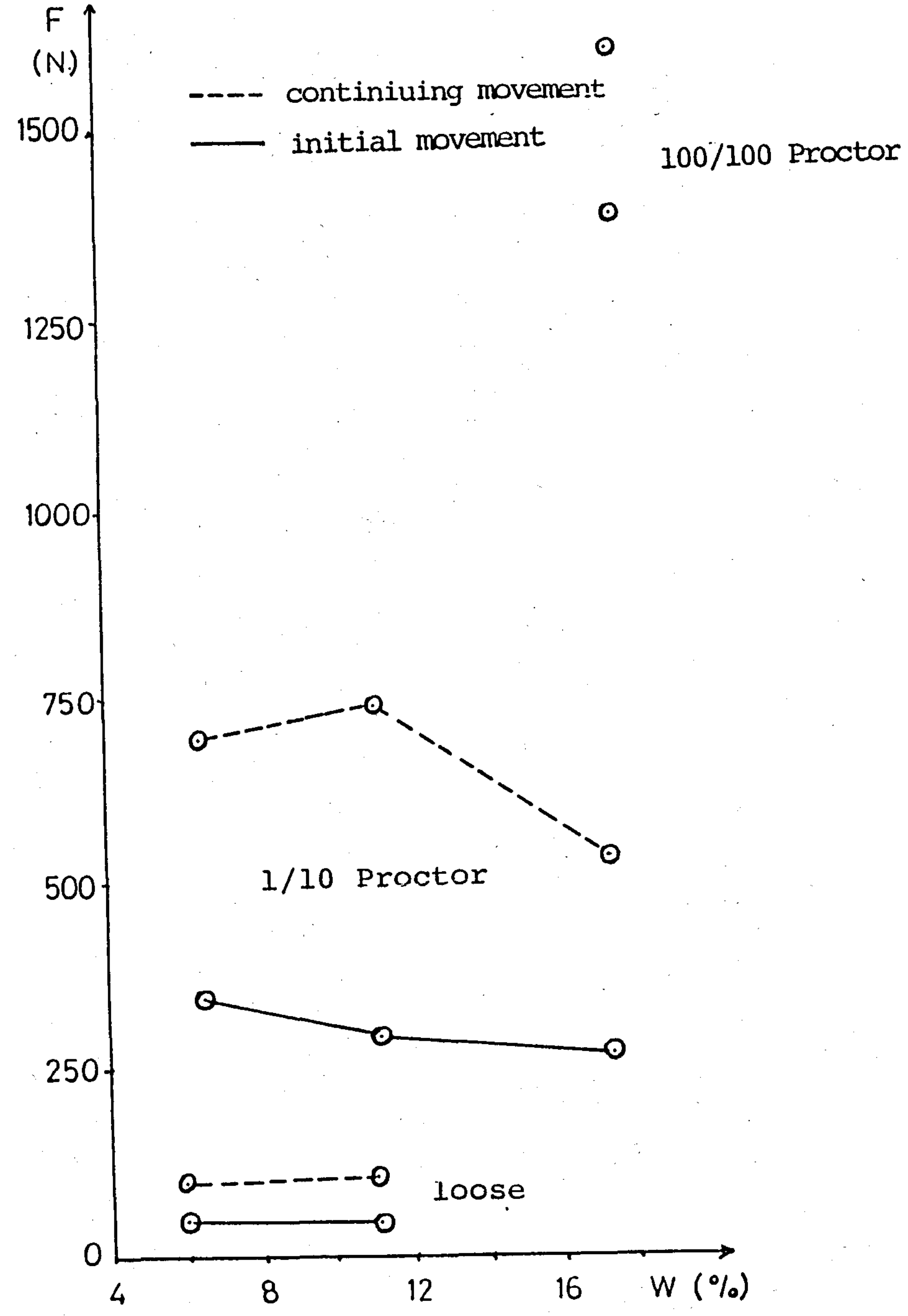


FIGURE 22. Pull out Force vs. water content
(1.5 inches coated with DTR41)

c. with coating no : DTS40

Pull out forces corresponding unit weight and water content values are shown in Figures 23 and 24.

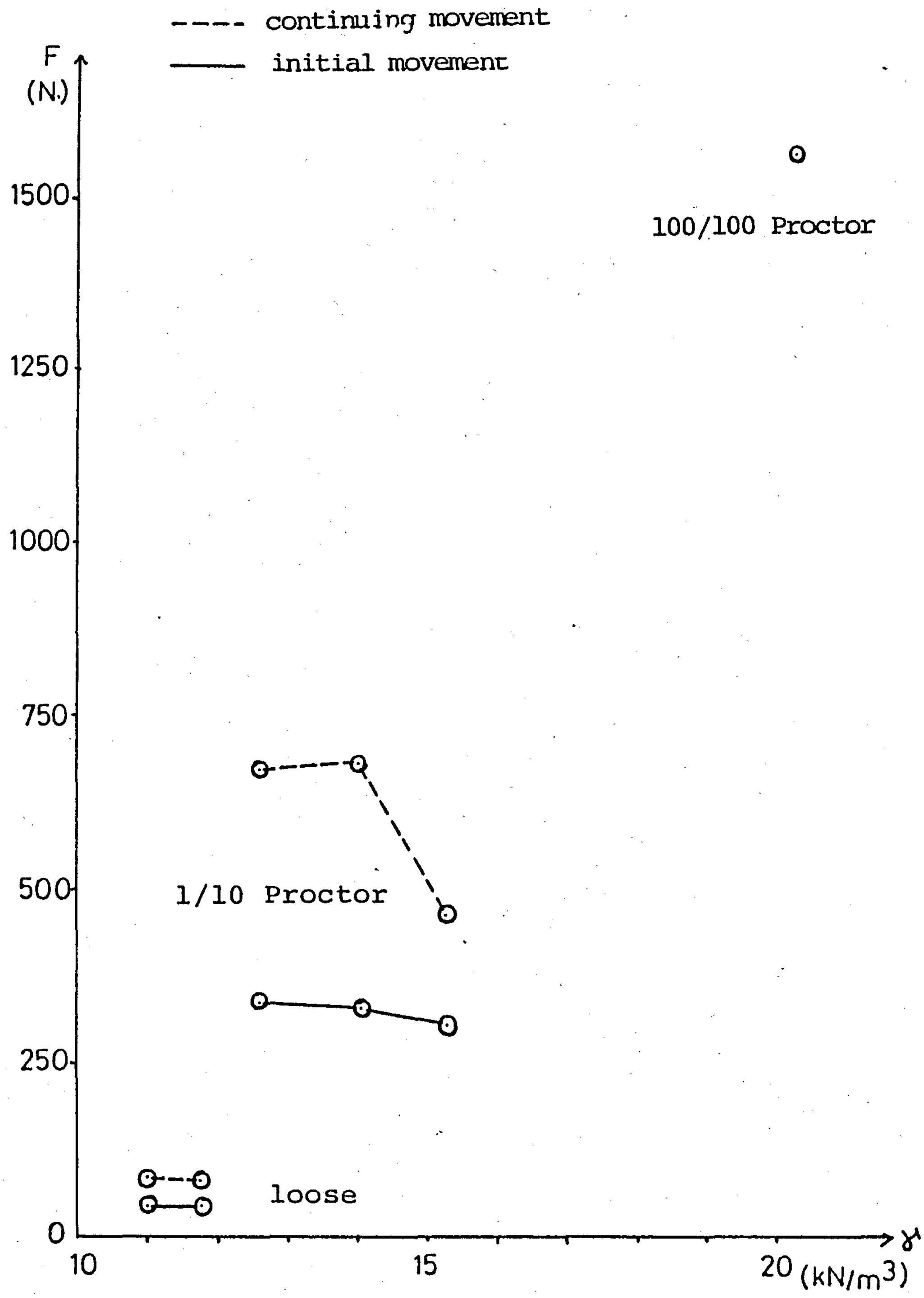


FIGURE 23. Pull out Force vs. unit weight

(1.5 inches coated with DTS40)

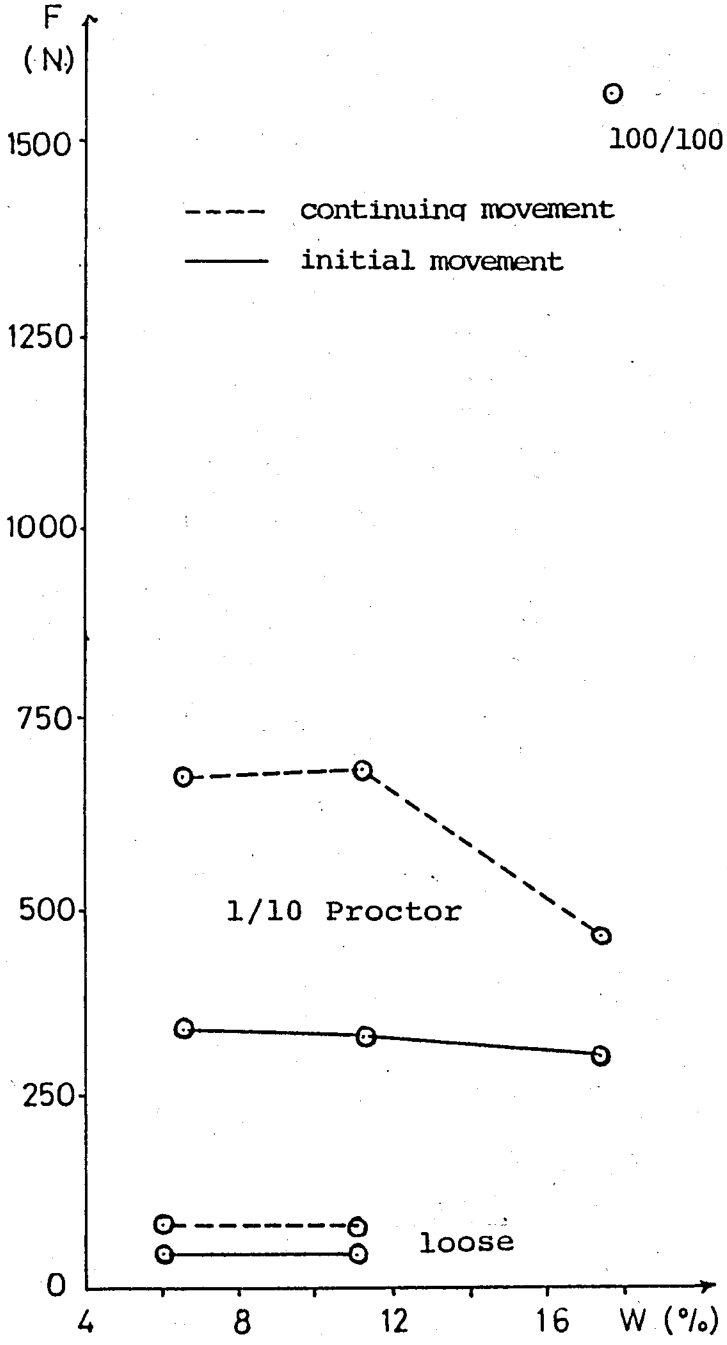


FIGURE 24 Pull out Force vs. water content

(1.5 inches coated with DTS40)

d. with reserve coating no : RDTR41

Pull out forces corresponding unit weight and water content values are shown in Figures 25 and 26.

