1980

**Water jetting a comprehensive examination of this method of compaction for cohesive trench backfill.**

Raffaele. Meo
*University of Windsor*

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LA THÈSE A ÉTÉ MICROFILMÉE TELLE QUE NOUS L'AVONS RÉCEVE
WATER JETTING

A COMPREHENSIVE EXAMINATION OF THIS METHOD OF COMPACTION FOR COHESIVE TRENCH BACKFILL

A Thesis
Submitted to the Faculty of Graduate Studies through the Department of Civil Engineering in Partial Fulfillment of the Requirements for the Degree of Master of Applied Science at the University of Windsor

by

Raffaele Leo

Windsor, Ontario, Canada 1979
This work is dedicated to all those people whose contributions, whether large or small, made it possible.
ABSTRACT

Although water jetting is generally acknowledged to be a cheaper method of compacting trench backfill when compared to mechanical equipment, its use has only been allowed on a very limited scale due to the fact that much is unknown about the mechanism at work.

The purpose of this report is to examine all aspects involved in the water jetting of cohesive backfill, both from a theoretical and experimental point of view, in order to understand the process involved in the compaction of the soil, and to arrive at a proper apparatus and methodology for carrying out water jetting works satisfactorily. This is achieved through the theoretical and experimental analysis of the hydraulics of water jetting; the monitoring and analysis of full scale field experiments; and the undertaking of laboratory research.

Each part of the apparatus, such as the source of water, the pressure supply, the conduit, the probe and the nozzle, is examined in detail and recommendations are made as to the best equipment to use.

The results and discussion of the full scale field experiments carried out in order to determine the effect the amount of applied energy and the type of nozzle
have on the behaviour of a water jetted soil are presented. The natural process of compaction is also examined.

The final phase involves the development of a laboratory apparatus and procedure in order to reproduce and predict the field behaviour of a water jetted soil.

This investigation found definite ways to improve water jetting operations, ranging from the selection of equipment so that energy losses are minimized to the development of a porous nozzle specifically designed for water jetting. The field experiments revealed that this mysterious method of compaction is simply a speeded up version of nature's own compaction mechanism. Also, the degree of compaction of the backfill, its settlement and vane shear strength, all were found to increase directly with applied energy, while the moisture content decreased. Finally, the laboratory study succeeded in the development of a laboratory apparatus and procedure, however only recommendations for further study could be made regarding the appropriate test cell or laboratory model to be used.

The final part of this thesis contains specific recommendations to the University of Windsor, the City of Windsor and interested contractors regarding what each can do to contribute to the further development of water jetting.
ACKNOWLEDGEMENTS

In the carrying out of this endeavor, the author has received the advice, encouragement and support of many individuals and agencies. Although it would be impossible to name everyone, their help has been and is sincerely appreciated. To all those people involved, a very heart-felt THANK YOU.

The Author wishes to express his gratitude to his advisor, Dr. J.T. Labs, for allowing him to follow his own research instincts, while at the same time giving firm guidance and encouragement when required. Also, the help provided by Dr. J.A. McCorquodale with the hydraulics section of the research is very much appreciated. Thanks also go to the National Research Council for providing partial financial assistance for this project.

The Fire Department and the Department of Public Works of the City of Windsor, Val-Ros Construction Company, Dominion Soil Investigations and Amherst Quarries Limited all provided materials and equipment in conjunction with the field tests. Their cooperation was critical to the implementation of the research project and thanks go to everyone involved. Mr. W.M. Kellestine of H.G. Golder and Associates should also be thanked for his advice regarding the collection of field data.
Sincere thanks go to the members of the test pit digging crew for the excavation of approximately 120 pits, all by hand. Thank you Gino, Sandy, Victor, Gary, Leo, Joe, Gerardo, Ennio and Antonio.

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PART II

INTRODUCTION
CHAPTER 1

INTRODUCTION

For years some people associated with the installation of sewers in the Essex County area have been proposing an innovative way of compacting native clay backfill of utility trenches, namely water jetting. This method uses a pressurized water jet to apply compactive energy to a soil. Basically, water is injected into the backfilled trench until the soil is completely saturated. Then compaction is achieved through vibration effects; breakdown of clay lumps; seepage forces; and the consolidation of the backfill under its own weight.

The proponents of water jetting argue that the results obtained with this method are at least equivalent to those obtained with mechanical compaction, while the cost is significantly reduced. Unfortunately, municipalities such as the City of Windsor have been reluctant to allow it to be used extensively, mainly because no standards or specifications are existent, and no one seems to be aware of a proper water jetting apparatus or technique.

The motivation behind this study was to examine all aspects of water jetting in detail, so that the missing
data and information necessary for the writing of specifications and carrying out the work satisfactorily could be afforded.

The objectives of this investigation are as follows:

(i) Determination of a proper water jetting apparatus.
(ii) Determination of a proper water jetting technique.
(iii) Determination of the effect of varying applied energy on the behaviour of a water jetted cohesive soil.
(iv) Determine whether water jetting is a speeded up version of the natural process of compaction.
(v) Development of a laboratory apparatus and procedure suitable for the reproduction and prediction of the field behaviour of a water jetted soil.

The first step in the implementation of the research project was to carry out a theoretical analysis of a hypothetical water jetting apparatus. Based on the results of this analysis, full scale apparatus experiments were undertaken, leading to the development of the porous nozzle and the design of a proper system for the purpose of water jetting. The next step was to use this apparatus to water jet full scale field trenches. And finally, once the results of the field work were known, laboratory experiments were undertaken in order to develop the apparatus which would lead to their reproduction.

This report is divided into five parts, so that the subject matter may be more easily identified. Part I
is an introductory section to the thesis and it includes a literature survey and the present state of the art. Part II deals with the hydraulics of water jetting and analyzes the apparatus involved. Part III reports in detail the results of the full scale field tests, which comprise the effect of applied energy and the type of nozzle on the behaviour of the backfill, along with the determination of the natural compaction process. Part IV provides the details of the laboratory work, while the conclusions reached and the recommendations that result from this study form the final section, Part V. As a result of the various investigations, both literary and experimental, the author believes he has been able to determine how water jetting works. He feels that this is a conclusion to the thesis, and because of its importance, Chapter 9, The Water Jetting Mechanism, has also been included in Part V.

Throughout the entire study, and in the writing of this report, the author has strived to maintain a practical approach to the problem. All field work was carried out according to actual sewer construction practice. In addition, much time has been spent in the observation of the construction of sewer projects both in the City of Windsor and Essex County. Therefore, the majority of information and results contained in the chapters that follow should be applicable directly to field water jetting practice.
CHAPTER 2

LITERATURE SURVEY

2.1 Previous Works Dealing with Water Jetting

A literature survey of all the leading technical publications in Europe and North America, carried out through the computerized facilities of the Roads and Transportation Association of Canada, revealed that the only material available on the topic was a paper published in 1978 by Dr. J. T. Laba and M. A. F. Sheta, both of the University of Windsor (1). This paper reported on an in depth laboratory study dealing with the effect of selected parameters on the behaviour of a soil sample. The study concluded that water jetting is more effective in backfills with mixed lump size, in deeper trenches, with higher jetting pressure, increased seepage forces and a smaller jetted area per jet. The effectiveness is decreased by jetting in layers and by increasing the amount of granular material in the backfill. Although the investigation seems to be extensive, its authors cautioned that the laboratory results could only be referred to as "trends" and could not be used
as a direct representation of field behaviour.

Further research by the author in the Windsor area turned up several other studies dealing with water jetting (2, 3, 4, 5, 6). The earliest report (2) is dated 1976, and it was carried out by M. M. Dillon Limited, Consulting Engineers and Planners, on behalf of the Corporation of the City of Windsor. Based on a preliminary field investigation, the report concludes that water jetting could be permitted as an alternate to mechanical compaction in areas where limited damage to surface works could occur. However, it was also pointed out that further detailed studies of the long term effects (stability and settlements) would be required before extensive use of this particular method of compaction could be allowed.

Research was subsequently taken up at the University of Windsor by undergraduate students, resulting in two reports in 1977 and 1978 (3, 5, respectively). Although both investigations had ambitious plans, the reality of the lack of adequate resources caused both reports to be inconclusive and insufficient to settle the water jetting question. This author was part of the two men team that researched and formulated the 1978 report, and that investigation has proved to be extremely valuable in providing the necessary background information for the present endeavor.
The latest piece of information comes in the form of a M.A.Sc. major paper (6). Very simply, this paper analyzes the results of field tests (degree of compaction) taken by the City of Windsor as part of routine inspection on projects where water jetting was allowed. Presently, the City of Windsor allows the use of water jetting in boulevard areas and in connection pits. The conclusions reached were that water jetting would be adequate in preventing long term settlement; that trenches water jetted in the last five years have not undergone any appreciable settlement as of yet; that water jetting is ineffective in compacting granular soils. Although the results of the study are very encouraging, it is most unfortunate that only general descriptions and no details are available regarding the water jetting method used in each case.

Each of the above reports dealt with its own aspect of water jetting, and each author took his own separate approach to the problem. None is complete enough to justify the use of, or a particular method for, water jetting. At this point, it can be safely said that although water jetting appears to be an acceptable method of compaction, there is still much doubt as to what is the correct way of doing it or how the process works.
2.2 Related Literature

During the 1973 Annual Conference of the Roads and Transportation Association of Canada, B.E.W. Dowse and P.R. Bedell, both of Golder Associates, Consulting Geotechnical Engineers, presented a paper dealing with the basic principles of trench backfill and pavement design (7). Although not directly linked with water jetting, these principles apply nonetheless and will be presented so that the reader may have a complete picture of the backfilling and compaction process.

2.2.1 The Subgrade

The theoretical design and evaluation procedure for pavements involve the measurement of the strength characteristics of the subgrade over which the pavement is to be constructed, together with the selection of the pavement structure so that deflection of the surface is within tolerable limits. The strength of the subgrade soil varies seasonally as shown in Figure 2.1; the degree of variation depends on the soil type, the strength of the pavement structure and the severity of the winter.

In practice, uniform subgrades are a rarity in urban municipalities due to the large number of municipal services which are entrenched below the street pavement. These trenches result in non-uniformity between the native undisturbed soil and the
backfill material; often, there is non-uniformity between the various backfill materials themselves. This lack of uniformity contradicts the most fundamental assumption for the theoretical design of pavements, making any attempt at a rational design very difficult.

2.2.2 Distribution of Stresses Under Wheel Loads

When a wheel load is applied to the pavement surface, a stress distribution into the soil subgrade occurs. Figure 2.3 illustrates a simplified stress distribution for a typical 9 kip wheel load. As can be seen, the applied stress decreases from 9 kips per square foot at the surface to 0.25 kips per square foot at a depth of 5 feet. The backfill material below this depth has no significant stress induced by the applied load, but merely has to be stable under its own weight. Normally, this 5 foot (1.5m) depth consists of two feet (0.60 m) of asphalt and granular base and three feet (0.90 m) of backfill material. Below a depth of 5 feet (1.5 m) the backfill does not substantially contribute to the strength of the pavement. Largely due to the uncertain behaviour of mechanically compacted backfill, City of Windsor specifications often require that the clay backfill be compacted for the entire depth of the trench to a minimum of 95% of the Standard Proctor value, when obviously such stringent regulations should not be required below a depth of 5 feet (1.5 m). Naturally,
this extra compaction also implies a significant additional expense, which could be avoided if water jetting were to be used.

2.2.3. Mechanical Compaction of Clay Backfill

During excavation the native clay is broken into lumps of individual density equivalent to the original undisturbed soil. When these lumps are replaced into the trench as backfill, a large volume of voids is created. In order to minimize the voids mechanically, a heavy weight and kneading action is applied to relatively thin layers of soil (0.30 to 0.60 m or 1.0 to 2.0 feet). This process, which is shown in Figure 2.2, requires the shear failure of each lump and its remoulding into a new shape which fills a void.

Immediately following placement and compaction, each lump is stable, bearing on the underlying lumps with several areas of contact. When seepage of rainwater and runoff reach these clay lumps, the small contact areas are softened, and they are no longer able to bear the overburden. Through a series of shear and creep failures, the soil lump undergoes deformation, until the softened areas of contact are large enough to support the overburden. At this stage, no further significant settlement will occur. Unfortunately, by this time large settlements may have already occurred, resulting in a very uneven pavement and
possibly roadway structure failure. Photograph 2.1 illustrates this problem as it occurred on a trunk storm sewer project in the City of Windsor: although all compaction requirements were satisfied, the mechanically compacted trench settled approximately 0.20 m (8 inch) in some areas. The photograph shows the void which was created under the eight inch thick concrete base as discovered after failure. In this case a bridge effect was created, eventually leading to failure of the road.

2.2.4. Zones of Backfill

In order to better understand the functions of the backfill mass at various depths, it is desirable to divide it into three zones, as shown in Figure 2.4:

(i) **Zone A**: This backfill is required for the bedding and cover of the buried service. Normally a granular material is used, with its degree of compaction controlled by the support requirements of the service. If water jetting is to be used, this zone should consist of a uniform granular material, such as clear stone, so that a free-draining bed is provided.

(ii) **Zone B**: This zone fills the area between the pavement structure and the pipe cover. Its main requirement is that it be stable under its own weight, traffic vibrations
and downward water seepage forces.

(iii) Zone C: This backfill forms part of the pavement structure. It must be capable of distributing part of the traffic loading and remain stable under the weight of the overburden and applied pavement loads.

The zone which occupies the largest volume is Zone B. This is the ideal place to use native clay backfill and water jetting, since it would eliminate settlement problems and provide for a more economical and convenient backfilling operation.

2.3 Advantages and Disadvantages of Water Jetting as a Method of Compaction

There are as many opinions on the use of water jetting as a method of compacting trench backfill as there are people who have examined the problem. In spite of these conflicts, there are still some clear advantages and disadvantages in using this method in lieu of mechanical compaction.

2.3.1 Advantages

(i) Cost: The cost reduction is one of the most significant advantages of water jetting when compared to mechanical compaction. Although figures vary from one project to another, a 1976 study estimated savings of 5% to 15% of the total cost of a sewer project (2).
With the increase in labour costs of recent years, these figures should be much higher today. Also, according to detailed cost records kept by a contractor on actual projects, the savings can be as high as 70% of the mechanical compaction cost alone (8).

(ii) Safety: Water jetting can be safer than mechanical compaction since men and machinery are not required to enter the trench behind the pipe laying operation. In addition, the trench can be backfilled very quickly, and right to the surface, thus eliminating the danger a deep excavation poses to both pedestrians and vehicular traffic. Normally only 8 m to 15 m (26 to 50 feet) of trench length would be required to be open at any particular time.

(iii) Subgrade Uniformity: Water jetting is a natural process, as is clearly shown by the results in Chapter 6. When native material is used, this method of compaction restores the entire subgrade to its original state before excavation, eventually eliminating any trace of the interphase between the trench and its surroundings. Because of the properties
of the backfill material and the undisturbed soil are very similar, any settlement will be very small and uniform in nature. This cannot be said for mechanical compaction, where, as shown in Section 2.2.3, large differential settlements are a very real possibility.

(iv) Interference with Traffic: Since mechanical equipment is not required to enter the excavation, much narrower trenches can be used when water jetting. This results in less excavation, less disposal of excess material and less surface restoration (2). This not only contributes to cost savings, but also makes for a much faster operation, therefore causing less inconvenience for the regular road user.

(v) Complete Compaction: In the majority of cases mechanical compaction cannot adequately compact the backfill adjacent to trench walls. Water Jetting eliminates this problem, as the water is able to seep into all voids, including those nearest the walls.

(vi) Utility Crossings: In built up areas frequent utility crossings require the construction of a large number of ramps down to the bottom of the trench
in order to provide access for the compaction equipment. This not only means an additional expense, but also smaller, less effective, manually operated plate tampers must be used around these crossings. These are painstaking tasks which are eliminated when water jetting is used in lieu of mechanical compaction.

2.3.2 Disadvantages

(i) **Time Delay**: This delay occurs because normally an entire section of sewer is completed before the water jetting is carried out. Also some time must be allowed for the backfill to settle and regain sufficient bearing strength before traffic can be allowed to travel over the trench (this can vary from a few days to over a week).

(ii) **High Residual Moisture Content**: After water jetting the moisture content of the backfill decreases from the saturation value to a value which is approximately 4% to 6% above the Proctor optimum value. This value is constant for any particular soil, and is known as the field capacity or the specific retention, the point below which the water cannot be drained. Although this
has generally been regarded as a disadvantage (2, 9). Dowse and Bedell (7) point out that a flexible pavement will perform better on a soft uniform grade than on a hard non-uniform subgrade, hence this may actually be an advantage. Further, they suggest that the best mechanical compaction results are obtained at a moisture content approximately 4% above the Proctor optimum. The high moisture content also precludes any significant amount of infiltration and the associated settlement.