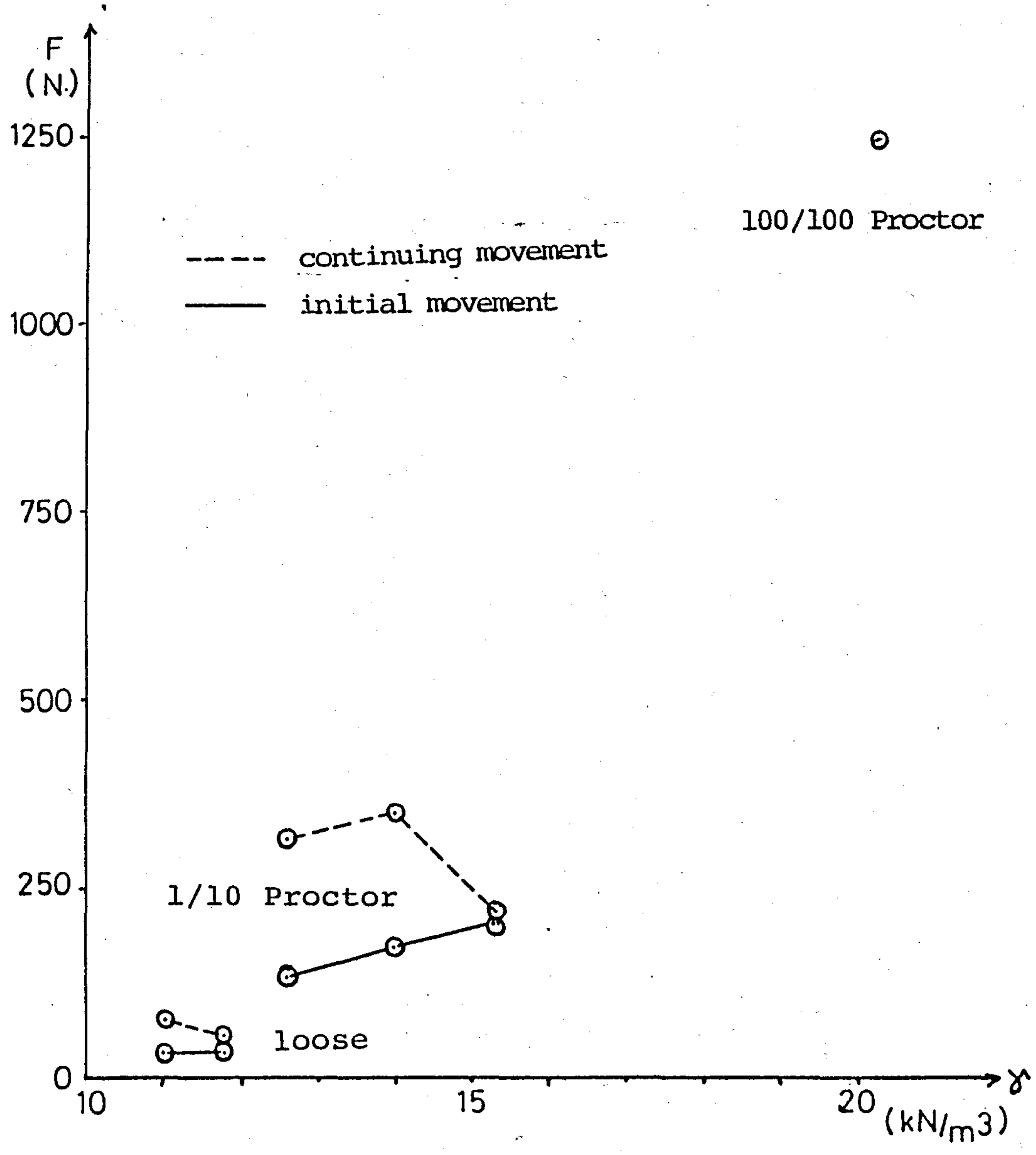


FIGURE 25 Pull out Force vs. unit weight

(1.5 inches coated with RDTR41)

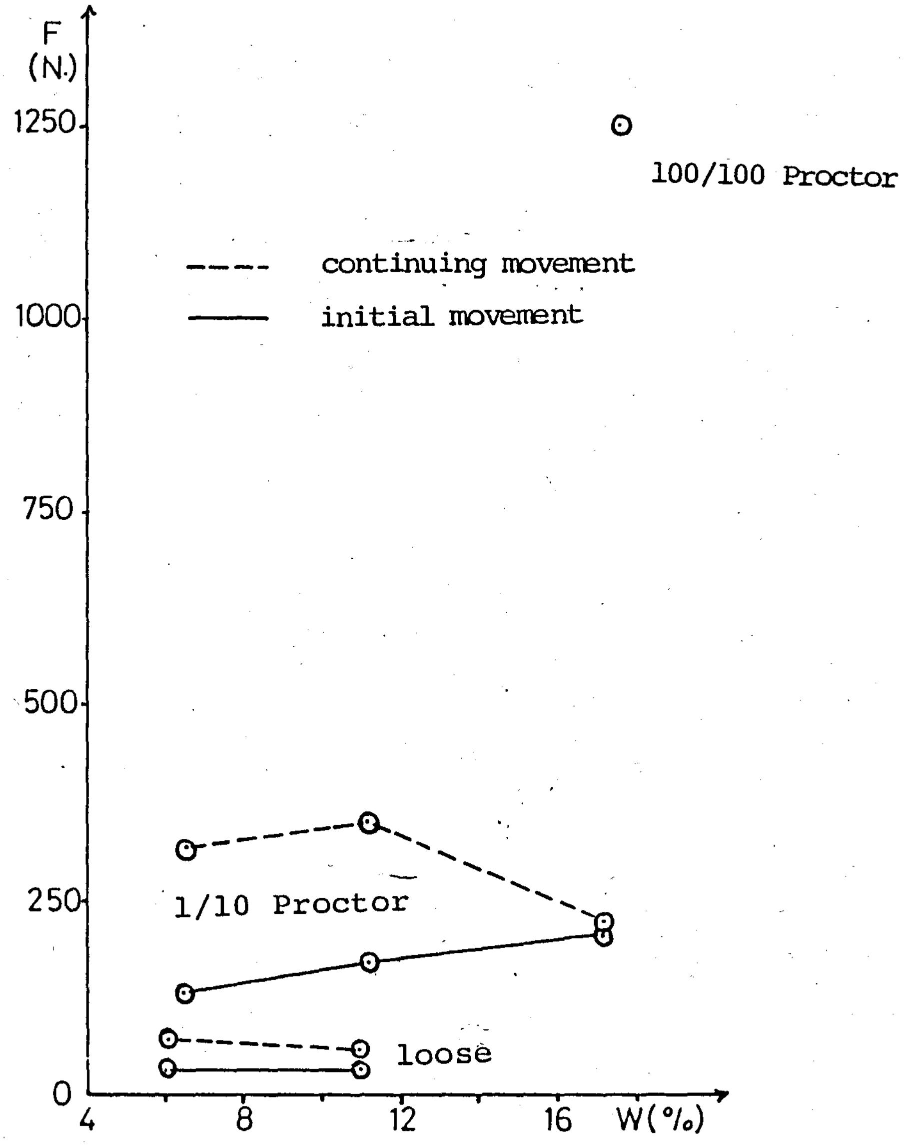


FIGURE 26. Pull out Force vs. water content
(1.5 inches coated with RDTR41)

6.1.2.2 Coefficient of Friction

Coefficient of friction values of Table 15. corresponding unit weight and water content values are plotted in Figures from 27 to 42.

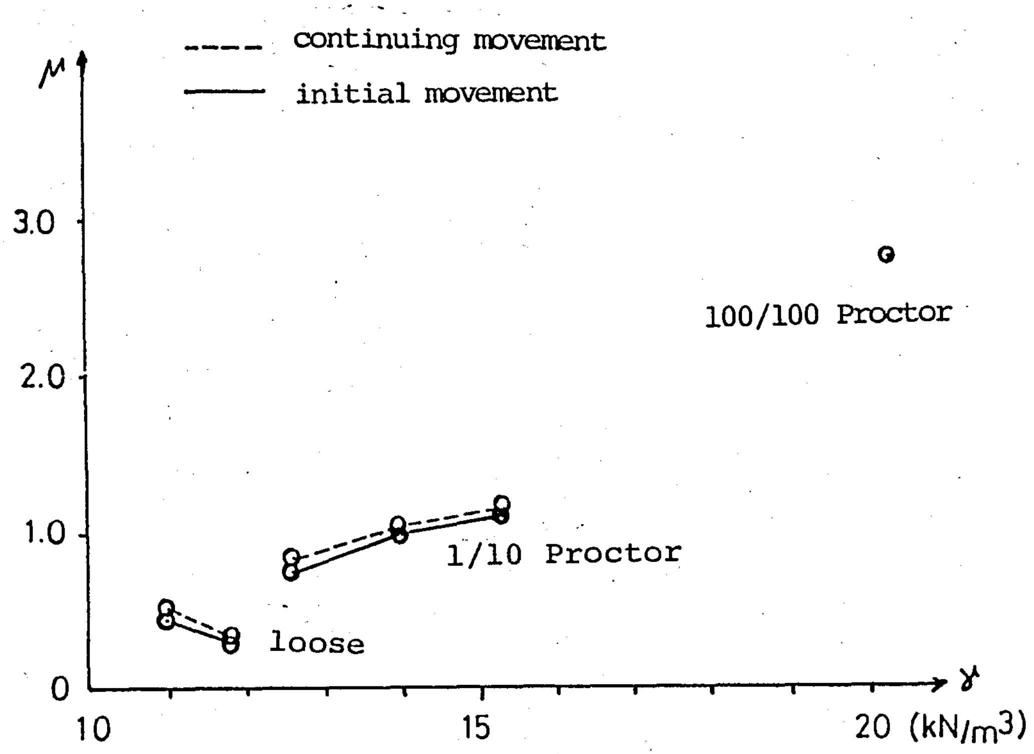


FIGURE 27. Coefficient of Friction vs. unit weight

(1.0 inch bare pipe)