(iii) **Bearing Capacity:** Water jetting reduces the cohesive forces of the clay significantly, thus decreasing its load carrying capability. It may take up to several weeks before acceptable bearing strength is recovered.

(iv) **Freezing Weather:** Water jetting cannot be carried out during periods of sub-freezing temperatures. As a result, the winter months are lost for sewer construction (this does not apply to areas which do not require restoration until the following spring or summer).

(v) **Additional Backfilling:** Even if the backfill level before jetting is several feet above the surrounding ground, once the water jetting
process has been carried out the trench surface settles to a level below the ground elevation. Additional clay or granular backfill must then be placed and compacted mechanically.

2.4 Present State of the Art

The first step towards the understanding of the water jetting process was taken on March 6, 1975. On that date, at the invitation of the Commissioner of Works of The City of Windsor, 17 men representing most of the consulting engineering firms in the city met to discuss the various methods in use for the compaction of native backfill, with particular reference to water jetting (10). Not surprisingly, when the meeting was over, 17 different ideas had been put forth.

Since water jetting was first used in the City of Windsor in the 1950's (9), its practicality as a method of compaction has periodically been debated. The areas where it has been used have performed well, however no one has monitored the process and no one knows how it works or what method should be used in carrying it out. Each contractor, each engineer and each labourer who has come in contact with the topic has formulated his own ideas; since no one can prove his own ideas correct or show the others' incorrect, a stalemate has been reached. These facts are obvious from the author's conversations with
the majority of contractors and consulting engineers in Windsor which have taken place over the past two years.

Presently, water jetting is allowed in the City of Windsor in boulevard areas only. In Essex County, where specifications are less stringent, the use of water jetting is not as limited. The apparatus and method of jetting change in varying degrees from one contractor to another and from project to project. Even within one construction company, different labourers use different procedures and equipment. It has been the author's observation on several projects that the men carrying out the water jetting are totally ignorant of what they are doing. All they know is that they have "to put some water in the trench using a hose and a pipe".

Figure 2.5 shows three of the several apparatus the author has observed in use. All of these systems show very little consideration for hydraulic principles, as each has enough fittings, valves, and other contraptions to reduce the flow of water to a trickle. Also, the jetting probe usually has a full opening at the tip, or at best the pipe end has been hammered flat to form a fan shaped nozzle. This does not provide for an efficient distribution of the water jetting energy.

In all fairness, it should be noted that a few contractors have developed a fair system of water jetting, usually through a process of trial and error. However, the fact remains that even the best of the existing methods and apparatus are insufficient to make water jetting an acceptable and proper compaction method.
PART II

HYDRAULICS OF WATER JETTING
CHAPTER 3

THE WATER JETTING APPARATUS

3.1 Conceptual Water Jetting Apparatus

A very important part of the water jetting process is how the water is delivered to and deposited into the voids of the backfill. Figure 3.1 illustrates a conceptual design of a water jetting apparatus. The basic components are the source of water, a pressure supply, a conduit, a probe and a nozzle.

3.1.1 The Water

Any type of water may be used for water jetting, as long as it does not contain substances harmful to the environment or sewer pipe and it is free of objects which may clog the equipment. Normally potable water would be preferred. The source of water may be a well, river, lake, tanker truck, fire hydrant or even a roadside ditch.

3.1.2 Pressure Supply

The pressure supply is required in order that the energy losses incurred during the transport of the water might be overcome. The source of pressure may be a portable pump, a pump mounted on a truck engine, as in the case of
a fire engine; fire hydrant pressure; elevation head pressure. Of these, fire hydrant pressure is by far the most desirable source to use, since it also acts as a source of water, is usually available where utility services are required, and it entails an overall simpler operation, thus reducing manpower and cost.

3.1.3 The Conduit

The conduit may consist of a flexible or semi-rigid system, with the last 15 metres (50 feet) being some type of flexible material. The selection of the type of conduit is important, since this is where the majority of the energy losses occur, causing a reduction in the energy delivered to the soil and the rate of flow. For fire hose, the selection of a 50 mm or 60 mm (2.0 or 2.5 inches) diameter instead of 40 mm (1.5 inches) can reduce friction losses by 65% and 92%, respectively (11). Normally, a 40 mm to 60 mm (1.5 to 2.5 inch) fire hose is used. Other sizes and types of material may also be used, as long as they are light weight and readily transported. Depending on the type of apparatus used, the length of the conduit may vary from 15 m to 300 m (50 to 1000 feet).

3.1.4 The Probe

The probe consists of a pipe up to 76 mm (3.0 inches) in diameter and light enough so that one man can handle it comfortably. Material composition includes iron, copper, aluminum and plastic. Its selection should consider weight,
cost, friction losses and durability. Depending on the depth of the trench, its length varies from 1.5 m to 6.0 m (5 to 20 feet).

3.1.5 The Nozzle

The most critical part of the water jetting apparatus is the tip of the probe or the jetting nozzle. Its importance arises from the fact that it determines the efficiency and effectiveness of the water jet energy distribution and application to the soil. Naturally, a system which distributes the energy evenly over a large area is desirable, since this should produce uniform compaction, strength and settlement.

3.2 The Recommended Water Jetting Apparatus

The ideal apparatus should be able to deliver water into the backfill with as few energy losses as is practically possible. This would ensure that the job is done quickly (higher flow rate) and more effectively (more energy applied to the soil). Based on the many hours of field observations and the various experiments which will be discussed in the next chapter, the author recommends that the apparatus shown in Figure 3.2 be used for water jetting purposes. In this instance, a fire hydrant is available, which would be the case the majority of times.

The fire hydrant acts both as a source of water and
as a supply of pressure. Normally, they are conveniently located along the public right of way at maximum intervals of 300 m (1000 feet); shorter intervals are often used. This means that under the worst circumstances, the length of conduit would be approximately 150 m (500 feet). Note that a pressure pump would be desirable on long lengths of conduit and any time the nozzle pressure falls to low levels (nozzle pressure is defined as the pressure just inside the end of the probe and it is equivalent to the velocity head of the water jet).

The conduit consists of a 60 mm (2.5 inches) fire hose. It is attached directly to the 60 mm (2.5 inches) fire hydrant port so that fitting losses are reduced. In most cases, the contractor will have to measure and pay for the water used. If an on line water meter is used, it must be of the same diameter as the hose, otherwise a significant contraction loss will occur (meters readily available are generally smaller than 60 mm). Should a suitable meter not be available, then the amount of water used can be estimated by knowing the time of flow and the nozzle pressure. The 60 mm (2.5 inches) should be used for the entire length of conduit, with the exception of the last 15 m (50 feet). Here a 60 mm (2.5 inch) hose full of water would be too heavy for one man to move from one probing to another. The use of a 50 mm or 40 mm (2.0 or 1.5 inch) hose reduces this weight by one half to two-thirds. The installation of a gate valve near the top of the probe would make the entire operation much more
controllable.

The probe should be of the same size as the last 15 m (50 feet) of conduit so that expansion or contraction losses are avoided. The material selected is copper, because of its relatively light weight and very low coefficient of friction.

The most important part of the apparatus is the selection of the proper nozzle. Due to its importance, discussion of this piece of equipment will be undertaken in the next chapter (Section 4.5).

3.3 Applicable Theoretical Formulae

In hydraulics applications, it is often convenient to define the concept of a stream tube. This is a control volume which is isolated in two dimensions but open in the third, so that mass, momentum and energy may enter at one end and leave through the other, but may not pass through the sides (12). Thus, the flow becomes one-dimensional (see Figure 3.3). By the principles of conservation, and by the definition of a streamtube, mass, momentum or energy can neither be created nor destroyed within its walls. Therefore, the mass flux, momentum flux and total energy flux entering must be the same as that of the fluid leaving.

From the law of conservation of mass it follows that

\[(\text{mass in}) = (\text{mass out})\]

\[\dot{\rho} Q_1 = \dot{\rho} Q_2 \]
Here \( \rho \) represents density and \( Q \) the flow rate.
For practical purposes, one may assume steady, incompressible flow \((\rho_1 = \rho_2)\) and using \( Q = VA \), where \( V \) is the average velocity and \( A \) the cross-sectional area of the pipe, Equation 3-1 becomes

\[
A_1 V_1 = A_2 V_2 = Q = \text{CONSTANT} \quad 3-2
\]

Equation 3-2 is known as the "continuity equation".

The law of conservation of momentum states that if no external forces are applied to a system, its linear momentum will remain constant \((13)\). In hydraulics this is stated as:

\[
\text{(Rate of change of linear momentum)} = (\text{External force applied})
\]

For steady, incompressible flow, this becomes

\[
F = \rho Q (V_2 - V_1) \quad 3-3
\]

where \( F \) is the external force.

From the law of conservation of energy, and assuming no work is put in or taken out of the system, the energy equation for steady incompressible flow in a pipe is

\[
\frac{p_1}{\gamma} + z_1 + \frac{V_1^2}{2\gamma} = \frac{p_2}{\gamma} + z_2 + \frac{V_2^2}{2\gamma} + h_L \quad 3-4
\]

where \( p/\gamma \) is the pressure head, \( z \) is the elevation head, \( V^2/2\gamma \) is the velocity head, and \( h_L \) represents all the energy
losses. These terms are shown in Figure 3.4.

Although these equations are used extensively in the analysis of hydraulic problems, they are not in a form which lends itself to quick analysis under field conditions. Therefore, these equations will be rearranged and expressed in terms of the nozzle pressure, \( P \). This pressure can be readily measured in the field using a pitot gauge.

### 3.3.1 Exit Velocity of Water Jet

By definition, the gauge pressure measured inside the pipe just before the jet exits into the atmosphere (see Figure 3.5) is equal to the velocity head of the jet (the gauge atmospheric pressure is zero). Therefore,

\[
P = \left( \frac{-V^2}{2g} \right) \times \frac{1}{0.102}
\]

where \( P \) has units of KPa, \( V \) is in \( \text{m/s} \), \( g \) is in \( \text{m/s/s} \), and 1 KPa is equivalent to 0.102 m of water. Rearranging, one obtains

\[V = 1.415 \sqrt{P}
\]

where \( V \) = exit jet velocity, \( \text{m/s} \)

\( P \) = nozzle pressure, KPa

### 3.3.2 Rate of Discharge

From the continuity equation, Equation 3-2, the
flow rate in cubic metres per second can be expressed in terms of the velocity \(V\) in metres per second and the area \(A\) in square metres as follows

\[ Q = VA \quad 3-6 \]

Using Equation 3-5, substituting \((\pi D^2)/(4 \times 1000^2)\) for the area (where the diameter, \(D\), is in millimetres) and converting cubic metres per second to litres per minute (multiply by 60000), one obtains

\[ Q = 0.0666 \ (D^2) \ (\sqrt{F}) \quad 3-7 \]

where \(Q\) = flow rate, l/m

\(D\) = pipe or equivalent nozzle diameter, mm

\(F\) = nozzle pressure, kPa

### 3.3.3 Force of the Water Jet

Equation 3-3 expresses the external force \(F\) as

\[ F = \rho \ Q \ (V_2 - V_1) \quad 3-3 \]

with units of newtons, metres and seconds.

If the jet stream is taken as the control volume, with point 2 at the nozzle and point 1 at the point of contact with a clay lump, then \(F\) represents the force which the water jet applies to the soil. The velocity at the nozzle is \(V_2\),
with $V_1$ being the terminal velocity as the water hits the soil (at the point of impact there is a stagnant point, hence velocity $V_1$ is zero). Also, $Q$ can be replaced with $V_2A_2$; therefore Equation 3-3 becomes

$$F = \rho A_2 V_2^2$$

where the units are still newtons, metres and seconds. If 1000 kg/m$^3$ is substituted for $\rho$, $A_2$ is replaced with $(\pi D^2)/(4 \times 1000^2)$ where $D$ is in mm; $V_2$ is replaced with Equation 3-5; then, upon simplification and rearrangement of the terms, one obtains

$$F = 0.001572 \ (P) \ (D^2)$$

where $F$ = force applied by the water jet to the soil, N

$P$ = nozzle pressure, KPa

$D$ = pipe or equivalent nozzle diameter, mm

It will be noted that Equations 3-5, 3-7, 3-9 only require the measurement of the nozzle pressure (the diameter would normally be constant) to determine how changes in the apparatus, such as the addition of one length of hose, affects the performance of the system in terms of the discharge flow rate and the force applied to the soil.

### 3.3.4 Energy of the Water Jet

An expression for the energy applied to a unit
volume of soil is as follows (13):

\[ E = (HP) \left( \frac{t}{\psi} \right) \]

3-10

where \( E \), J/m³, is the energy applied per unit soil volume \( \psi \); HP is the power and \( t \) is the jetting time required to saturate the soil in volume \( \psi \). The power can be represented by

\[ HP = \gamma Q H \]

3-11

where \( H \) is the water head at the probe exit and thus equal to \( \psi^2/2g \), which in turn can be represented by the measured nozzle pressure \( P \). \( Q \) is the product of the area and velocity, hence it can be replaced with the product of \((\pi D^2)/(4 \times 1000^2)\), where \( D \) is in mm, and Equation 3-5. Using the unit weight of water as 9810 N/m³ and substituting into Equation 3-10, upon simplification and rearrangement, one obtains

\[ E = 0.001112 \left( \frac{t}{\psi} \right) (D^2) (P^{1.5})/\psi \]

3-12

where \( E \) = Applied energy per unit soil volume, J/m³
\( t \) = Jetting time required to saturate soil volume \( \psi \), s
\( D \) = Pipe or equivalent nozzle diameter, mm
\( P \) = Nozzle pressure, KPa
\( \psi \) = Volume of soil jetted in time \( t \), m³
Equation 3-12 gives an expression for calculating the water jetting energy applied to a unit volume of soil using parameters which can be readily determined in the field.

3.3.5 Equivalent Formulas in the Imperial System of Units

The following are the equations for velocity, flow rate, water jetting force and applied energy in the Imperial System of Units:

\[
\begin{align*}
V &= 12.192 \sqrt{P} & \text{3-13} \\
Q &= 24.856 (D^2)(\sqrt{P}) & \text{3-14} \\
F &= 1.571 (P)(D^2) & \text{3-15} \\
E &= 9.577 (t)(D^2)(p^{1.5})/\psi & \text{3-16}
\end{align*}
\]

where

- \( V \) has units of ft/sec
- \( P \) has units of psi
- \( Q \) has units of GPM
- \( D \) has units of in
- \( F \) has units of lb
- \( E \) has units of ft-lb/ft\(^3\)
- \( t \) has units of sec
- \( \psi \) has units of ft\(^3\)
CHAPTER 4

DEVELOPMENT OF THE WATER JETTING NOZZLE

4.1 Introduction

As has already been emphasized in the previous chapters, the nozzle is a very important part of the water jetting apparatus. Unfortunately, to this point, no one has paid much attention to it; the most commonly used nozzle is no nozzle at all, that is, a full pipe opening is employed (see Figure 4.1 (a)). Occasionally, the end of the pipe has been hammered flat to form a fan shaped nozzle, as shown in Figure 4.1 (b).

The major objection to the above nozzles is the fact that a single, very powerful jet of water is directed at a very small area of the trench. Only about 1% of the trench area receives a direct application of energy. This can cause several problems, including uneven settlement and incomplete saturation. In fact, when the initial degree of compaction is fairly high, with a corresponding lower voids ratio, the water may find it too difficult to travel horizontally into the dry areas. Instead it comes back up along the pipe. The author has observed this phenomena on several occasions, with the surface of the trench and the surrounding area being completely
flooded from the water coming back up along the jetting probe. On one project, most of the sand used for Zone A backfill was washed up to the surface; obviously, sand backfill should not be used when contemplating water jetting as a method of compaction.

Figure 4.1 shows some of the nozzles that were considered as a possible improvement over the existing systems. The author only considers the perforated cone and the porous nozzle as acceptable for water jetting, with the latter being preferred. The sections that follow outline a series of investigations undertaken in order to arrive at this conclusion.

4.2 Theoretical Analysis of Hypothetical Water Jetting Apparatus

Prior to any conception of a porous nozzle, a theoretical, and later experimental, investigation was undertaken to determine what effect the gradual reduction of the area of the pipe tip would have on the system. The effectiveness of the water jetting apparatus as the tip area varied was measured using the force of the jet as a parameter. The system shown in Figure 4.2 was assumed, and analyzed using Equations 3-2, 3-3 and 3-4. The friction losses were calculated using the Darcy-Weisbach equation, with the fitting losses represented as a percentage of the velocity head (15). The value of $h_L$ in the energy equation is calculated from

\[ h_L = f \frac{L}{D} \frac{V^2}{2g} + \frac{K V^2}{2g} \]  

4-1
where $f$ is the friction loss coefficient, $L$ is the length of conduit, $D$ is the diameter of the conduit, $V$ is the average flow velocity, $g$ is the gravitational constant and $K$ is the fitting coefficient. The energy equation was rearranged in order to solve for the velocity at the tip, $V_2$:

$$V_2 = \left[ \frac{(p_1 + z_1 - z_2)2g}{1 + \frac{1}{2}K + \left(\frac{F_p}{D_p/D_n}\right)^2 + \frac{F_p}{L_p/D_p} - \left(\frac{A_2}{A_1}\right)^2} \right]^{\frac{1}{2}}$$  

4-2

The subscripts $n$ and $p$ refer to the hose and probe, respectively. Once $V_2$ was known, the force was calculated using a rearranged form of Equation 3-3 as follows:

$$F = \rho A_2 V_2^2$$  

4-3

The two variables analyzed were the length of the hose and the area of the tip of the probe ($A_2$). The results of this exercise are shown in Figure 4.3 and Table 4.1, as a function of the area ratio, defined as the area of probe opening divided by the area of the conduit. For each length of conduit, there is an optimum area of probe opening. For short lengths of hose, it is advantageous to have a large opening; this is because in that case the fitting losses are of a larger magnitude than the friction losses. The optimum value of the area ratio decreases as the length of conduit increases; this is due to the fact that friction losses become increasingly larger with increased conduit length. Figure 4.3 also shows the desirability of keeping the length of any conduit as short as possible (it is assumed a larger jetting force yields better
compaction results).

It should be obvious from this exercise that the type of nozzle used with any particular apparatus must be carefully selected, so that the most effective use is made of the water jet energy. In general, only two nozzles would be required: one with an area ratio of about 0.75 and the second with a ratio of about 0.30 (the former for short lengths, the latter for long lengths). However, if only one nozzle of area ratio 0.30 is used, Table 4.2 shows that for the worst case the loss of efficiency is less than 7%.

In order to check the validity of the theoretical results obtained in this section, full-scale experiments were set up. These are discussed in the next section.

4.3 Full Scale Water Jetting Nozzle Experiments

The equations of Chapter 3 have been developed for a full pipe opening or a slightly reduced conical opening. After spending many fruitless hours of research, the author was not able to find any similar formulas which would be applicable to a porous nozzle. No reference could be found which could either refute or confirm the applicability of the Chapter 3 equations to the latter type of nozzle. Hence, the only alternative was to carry out experiments in an attempt to check the validity of the equations when applied to a porous nozzle.

The University of Windsor fire hydrants behind Essex Hall proved to be ideal for this purpose. The experimental
set up is illustrated in Figure 4.4. Basically, a 60 mm (2.5 inch) fire hose was connected to the fire hydrant; the other end of the hose was clamped to a table, with either a porous or conical nozzle attached to it. The experimental procedure consisted of turning the fire hydrant on; using a pitot gauge, a simple pressure reading was taken for a conical nozzle; for the porous nozzle, a measurement was taken at every opening. This was repeated for several lengths of hose, varying from 8 m (25 feet) to the maximum length available, 100 m (325 feet). The area ratio (defined as the total area of the nozzle normal to the flow divided by the area of the fire hose normal to the flow) was varied five times. For the porous nozzle, the area of opening was the sum of all the individual small area; the individual diameters varied from 6 mm to 8 mm (0.25 to 0.31 inches). To obtain a larger area ratio, the number of small openings was simply increased.

4.4 Analysis and Discussion of the Results

The data obtained is shown in Table 4.3. The parameter chosen for comparison is the water jet force, which was calculated using Equation 3-9. For the porous nozzle, the jetting force is calculated for each individual opening; then the total force is the sum of all the small forces. Figure 4.5 shows the results obtained for a conical opening. For each length, there is an optimum value of the opening as a percentage of the area of the hose. The trend is similar to that of Figure 4.3, but of course not the same in magnitude, since the two systems are different.
Figure 4.6 shows the results for a porous nozzle. Again, there is an optimum area ratio depending on the length of hose used. A comparison of Figures 4.5 and 4.6 shows that the values and the shape of the two curves are practically identical. This is further illustrated in Figure 4.7. Here the individual points for the porous nozzle have been plotted from Figure 4.6. Then, without any consideration of where the latter points are, the curves for a conical nozzle are traced from Figure 4.5. The result is obvious: there is no difference between the water jetting force generated by a conical or porous nozzle. The conclusion then is that the equations of Chapter 3, which were developed for a full pipe opening, apply equally to a porous nozzle.

In order to simplify use of the equations, it is desirable to define an equivalent diameter, $D_e$, for a porous nozzle. This equivalent diameter is derived below.

\[
\frac{\text{Total Area}}{\pi/4} = (\pi/4)(D_e)^2 = \pi \frac{\pi}{4} (d_1)^2
\]
\[
(D_e)^2 = \pi (d_1)^2
\]
\[
D_e = (\pi d_1)^{1/2}
\]

The equivalent diameter may be used in Equations 3-5, 3-7, 3-9, and 3-12, along with the average nozzle pressure, to obtain the required variable in one step rather than performing as many operations as there are mini-openings.

4.5 Recommended Nozzle

Based on Figure 4.6, it would appear that an area
ratio of 0.30 to 0.40 would provide a nozzle which would give an efficiency close to the optimum for most practical lengths of hose (about 150 m maximum). This area ratio is the same whether a porous or conical nozzle is used. The only question which remains to be answered is which of the two nozzles is preferable to use. Based on over two years of water jetting observations, and the experiments carried out, this author strongly believes that a porous nozzle is the only type that should be allowed when water jetting is to be used as a method of compaction. Figure 4.8 shows a porous nozzle designed for an area ratio of 0.36 (assuming 60 mm or 2.5 inch fire hose). This nozzle was used in the water jetting field experiments discussed in the next two chapters.

The following points clearly indicate the acclamation of the porous nozzle and the rejection of the full opening (refer to Figure 4.9):

(i) The porous nozzle distributes the applied energy evenly over an area which is an estimated 51 times the area covered by a conical nozzle (see pictorial comparison in Photos 4.1 and 4.2).

(ii) Because each minijet of the porous nozzle acts over a very small area, the actual energy delivered to a clay lump is an estimated five times that of the conical nozzle.

(iii) Since the energy per unit area is higher, the clay lumps are broken down easily and in larger numbers. This, combined with the effect of the
horizontal mini-jets break up the soil lumps, then the diagonal and vertical jets force them down, increasing the compaction.

(y) The amount of energy in any particular direction can be controlled by changing the size and/or the number of openings in that direction. Also, the opening diameter at the vertex of the nozzle can be increased so that the probe may sink more freely.

The only possible disadvantage that the porous nozzle could have is due to the fact that before the probe is inserted into the trench, the horizontal jets may wet the labourer carrying out the water jetting. This problem can be readily solved with the use of a sliding sleeve over the nozzle.

The chapters that follow will provide further evidence which will prove that the use of a porous nozzle when water jetting results in better compaction when compared to a full opening pipe.
PART III

FULL SCALE WATER JETTING FIELD TESTS
CHAPTER 5

EXPERIMENTAL PREPARATION AND PROCEDURE
FOR THE WATER JETTING FIELD TESTS

Once a satisfactory water jetting apparatus had been designed and assembled, the next step was to carry out full scale field tests. By definition, compaction is the application of energy to a soil in order to reduce its volume of voids. Therefore, it was only natural that out of the many parameters which may affect the behaviour of a water jetted trench backfill, the author selected the amount of energy applied to the soil as the single most important parameter to study. This would form the bulk of the field investigation.

It has always been the author's conviction that water jetting is merely a speeding up of nature's own compaction mechanism. This would be an excellent opportunity to either prove or disprove this belief. Therefore this investigation makes up the second part of the study.

Finally, all the advantages a porous nozzle has over a full pipe opening (listed in Section 4.5) would be meaningless if the nozzle would not yield
better results. A comparison of the two types of nozzle concludes the field investigation.

The objectives of the field study may be summarized as follows:

i) To determine the effect of applied water jetting energy on the behaviour of native clay backfill.

ii) To determine whether water jetting is a speeded up version of the natural process of compaction.

iii) To compare the results obtained when using a porous nozzle to those of a full pipe opening.

5.1 The Planning Phase

Once the objectives of the field study were determined, it was decided to monitor the behaviour of the backfill in terms of its degree of compaction, settlement, moisture content, vane shear strength and plate bearing strength.

In order to overcome the natural scatter of soil tests, and for these to be statistically significant, a large number of readings would be required (16). For every new reading to be taken on undisturbed soil, a fairly large trench of dimensions 6 m long, 1.8 m wide, and 3 m deep (20, 6 and 10 feet, respectively) was used for each experiment. A total of seven trenches were planned: four for varying applied energy, two for the comparison of the porous and full opening nozzles and one trench for the examination of the natural process
of compaction (see Figure 5.1). A buffer zone of undisturbed soil 3 m (10 feet) wide would prevent any interference from one trench to another.

Each trench, with the exception of the one used for the natural process study, would have a clear stone bedding approximately 0.60 m thick; this represents the amount of granular material that would be found around a sewer pipe 0.50 m (18 inches) in diameter. A profile of a typical trench is shown in Figure 5.2. Note the settlement plates on the surface and the 150 mm (6 inch) plastic pipe used for pumping water out of the granular layer.

The general location of the experiments is shown in Figure 5.3. This site was selected because the soil is representative of the type normally found in the Windsor area; also, a fire hydrant is located approximately 60 m (200 feet) from the proposed location of the trenches.

Several agencies were involved in the supply of the required materials and equipment. Amherst Quarries Limited agreed to donate 54 tonnes (60 tons) of 22 mm to 32 mm (7/8 to 1\(\frac{1}{4}\) inches) clear stone. Val-Ros Construction Company Limited loaned the heavy machinery and operator for the excavation and backfilling of the trenches. The Fire Department of the City of Windsor agreed to supply the fire hose along with a fire engine to be used as a pressure pump. To complete the preparation for the experiments, Nuclear Density Testing was arranged through
5.2 Excavation and Backfilling Operations

The trench excavation was carried out on 1978-09-26. It was anticipated that this would give sufficient time for the majority of the testing to be carried out without severe interference from inclement weather. Prior to the excavation commencement, bench marks were set up and the elevation of the original ground was surveyed for each trench.

Excavation was begun at Trench #1 (see Photo 5.1). All of the topsoil was stripped and set aside along with the sod. The shovel operator was instructed to fill the bucket by extending the boom fully and then retracting it, digging in layers approximately 150 mm (6 inches) thick. This procedure has the effect of breaking the original soil into relatively small lumps, a desirable backfill characteristic when water jetting. The size of the resulting particles can be seen in Photo 5.2. In order to examine the natural process of compaction, no clear stone was placed at the bottom of Trench #1. The excavated material was simply replaced into the trench without any compactive effort. Since this trench would not be water jetted, no pipe or granular bedding was necessary for drainage.

Excavation of the remaining trenches continued. Frequent elevation checks were made in order to ensure proper depth and grade. Using a level and a rod, the profile of the trench bottom and the clear stone surface
were determined every 0.90 m (3 feet). The plastic pipe was
installed at the same time as the granular bedding was
dumped into the trench. For ease of drainage, a minimum
of 150 mm (6 inches) of clear stone was placed between
the end of the pipe and the subgrade.

Once the plastic pipe had been placed and the
clear stone levelled and surveyed, the excavated material
was dumped into the trench, taking care that no compactive
effort was applied. The backfill was piled about 0.60 m
(2 feet) higher than the surrounding ground. This gives
an indication of the large increase in the volume of voids
in the soil. The backfill was levelled manually with
shovels; elevation markers (50 mm or 2 inch square steel
plates attached to a rod) were then planted at spacings
of 0.90 m (3 feet).

The type of soil encountered is classified as
a till-like silty clay. Appendix IV contains a detailed
soil analysis. The original soil moisture content was
about 14%, making the soil fairly dry and prone to
crumbling. This resulted in the small lump size which
has already been shown in Photo 5.2.

5.3 Water Jetting Procedure

Water jetting of the trenches took place the
day following excavation and backfilling. The apparatus
used is illustrated in Figure 5.4. In order to obtain
sufficient flow of water to the fire engine's pressure
pump, twin 64 mm (2.5 inches) fire hoses, each 30 m (100 feet) long, were connected directly to the 64 mm (2.5 inches) fire hydrant ports. From the pressure pump a further 30 m (100 feet) of the same fire hose led to a flow static pressure gauge and a 50 mm (2 inches) copper pipe. The tip of the probe consisted of the porous nozzle which has already been shown in Figure 4.8. Note that the equivalent diameter of the porous nozzle is 40 mm (1.5 inches), the same as the full opening iron pipe which was used for the nozzle comparison experiments. Photo 5.3 shows the two probes side by side.

The first trench was jetted at a pressure of 35 kPa (5 psi). This pressure was measured at the nozzle openings using a Pitot Gauge with the flow being discharged into the atmosphere. The flow static pressure gauge registered the same value. The probe was first inserted at the one-quarter point of the 6 m (20 feet) long trench. It sank relatively easily, requiring only occasional external force to continue its downward movement. In about 20 to 30 seconds the probe reached the granular layer of the 3 m (10 feet) deep trench; here it was allowed to rest until the clear stone was saturated. As the water level in the trench rose, the nozzle became submerged. This resulted in a small decrease in the flow static pressure (for a typical laboratory case, Figure 5.5 and Table 5.1 show this reduction to be about 7.5%). This indicated that it was time to move the probe up about 0.30 m (1 foot).
This procedure was repeated until the probe had reached the surface, at which time it was inserted at the three-quarter point of the trench and the whole process was started over (see Photos 5.4 through 5.9).

Three more trenches were jetted with the porous nozzle, at pressures of 138 KPa, 328 KPa, and 504 KPa (20, 47.5, and 73 psi) respectively, all in the same manner. It should be noted that after some time one can feel when it is time to move the probe up and the flow static pressure gauge really becomes unnecessary.

At this point the porous probe was replaced with a 40 mm (1.5" inches) iron pipe with a full opening. The pressure for the first jetting was set at 35 KPa (5 psi) and jetting was started. Unfortunately, the pump operator inadvertently bumped the pump's throttle, causing the pressure to continuously fluctuate. In the confusion that followed, and by the time that the problem was corrected, the trench had already been flooded through a very improper water jetting procedure. Subsequently, it was decided that the results from this trench could not be compared to those obtained from the other trenches. With much relief, the next trench was jetted at a pressure of 449 KPa (65 psi) without encountering any difficulties.

Even with all the water spraying all over the place, no water entered the trench to be used for the determination of the natural compaction process.

With the above jetting procedure, each probing
covered an area approximately $5 \text{ m}^2$ (50 square feet). In each case, the criteria used to determine when the water jetting process was complete was a visual one, namely, when the backfill had settled a significant amount and the water had bubbled to the surface, the soil was assumed to be saturated and the jetting completed.

5.4 Data Collection

An important part of any experimental work is the collection of data required to monitor the experiment's behaviour. The factors judged appropriate for this project were the degree of compaction, the settlement, the moisture content, the vane shear and the plate bearing strength. The variable "time" was studied over a ten-month period, from 1978-09-27 to 1979-08-04.

The degree of compaction and moisture content readings were obtained using a Nuclear Density Machine (NDM). This was carried out 10 days, 24 days, 45 days and 10 months after water jetting. Four test pits $0.60 \text{ m}$ wide, $0.60 \text{ m}$ long and $0.60 \text{ m}$ deep (2 feet by 2 feet by 2 feet) were dug manually for each trench. Photo 5.9 shows these four pits along with the Nuclear Density Machine in the background. The arithmetic mean of the four readings, taken at a depth of $0.60 \text{ m}$ (2 feet), represents the value for the entire trench. Samples were taken from each test pit in order to check the nuclear moisture readings against the more traditional oven moisture contents.
The settlement was determined from the difference in surface elevation from one day to another. A surveyor's rod and level were used to obtain readings accurate to 0.01 feet (0.30 mm). These measurements were taken throughout the ten month life of the project, initially every day and at intervals of several weeks near the end.

The vane shear readings were taken on the bottom of the test pits used for the density readings and at the same time intervals. A hand-held vane shear instrument was used to obtain four readings from each pit, thus giving a total of 16 for one trench. The mean of all the readings is assumed to be representative of the shear strength of the entire trench. The areas tested were selected at random; this resulted in about one-half of the readings falling on soil lumps, with the other half being taken on areas between lumps and filled with fine soil.