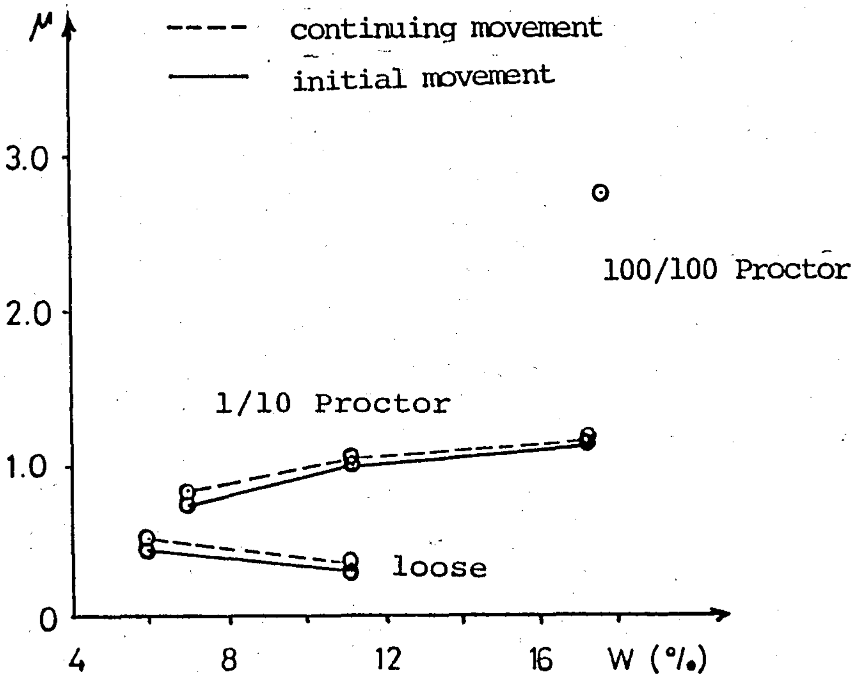


FIGURE 28. Coefficient of Friction vs. water content (1.0 inch bore pipe)

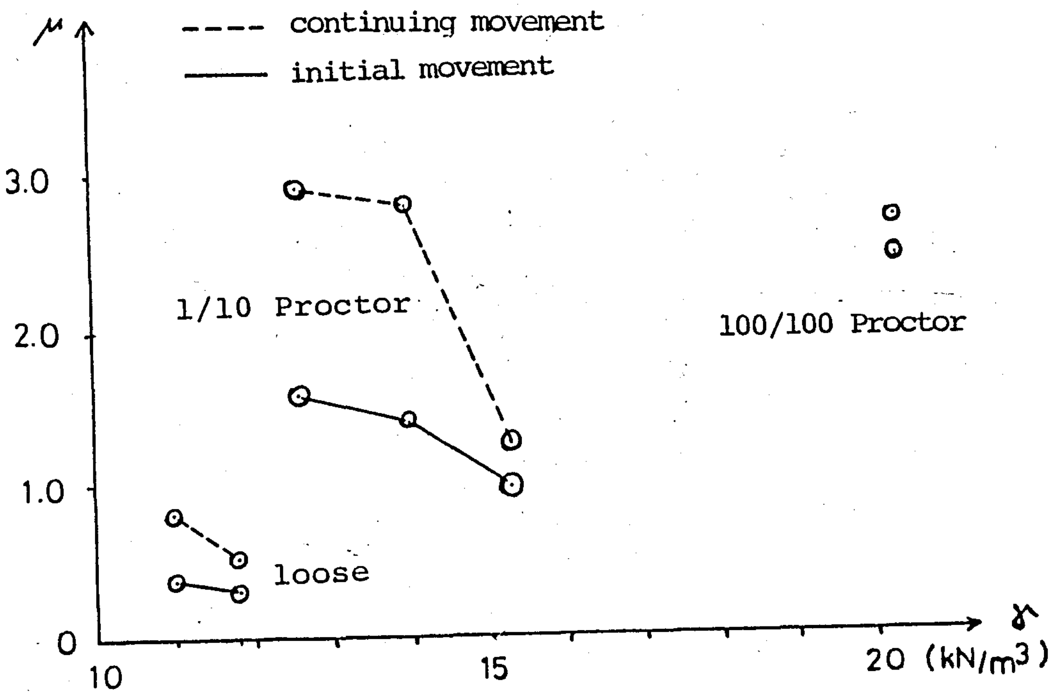


FIGURE 29. Coefficient of Friction vs. unit weight (1.0 inch coated with RTR41)

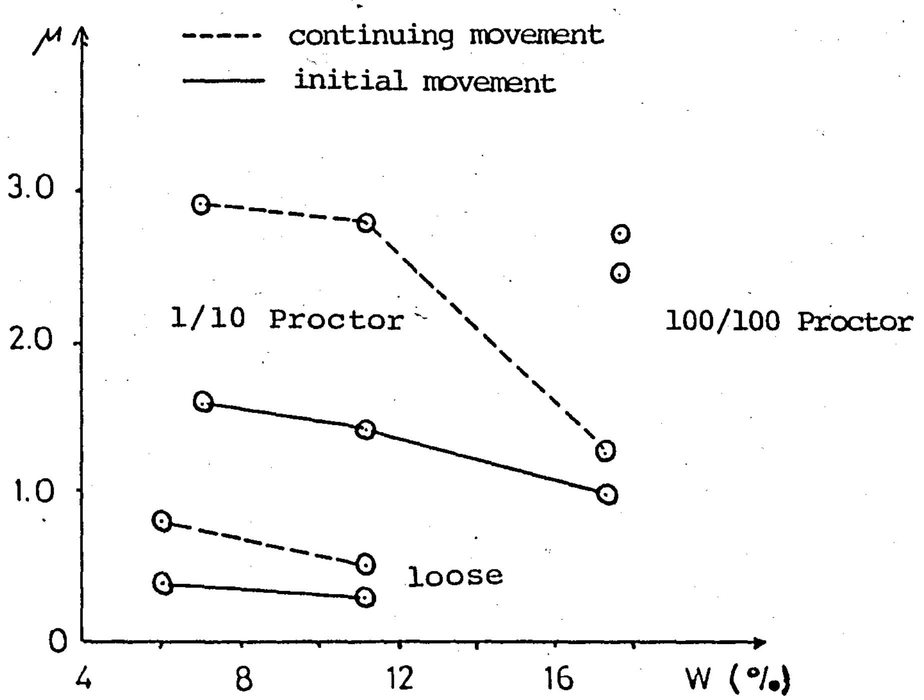


FIGURE 30 Coefficient of Friction vs. water content (1.0 inch coated with DTR41)

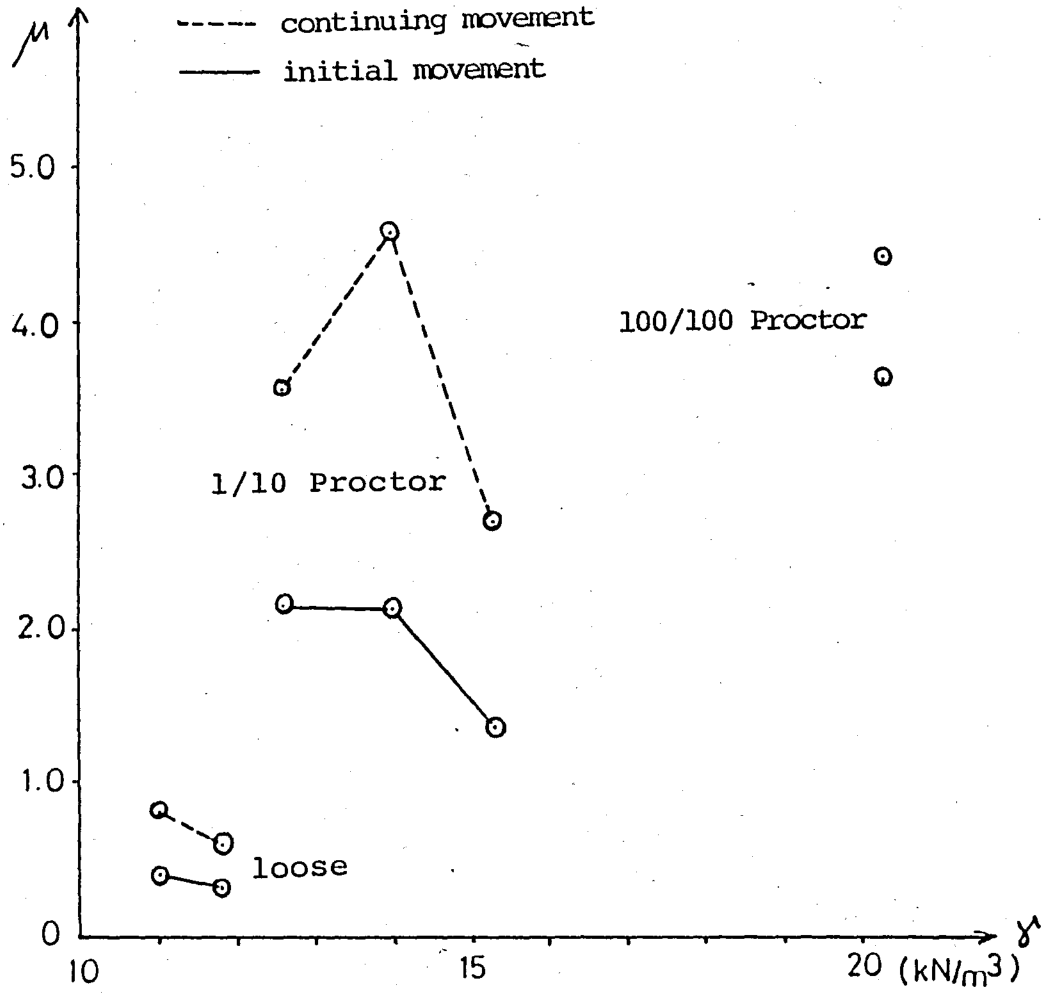


FIGURE 31 Coefficient of Friction vs. unit weight

(1.0 inch coated with DTS40)