The plate bearing tests were taken only once, since the difficulty encountered in the transportation and handling of the heavy counterweight (about 1200 kg or 2600 pounds) proved to be too large to overcome. The one set of readings, taken 24 days after jetting, is inconsistent due to equipment malfunction; therefore these results will not be discussed in any detail.

Water was pumped out of the trenches through the plastic pipe using a centrifugal pump. Each trench would be pumped until the granular bedding had been drained. The volume of water pumped out was measured for comparison with the amount injected into the trench.
Weather data was collected from the nearby Windsor Airport Weather Station. This proved to be very valuable in assessing the natural process of compaction.
CHAPTER 6

ANALYSIS AND DISCUSSION OF FIELD RESULTS

5.1 Introduction

As outlined previously, the performance of the various experiments carried out is to be evaluated in terms of the trench backfill's degree of compaction, settlement, moisture content and vane shear strength.

The degree of compaction is due main consideration, since it is the basis for the existing backfill compaction specifications for the City of Windsor. In this study the degree of compaction is defined as follows:

\[ D.C. = \left( \frac{\gamma_d}{\gamma_{d_{\text{max}}}} \right) \times 100 \]  

where D.C. = degree of compaction, %

\( \gamma_d \) = dry soil density measured with the Nuclear Density Machine

\( \gamma_{d_{\text{max}}} \) = Standard Proctor maximum dry density

The main purpose for compacting trench backfill is to minimize its future settlement, so that satisfactory and permanent surface restoration can be carried out. When water jetting it is important to know when the majority
of the settlement has occurred. It would also be desirable to have an idea as to the magnitude of settlement to expect. Both of these items are presented when settlement is discussed as a function of time, applied energy and type of nozzle.

By its very nature, water jetting causes a soil to become saturated. With time, drainage, and absorption of the water by the soil lumps, the moisture decreases to more common levels. It has often been stated that high residual moisture contents are a severe disadvantage of water jetting as a method of compaction for native cohesive soils, however, this may no longer be true in light of the Dowse and Sedell report (7). This chapter considers the moisture content as a function of time, energy applied to the soil and type of nozzle.

Vane shear is the final factor taken into consideration. Determination of the effect of water jetting on the shear strength of a soil is important since the backfill mass often must be able to support external loads in addition to its own weight.

6.2 The Effect of the Applied Energy on the Backfill Behaviour

As indicated in Section 5.1, four separate trenches of approximately the same dimensions (hence same volume V) were used. Also, since the same probe and nozzle were used in all four cases, the diameter D is
constant. Therefore, with reference to Equation 3-12, the only two variables are the duration of the jetting and the nozzle pressure. Table 6.1 contains these two entities as measured in the field along with the applied energy as calculated from Equation 3-12. Note that the nozzle pressures (and therefore corresponding applied energies) of 504 KPa and 328 KPa (73 and 47.5 psi) represent values which would require the use of a pressure pump, while 138 KPa and 35 KPa (20 and 5 psi) are values of pressure normally attainable from the residual fire hydrant pressure.

6.2.1 The Degree of Compaction

The various degrees of compaction obtained are listed in Table 6.2 and illustrated in Figure 6.1. An increase in the applied energy has the effect of increasing the degree of compaction of the trench backfill. The rate of increase (the slope of the curve at any particular point) is much larger at lower energy than higher energy levels. This means that if a contractor is applying a low amount of energy to the backfill, that is, he is using low nozzle pressure, then his results could be improved significantly just by increasing the applied energy (larger nozzle pressure) by a small amount. This improvement can usually be accomplished through the elimination of friction and minor losses in the water jetting apparatus.
The reasons for the increase in the degree of compaction with applied energy can be found in the water jetting compaction mechanism, as outlined later in Chapter 9. The vibrations, vertical movement and the breakdown of the clay lumps are all a direct function of the energy contained within each individual jet. As this energy increases, the effect of these factors on the backfill increases accordingly, with the net result being a higher degree of compaction. Naturally, the density of the soil cannot increase ad infinitum, thus the rate of increase is reduced with ever larger amounts of applied energy. Obviously, there is an optimum point, dictated by economics and specification requirements, where an acceptable degree of compaction can be achieved at a reasonable cost.

The second effect which is evident in Figure 5.1 is that of time. As can be seen, the degree of compaction at any applied energy increases with time. This is explained once again with reference to the compaction mechanism outlined in Chapter 9. As time passes, the downward seepage forces, combined with the softened bearing areas of the soil lumps, and in conjunction with the process of consolidation, cause the soil mass to become more densely packed, thus increasing its degree of compaction.

The readings vary from about 80% to 86%. This relatively small range should not be disregarded and attributed to natural soil scatter, as each point
represents the average of four readings. This accounts for any natural soil scatter. Figure 6.1A presents the degree of compaction standard deviation for each set of four readings (see Table 6.2A for values). Generally, the standard deviation is low, with an overall mean of 2.85%. This represents only 3.5% of the arithmetic mean of all the density readings. Further, the standard deviation decreases as applied energy increases. This can only signify that the higher energy jet can penetrate deeper into the backfill, thus saturating and compacting it completely. In order to improve the standard deviation at lower jetting energies, the probe spacings should be reduced to insure a more even application of energy and complete saturation. A final observation is that the standard deviation decreases with time at any applied energy. This reduction in scatter means that eventually the backfill mass reaches a uniform degree of compaction.

The compaction values obtained are too low to pass the present City of Windsor specifications. The reason for the low readings is the shallow depth at which the tests were taken. Densities in excess of 90% have been reported for actual sewer projects in the city (6), however, the average test depth was always in excess of four feet.

In spite of the seemingly low densities obtained in this field study, as will be shown in the next section, the performance of the backfill mass has been excellent,
with practically no residual settlement being evident. This further reinforces the conclusion reached by Dowse and Bedell (7) that the present system of compaction quality control for cohesive soils in order to prevent settlements is inadequate, and a new system should be developed. The subgrade simulator method that they propose seems to be a reasonable one to use, especially in conjunction with water jetting.

The density readings of 80% to 86% compare very favourably with the original undisturbed soil density of 83.5%. This means that after jetting a trench and its surrounding area have a nearly uniform degree of compaction; with native soil used as backfill, eventually all traces of an excavation will disappear completely. This would restore the subgrade to its original uniformity, making pavement design more realistic.

The degree of compaction of the backfill before water jetting was a loose 63%. This implies a fairly large volume of voids, therefore the water injected at low pressures migrated through these spaces readily, ensuring complete saturation and consequently a comparatively high degree of compaction. There is no doubt that the variation in degree of compaction between low and high energy levels will be larger than 6% when the initial backfill density is higher, hindering saturation of the backfill. Thus, with a dense backfill it is even more advantageous to use a larger nozzle pressure.
6.2.2 The Settlement

The behaviour of the trench backfill as it pertains to its settlement is shown in Figure 6.2. Corresponding values are in Table 6.3. On the average, 90% of the settlement occurred within one day of jetting (actually this took place within minutes of jetting, but it could not be measured accurately until the next day). Within three days 96% of the final settlement had taken place. Because a soil will consolidate for long periods of time, for practical purposes it is assumed that the final value of settlement used to obtain the above percentages occurs 92 days after jetting; elevation checks taken 210 days and 10 months from the start of the experiment have proved this assumption to be correct.

The magnitude of the settlement varies from 50 cm to 65 cm (1.6 to 2.1 feet), and at any time, the amount of settlement varies directly with the applied energy (all trenches are of the same depth). This relationship can be better illustrated with reference to Figure 6.3 (see Table 6.4 for values). Here it is shown that for the case of constant trench depth, both the initial and final settlements are linearly proportional to the applied energy. The reasons for this relationship can be attributed to the vibration effect, vertical movement and breakdown of the clay lumps as already explained in the previous section. The process of consolidation, cohesion reduction and seepage forces
affect a backfill mass the same way, regardless of the water jetting energy initially applied. This explains why the final settlement line is simply shifted higher and parallel to the one for the initial settlement. The latter three factors contribute approximately 10% of the total settlement, with the other 90% being caused by the action of the water jet. This further emphasizes the need for a proper nozzle, such as the porous nozzle used for these experiments, in order to obtain the highest compaction efficiency for the smallest energy input.

6.2.3 The Moisture Content

A major disadvantage in carrying out full scale field tests is that there is no way of controlling the weather. When dealing with moisture contents even a small amount of precipitation can upset the readings. This is exactly the problem encountered in this study. Table 6.5 and Figure 6.4 illustrate the soil's moisture content as a function of the energy applied to it and how it behaved with time. With the exception of the curve for moisture content after 10 days, there is an overall large scatter of readings. This of course was caused by the rain which fell between the testing periods. The overall standard deviation is about 2.0%, corresponding to 9.5% of the mean of all the readings.

Between zero and 10 days after jetting there was
a total of 24 mm (0.94 inches) of rainfall. However, because the trenches were still quite wet from the water jetting, this precipitation did not have a significant effect on the readings, resulting in good correlation. Therefore, the 10 day curve is really the only one which truly describes the effect of water jetting energy on the moisture content of the soil. This curve clearly shows that as the water jetting energy applied to the soil increases, the moisture content decreases. This behaviour is explained by the fact that higher jetting energies result in higher degrees of compaction (see Section 6.2.1). This means that the total volume of voids has been reduced, resulting in less space for the water to fill. The total volume of water, which is equal to the total volume of voids for the case of a saturated soil, thus is reduced as the jetting energy increases, obviously giving lower moisture content readings.

Between 10 and 24 days after jetting, a total of 34 mm (1.34 inches) of rain fell. Because each trench had different topographical features, different volumes of water accumulated into each one. Also, because the surface of the settled trench was below that of the surrounding ground, some runoff was collected. This water seeped into the backfill, resulting in higher moisture contents when compared to the 10 day curve. Further, the test pits for each successive set of tests were excavated next to those used for the preceding testing. Once the
necessary readings had been taken, each test pit was
backfilled and compacted. It is likely that no two pits had
the same degree of compaction, thus different amounts
of water seeped into each one. This further affected
the readings, contributing to the scatter.

At 45 days the moisture curve is falling slowly,
still hindered by intermittent rainfall. Note that the
shape of the curve is flatter than the previous two, a
result of the backfill approaching its specific retention.
This value is reached sometime between 45 days and 10 months,
with the latest curve giving a specific retention or
field capacity of just over 20%, approximately 5% above
the Standard Proctor optimum water content. It should
be noted that although the moisture in a soil cannot be
drained below the field capacity, it can evaporate, thus
resulting in natural moisture contents which are lower than
the soil's specific retention.

6.2.4 The Vane Shear Strength
As will be explained in detail in Chapter 9,
water jetting tends to significantly reduce the clay's
cohesive strength. For the soil used in this experimental
work the undisturbed vane shear strength as measured in
the field at a depth of 0.60 m (2 feet) was approximately
95 kPa (1.0 tons per square foot). Examination of
Figure 6.5 and Table 6.6 will indicate that 10 days after
jetting the vane shear strength at a depth of 0.60 m
(2 feet) is only about 22 kPa, a reduction of over 75%. This large loss of shear occurs because the apparent cohesion of the clay is destroyed when the soil is saturated. This results in each individual soil lump having a lower shear strength. In addition, the voids which were present before water jetting are now filled with the fine particles of the backfill. As long as there is water in the void, these particles are almost in suspension, with no real shear strength. As the water leaves the void, the soil particles slowly grow stronger bonds to attain a higher level of shear strength.

Figure 6.5 indicates that there is a slight increase in vane shear with higher applied energy. This can be traced back to the higher degree of compaction and lower moisture content associated with larger values of applied energy. The shear strength increases very slowly with time, and after 10 months approximately 75% to 95% of the original vane shear strength has been recovered. The larger percentage value corresponds to the largest applied energy.

It is interesting to note that only after 10 days, the vertical walls of the test pits (0.60 m or 2 feet deep) were stable under the weight of a man standing on the edge of the excavation. This indicates that the large reduction in shear strength which occurs after jetting is not as critical as one might at first believe.
It is generally acknowledged that a hand held vane shear instrument results in standard deviations in the range of 20% to 25%. For the data of this study, this range varied from 9% to 32%, with an overall value of standard deviation of 7.3 kPa. This corresponds to 17.7% of the arithmetic mean of all the readings taken.

6.3 The Natural Process of Compaction

This part of the study was undertaken in order to prove or disprove the author's belief that water jetting is merely a speeded up version of nature's own compaction mechanism. A trench was first excavated; then the material dug was placed back into the trench without applying any mechanical compaction or water jetting energy. The only compaction effort came from the rainfall as it hit the trench surface and as the rainwater seeped down through the backfill mass. The results of the monitoring programme are presented and compared with a trench water jetted at low energy using a porous nozzle.

6.3.1 The Degree of Compaction

The degree of compaction of the undisturbed soil was 83.5%. After excavation and backfilling, the large increase in volume of voids had caused the overall backfill density to be reduced to 63.0% of the Standard Proctor value. Figure 6.6 illustrates how the compaction
gradually increased with time (also see Table 6.7). Beginning with 1978-09-27, when water jetting was carried out and thus time is zero, the degree of compaction slowly increased with each rainfall (see Figure 6.8 for rainfall bar graph). Throughout the winter and spring months, more rainwater and/or snowmelt seeped into the trench, saturating the backfill, in effect water jetting it. The same basic mechanism which causes water jetting to compact a soil mass is at work. Eventually, after 10 months, the backfill reaches its original undisturbed density, that same density which the water jetted trench attains within days. Obviously, with regards to density, water jetting is in fact a speeded up version of nature's own compaction mechanism.

6.3.2 The Moisture Content

Figure 6.7 and Table 6.8 present the behaviour of the moisture content of the backfill for a water jetted trench and for one which was left for nature to compact. For the trench which was not water jetted, the original moisture content is that of the original undisturbed soil. It vacillates according to the weather's wet and dry cycles.

Any soil which is dry will tend to absorb water until the moisture content reaches its field capacity. At that point the excess water will drain. This is exactly what happens with the unjetted backfill: after 10 months
the moisture content is near the field capacity value. Note that water jetting causes a soil to have a high moisture content initially; however, it decreases quickly to approach the soil's specific retention in a time much less than that required for the natural process moisture to increase and reach the same value.

5.3.3 The Settlement

The natural compaction process is perhaps best illustrated in Figure 6.8, with the corresponding data in Tables 5.9 and 6.10. Here the settlement of the unjetted trench is presented as a function of time, with the amount of rainfall also shown for rapid reference.

It will be noted that after each rainfall there is an increment in settlement. There is a time lag required for the rainwater to seep into the backfill and act as a compaction and consolidation agent. Eventually, after about three months, the total settlement reaches a value similar to that obtained after two days for a water jetted trench. The rate of settlement for the unjetted soil is totally dependent on rainfall and snowmelt infiltration.

The graph clearly illustrates the problems which may be encountered with mechanical compaction. If the latter is carried out at moisture contents below the soil's specific retention, than the backfill will absorb moisture and settle in a manner similar to the
unjetted trench shown in Figure 6.8. Water jetting completely eliminates this problem: as can be seen, no amount of precipitation can cause any further settlement.

6.3.4 The Vane Shear Strength

Due to the fact that the backfill of the unjetted trench was dry and crumbly, no vane shear readings could be taken until 10 months after the experiment had begun. At that time, the shear strength was measured to be 37 kPa. This represents about 36% of the shear strength of a trench 10 months after it was water jetted and about 35% of the undisturbed shear strength of the soil. It is interesting to note that the water jetted trench exceeded this value within 45 days of water jetting.

6.3.5 Conclusion

From the results presented in the above sections, the overwhelming conclusion can be only one: water jetting is a speeded up version of and one of the most natural of nature's mechanisms.

6.4 Porous Nozzle and Full Probe Opening Comparison

As has been repeatedly stated in the preceding chapters, the nozzle forms a very important part of the water jetting apparatus. The porous nozzle developed in Chapter 4 has many advantages over the conventional full probe opening, as has already been pointed out in
Section 4.5. The portion of the field study that follows was designed to provide a comparison of these two types of nozzles. Two trenches of similar dimensions and backfill were water jetted at the same energy level, one using the full pipe opening and the other using the porous nozzle.

### The Degree of Compaction

Although the same energy was applied to both trenches, Figure 5.5 indicates that the porous nozzle resulted in better degrees of compaction. The data is listed in Table 6.11. At any particular time the density of the trench jetted with the porous nozzle is higher than that obtained with the full pipe opening. The reasons for this were outlined in Section 4.5 and will not be repeated.

#### 6.4.2 The Settlement

Settlement values are recorded in Table 6.12 and illustrated in Figure 6.10. At any one particular time, the porous nozzle gives a settlement which is about 23% larger than that obtained with the full probe opening. The desirability of obtaining as much settlement as possible is obvious, as it leads to higher degrees of compaction, higher shear strength and the elimination of residual settlements.

#### 6.4.3 The Moisture Content

The data for this parameter can be found in
Table 6.13 and Figure 6.11. The porous nozzle results in the soil having a lower moisture content, causing it to approach its field capacity much faster than the soil jetted with the full pipe opening. This can be linked to the higher degree of compaction, which implies a lower volume of voids and thus less water in the backfill. Also, the denser soil makes it more difficult for surface runoff to percolate into the backfill.

5.4.4 The Vane Shear Strength

A combination of higher degrees of compaction, larger settlements and lower moisture contents can only result in larger magnitudes of vane shear strength. This is confirmed by the data in Table 6.14 as illustrated in Figure 6.12. It can be seen that the above combination helps the porous nozzle shear strength to reach values as much as 22% larger than the full pipe opening shear. After 300 days, the porous nozzle trench has reached 95% of the original shear, while the full pipe opening trench has retained only 75% of its initial strength.

5.4.5 Conclusion

Although brief, each one of the preceding four sections points out the advantages of a porous nozzle and confirms its superiority over a full probe opening. It is important to note that the backfill had an initial density of only 63%. Under such conducive
conditions the water injected with any nozzle could travel rather easily through the backfill. Therefore, the full effectiveness and superiority of the porous nozzle has not been demonstrated. It is expected that a full probe opening will be unable to completely saturate an initially dense soil, thus resulting in poor compaction (the author has observed this happen in the field on several occasions). It is further expected that the porous nozzle, by its very nature, will encounter little difficulty in saturating a dense trench backfill and providing good compaction.

The above field results further reinforce the statement made in Chapter 4: "A porous nozzle is the only type that should be allowed when water jetting is to be used as a method of compaction".
PART IV

LABORATORY EXPERIMENTS
CHAPTER 7

LABORATORY APPARATUS AND PROCEDURE

7.1 Introduction

Once the field experiments were well underway and some results were already available, it was felt that an attempt should be made to develop a laboratory procedure in order to determine in advance the effect water jetting would have on a soil. If a suitable laboratory apparatus and procedure could be developed, then the effect any parameter would have on the water jetted soil could be determined readily through the testing of a small sample.

The objectives of the laboratory investigations could be stated as follows:

(i) To develop a laboratory apparatus and procedure that will reproduce and predict the field behaviour of a water jetted soil.

(ii) To use the test and apparatus developed in (i) to study the effect of various parameters on the behaviour of a water jetted soil.

If the above stated objectives could be achieved, then numerous experiments could be carried out in the
laboratory conveniently and in short periods of time. The results obtained could be extrapolated to predict field behaviour; the mystery of water jetting would be finally solved and a new art would be born. If all this sounds too good to be true, that is because that is exactly the case. In spite of spending many months and numerous attempts to arrive at a suitable solution, the author encountered only limited success, and certainly not enough to truly fulfill the objectives of the laboratory study.

Nonetheless, the work carried out and the results obtained are reported in detail in the hope that they may provide guidance for anyone wishing to pursue this area of water jetting still further.

7.2 Principles of Modelling

The first impulse in developing a model was to make use of the laws of hydraulic modelling. The physical dimensions of a sewer trench were readily scaled down using any arbitrary length ratio. Following the same procedure, the water jetting apparatus used for the field experiments was also reduced to model size. However, an enormous stumbling block met any attempt to model a cohesive soil. To the author's knowledge this has never been successfully done before and this would not be the first time. The problem of course is how to scale down a clay particle which is already less than
0.001 mm (0.00004 inches) in diameter. Following this initial setback, it was decided to take a different approach, something similar to a combination of the Proctor test and the consolidation test. In essence, the laboratory test involves the taking of a sample from the field trench at the field test depth. The sample is then placed in a container in the laboratory (see Figure 7.1); the field overburden pressure above the removed soil sample is calculated and an equal surcharge is applied to the sample in the laboratory. At this point the soil sample is ready to be water jetted. Using a probe which is geometrically similar to the one used for the field water jetting, the same energy applied per unit volume of soil in the field is delivered to the sample. To simulate field drainage, water leaves the soil through a drain at the bottom of the container. A soil lump located in the centre of the sample should not be able to distinguish whether it is in the field trench or in the laboratory model.

The above procedure should give values of degree of compaction, moisture and vane shear strength which are applicable to field conditions directly. Only the settlement, which is mainly a function of trench depth, will require interpolation before it can be used to predict the field settlement.
7.3 The Laboratory Apparatus

The laboratory equipment consists of the container and the water jetting apparatus. The container is simply a plexiglass box 78 cm long, 20 cm wide and 50 cm high (30.7 by 7.9 by 19.7 inches), as shown in Figure 7.2. Two partitions divide the model into three separate and watertight compartments, each 25 cm long, 20 cm wide, and 40 cm high (9.8 by 7.9 by 15.7 inches); this allows three samples to be tested simultaneously. Photo 7.1 shows one such experiment in progress.

In order to simulate field conditions and drain the water after jetting, a granular bed 6 cm (2.4 inches) thick consisting of 13 mm and 6 mm (0.5 and 0.25 inches) gravel was placed on the bottom of each compartment. A filter cloth, Terrafix 200 NA, was placed between the gravel layer and the soil sample; this would almost eliminate soil loss into the granular layer completely. Three outlets, one for each cell, allowed for and controlled through valves the drainage of water. In order to apply the surcharge uniformly, a 20 mm thick (0.75 inches) plywood plate was placed on the surface of the sample. This plate, of dimensions just slightly smaller than a cell, had numerous small holes drilled into it to allow for evenly distributed water seepage.

The water jetting apparatus consists of a 12.5 mm (0.5 inches) flexible hose connected to a flow static pressure gauge at one end and to a faucet at the
other (see Figure 7.3 and Photo 7.2). A second flexible hose joins the pressure gauge and the jetting probe. The latter consists of a 12.5 mm (0.5 inches) copper pipe, with a porous tip. Thirteen 2 mm (0.078 inches) openings are part of the flow area, resulting in an equivalent diameter of 6.7 mm (0.26 inches). This gives an area ratio, defined as the total area of opening divided by the area of the flexible hose, of 0.31. This compares with the field nozzle area ratio of 0.36.

7.4 Sample Preparation and Data Collection

For each experiment to be representative of the field conditions, the soil sample had to have the same properties as the backfill used in the field experiments. Of course the same soil was used for both. In addition, the moisture content and the degree of compaction of the sample before jetting were controlled. Because of the small size of the model, large clay lumps were broken down into particles less than 50 mm (2 inches) in diameter.

The same soil sample was used for all experiments. After one test was completed, the wet sample would be removed from the compartment, usually in large lumps, and allowed to dry for one to two days. Then the large lumps were broken into small pieces by hand only. The clay was then allowed to dry for about one more day before it was checked for moisture content. If it was wetter than the natural field moisture, then it would be
left to dry some more; if too dry, some water would be sprayed on it as the sample was placed in sealed plastic containers. The moisture content would not change significantly in these containers, while at the same time storage for several days would allow the sample to reach a uniform moisture value.

When an experiment was to be carried out, each of the model's three compartments would be filled with soil. The wet weight of each sample would be measured and six moisture samples would be taken in order to determine its initial moisture content and dry weight. The perforated plywood plate was placed on top of the clay and the required surcharge would be applied using 22 kg. (50 pounds) weights. The sample would be allowed to consolidate under the surcharge for 15 to 30 minutes. Readings were then taken at the four corners of the plywood plate, measuring the distance from the top of the model to the top of the plate. Knowing the model height, \( H_m \); thickness of the gravel bed, \( H_b \); thickness of the plywood plate, \( H_p \); and using the mean of the four readings, \( H_o \), the initial sample height, \( H_o \), was determined as follows:

\[
H_o = H_m - H_b - H_p - R_o
\]  

Similarly, when the experiment was over, four readings were taken at the same locations as above to
obtain the average reading \( R_f \) and the final sample height after jetting, \( H_f \):

\[
H_f = H_0 - H_p - H_v - R_f
\]

7.2

In the same manner, readings could be obtained at any time during the life of the experiment. When a continuous history of the settlement was desired, Herber dial gauges accurate to 0.025 mm (0.001 inches) were used.

Once the final readings were taken, the samples would be removed from the test cell and weighed. Six moisture samples were taken from each compartment, two each at the top, centre and bottom of the sample. This procedure would account for any variation in moisture content and eliminate any detrimental effects due to soil loss during jetting.

As the sample was being removed, five vane shear readings were taken at each location near the surface, centre and bottom of the sample. The average of these 15 readings was assumed to be representative of the shear strength of the soil.

7.5 Water Jetting Procedure

Once the soil sample had been prepared and placed into the compartment, the water jetting apparatus shown in Figure 7.3 and illustrated pictorially in Photo 7.2 was used to apply energy to the soil. Because of the
small size of the nozzle openings, the pitot gauge used to measure the nozzle pressure for the field experiments could not be used for the laboratory probe. Therefore, the flow static pressure gauge was used. In order to account for the friction and fitting losses which occurred between the gauge and the nozzle tip, the laboratory data of Table 7.1, shown in Figure 7.4, was obtained experimentally; all the pressure readings were corrected accordingly.

An experimental check was made to determine whether the laboratory jetting flow rate could be determined using Equation 3-7. As can be seen from Figure 7.5, this was not the case (see also Table 7.2). Similarly, Equation 3-12 could not be used to calculate the energy applied to the soil. Instead, it was decided to obtain the experimental flow rate from Figure 7.5; then Equations 3-10 and 3-11 would give the applied energy per unit volume of soil.

The actual water jetting procedure involved the insertion of the probe (with the water turned on at the desired pressure) into the soil sample through an opening in the centre of the plywood plate. The pipe reached the granular bed quickly; looking through the transparent plexiglass walls of the model, the tip of the nozzle was kept just above the rising water level. During the jetting, the drains were slightly open to simulate field drainage conditions. Once the probe had reached the top of the sample,
The jetting time was determined. In order to insure that the seepage force applied would be the same as that in the field, 5 to 10 cm (2 to 4 inches) of water were placed gently on the surface of each sample (no energy was applied to the soil). This extra water represents the water which is in the voids above the sample in the field trench and has to drain through it, thus applying a seepage force. Photo 7.1 illustrates the model minutes after jetting has been completed. Notice the gravel bed, filter cloth, plywood plate, surcharge and drains.

The jetted sample was allowed to consolidate for a period of 21 days, after which time final readings as already described in Section 7.4 were taken.

After several experiments had been carried out it was noted that if the length of the consolidation period was reduced from 21 to 5 days, values less than 1 lower would result. This difference was deemed negligible, and the balance of the experiments were only 5 days in duration.
CHAPTER 8

ANALYSIS AND DISCUSSION OF LABORATORY RESULTS

8.1 Introduction

The first priority in carrying out the laboratory experiments was to reproduce the data obtained in the field. If successful, this step would prove that the apparatus and test procedure described in the previous chapter were correct in predicting field behaviour. Other parameters would then be investigated in order to fulfill the second objective.

As in the case of the field portion of the study, the analysis is based on the degree of compaction, settlement, moisture content and vane shear strength of the soil. All these are discussed as a function of the energy applied to a unit volume of soil.

Using the wet unit weight of the soil, the field surcharge after jetting at a depth of two feet was calculated to be 13.0 kPa (270 psf). After nine laboratory samples had been jetted with this surcharge applied, it became obvious that the effect of this overburden was too large, since the laboratory degree of compaction and settlement values were much too large when compared to the
field data. Consequently, the surcharge was reduced to 9.0 kPa (188 psf). This gave laboratory values closer to the field results, but still higher. The overburden was then reduced to 4.5 kPa (94 psf); this resulted in data lower than that obtained in the field. Therefore, it was decided that two sets of experiments would be carried out, with surcharges of 9.0 kPa (188 psf) and 4.5 kPa (94 psf), respectively. It was felt that this would provide results in a range which would encompass the field values. The section that follows analyses and discusses these results.

Although the first part of the objectives was not entirely successful, as will be shown in the next section, one parameter, the initial degree of compaction, was evaluated anyway in an attempt to fulfill the second part of the laboratory objectives. These results are reported in the last section of this chapter.

3.2 The Effect of Applied Energy on the Laboratory Soil Sample Behaviour

3.2.1 The Degree of Compaction

The laboratory data, contained in Table 3.1, is shown in Figure 3.1, along with the field degree of compaction curve 10 months after jetting.

A comparison of the curves shown reveals that the trend is similar in all three cases. This would suggest that there is a magnitude of surcharge between 4.5 kPa (94 psf) and 9.0 kPa (188 psf) such that the
laboratory and field curves overlap. This value appears to be approximately 45% of the actual field surcharge. The reason for this is probably due to the effect of the smooth walls of the container; no friction is developed between the soil particles and the wall, therefore the full effect of the surcharge is felt by the soil sample. In the field the overburden effect is reduced through friction and cohesion developed between soil lumps, leading to partial dispersion of the applied stress. Possible solutions to this problem could be the impregnation of rough sand particles on the walls of the container; use of a larger sample in a larger test cell; development of a correlation curve for surcharge to be applied to the present apparatus such that the same field and laboratory results are obtained.

The laboratory data shows a large scatter along with poor reproducibility at any given value of applied energy. This, combined with the surcharge problem described above, clearly illustrates the need for further research in this area before the laboratory approach can be used to predict the behaviour of a water jetted soil in the field.

8.2.2 The Settlement

The magnitude of settlement is directly proportional to the height of the sample. Because the field trenches are about 10 times larger than the laboratory sample,
no direct comparison is possible. For this reason, the settlement ratio, defined as the amount of settlement divided by the height of the sample or trench, is used to compare the field and laboratory results. Figure 8.2 presents the settlement ratio as a function of applied energy; the data can be found in Table 8.2. The figure also shows the 10-month field settlement ratio.

The laboratory results again show a large scatter and poor reproducibility. The method of least squares has been used to determine the line of best fit, resulting in a correlation coefficient of 0.63.

Even at a surcharge of 4.5 kPa (92 psf), compared to 13.0 kPa (270 psf) in the field, the laboratory settlement ratio is about 30% higher than that obtained for the field trench. The reason for this is the effect of the friction and cohesion as explained in the previous section. In addition, friction between the trench walls and the backfill hinders the amount of settlement in the field. In the laboratory test cell, the water jet easily reaches the wall, lubricating it and removing any friction, thus facilitating settlement. To improve on this situation, the same suggestions as the previous section apply.

8.2.3 The Moisture Content

Figure 8.3 and Table 8.3 present a comparison of the 10-day field moisture content at a surcharge of 13.0 kPa (270 psf) with the 5-day laboratory moisture at
surcharges of 9.0 and 4.5 kPa (188 and 94 psf). The method of least squares gives the best fit as shown, with correlation coefficients of 0.41 and 0.80 for the 4.5 kPa (94 psf) and 9.0 kPa (188 psf) surcharge, respectively.

The higher overburden results in moisture contents approximately 10% lower than the 4.5 kPa (94 psf) surcharge. This is due to the former sample being more densely compacted by its larger surcharge, thus it has a smaller volume of voids for the water to fill.

Both laboratory curves are below the field moisture level. This can be explained in part by the overpowering laboratory surcharge reducing the volume of voids and in part by the larger volume of water which had to be drained through the field trenches. This of course caused the field test area to have a high moisture content for a longer period of time.

8.2.4 The Vane Shear Strength

A plot of the 21 day laboratory vane shear of a soil sample subjected to a 9.0 kPa (188 psf) surcharge is shown in Figure 8.4 (see Table 8.4 for data), along with the 10 and 24 day field vane shear strength (surcharge of 13.0 kPa or 270 psf).

The vane shear gives the best correlation yet between field and laboratory results. This is because the amount of surcharge does not have as significant an effect on this parameter as it does on the others previously
discussed. In fact, it was noted that for the same applied energy, similar values of vane shear were obtained regardless of the surcharge applied. The shear strength is mainly dependent on cohesion, which builds up very slowly, and is itself dependent on the water in the soil, as will be explained in Section 9.3, and not on the overburden.

8.2.5 Conclusion

From the above discussion, it would appear that the first objective of the laboratory experiments has not been accomplished entirely. In every case, the laboratory trend is similar to that obtained in the field, but the magnitude is not the same (with the exception of the vane shear strength). This means that the concept or principle of modelling, as outlined in Chapter 7, is correct, but the physical characteristics of the test cell are not.