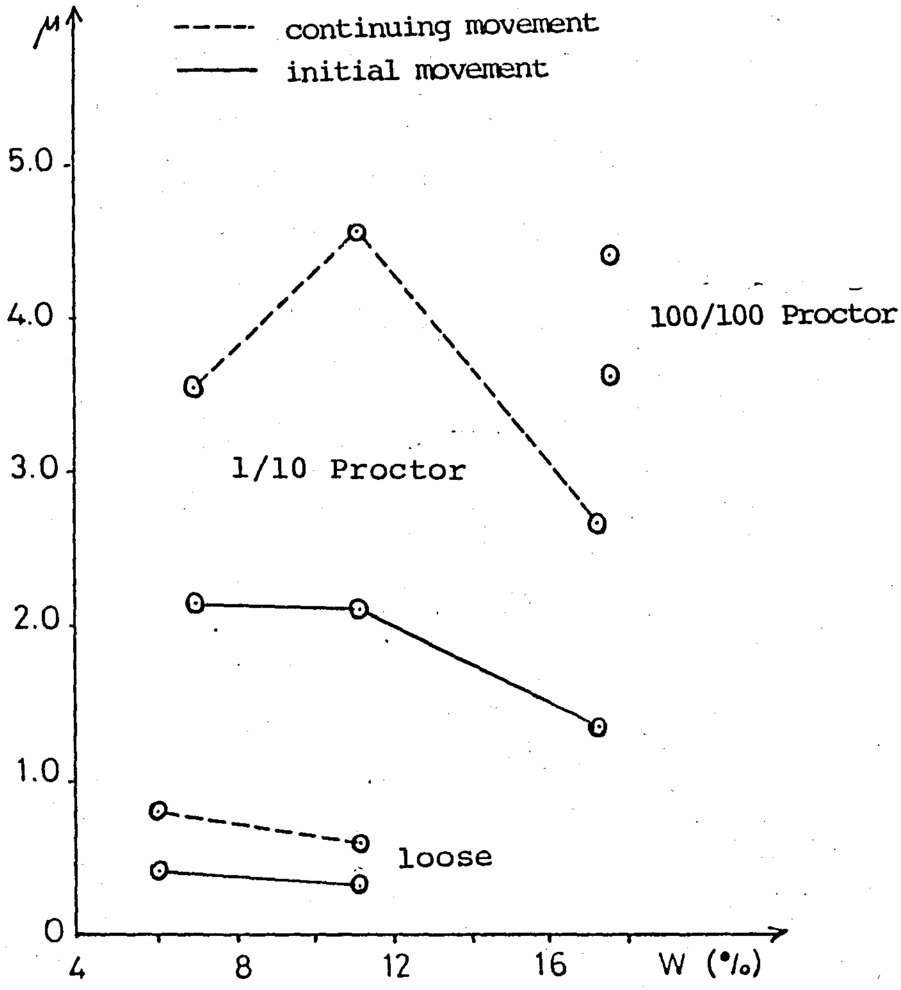


FIGURE 32. Coefficient of Friction vs. water content (1.0 inch coated with DTS40)

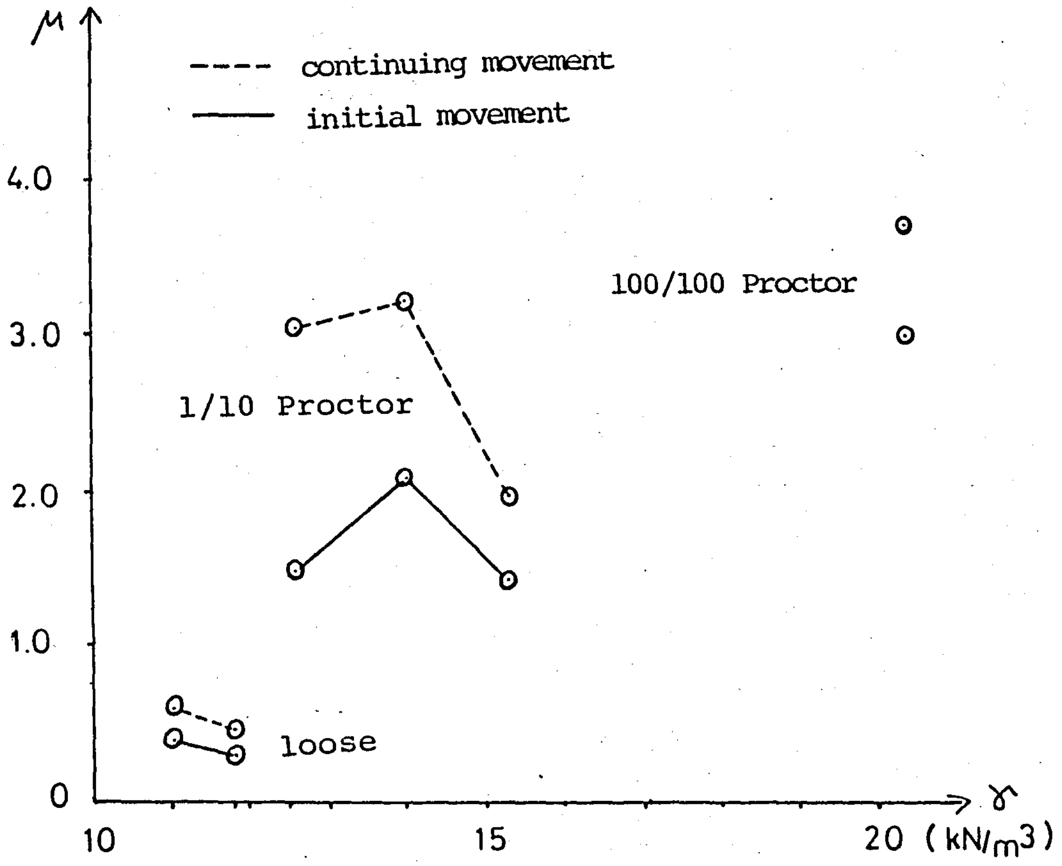


FIGURE 33. Coefficient of Friction vs. unit weight
(1.0 inch coated with RDTS40)

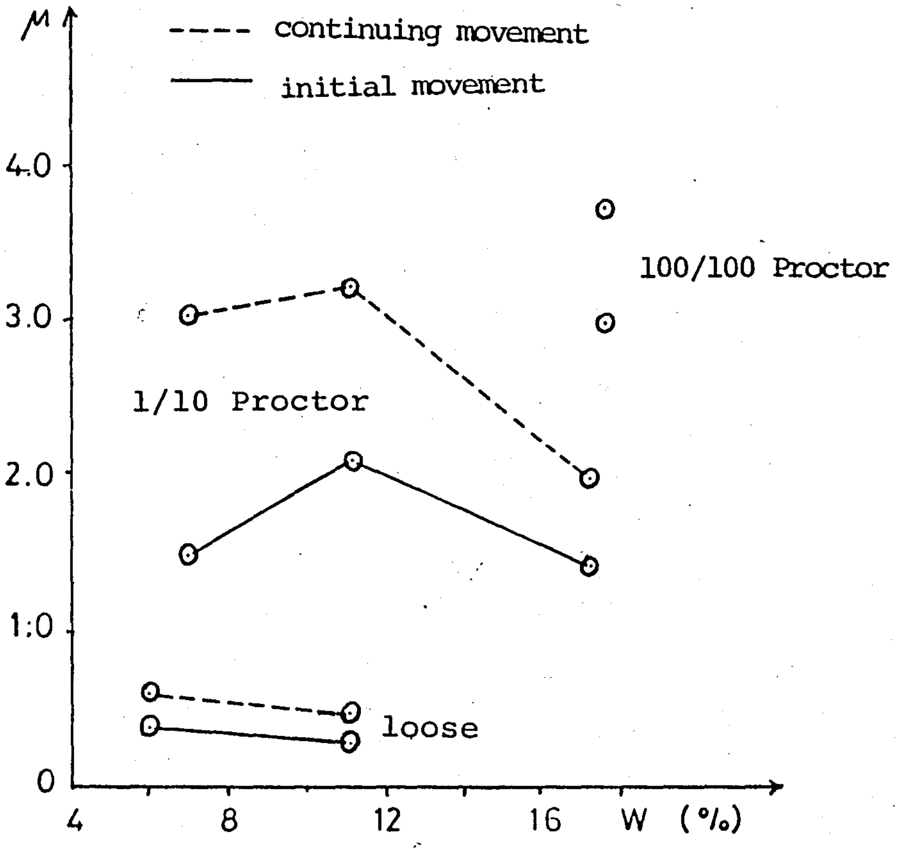


FIGURE 34. Coefficient of Friction vs. water content

(1.0 inch coated with RDTS40)

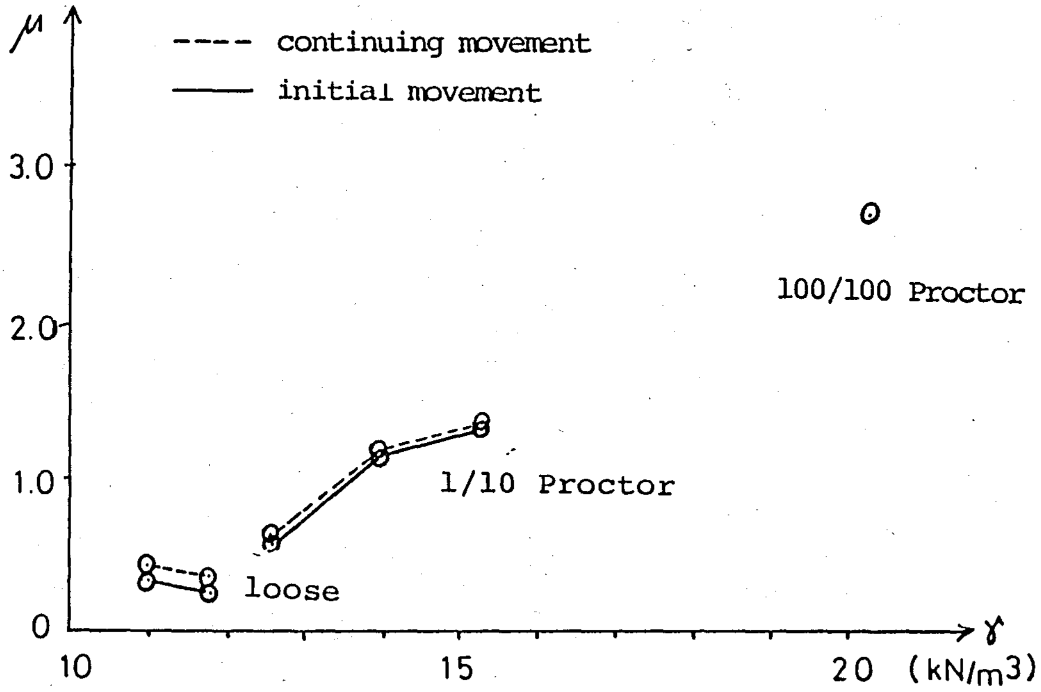


FIGURE 35 Coefficient of friction vs. unit weight (1.5 inches bore pipe)

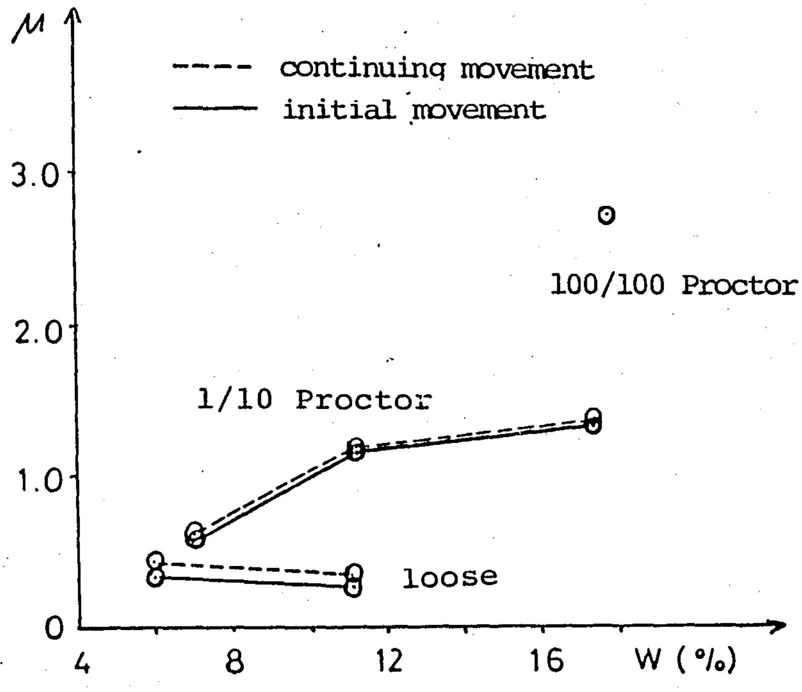


FIGURE 36 Coefficient of friction vs. water content (1.5 inches bore pipe)

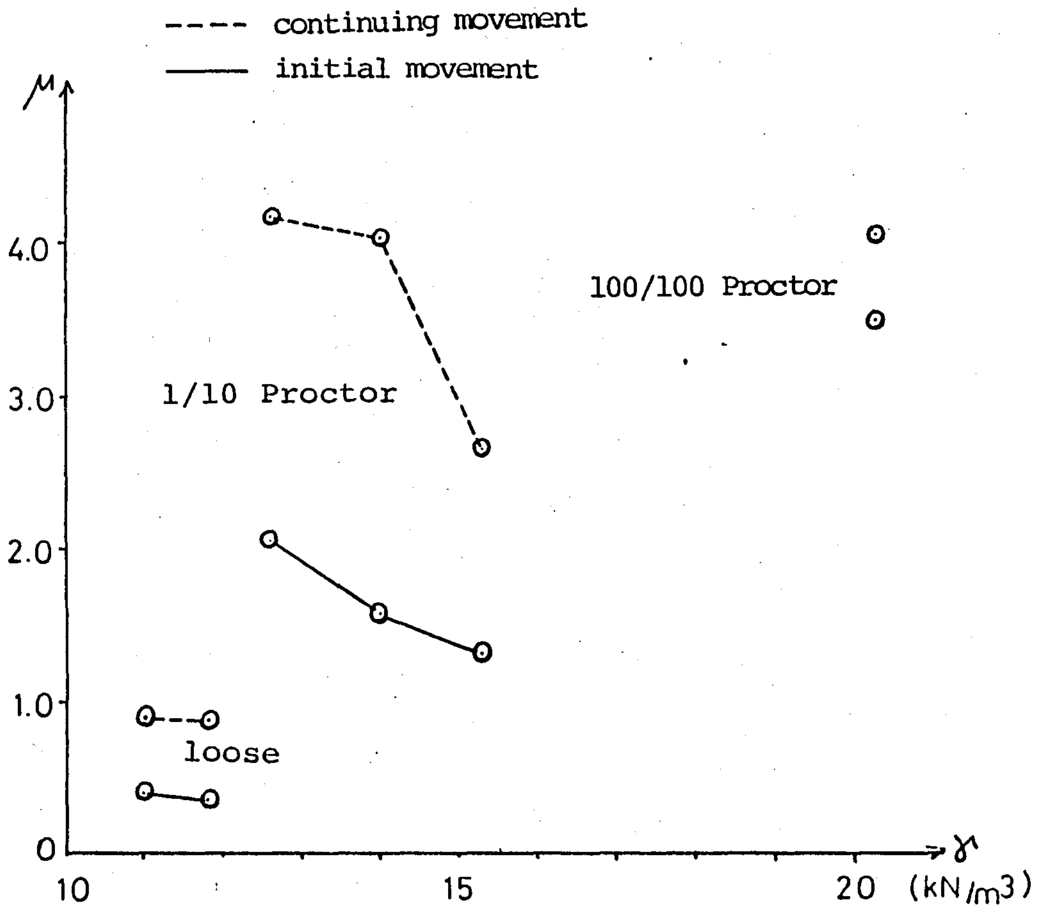


FIGURE 37. Coefficient of Friction vs. unet weight
(1.5 inches coated with DTR41)

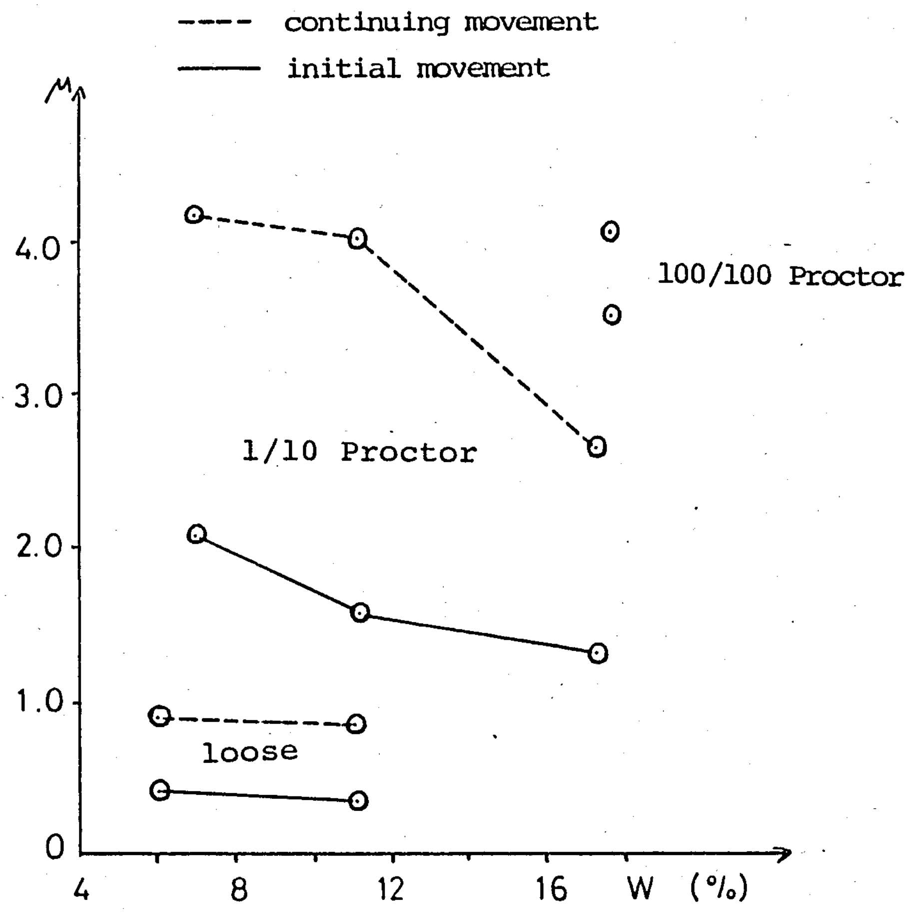


FIGURE 38. Coefficient of Friction vs. water content
(1.5 inches coated with DTR41)

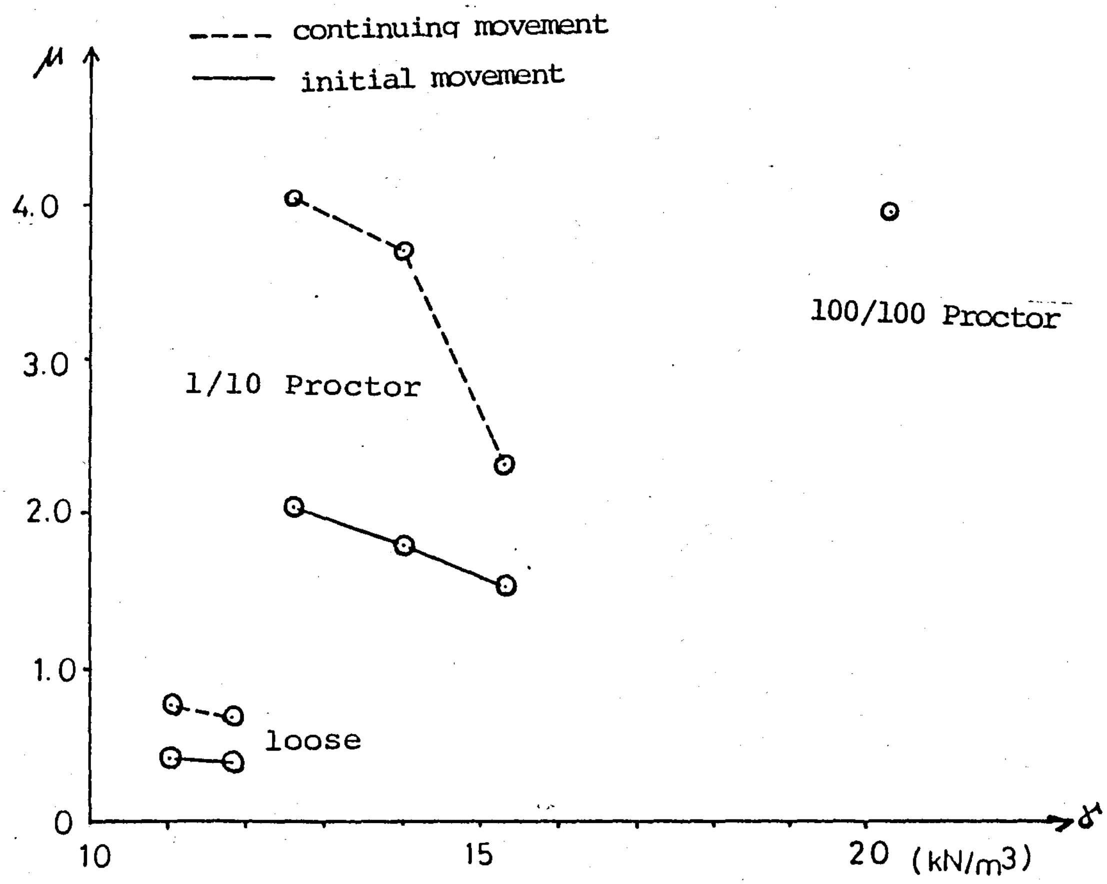


FIGURE 39. Coefficient of Friction vs. unit weight (1.5 inches coated with DTS40)