The testing apparatus described in the previous chapter can only provide results which can be applied to field conditions in a limited qualitative manner. In order to obtain laboratory values representative of the field behaviour, it is necessary to change the characteristics of the test cell, while keeping the test procedure and water jetting apparatus used in this research intact. Chapter 11 contains several specific recommendations for further study in this area.
8.3 Effect of the Initial Degree of Compaction on the Behaviour of a Laboratory Soil Sample

Several laboratory tests were carried out in an attempt to determine what effect the backfill's initial degree of compaction has on its final density. The results obtained are reported in terms of the final degree of compaction and the settlement ratio. It must be remembered that these are only trends and applicable to field conditions only qualitatively.

Figure 8.5 shows a plot of the data contained in Table 8.5. The method of least squares has been used to determine the relationship between initial and final densities. Knowledge of this relationship is important, as some contractors insist on applying as much casual mechanical energy as they can (for example, a bulldozer driven over the backfilled trench several times). This of course requires more time and an additional expenditure. Although very poor correlation was obtained, the general tendency is for the final degree of compaction to be independent of the initial density of the backfill. This means that the increment in density due to water jetting decreases as the initial degree of compaction increases. However, the reader should be cautioned that the scatter is too large to make any definitive conclusion.

On the other hand, there is a definite relationship between initial density and the settlement ratio, as is shown in Figure 8.6 (data in Table 8.6). Here the
least squares analysis gives a correlation coefficient of 0.95. For samples of equal height, the denser soil will have a smaller volume of voids, therefore it cannot consolidate to the same extent as a loose soil. This trend can be applied to field conditions qualitatively in that it implies that some casual mechanical compaction, while not affecting the final degree of compaction significantly, can reduce to a large extent the amount of settlement. This means that a lesser volume of mechanically compacted backfill is required to bring the trench to its final grade, with a corresponding cost savings.

The preceding paragraph illustrates the usefulness of a proper laboratory test in gaining more information about the process of water jetting. Even though field confirmation of any laboratory results would be required, each experiment, when carried out properly, can yield a little more knowledge about this method of compaction, until all the mysteries are finally solved.
PART V

CONCLUSIONS AND RECOMMENDATIONS
CHAPTER 9

THE WATER JETTING MECHANISM

"I know water jetting works, just do not ask me how". For years this has been the typical answer for anyone who believed water jetting to be a viable method of compaction to any inquiries as to the mechanism involved. As a result of the numerous water jetting observations made in the field and in the laboratory, combined with literature research into the basic composition, structure and bonding of clay particles, the author wishes to present the water jetting mechanism which follows. It is assumed that a porous nozzle will be used in carrying out the water jetting.

9.1 Vibration Effects

The clay backfill is made up of particles which may vary in size from fractions of a millimetre to more than one-half metre. This composition causes the clay to act similar to a granular backfill, especially when it is fairly dry. One of the most effective ways of compacting a granular mass is through vibration. When water jetting a native clay with a porous nozzle,
there is a large amount of turbulence in the water; this sets up a vibration effect. Also, as each jet hits a clay lump, it causes the latter to move; the soil lump in turn moves other particles, and a series of movements or vibrations result. This vibration makes the soil lumps rearrange themselves so that the volume of voids is reduced, exactly as in the case of a granular soil. This is the first step in compaction by water jetting.

9.2 Breakdown of Clay Lumps

As each clay lump is subjected to the impact of a minijet, it is first scoured and then broken up, while at the same time it is being compressed and pushed down. This creates a large number of particles of varying size, resulting in a well graded soil. Also, Figure 9.1 illustrates how the water attempting to leave a void causes further scouring. This is due to the increase in the velocity of the water as it passes through a small opening. It should be noted that this process only takes place when the rate of water inflow through the probe is larger than the rate of water dissipation into the voids of the backfill.

The vibration effect, combined with the ability of the jet and the water seeping downward to carry along soil particles, relocates the small broken clay lumps into the voids formed by the larger clay particles. This of course leads to a denser soil.
9.3 Reduction of Cohesive Force

Cohesion is a force or a bond whereby clay particles stick together to form large lumps. These bonding forces are primarily due to the Van der Waals forces of intermolecular attraction and to the surface tension forces present at the air-water interphase in unsaturated soils. The latter is known as apparent cohesion, while the former is referred to as true cohesion. In some soils, chemical bonding and electrical attraction also make a minor contribution to the cohesive strength (18, 19, 20).

The surface tension forces and their action are shown in Figure 9.2. These forces are only present when there is an air-water interphase and disappear completely when a soil is saturated.

The Van der Waals forces are inversely proportional to the seventh power of the distance between particles, hence they decrease very rapidly as these particles are moved only slightly apart.

When water jetting, the soil is saturated, therefore the surface tension forces are destroyed, with a corresponding loss in cohesion. At the same time water begins to penetrate the clay lump. As it is absorbed, the water film which surrounds each particle becomes thicker, pushing them apart, thus increasing the intermolecular distance and decreasing the Van der Waals forces significantly. The net result of this process is a large
reduction in cohesive and shear strength (see Section 6.2.4). The clay becomes soft, and the area of contact between soil lumps is no longer sufficient to support the weight of the overburden above it. The lumps have no choice but to be deformed and reshaped until the contact area is once again large enough to bear the load imposed upon it. However, by this time, the entire soil mass has been compressed and reduced in volume, thus contributing to increased density.

9.4 The Seepage Force

The driving force which causes water to flow may be represented by the hydraulic gradient, defined as the drop in water head divided by the distance over which the drop occurs (21). As the water flows, it has a force along its direction of flow known as the seepage force; this force is equal to the product of the hydraulic gradient and the unit weight of water (22).

After water jettin has been carried out, the backfill mass is saturated; in addition, normally the surface of the trench is flooded with water. All this water must drain downwards through the backfill and into the granular bedding; from there it is removed by pumping or by drainage into the sewer pipe. This downward flow applies a seepage force to the already weakened clay (see previous section), thereby compressing it still further and increasing its density.
9.5 The Process of Consolidation

Consolidation is defined as the gradual decrease in volume of voids under the action of a continuously acting static load over a period of time. This process begins almost as soon as water jetting is completed and the pore water starts to drain. Under its own weight, the backfill mass reduces its volume of voids, making the final contribution towards a denser soil.
CHAPTER 10

CONCLUSIONS

The conclusions reached as a result of this endeavour will be presented for each part of the study. Overall conclusions follow at the end.

10.1 State of the Art

It is obvious from the literature survey and the present construction practices that to date there exists no satisfactory apparatus or methodology for water jetting trench backfill.

10.2 Hydraulics Experiments

(i) The flow rate, velocity, force and energy of the water jets of a porous nozzle can be determined using the long-accepted equations derived from basic hydraulic principles for a full pipe opening.

(ii) The design of any water jetting apparatus should be such that energy losses are minimized. The conduit should consist of 64 mm (2.5 inches) fire hose as opposed to 40 mm (1.5 inches).

(iii) For the purpose of water jetting, the porous nozzle
is far superior in every aspect when compared to a full pipe opening. The porous nozzle should be the only one allowed for water jetting clay backfill.

(iv) For any given water jetting apparatus there is an optimum area of opening such that the flow rate, velocity, force and energy of the water jet is maximized. A small opening is desirable when using long lays of hose, while a large area is best on short lengths.

10.3 Field Tests

(i) The degree of compaction, settlement and vane shear strength of a water jetted soil increase directly with the amount of applied energy and with time.

(ii) The moisture content of a water jetted soil decreases directly with the amount of applied energy and with time. Eventually, every soil reaches its field capacity moisture content.

(iii) The uniformity in degree of compaction of the water jetted trench backfill, as measured by the standard deviation, increases with the amount of applied energy and with time.

(iv) Water jetting is a speeded up version of nature's own compaction process, achieving in several days what nature takes years to accomplish.
When compared to a full pipe opening, the use of a porous nozzle when water jetting results in the backfill having a higher degree of compaction, larger initial and final settlements, lower moisture contents and higher shear strength.

10.4 Laboratory Experiments

The test procedure and principles of modelling developed in Chapter 7 appear to be correct in reproducing field results. However, further work is required with respect to the physical dimensions and characteristics of the test cell before the laboratory results can be applied directly to predict field performance.

10.5 Overall Conclusion

Considering all of the information gathered and the knowledge gained, and using the apparatus and procedure described in the previous chapters, water jetting can be a viable, cheaper alternative to mechanical compaction of clay backfill for utility trenches.
CHAPTER 11

RECOMMENDATIONS

11.1 Recommendations to the University of Windsor

Further work should be carried out in order to develop a laboratory test cell for the prediction of water jetted soil field behaviour. This work can be continued by graduate or undergraduate students, however, whatever the case, close coordination by the supervising professor is required, so that in the end all the individual fragments can be pieced together to reach the original objective. This author is available at any time for consultation and overall supervision of any water jetting experiments.

The following sequence is suggested for further laboratory work:

(i) Increase the size of the test cell to about double the present size. A circular cylinder 30 cm (11.8 inches) in diameter and 35 cm (13.8 inches) high is recommended. The walls should be rough to develop friction, or the surcharge should be reduced to about 45% of the field value.

(ii) Using the same soil, water jetting apparatus and procedure engaged in this study, attempt
to duplicate both the trend and magnitude of this project's field results.

(iii) If (ii) above is successful, investigate other parameters, such as initial backfill density, initial backfill moisture, type of soil, soil lump gradation, soil area per jet, seepage forces, type of drainage conditions, relative importance of the five factors outlined in Chapter 9.

(iv) If (ii) is not successful, and only trends can be obtained in the laboratory, it is recommended that (iii) above be carried out as full scale field tests.

11.2 Recommendations to the City of Windsor

As the City of Windsor would be the main beneficiary (reduced cost and possibly better performance) from a proper application of water jetting, they should participate more actively in the pursuit of answers.

As a result of this field investigation, there is now a suitable water jetting apparatus and method available, as described in Chapters 3 and 5. It is strongly recommended that the City of Windsor tender several sewer contracts in 1980 specifying water jetting as the method of compaction. Mechanical compaction should be called for as an option, so that a comparison of costs can be made and the cheaper method selected. This is the only way to determine the actual cost savings involved when using water jetting in
lieu of mechanical compaction. In order to provide a factor of safety, and until more data is available on field performance, the trenches to be water jetted should be in the boulevard. The perfect testing place would be in new subdivisions. As experience and knowledge is gained from these projects, a decision can be made whether trenches located underneath pavements can be water jetted as well.

Any sewer project selected for water jetting should be treated as an experiment, therefore extensive data must be recorded; this includes apparatus details, method of jetting, initial backfill conditions, soil type, degree of compaction, settlement, moisture content, shear strength, Benkelman Beam tests and any other type which may become necessary.

Ideally, one person should be continuously involved in all aspects of these test cases. This would insure the most experience is gained. This author would be more than happy to provide his services, not only for these field tests on actual projects, but also to provide a liaison with past studies and any current studies underway at the University of Windsor.

Some sample specifications have been prepared and can be found in Appendix V. It is hoped that these will bring proper water jetting on sewer projects one step closer to reality.
11.3 Recommendations to Water Jetting Contractors

If contractors truly wish water jetting to become an accepted method of compaction, and they say they do, then they should make a serious attempt to improve the techniques and methods they use in carrying out their work. Reading, understanding and applying the contents of this thesis is the first step.

The following items may contribute to a contractor's ability to carry out any water jetting satisfactorily:

(i) Use only an apparatus and technique similar to that described in Chapters 3 and 5.

(ii) Use only a porous nozzle.

(iii) Adhere to the intent of the specifications in Appendix V.

(iv) Water jetting should be carried out only by those labourers which have been properly trained to do so.

(v) Use your experience and observations to improve any aspect of water jetting.

(vi) Cooperate with any City of Windsor experimental project.
REFERENCES


NOMENCLATURE

Dimensions are given in terms of mass \((m)\), time \((t)\), and length \((L)\).

- \(A\): Cross sectional area of pipe or hose
- \(d\): Diameter of individual porous nozzle opening
- \(D_e\): Equivalent diameter of porous nozzle
- \(D_c\): Degree of compaction
- \(E\): Applied energy per unit volume of soil \(L^3/T^2\)
- \(f\): Friction loss coefficient
- \(F\): Water jet force
- \(g\): Gravitational constant
- \(H\): Energy losses
- \(H_w\): Water head at tip of the probe

Power

- \(h\): Fitting loss coefficient
- \(L\): Length of conduit
- \(P\): Pressure
- \(p\): Needle pressure
- \(Q\): Flow rate of water \(L^3/T\)
- \(t\): Time of jetting
- \(u\): Average velocity \(L/T\)
- \(V\): Volume of backfill \(L^3\)
- \(Z\): Elevation above datum
### Greek Letters

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<tr>
<th>Symbol</th>
<th>Description</th>
<th>Unit</th>
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<tr>
<td>( \rho )</td>
<td>Density of water</td>
<td>( \text{N/kg} )</td>
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<tr>
<td>( \gamma )</td>
<td>Unit weight of water</td>
<td>( \text{N/m}^2 )</td>
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<tr>
<td>( \gamma_d )</td>
<td>Dry soil unit weight</td>
<td>( \text{N/m}^2 )</td>
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<tr>
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### Subscripts

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<td>1</td>
<td>Point one of control volume</td>
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<td>2</td>
<td>Point two of control volume</td>
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### Laboratory Symbols

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<tr>
<td>( h_0 )</td>
<td>Thickness of gravel bed</td>
<td>( \text{m} )</td>
</tr>
<tr>
<td>( H_f )</td>
<td>Final sample height</td>
<td>( \text{m} )</td>
</tr>
<tr>
<td>( H_m )</td>
<td>Height of the model</td>
<td>( \text{m} )</td>
</tr>
<tr>
<td>( h_i )</td>
<td>Initial sample height</td>
<td>( \text{m} )</td>
</tr>
<tr>
<td>( h_p )</td>
<td>Thickness of plywood plate</td>
<td>( \text{m} )</td>
</tr>
<tr>
<td>( x_f )</td>
<td>Distance from top of model to top of plywood plate, final</td>
<td>( \text{m} )</td>
</tr>
<tr>
<td>( x_i )</td>
<td>Distance from top of model to top of plywood plate, initial</td>
<td>( \text{m} )</td>
</tr>
</tbody>
</table>
Photo 2.1 Settlement of a Mechanically Compacted Trench
(Photograph courtesy of M.M. Dillon Limited)

Photo 4.1 Water Jet from a Pipe with Full Opening
at a Nozzle Pressure of 328 kPa (47.5 psi)
Photo 4.2 Water Jet from a Porous Nozzle at a Pressure of 328 kPa (47.5 psi)

Photo 5.1 Trench Excavation
Photo 5.2 Backfill Lump Size

Photo 5.3 Water Jetting Probes, with Full Opening and Porous Nozzle
Photo 5.4  Probe at the Bottom of the Trench

Photo 5.5  Probe at Mid-depth of the Trench with Settlement Already Initiated
Photo 5.6  Water Bubbles to the Surface Near the End of the Probing

Photo 5.7  Completely Water Jetted Trench
Photo 5.8. Trench Surface One Day After Jetting

Photo 5.9 Test Pits with Nuclear Density Machine in the Background
Photo 7.1 Laboratory Testing Apparatus

Photo 7.2 Laboratory Water Jetting Apparatus
FIGURE 2.1 Seasonal Variation in Strength of Flexible Pavements (7)

FIGURE 2.2 Mechanical Compaction of Clay Soil (7)
FIGURE 2.3 Approximate Distribution of Stress in a Service Trench (7)
FIGURE 2.4 Various Zones of Trench Backfill (7)
FIGURE 3.1 Conceptual Water Jetting Apparatus
FIGURE 3.3 Streamtube (12)

FIGURE 3.5 Pressure Measurement Using a Pitot Gauge
a) Full Opening

b) Fan Shaped

c) Conical
d) Wye

e) Cross

f) Multi-probe

g) Perforated Cone

h) Porous Nozzle

FIGURE 4.1 Various Types of Nozzles
Length of Hose Varies
60 mm Fire Hose
f = 0.020

\[ \frac{P_1}{\gamma} = 276 \text{ kPa} \]

\[ P_1 + \frac{z_1 + \frac{v_1^2}{2g}}{\gamma} = P_2 + \frac{z_2 + \frac{v_2^2}{2g}}{\gamma} + h_L \]

FIGURE 4.2 Hypothetical Water Jetting Apparatus
FIGURE 4.3 Theoretical Jetting Force Versus Area Ratio
FIGURE 4.5 Water Jetting Force Versus Area Ratio for Conical Probe Opening
Figure 4.6 Water Jetting Force Versus Area Ratio for Porous Probe Opening.
Figure 4.7 Comparison of water jetting force for conical and porous nozzles.
FIGURE 4.8 Typical Porous Nozzle
FIGURE 4.9 Jetting Action of a Full Opening and Porous Nozzle

\[ F_1 = 0.001572 \times P \times D^2 = 450 \text{ N} \]

\[ \text{Jetted Area} = \left( \pi \times 0.15^2 \right) / 4 = 0.0177 \text{ m}^2 \]

\[ \text{Applied Load} = \frac{450}{0.0177} = 25.4 \text{ KPa} \]

\[ A_2 = 51 A_1 \]

\[ D_{\text{equivalent}} = 38 \text{ mm} \]

\[ d = 7 \text{ mm} \]

\[ r_2 = 0.001572 \times P \times d^2 = 15.5 \text{ N} \]

\[ F_2 = (29 \text{ openings}) \times 15.5 = 450 \text{ N} \]

\[ \text{Jetted Area} = \left( \pi \times 0.60^2 \right) / 2 + \pi \times 0.60 \times 0.18 = 0.905 \text{ m}^2 \]

\[ \text{Applied Load} = \frac{15.4}{0.000113} = 136.3 \text{ KPa} \]

\[ \text{Load}_2 = 5 \text{ Load}_1 \]
FIGURE 5.1 Field Trenches Layout

<table>
<thead>
<tr>
<th>Trench</th>
<th>Experiment</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Natural Compaction Process (Not Water Jetted)</td>
</tr>
<tr>
<td>2</td>
<td>Water Jetted at 261 000 J/m³ (Porous)</td>
</tr>
<tr>
<td>3</td>
<td>&quot; &quot; &quot; &quot; 190 000 &quot; &quot;</td>
</tr>
<tr>
<td>4</td>
<td>&quot; &quot; &quot; &quot; 72 000 &quot; &quot;</td>
</tr>
<tr>
<td>5</td>
<td>&quot; &quot; &quot; &quot; 11 000 &quot; &quot;</td>
</tr>
<tr>
<td>6</td>
<td>&quot; &quot; &quot; &quot; 261 000 &quot; (Full)</td>
</tr>
<tr>
<td>7</td>
<td>&quot; &quot; &quot; &quot; 11 000 &quot; &quot;</td>
</tr>
</tbody>
</table>

Note: Trenches are 1.5 m (5') wide and 6.0 m (20') long.

H.P. (B.M. #3) F.H. H.P. (B.M. #4) F.H. Burke Road
Twin 64 mm Fire Hoses, Each 30 m Long

Flow Static Pressure Gauge

64 mm Fire Hose 30 m Long

50 mm Copper Pipe, 3 m Long, with Porous Tip or 40 mm Iron Pipe, 3 m Long, Full Opening

FIGURE 5.4 Water Jetting Apparatus for Field Tests
FIGURE 5.5 Nozzle Pressure Comparison for Atmospheric and Submerged Discharge
FIGURE 6.3 Trench Settlement Versus Applied Energy
FIGURE 6.4 Moisture Content Versus Applied Energy
FIGURE 6.5 Vane Shear Strength Versus Applied Energy
FIGURE 6.6 Degree of Compaction Versus Time for Natural Process.
FIGURE 6.7 Moisture Content Versus Time for Natural Process
Figure 6.8
SETTLEMENT VE
TRENCH NOT JETTED.

TRENCH JETTED AT $E = 11 \times 10^3$ J/m$^3$.

TIME, Days

1978-11-19
FIGURE 6.8
SETTLEMENT VERSUS TIME FOR THE NATURAL PROCESS
FIGURE 6.9 Degree of Compaction Versus Time for Nozzle Comparison
FIGURE 6.10  Settlement Versus Time for Nozzle Comparison
FIGURE 7.1 Comparison of Field Trench and Laboratory Sample
FIGURE 7.4  Laboratory Jetting Apparatus Nozzle Pressure as a Function of Flow Static Pressure
FIGURE 7.5  Laboratory Jetting Apparatus Flow Rate as a Function of Nozzle Pressure

EQ. 3-7
\[ q = 24.856 (0.26)^2 \sqrt{P} \]
FIGURE 8.1 Laboratory Degree of Compaction Versus Applied Energy
FIGURE 8.4 Laboratory Vane Shear Strength Versus Applied Energy
FIGURE 8.5 Laboratory Final Degree of Compaction Versus Initial Degree of Compaction

E = 34,500 J/m$^3$
SURCHARGE = 4.5 kPa
FIGURE 9.2 Cohesion Due to Surface Tension Forces
<table>
<thead>
<tr>
<th>Length of Hose, m</th>
<th>(Area of Opening)/(Area of Hose)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>0.09</td>
</tr>
<tr>
<td>15</td>
<td>---</td>
</tr>
<tr>
<td>25</td>
<td>---</td>
</tr>
<tr>
<td>30</td>
<td>---</td>
</tr>
<tr>
<td>60</td>
<td>---</td>
</tr>
<tr>
<td>110</td>
<td>---</td>
</tr>
<tr>
<td>230</td>
<td>53</td>
</tr>
<tr>
<td>305</td>
<td>40</td>
</tr>
</tbody>
</table>

TABLE 4.1 Water Jet Force, newtons, as a Function of the Area Ratio
<table>
<thead>
<tr>
<th>Length of Hose (m)</th>
<th>$P(0.30)$ (N)</th>
<th>$P$(Optimum) (N)</th>
<th>Difference (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>60</td>
<td>110</td>
<td>118</td>
<td>6.8</td>
</tr>
<tr>
<td>110</td>
<td>88</td>
<td>88</td>
<td>0.0</td>
</tr>
<tr>
<td>230</td>
<td>58</td>
<td>59</td>
<td>1.7</td>
</tr>
<tr>
<td>305</td>
<td>47</td>
<td>49</td>
<td>4.1</td>
</tr>
</tbody>
</table>

**TABLE 4.2** Comparison of the Optimum Force to that Corresponding to Area Ratio of 0.30

<table>
<thead>
<tr>
<th>PRESSURE</th>
<th>Atmospheric (KPa)</th>
<th>Submerged (KPa)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>37.3</td>
<td>34.5</td>
</tr>
<tr>
<td></td>
<td>70.4</td>
<td>64.9</td>
</tr>
<tr>
<td></td>
<td>104.9</td>
<td>93.8</td>
</tr>
<tr>
<td></td>
<td>127.0</td>
<td>115.9</td>
</tr>
<tr>
<td></td>
<td>172.5</td>
<td>162.8</td>
</tr>
<tr>
<td></td>
<td>211.1</td>
<td>196.0</td>
</tr>
<tr>
<td></td>
<td>265.0</td>
<td>252.5</td>
</tr>
<tr>
<td></td>
<td>282.8</td>
<td>261.7</td>
</tr>
</tbody>
</table>

**TABLE 5.1** Comparison of Pressure when Discharged into Atmosphere and when Submerged
### TABLE 4.3 Water Jet Force, newtons, as a Function of Area Ratio and Length of Hose

<table>
<thead>
<tr>
<th>Area Ratio</th>
<th>Length of Hose, m</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>8</td>
</tr>
<tr>
<td>1.00</td>
<td>240</td>
</tr>
<tr>
<td>0.83</td>
<td>554</td>
</tr>
<tr>
<td>0.56</td>
<td>655</td>
</tr>
<tr>
<td>0.26</td>
<td>447</td>
</tr>
<tr>
<td>0.16</td>
<td>278</td>
</tr>
</tbody>
</table>

a) Conical Opening

<table>
<thead>
<tr>
<th>Area Ratio</th>
<th>Length of Hose, m</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>8</td>
</tr>
<tr>
<td>0.53</td>
<td>633</td>
</tr>
<tr>
<td>0.42</td>
<td>592</td>
</tr>
<tr>
<td>0.31</td>
<td>517</td>
</tr>
<tr>
<td>0.26</td>
<td>433</td>
</tr>
<tr>
<td>0.15</td>
<td>298</td>
</tr>
</tbody>
</table>

b) Porous Nozzle
<table>
<thead>
<tr>
<th>Trench</th>
<th>Nozzle Pressure KPa</th>
<th>Jetting Time s</th>
<th>Applied Energy J/m³</th>
</tr>
</thead>
<tbody>
<tr>
<td>2</td>
<td>304</td>
<td>406</td>
<td>261,300</td>
</tr>
<tr>
<td>3</td>
<td>328</td>
<td>563</td>
<td>190,100</td>
</tr>
<tr>
<td>4</td>
<td>138</td>
<td>776</td>
<td>71,600</td>
</tr>
<tr>
<td>5</td>
<td>35</td>
<td>990</td>
<td>11,400</td>
</tr>
<tr>
<td>6</td>
<td>449</td>
<td>494</td>
<td>267,000</td>
</tr>
</tbody>
</table>

**TABLE 6.1** Applied Energy for the Various Trenches

<table>
<thead>
<tr>
<th>Applied Energy J/m³</th>
<th>10 days</th>
<th>24 days</th>
<th>45 days</th>
<th>10 months</th>
</tr>
</thead>
<tbody>
<tr>
<td>11,400</td>
<td>80.4</td>
<td>80.5</td>
<td>81.2</td>
<td>82.1</td>
</tr>
<tr>
<td>71,600</td>
<td>80.6</td>
<td>82.5</td>
<td>82.7</td>
<td>83.7</td>
</tr>
<tr>
<td>190,100</td>
<td>80.9</td>
<td>83.1</td>
<td>---</td>
<td>85.3</td>
</tr>
<tr>
<td>261,300</td>
<td>81.2</td>
<td>83.0</td>
<td>84.4</td>
<td>85.8</td>
</tr>
</tbody>
</table>

**TABLE 6.2** Applied Energy Versus Degree of Compaction,

<table>
<thead>
<tr>
<th>Applied Energy J/m³</th>
<th>10 days</th>
<th>24 days</th>
<th>45 days</th>
<th>10 months</th>
</tr>
</thead>
<tbody>
<tr>
<td>11,400</td>
<td>7.88</td>
<td>5.49</td>
<td>5.32</td>
<td>0.40</td>
</tr>
<tr>
<td>71,600</td>
<td>4.87</td>
<td>3.26</td>
<td>2.54</td>
<td>1.00</td>
</tr>
<tr>
<td>190,100</td>
<td>2.59</td>
<td>2.32</td>
<td>1.20</td>
<td>0.94</td>
</tr>
<tr>
<td>261,300</td>
<td>2.03</td>
<td>2.63</td>
<td>1.10</td>
<td>0.20</td>
</tr>
</tbody>
</table>

**TABLE 6.2A** Standard Deviation, %, for the Degree of Compaction Readings.
<table>
<thead>
<tr>
<th>TIME, Days</th>
<th>SETTLEMENT, cm</th>
<th>Applied Energy, J/m$^3 \times 10^3$</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>11</td>
<td>72</td>
</tr>
<tr>
<td>1</td>
<td>49.1</td>
<td>51.3</td>
</tr>
<tr>
<td>2</td>
<td>49.4</td>
<td>51.9</td>
</tr>
<tr>
<td>3</td>
<td>51.6</td>
<td>55.3</td>
</tr>
<tr>
<td>5</td>
<td>51.9</td>
<td>---</td>
</tr>
<tr>
<td>7</td>
<td>52.2</td>
<td>55.7</td>
</tr>
<tr>
<td>14</td>
<td>52.5</td>
<td>56.4</td>
</tr>
<tr>
<td>30</td>
<td>53.0</td>
<td>56.6</td>
</tr>
</tbody>
</table>

**TABLE 6.3 Trench Settlement Versus Time**

<table>
<thead>
<tr>
<th>Applied Energy J/m$^3$</th>
<th>Initial Settlement cm</th>
<th>Total Settlement cm</th>
</tr>
</thead>
<tbody>
<tr>
<td>11,400</td>
<td>49.1</td>
<td>53.9</td>
</tr>
<tr>
<td>71,600</td>
<td>51.3</td>
<td>57.1</td>
</tr>
<tr>
<td>190,100</td>
<td>54.3</td>
<td>59.9</td>
</tr>
<tr>
<td>261,300</td>
<td>61.4</td>
<td>66.1</td>
</tr>
</tbody>
</table>

**TABLE 6.4 Trench Settlement Versus Applied Energy**
<table>
<thead>
<tr>
<th>Applied Energy J/m³</th>
<th>10 days</th>
<th>24 days</th>
<th>45 days</th>
<th>10 months</th>
</tr>
</thead>
<tbody>
<tr>
<td>11,400</td>
<td>27.1%</td>
<td>27.2%</td>
<td>23.7%</td>
<td>21.2%</td>
</tr>
<tr>
<td>71,600</td>
<td>26.6</td>
<td>24.2</td>
<td>20.8</td>
<td>19.7</td>
</tr>
<tr>
<td>190,100</td>
<td>25.5</td>
<td>27.0</td>
<td>23.9</td>
<td>20.7</td>
</tr>
<tr>
<td>261,300</td>
<td>24.0</td>
<td>25.4</td>
<td>22.4</td>
<td>19.6</td>
</tr>
</tbody>
</table>

**TABLE 6.5 Moisture Content Versus Applied Energy**

<table>
<thead>
<tr>
<th>Applied Energy J/m³</th>
<th>10 days</th>
<th>24 days</th>
<th>45 days</th>
<th>10 months</th>
</tr>
</thead>
<tbody>
<tr>
<td>11,400</td>
<td>21.1 KPa</td>
<td>25.7 KPa</td>
<td>33.3 KPa</td>
<td>72.4 KPa</td>
</tr>
<tr>
<td>71,600</td>
<td>21.4</td>
<td>24.3</td>
<td>35.4</td>
<td>81.4</td>
</tr>
<tr>
<td>190,100</td>
<td>23.7</td>
<td>25.3</td>
<td>34.1</td>
<td>83.5</td>
</tr>
<tr>
<td>261,300</td>
<td>22.3</td>
<td>24.9</td>
<td>37.1</td>
<td>91.5</td>
</tr>
</tbody>
</table>

**TABLE 6.6 Vane Shear, KPa, Versus Applied Energy**

<table>
<thead>
<tr>
<th>Time, days</th>
<th>10</th>
<th>24</th>
<th>45</th>
<th>300</th>
</tr>
</thead>
<tbody>
<tr>
<td>Trench not Jetted</td>
<td>15.3%</td>
<td>16.6</td>
<td>13.9</td>
<td>22.2</td>
</tr>
<tr>
<td>Trench Jetted</td>
<td>22.1%</td>
<td>27.2</td>
<td>23.7</td>
<td>21.2</td>
</tr>
</tbody>
</table>

**TABLE 6.8 Moisture Content Versus Time for Natural Process**

<table>
<thead>
<tr>
<th>Time, days</th>
<th>10</th>
<th>24</th>
<th>45</th>
<th>300</th>
</tr>
</thead>
<tbody>
<tr>
<td>Trench not Jetted</td>
<td>65.6%</td>
<td>66.8</td>
<td>71.0</td>
<td>83.7</td>
</tr>
<tr>
<td>Trench Jetted</td>
<td>80.4%</td>
<td>80.5</td>
<td>81.2</td>
<td>82.1</td>
</tr>
</tbody>
</table>

**TABLE 6.7 Degree of Compaction Versus Time for Natural Process**
<table>
<thead>
<tr>
<th>TIME days</th>
<th>SETTLEMENT, cm</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Not Jetted</td>
</tr>
<tr>
<td>1</td>
<td>2.1</td>
</tr>
<tr>
<td>2</td>
<td>---</td>
</tr>
<tr>
<td>3</td>
<td>2.3</td>
</tr>
<tr>
<td>5</td>
<td>5.7</td>
</tr>
<tr>
<td>7</td>
<td>6.3</td>
</tr>
<tr>
<td>14</td>
<td>7.4</td>
</tr>
<tr>
<td>30</td>
<td>18.0</td>
</tr>
<tr>
<td>37.4</td>
<td>---</td>
</tr>
<tr>
<td>44</td>
<td>19.0</td>
</tr>
<tr>
<td>59</td>
<td>20.0</td>
</tr>
<tr>
<td>92</td>
<td>50.0</td>
</tr>
<tr>
<td>210</td>
<td>52.9</td>
</tr>
</tbody>
</table>