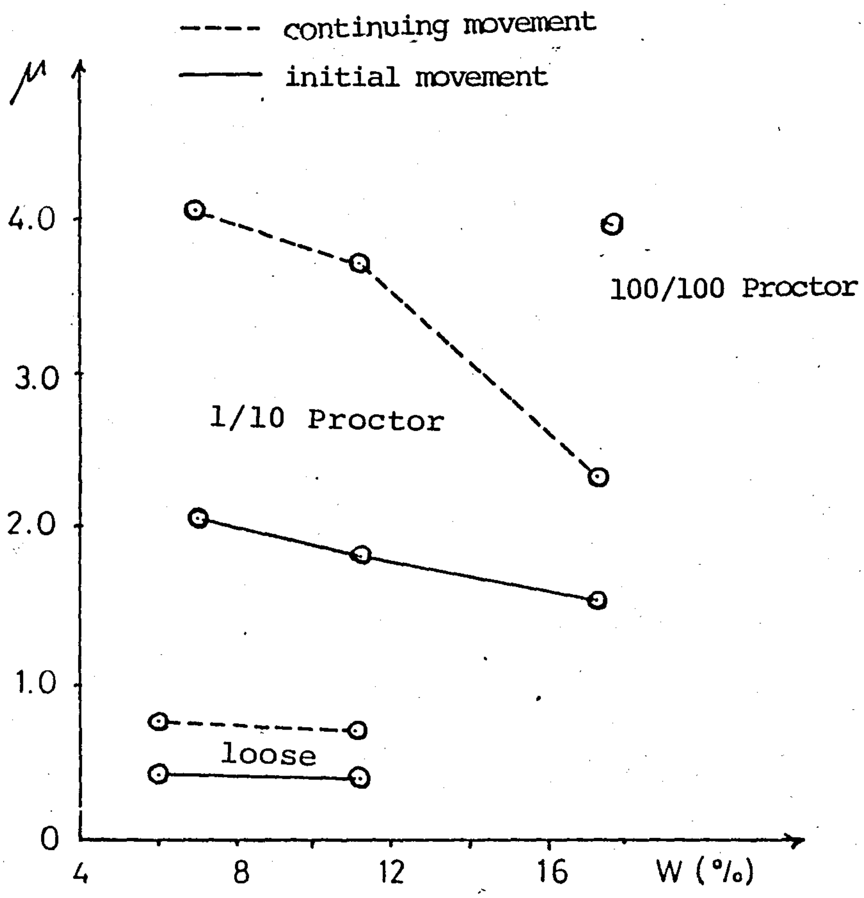


FIGURE 40. Coefficient of Friction vs. water content (1.5 inches coated with DTS40)

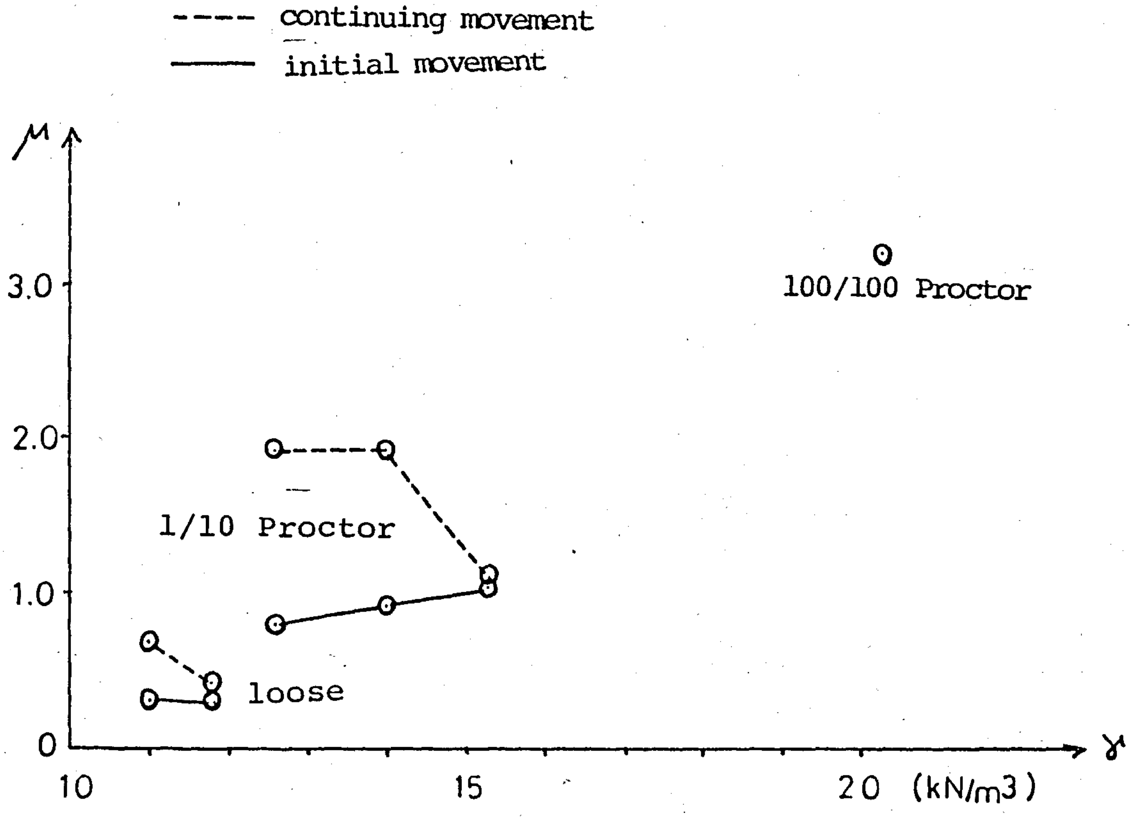


FIGURE 41. Coefficient of Friction vs. unet weight

(1.5 inches coated with RDTR41)

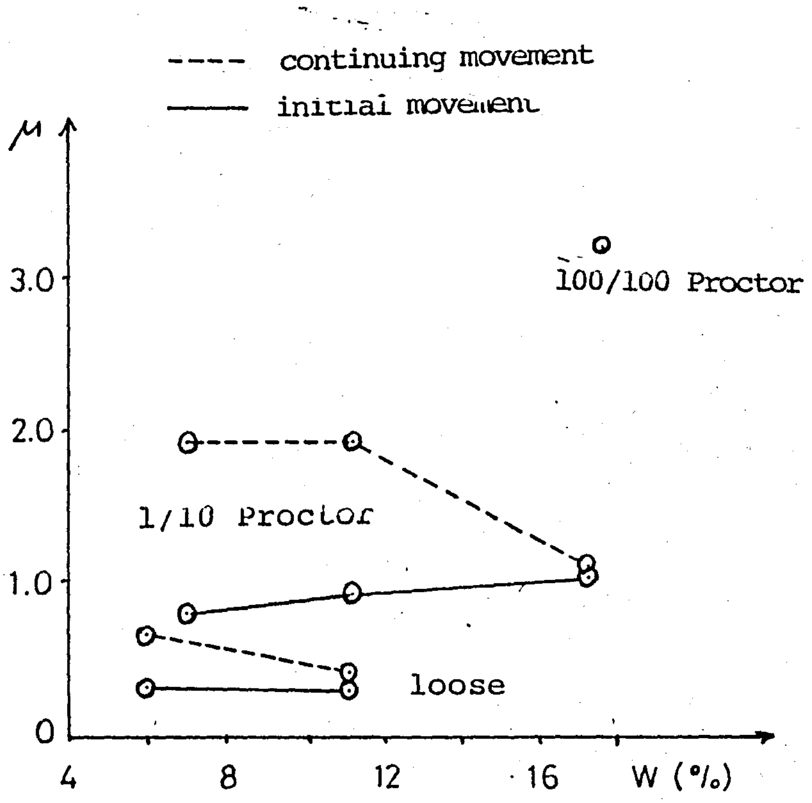


FIGURE 42. Coefficient of Friction vs. water content (1.5 inches coated with RDTR41)

6.2 DISCUSSIONS

6.2.1 Pipe-Soil Friction Fundamentals

Basic friction formula was used for the calculation of the coefficient of friction values.

$$F = \mu \cdot N \qquad (1)$$

This formula is valid when there is no cohesion between soil and the pipe. If a cohesion along with the friction is assumed between the soil and the pipe, the shear resistance would be :

$$\zeta = C + \sigma \cdot \tan \phi \qquad (22)$$

If each side of the equation is multiplied by the surface area, A_S

$$\zeta \cdot A_S = C . A_S + \sigma \cdot A_S \cdot \tan \phi$$

$$F = c . A_S + N \cdot \tan \phi \qquad (23)$$

where

$F = \zeta . A_S$ = required pull out force

ζ = shear resistance (stress)

A_S = surface area of the pipe

C = cohesion intercept

$N = \sigma . A_S$ = normal force

σ = normal stress

$\tan \phi = \mu$ = coefficient of friction

ϕ = angle of friction

No cohesion was observed between the pipe (coated or without coating) and the soil during the simple tests. Therefore cohesion between the pipe and the soil was assumed to be nearly equal to zero. Then the equation 23 turns to the equation 1

$$F = \mu . N \tag{1}$$

6.2.2. Influence of Pipe Diameter :

No relation between the pipe diameter and the pull out force was found. When the pipe diameter increased, the required forces were increased. But these increases were not corresponding to the percentage increase in pipe diameter.

6.3 Influence of Coating :

Coated pipes had greater pull out forces than the bare pipe's. Coatings had taken a major role causing increases in friction forces. Since 50 percent overlaps were made on the pipes, the protrusions were seen on the pipes. These protrusions prevented to pull out the pipes.

Some soil particles remained between the protrusions of the overlaps and behaved like a rough surface together with pipe. Therefore the required pulling forces were higher than the bare pipe's forces.

When the pipe was normally coated, the protrusions of the coating overlaps were against to the pulling direction and they caused the increase in friction force.

In reservely coated pipes, the pulling was along the coating direction. Since the protrusions were along the pulling direction, they did not cause high friction forces during the pulling process.

Therefore; reservely coated pipes have less friction values than the normally coated pipes.

6.2.4 Influence of Compaction Energy

An increase in compaction energy caused an increase in required pull out forces.

The pull out forces increased 3-9 times of the loose condition's when 1/10 Proctor Energy was used. If 100/100 Proctor Energy was used, the required pull out forces increased 2-5 times of the 1/10 Proctor Energy conditions. Therefore; compaction energy is the main factor which influences the required forces. This increase is believed to be due to the increase in the horizontal stresses in the soil.

After compaction, soil behaves as overconsolidated material. Thus the total normal force on the pipe also increases, which in turn causes an increase in the magnitude of the pull out force.

6.2.5 Influence of Water Content

It was observed that pull out forces decreased while the water content of the soil was increasing in loose soil conditions. This decrease is because of the lubrication of the soil particles.

At first a slight increase then a large decrease were observed in pull out forces while the water content of the soil was increasing in 1/10 Proctor Energy Condition. The increases were up to nearly optimum moisture content (16.5 percent). If more water was given to the soil, the soil particles acted on the pipe as lubricated and therefore decreases in pull out forces were observed.

For a coated pipe at 1/10 Proctor Energy Condition, it can be said that an increase in water content causes a decrease in pull out force.

VII. CONCLUSIONS

Although the experimental set-up was a simple system, acceptable coefficient of friction values were obtained. If a more sophisticated system is developed, further correlation could be obtained.

The most important conclusions of this study are :

1. The coefficient of friction values increase with the increase in compaction energy.
2. At high compaction the coefficient of friction values increase when the pipes are coated with tapes.
3. Under a given compaction the coefficient of friction values decrease with the increase in water content of the soil.
4. The coefficient of friction is not dependent on the size of the pipe diameter.

APPENDICES

APPENDIX I

SOIL EXPERIMENTS

The results of the necessary soil experiments are given In Appendix I.