**TABLE 6.9** Trench Settlement Versus Time for Natural Process
<table>
<thead>
<tr>
<th>Day</th>
<th>Precipitation, mm</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>4.6</td>
</tr>
<tr>
<td>3</td>
<td>3.4</td>
</tr>
<tr>
<td>6</td>
<td>10.2</td>
</tr>
<tr>
<td>8</td>
<td>5.8</td>
</tr>
<tr>
<td>15</td>
<td>9.0</td>
</tr>
<tr>
<td>18</td>
<td>5.2</td>
</tr>
<tr>
<td>19</td>
<td>19.4</td>
</tr>
<tr>
<td>27</td>
<td>5.6</td>
</tr>
<tr>
<td>29</td>
<td>6.0</td>
</tr>
<tr>
<td>30</td>
<td>6.0</td>
</tr>
<tr>
<td>41</td>
<td>2.6</td>
</tr>
<tr>
<td>42</td>
<td>2.2</td>
</tr>
<tr>
<td>48</td>
<td>6.0</td>
</tr>
<tr>
<td>49</td>
<td>14.4</td>
</tr>
<tr>
<td>52</td>
<td>20.0</td>
</tr>
<tr>
<td>58</td>
<td>14.5</td>
</tr>
<tr>
<td>62</td>
<td>9.2</td>
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<tr>
<td>68</td>
<td>11.8</td>
</tr>
<tr>
<td>72</td>
<td>7.5</td>
</tr>
<tr>
<td>85</td>
<td>10.2</td>
</tr>
<tr>
<td>96</td>
<td>12.2</td>
</tr>
</tbody>
</table>

TABLE 6.10 Rainfall Data for the Study Period
### TABLE 5.11 Degree of Compaction, %, for Nozzle Comparison

<table>
<thead>
<tr>
<th>Nozzle</th>
<th>10 days</th>
<th>24 days</th>
<th>45 days</th>
<th>300 days</th>
</tr>
</thead>
<tbody>
<tr>
<td>Porous</td>
<td>81.2</td>
<td>83.0</td>
<td>84.4</td>
<td>85.8</td>
</tr>
<tr>
<td>Full Opening</td>
<td>---</td>
<td>81.2</td>
<td>82.1</td>
<td>83.3</td>
</tr>
</tbody>
</table>

### TABLE 5.12 Settlement for Nozzle Comparison

<table>
<thead>
<tr>
<th>Time days</th>
<th>Settlement, cm</th>
<th>Porous</th>
<th>Full Opening</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>53.9</td>
<td>53.1</td>
<td></td>
</tr>
<tr>
<td>2</td>
<td>51.4</td>
<td>53.6</td>
<td></td>
</tr>
<tr>
<td>3</td>
<td>52.4</td>
<td>56.5</td>
<td></td>
</tr>
<tr>
<td>5</td>
<td>53.2</td>
<td>56.8</td>
<td></td>
</tr>
<tr>
<td>7</td>
<td>53.5</td>
<td>57.1</td>
<td></td>
</tr>
<tr>
<td>14</td>
<td>54.0</td>
<td>57.6</td>
<td></td>
</tr>
<tr>
<td>30</td>
<td>55.2</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

### TABLE 6.13 Moisture Content, %, for Nozzle Comparison

<table>
<thead>
<tr>
<th>Nozzle</th>
<th>Time</th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>10 days</td>
<td>24 days</td>
<td>45 days</td>
<td>300 days</td>
</tr>
<tr>
<td>Porous</td>
<td>24.0</td>
<td>25.4</td>
<td>22.4</td>
<td>19.6</td>
</tr>
<tr>
<td>Full Opening</td>
<td>24.0</td>
<td>24.4</td>
<td>23.3</td>
<td>23.2</td>
</tr>
<tr>
<td>Nozzle</td>
<td>Time</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>-------------</td>
<td>--------</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>10 days</td>
<td>24 days</td>
<td>45 days</td>
<td>300 days</td>
</tr>
<tr>
<td>Porous</td>
<td>22.3</td>
<td>24.9</td>
<td>37.1</td>
<td>91.5</td>
</tr>
<tr>
<td>Full Opening</td>
<td>22.9</td>
<td>26.4</td>
<td>34.6</td>
<td>71.2</td>
</tr>
</tbody>
</table>

**TABLE 5.14** Vane Shear, kPa, for Nozzle Comparison

<table>
<thead>
<tr>
<th>Flow Static Pressure, psi</th>
<th>3.2</th>
<th>10.4</th>
<th>19.8</th>
<th>30.0</th>
<th>39.0</th>
</tr>
</thead>
<tbody>
<tr>
<td>Nozzle Pressure, psi</td>
<td>2.4</td>
<td>8.9</td>
<td>17.5</td>
<td>26.5</td>
<td>36.0</td>
</tr>
</tbody>
</table>

**TABLE 7.1** Nozzle Pressure Versus Flow Static Pressure

<table>
<thead>
<tr>
<th>Nozzle Pressure, psi</th>
<th>4.0</th>
<th>9.1</th>
<th>20.3</th>
<th>26.0</th>
<th>34.5</th>
</tr>
</thead>
<tbody>
<tr>
<td>Flow Rate GPM</td>
<td>2.48</td>
<td>3.57</td>
<td>5.14</td>
<td>5.90</td>
<td>6.63</td>
</tr>
</tbody>
</table>

**TABLE 7.2** Experimental Flow Rate as a Function of Nozzle Pressure
### Table 8.1 Laboratory Degree of Compaction Versus Applied Energy

<table>
<thead>
<tr>
<th>4.5 KPa Surcharge</th>
<th>9.0 KPa Surcharge</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Applied Energy, J/m³</strong></td>
<td><strong>Degree of Compaction, %</strong></td>
</tr>
<tr>
<td>30,100</td>
<td>79.6</td>
</tr>
<tr>
<td>32,100</td>
<td>83.3</td>
</tr>
<tr>
<td>36,500</td>
<td>81.2</td>
</tr>
<tr>
<td>36,800</td>
<td>81.9</td>
</tr>
<tr>
<td>37,200</td>
<td>80.3</td>
</tr>
<tr>
<td>71,200</td>
<td>81.1</td>
</tr>
<tr>
<td>101,900</td>
<td>84.0</td>
</tr>
<tr>
<td>118,200</td>
<td>83.6</td>
</tr>
<tr>
<td>130,700</td>
<td>86.9</td>
</tr>
<tr>
<td>40,800</td>
<td>82.6</td>
</tr>
</tbody>
</table>

### Table 8.2 Laboratory Settlement Ratio Versus Applied Energy

<table>
<thead>
<tr>
<th>4.5 KPa Surcharge</th>
<th>9.0 KPa Surcharge</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Applied Energy, J/m³</strong></td>
<td><strong>Settlement Ratio</strong></td>
</tr>
<tr>
<td>32,100</td>
<td>0.201</td>
</tr>
<tr>
<td>32,600</td>
<td>0.233</td>
</tr>
<tr>
<td>34,500</td>
<td>0.251</td>
</tr>
<tr>
<td>36,500</td>
<td>0.203</td>
</tr>
<tr>
<td>36,800</td>
<td>0.278</td>
</tr>
<tr>
<td>71,200</td>
<td>0.258</td>
</tr>
<tr>
<td>101,900</td>
<td>0.247</td>
</tr>
<tr>
<td>118,200</td>
<td>0.265</td>
</tr>
<tr>
<td>130,700</td>
<td>0.263</td>
</tr>
</tbody>
</table>

TABLE 8.1 Laboratory Degree of Compaction Versus Applied Energy

TABLE 8.2 Laboratory Settlement Ratio Versus Applied Energy
| Applied Energy, J/m³ | Moisture Content, % | 4.5 KPa Surcharge | | 9.0 KPa Surcharge |
|---------------------|---------------------|------------------|------------------|
| 30,100              | 23.9                | 12,600           | 23.2             |
| 32,100              | 23.8                | 70,000           | 23.0             |
| 32,600              | 25.0                | 83,900           | 22.8             |
| 34,500              | 25.8                | 102,400          | 22.3             |
| 40,800              | 24.2                | 144,000          | 21.8             |
| 71,200              | 24.1                | 215,500          | 22.2             |
| 118,200             | 23.8                | ---              | ---              |

**TABLE 8.3** Laboratory Moisture Content Versus Applied Energy

<table>
<thead>
<tr>
<th>Applied Energy J/m³</th>
<th>Vane Shear KPa</th>
</tr>
</thead>
<tbody>
<tr>
<td>15,300</td>
<td>21.7</td>
</tr>
<tr>
<td>28,200</td>
<td>21.6</td>
</tr>
<tr>
<td>52,000</td>
<td>22.6</td>
</tr>
<tr>
<td>60,000</td>
<td>25.0</td>
</tr>
<tr>
<td>70,400</td>
<td>22.6</td>
</tr>
<tr>
<td>121,900</td>
<td>23.8</td>
</tr>
<tr>
<td>144,000</td>
<td>25.1</td>
</tr>
<tr>
<td>215,500</td>
<td>24.7</td>
</tr>
</tbody>
</table>

**TABLE 8.4** Laboratory Vane Shear Versus Applied Energy
### TABLE 8.5
Laboratory Final Degree of Compaction Versus Initial Degree of Compaction

<table>
<thead>
<tr>
<th>Initial Degree of Compaction, %</th>
<th>Final Degree of Compaction, %</th>
</tr>
</thead>
<tbody>
<tr>
<td>57.3</td>
<td>82.6</td>
</tr>
<tr>
<td>58.9</td>
<td>79.6</td>
</tr>
<tr>
<td>61.0</td>
<td>81.9</td>
</tr>
<tr>
<td>64.6</td>
<td>82.9</td>
</tr>
<tr>
<td>64.8</td>
<td>81.4</td>
</tr>
<tr>
<td>66.8</td>
<td>81.2</td>
</tr>
<tr>
<td>68.5</td>
<td>83.3</td>
</tr>
<tr>
<td>70.3</td>
<td>80.3</td>
</tr>
</tbody>
</table>

### TABLE 8.6
Laboratory Settlement Ratio Versus Initial Degree of Compaction

<table>
<thead>
<tr>
<th>Initial Degree of Compaction, %</th>
<th>Settlement Ratio</th>
</tr>
</thead>
<tbody>
<tr>
<td>57.3</td>
<td>0.335</td>
</tr>
<tr>
<td>58.9</td>
<td>0.287</td>
</tr>
<tr>
<td>61.0</td>
<td>0.278</td>
</tr>
<tr>
<td>61.9</td>
<td>0.258</td>
</tr>
<tr>
<td>63.4</td>
<td>0.265</td>
</tr>
<tr>
<td>64.5</td>
<td>0.263</td>
</tr>
<tr>
<td>64.6</td>
<td>0.251</td>
</tr>
<tr>
<td>64.8</td>
<td>0.233</td>
</tr>
<tr>
<td>65.5</td>
<td>0.247</td>
</tr>
<tr>
<td>66.8</td>
<td>0.203</td>
</tr>
<tr>
<td>68.5</td>
<td>0.201</td>
</tr>
<tr>
<td>70.3</td>
<td>0.143</td>
</tr>
</tbody>
</table>
APPENDIX IV

SOIL ANALYSIS AND CLASSIFICATION
APPENDIX IV

SOIL ANALYSIS AND CLASSIFICATION

The natural moisture content of the soil before jetting was found to be an average 14.3%, with a corresponding degree of compaction of 83.5% of the Standard Proctor maximum dry unit weight. The average undisturbed in situ Vane shear strength, as determined throughout the entire trench depth, was found to be 174 KPa (1.8 tons per square foot); the corresponding unconfined compression test resulted in an average shear of 195 KPa, or 2.0 tons per square foot. All the test procedures used in this section were obtained from Reference 17, and they all conform to the appropriate ASTM specifications.

The grain size distribution for the soil is shown in Figure IV.1. The composition of the material, along with other properties, are listed in Table IV.1. The soil is classified as a silty clay according to Peret's Triangle, however, due to the nature of the soil, a better description would be till-like silty clay.

The Standard Proctor test results are plotted in Figure IV.2. As can be seen, the maximum dry density is 116.1 lb/ft$^3$ (1.856 g/cm$^3$) at an optimum moisture content of 14.8%.
<table>
<thead>
<tr>
<th>Soil Composition</th>
<th>Clay</th>
<th>40%</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Silt</td>
<td>39%</td>
</tr>
<tr>
<td></td>
<td>Sand</td>
<td>21%</td>
</tr>
<tr>
<td>Atterberg Limits</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Liquid Limit</td>
<td>28%</td>
</tr>
<tr>
<td></td>
<td>Plastic Limit</td>
<td>19%</td>
</tr>
<tr>
<td></td>
<td>Plasticity Index</td>
<td>9%</td>
</tr>
<tr>
<td>Specific Gravity</td>
<td></td>
<td>2.7</td>
</tr>
</tbody>
</table>

*Inorganic Clay of Medium Plasticity

**TABLE IV.1. Soil Properties and Classification**
FIGURE IV.1 Grain Size Distribution Diagram
COMPACION CONTROL REPORT

1. Laboratory Compaction Test Data
   A. Description of Soil: **TILL-LIKE SILTY CLAY**
   
   Material Mark __________________________ Classification __________________________
   Source of Material __________________________
   Natural Water Content ________ % Natural Dry Density ________ PCF
   Liquid Limit __________________________ % Plastic Limit __________________________ % Plasticity Index ________
   
   B. Test Procedure Used: **STANDARD PROCTOR**
   
   C. Test Results:
   - Optimum Water Content ________ %
   - Maximum Dry Density ________ PCF (at a Wet Density of ________ PCF)

**Figure IV.2 Standard Proctor Test**
APPENDIX V

SUGGESTED WATER JETTING SPECIFICATIONS
APPENDIX V

SUGGESTED WATER JETTING SPECIFICATIONS

1. The backfill shall consist of native material, with the exception of all topsoil and sod, which shall be removed and disposed of by the contractor. In addition, any other material deemed unsuitable by the Engineer shall also be removed and disposed of by the contractor.

2. Whenever excess excavated material suitable for trench backfill is encountered, the contractor shall stockpile and transport this excess backfill at his expense to any area of the work where insufficient native backfill exists. The contractor shall exercise particular care to minimize wasting suitable native backfill (23). The contractor is responsible for the disposal of any excess material at his expense.

3. Only free draining granular material shall be used for all pipe bedding and cover. This applies to the main sewer as well to any connections. The granular material shall consist of 7/8" to 1" clear stone, unless permission in writing to use another material is first obtained from the Engineer. Materials which may be washed away, such as sand, shall not be used.

4. Two four inch diameter galvanized pipes with a screen on the outside and a removable plug on the inside shall be installed, one on each side of the sewer pipe.
on the upstream end of each manhole. The invert of these drains shall be the same as that of the upstream pipe. If necessary for the purpose of complete saturation of the backfill, the contractor shall keep these drains closed during water jetting operations. The cost of the complete drains shall be part of the price paid for the manhole.

5. The apparatus used for water jetting shall be such that the nozzle pressure is as large as possible. The Engineer reserves the right to stop jetting operations when he feels the pressure is insufficient, and these shall not be resumed until the Engineer has approved the changes made to increase the nozzle pressure.

6. Only a porous type nozzle shall be used for water jetting. A full pipe opening or a flattened pipe end shall not be used.

7. The contractor shall make all necessary arrangements for the supply and application of water for use in the water jetting operations (23).

8. Water jetting operations shall be carried out as soon as the trench has been backfilled between two adjacent manholes and a sufficient buffer zone has been backfilled past the manhole nearest to the open trench where pipe is being installed.

9. Water jetting shall be carried out in such a way as to completely saturate the backfill. The contractor shall undertake additional probings whenever directed by the Engineer to do so. The contractor will be responsible for any damage or cleanup due to water overflowing the trench.
10. The trench shall be brought to proper grade with mechanically compacted Granular 'B' backfill. This work shall be carried out as soon as possible after the clay backfill has been water jetted.

11. All of the above work shall be considered incidental to the unit price paid for the "Supply and Placement of Sewer Pipe" in the Form of Tender and no separate payment will be made for any such work.
VITA AUCTORIS

1955 Born, October 31 in Volutrara Irpina, Italy.

1968 Emigrated to Canada arriving in Windsor, Ontario November 11.

1974 Graduated as an Ontario Scholar from F.J. Brennan H.S.

1978 Graduated with B.Sc. in Mathematics at the University of Windsor, Windsor, Ontario.

1978 Graduated with B.A.Sc. in Civil Engineering at the University of Windsor, Windsor, Ontario.

1978 Enrolled in the Faculty of Graduate Studies, University of Windsor, in a programme leading to the degree of Master of Applied Science in Civil Engineering.

1979 Accepted a position with The Corporation of the City of Windsor, Department of Public Works, as an engineer in the Roads Division.