VISUAL DESCRIPTION OF THE SOIL is "Light brown sandy and silty clay"

1. ATTERBERG LIMITS DETERMINATION

Atterberg limits were determined as follows :

Liquid limit, $w_L = 35.0$ %

Plastic limit, $w_p = 23.3$ %

Plasticity index, $I_p = 11.7$ %

2. SIEVE ANALYSIS

200 grams soil was taken and washed, percent passing of No.200 sieve was found as 56.9 percent. Then sieve analysis was made and the results are given in Table 19.

TABLE 19 Sieve Analysis Results

Sieve No:	Retained (grams)	Retained (%)	Passing(%)
4	-	-	100
10	8.50	4.25	95.75
20	30.80	15.40	80.35
40	14.30	7.15	73.20
60	8.50	4.25	68.95
100	10.00	5.00	63.95
200	14.10	7.05	56.90
PAN	113.80	56.90	-

3. HYDROMETER ANALYSIS

Hydrometer Analysis was done and percent clay was found as 4.58 percent. Results of Hydrometer Analysis are given in Table 20.

TABLE 20. Hytrometer Analysis Results

Diameter,D, mm.	Finer (%)
0.042	47.94
0.031	42.36
0.026	40.12
0.023	37.88
0.016	34.53
0.012	30.06
0.0089	26.71
0.0066	21.24
0.0047	16.88
0.0035	11.51
0.0025	7.04
0.0015	2.12

4. SPECIFIC GRAVITY OF THE SOIL G_s

Specific gravity test was performed and found to be as 2.74.

$G_s = 2.74$

5. COMPACTION TEST

Standart Proctor Test was performed tothe soil. The results are given as follows :

Optimum Moisture Content, $w_{opt} = 16.5$ %

Maximum Dry unit weight, $\gamma_{dmax} = 17.9$ %.

6. SOIL CLASSIFICATION

a) Unified Soil Classification

Based on a w_L of 35.0 percent and I_p of 11.7 percent, the soil is a CL.

Therefore the soil is "Light brown sandy (and little gravelly) and silty clay, CL."

b) AASHTO Soil Classification

The soil is in A-6(5) category. Therefore the soil is "Light brown, sand and silty (with little gravelly) clay, A-6(5)"

7. TRIAXIAL TEST

Triaxial test were performed to the used soil. Cohesion intercepts , c's were found to be as :

a) Loose soil

cohesion intercept , $c = 0.15$ kg/cm^2

internal soil angle, $\phi = 7.6$

b) Dense soil (Compacted at 1/10 Proctor Energy)

cohesion intercept, $c = 0.25$ kg/cm^2

internal soil angle, $\phi = 8.5$

c) Dense soil (Compacted at 100/100 Proctor Energy)

cohesion intercept, $c = 0.60$ kg/cm^2

internal soil angle $\phi = 6.5$

APPENDIX II

TYPES OF COATINGS

DENSOLEN TAPE S40

Densolen Tape S40 is a three-ply tape. It consists of a stabilized polyetyhlene backing with a plastic butyl rubber on both sides.

Thickness of the Tape S40 is given in Table 21

TABLE 21 Thickness Tape S40

Thickness of Polyethylene-carrier film	> 0.25 mm.(10 mils.)
Thickness of Butyl coating	≈ 0.50 mm.(20 mils.)
Total thickness of Tape S40	> 0.75 mm.(30 mils.)

Properties of the Tape S40 are given in Table 22

TABLE 22 Properties of the Tape S40.

Elongation at break	: > 400 %
Tensile strength	: > 40 N/10 mm.
Adhesion strength tape/tape	: > 25 N/10 mm.
Application temperature	: -10°C ; 50°C
Saponification value of PE-film	: unsaponifiable
Saponification value of butyl coating	: < 2 mg KOH/g.
Permeability to water vapour at 23°C	: $< 5\times10^{-2}\ \frac{g.}{m^2 24h}$
Permeability to oxygen at 23°C	: $< 1\times10^{4}\ \frac{g.}{m^2 24h.bar}$
Dielectric strength	: > 30 kV/mm.
Volume resistivity	: $> 10^{15}$ ohm.cm.

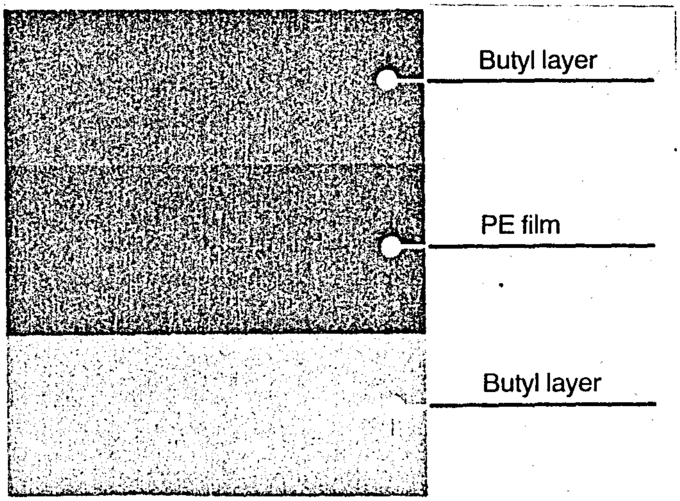


FIGURE 43. Densolen Tape S40.

Composition of the Tape S40 is given in Figure 43.

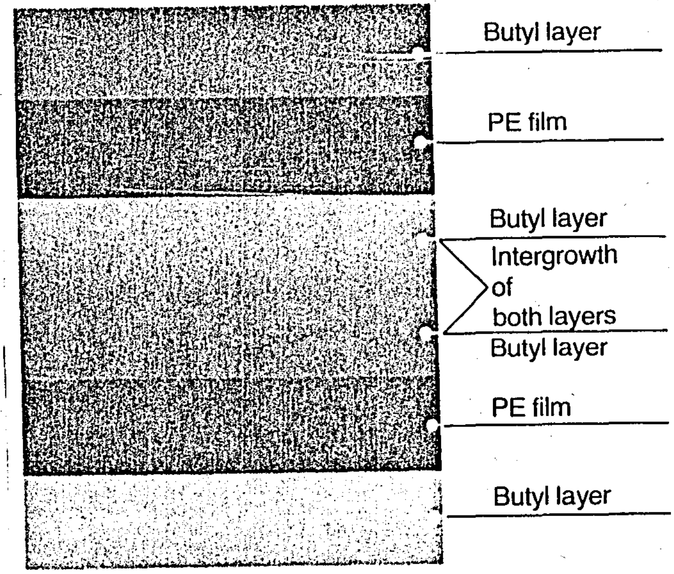


FIGURE 44 Overlap zone of Densolen Tape S40.

Due to the self-amalgamation of the Tape S40 in the overlap zone or within the individual wrappings, a tubular, dense coating of very high mechanical resistance and stability is obtained which reliably protects the metal surfaces against corrosion. The overlap zone is shown in Figure 44.

DENSOLEN Tape R41

Densolen Tape R41 is a two-ply plastics tape. It consists of a stabilized polyethylene backing with an adhesive plastic butyl rubber layer on one side.

Thickness of the Tape R41 is given in Table 23.

TABLE 23. Thickness of Tape R41

Thickness of Polyethylene-carrier film	> 0.25 mm. (10 mils)
Thickness of Butyl coating	≈ 0.50 mm. (20 mils)
Total thickness of Tape R41	> 0.75 mm. (30 mils)

Densolen Tape R41 shows some properties of Densolen Tape S40, except for the adhesion strength. Tape R41 has an adhesion strength (tape/tape) more than 4 N/10 mm.

PRIMER HT

Densolen Primer HT was used as the primer between steel pipe and the coating tape. Primer HT is a solution of butyl rubber and unsaponifiable resins in petroleum spirit.

Primers improve the peel strength of tapes on the pipe surface and give increased corrosion resistance. Primers absorb dust and traces of moisture and neutralize their harmful effects. The composition of the primer adapted to the tape guarantees a high peel strength on the pipe surface.

BASIC COATING MATERIAL, POLYETHYLENE

The basic coating material is obtained by high or low pressure polymerization of ethylene. Polyethylene is extruded to form a continuous strip or ribbon, solidified by cooling, then cut into granules and reduced to powder. Polyethylene is slightly translucent and a low-density hard solid.
The PE-material must be fully-stabilized.In order to obtain good resistance to ultraviolet rays 2% - 3 % lampblack is added to PE and thoroughly mixed.
Properties of Polyethylene are given in Table 24.

TABLE 24. Properties of Polyethylene

Density of ultraviolet resistant PE	0.93-0.95 g/cm^3
Water absorption in 24 hours	0.03 % in weight
Softening point	85-95°C
Melting point	110-160°C
Application temperature	-10°C; 65°C permanent
Breaking strength	> 14 N/mm^2
Elongation at break	200 % (extrusion)
Hardness shore	100 % (fusion bond)
Adhesion to steel surface	175 n/5 cm. at 23° 2°C
(5 cm. wide strip)	100 n/5 cm. at 40° 2°C
Dielectric strength	25-30 kV/mm.
Volume resistivity	>10^{15} ohm-cm.
Heat conductivity	0.3 kcal/mh°C
Melting index	mfi max. 0.5 g/10 min (extruded)
	mfi max. 2 g/min (fusion bond)

APPENDIX III

DIN 30670 STANDARD (MM)

POLYETHYLENE SHEATHING OF STEEL TUBES

1. TERMS AND DEFINITIONS

1.1 Minimum coating thickness :

The minimum coating thickness is the minimum thickness of the polyethylene layer which must exist at every spot

1.2 Elongation due to tearing :

The elongation due to tearing is the change in length of the sample related to its original gauge length during the tearing of the polyethylene material of the sheating.

1.3 Resistance to peeling (stripping)

The resistance to peeling is the force required to peel of strip of the polyethylene sheating over a defined peeling stretch (length) under test conditions

2. REQUIREMENTS

2.1 Requirements relating to the surface of the steel tube.

2.1.1 Immediately prior to the application of the sheathing, the material surface of the steel tube must be technically free of dirt, oil, grease, welding beads and moisture, and then it must be either sand-blasted or pickled.

2.1.2. The degree of cleanliness of the sand-blasted surface

2.1.3 Pickling

2.2 Requirements relating tothe sheathing.

2.2.1. Minimum coating thickness.

up to DN 100 1.8 mm. Standard, and 25 mm. reinforced

2.2.3 Resistance to peeling (stripping)

2.2.3.1 The resistance to peeling of polyethylene sheathings is preferably determined according to the test method I. In this respect the mean force necessary to pull of the sheathing shall amount to 35 N per cm. width of the strip at least.

Test Method I.

- Prerequisites for use of this method :

Adherence to a constant stripping velocity and of a stripping angle of 90^{o} to the surface of the tube.

- Appliances required for the test :

A double-ended saw or an appropriate cutting device, and a stripping device with a recording dynamometer.

- For the test, the polyethylene sheathing is cut into e.g. a double-ended saw, right down to the wall of the steel tube, in the shape of a strip of at least 20 and at 50 mm. width right around the periph ry. A cut is then made at right angles to the sawn edges to separate the strip from the tube, and the strip is lifted off the tube with the aid of a knife over a length of 20 mm. approx. Then the strip is pulled off the tube in the stripping device at a speed of 10 mm/minute. The force necessary to accomplish this is recorded. The mean value from this recording is formed and expressed in N, and the first and last 20 mm. of the stripping travel are disregarded for the purpose of this evaluation. In the test section used must not incorporate any averaged element of section featuring a mean stripping force which is more than 25% below the required mean value. By "element of section" is meant any portion of section stiuated within the test section and measuring 20 mm. length.

2.2.3.2 The resistance to peeling of polyethlene sheathings on tubes of size DN100 can also be measured in accordance with the test method II. In this respect, times amounting to 0.4 D in minutes at least must be measured for the operation of pulling off the sheathing over the section of tube.

Test Method II.

- Appliances required for the test :

A double-ended saw or an appropriate cutting appliance, a clamp and a stop watch.

- For the test, the polyethylene sheathing is cut into right down to the wall of the steel tube, in the form of a strip at least 20 and at most 50 mm. wide. The strip is then cut off at right angles to the sawn edges at bottom of the tube periphery and at the level of the horizontal axis of the tube. The end of the strip at the horizontal cross-cut is then prized off the tube with a knife and peeled off down to a 45° angle from horizontal. A weight equal to 3.5 kg/cm. width of strip is then attached to the free end of the strip.

The peeling or stripping time for the 45° zone terminating at the bottom of the tube is then measured. It must amount to at least 0.4 D in minutes, with the tube diameter D(expressed in cm.)

This means that the mean stripping velocity amounts to 10 mm/minute.

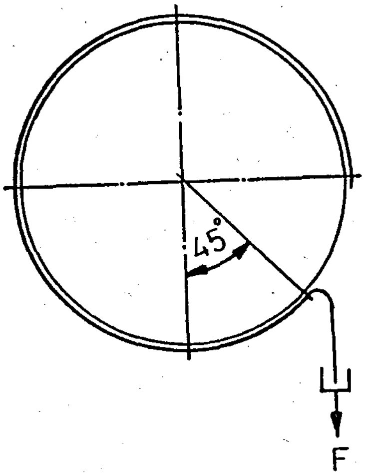


FIGURE 4 5 Peeling test of coating around pipe.

3. TESTING OF THE COATING THICKNESS

For the purposes of this, at least 10 measurements shall be made at locations uniformly distributed over the length and periphery of the tube.

The frequency of the coating thickness measurements is left to the manufacturer's discretion.

The coating thickness shall be measured with the aid of non-destructively operating instruments, e.g. on a magnetic or an electromagnetic basis, which enable the coating thickness to be determined within a measuring uncertainly of ∓ 10 %.

APPENDIX IV

REQUIRED COMPACTIEN ENERGY

COMPACTION

Standard Proctor Energy was used for the compaction process. 6 layers, each 5 cm. in thickness were prepared. Standard Proctor Energy is, CE = 594.8 kJ/m^3.

Sizes of the Container is given below:

Diameter of the container = 0.37 m.

Height of the container = 0.30 m.

Therefore volume of the Container is, V = 0.0323 m^3

Compaction Factors are :

weight of hammer, W = 24.5 N.

height of fall, H = 0.305 m.

number of layers, L = 6

mold volume, V = 0.0323 m^3

blows per layer, B = unknown

standard proctor energy, CE = 594.8 k3/m^3

Standard Proctor Energy formula is given below.

$$CE = \frac{W.H.L.B}{V} \times 10^{-3} \quad (\text{in } kJ/m^3) \qquad (1)$$

By substituting the compaction factors into the equation (1)

$$594.8 = \frac{(24.5)(0.305)(6)B}{0.0323} \times 10^{-3}$$

$$B = 428 \text{ blows per layer.}$$

428 blows per layer were used for the compaction with 100/100 proctor.

For the compaction with 1/10 Proctor, 43 blows per layer were used.

APPENDIX V

CALCULATION OF NORMAL FORCE BY INTEGRATION

Normal Forces acting around the pipes can be calculated by direct integration.

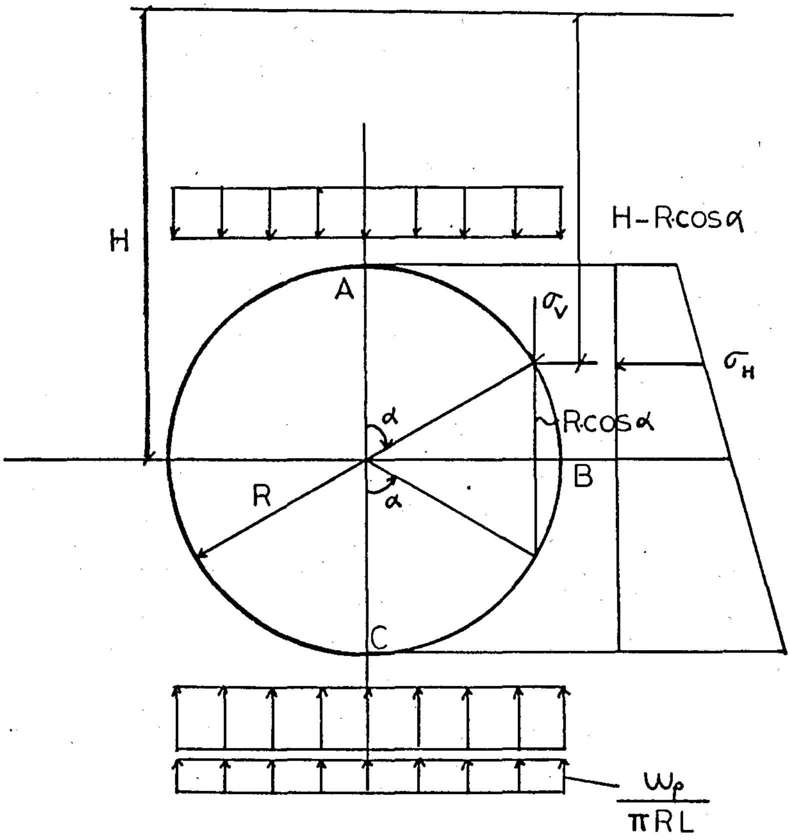


FIGURE 46 Stresses around the pipe.

Normal stresses can be calculated in two parts which are from A to B and from C to B by integration (Figure 46)

$$A \rightarrow B : \gamma(H-R\cos\alpha)\cos\alpha + \gamma(H-R\cos\alpha).K_o\sin\alpha \qquad (1)$$

$$C \rightarrow B : \gamma(H-R\cos\alpha)\cos\alpha + \gamma(H+R\cos\alpha).K_o \sin\alpha + \frac{w_p}{\pi R}\cos\alpha \qquad (2)$$

If the Normal force is considered acting on a segment area; R.d α. unit length (Figure 47)

$$A \rightarrow B : dN = R.d\alpha \, [\gamma(H-R\cos\alpha)\cos\alpha + \gamma(H-R\cos\alpha).K_o.\sin\alpha \qquad (3)$$

$$C \rightarrow B : dN = R.d\alpha \, |\gamma(H-R\cos\alpha)\cos\alpha + \gamma(H+\cos\alpha.R).K_o.\sin\alpha + \frac{W_p}{\pi R}\cos\alpha \qquad (4)$$

Total Normal Force around a unit length of pipe is;

$$N = 2 \int_A^B dN + 2 \int_C^D dN \qquad (5)$$

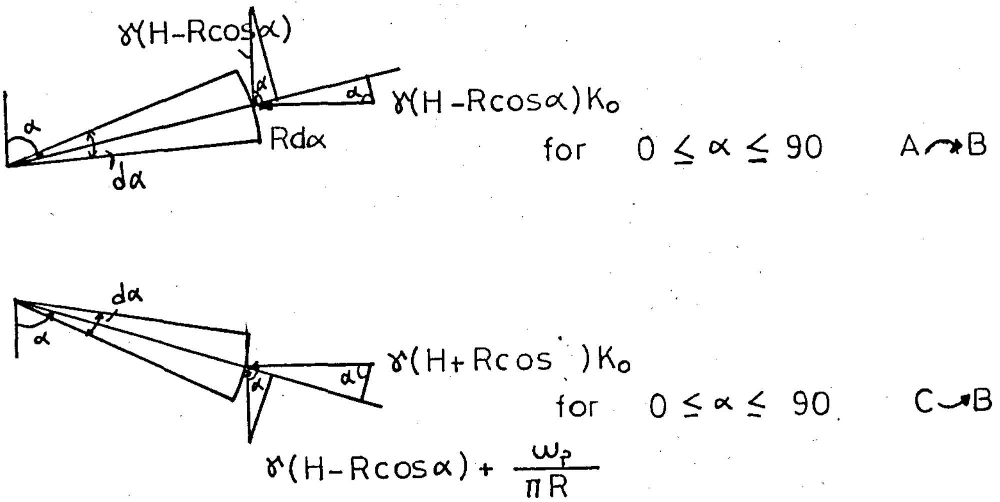


FIGURE 47. Stress acting on a segment area

$$N = 2\,R\gamma\left[\int_0^{90} H\cdot\cos\alpha d\alpha - \int_0^{90} R\cos^2\alpha d\alpha + \int_0^{90} H.K_o\sin\alpha d\alpha - \int_0^{90} R.K_o \cos\alpha\sin\alpha\, d\alpha\right] +$$

$$2R\gamma\left[\int_0^{90} H.\cos\alpha d\alpha - \int_0^{90} R\cos^2\alpha\, d\alpha + \int_0^{90} H.K_o\sin\alpha d\alpha + \int_0^{90} R.K_o\cos\alpha\,\sin\alpha d\alpha\right| +$$

$$2R\int \frac{w_p}{\pi R}\cos\alpha\, d\alpha \qquad (6)$$

$$N = 4R\gamma H \int_{0}^{90} \cos\alpha - 4R^{2}\gamma \int_{0}^{90} \cos^{2}\alpha d\alpha + 4R\gamma HK_{o} \int_{0}^{90} \sin\alpha d\alpha + 2R \frac{w_{p}}{\pi R} \int_{0}^{90} \cos\alpha d\alpha \qquad (7)$$

where

$$\int_{0}^{90} \cos\alpha \, d\alpha = 1$$

$$\int_{0}^{90} \cos^{2}\alpha d\alpha = \frac{\pi}{4}$$

$$\int_{0}^{90} \sin\alpha \, d\alpha = 1$$

placing the integral values into Eq. 5

$$N = 4R\gamma H - 4 R^{2}\gamma\frac{\pi}{4} + 4R\gamma HK_{o} + \frac{2w_{p}}{\pi} \qquad (8)$$

$$N = 4RH\gamma(1+K_{o}) - \pi R^{2}\gamma + \frac{2w_{p}}{\pi} \qquad (9)$$

Then, the total Normal Force around the pipe;

$$N.L = 4RHL\gamma(1+K_{o}) - \pi R^{2} L \gamma + \frac{2L}{\pi} w_{p} \qquad (10)$$

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