ANALYSES OF STRESSES DEVELOPED IN PIPELINES BURIED IN FREEZING GROUND

FINAL REPORT

MAY, 1985

ANALYSES OF STRESSES DEVELOPED IN PIPELINES BURIED IN FREEZING GROUND

FINAL REPORT

for

EARTH PHYSICS BRANCH
ENERGY, MINES AND RESOURCES CANADA

GEOTECHNICAL SCIENCE LABORATORIES
CARLETON UNIVERSITY
OTTAWA, CANADA
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The deformed pipeline lies below the frost-covered surface along the line of measuring devices.

TABLE OF CONTENTS

PAGE

FOREWORD 1

LIST OF FIGURES . . . . . .(iii)

I EXPERIMENTAL DESIGN 3
1.1 General 3

II EXPERIMENTAL CONDITIONS 5
2.1 Test Facility 5
2.2 Instrumentation 5
2.3 Operating Conditions 8

III EXPERIMENTAL OBSERVATIONS, SECOND FREEZE PERIOD, AND ANCILLARY STUDIES 8
3.1 General 8
3.2 Thermal Regime 8
3.3 Pipe Deformation 11
3.4 Surface Expression of Frost Heave 14
3.5 Stresses Developed Within Frozen Ground 14
3.6 Stress Within Annulus of Frozen Soil 22
3.7 Strain of Frozen Ground by Secondary Frost Heave . 24
3.8 Cracking of Ground, Lateral to Pipe 24
3.9 Numerical Modelling 28

IV DISCUSSION OF FINDINGS 29
4.1 Significance of Ground Conditions 29
4.2 Pipe Stresses 30

V STATUS OF CANADA-FRANCE PROJECT 32

VI GENERAL CONCLUSIONS 34

REFERENCES 38

LIST OF FIGURES

Figure 2.1 Longitudinal section of trough.

Figure 2.2 Cross-section of trough.

Figure 3.1 Temperatures below pipeline on various dates, silt section.

Figure 3.2 Temperatures below pipeline on various dates, sand section.

Figure 3.3 Deformation of pipeline.

Figure 3.4 Stress and strain along pipe during second freeze.

Figure 3.5a Ground surface elevations, day 107.

Figure 3.5b Ground surface elevations, day 200.

Figure 3.5c Ground surface elevations, day 300.

Figure 3.5d Ground surface elevations, day 423.

Figure 3.6 Surface relief along section B-B, silt, transverse to pipe.

Figure 3.7 Surface relief for various days along section A-A, sand, transverse to pipe.

Figure 3.8 Total stress at three depths below pipe, in silt (at section B-B).

Figure 3.9 Frost heave by layer and time for vertical profile.

Figure 3.10 Total heave from observations with telescopic rods.

Figure 3.11 Plan of cracks at soil surface. D = depth, W = width (see text).

FOREWORD

The present document constitutes the final report under Contract No. OST83-00364 (effective January 1, 1984 to December 31, 1984) Department of Supply and Services Canada: "Analyses of stresses developed in pipelines buried in freezing ground", Principal Investigator P.J. Williams. This contract was carried out using facilities provided at the Centre de Geomorphologie, Caen, Normandy, through the joint Canada/France research project: "The behaviour of buried pipelines under negative temperatures". The continuing Canadian involvement in this joint project is based on contracts between the Geotechnical Science Laboratories, Carleton University and the Department of Supply and Services, serial number of the latest contract being OSU83-00157: "Investigation of soil freezing in association with a buried chilled pipeline in a large scale test facility, phase 4", Principal Investigator P.J. Williams, Co-Principal Investigator M.W. Smith.

The present report concerns the third and final year of studies covered by contracts specifically related to pipe stress. As a result of modifications in allocation of Federal Government research funds, the studies will be discontinued for 1985, although some continuing observations will be subsumed under contract OSU83-00157 (cited above).

An interim report on the present study was included with the report "Investigation of soil freezing in association with a buried chilled pipeline in a large scale test facility, phase 3", dated August 1984. The reader is referred to this and earlier reports (see references) on the project for a fuller description of the experimental facility.

A substantial amount of information on the Canada-France pipeline project more generally has now been published and is listed at the end of this report.

This report was prepared by the Principal Investigator with contributions from Professor W.H. Bowes, Department of Civil Engineering, Carleton University; Professor B. Ladanyi and Mr. M. Lauzon of Centre d'Ingénierie Nordique, Ecole Polytechnique; Mr. Scott Dallimore, formerly Ottawa manager of the project and now with Energy, Mines and Resources Canada; and Mr. D. Patterson, currently Ottawa manager.

The joint Canada/France research project involves a combined Canadian and French team of scientists, students and technicians. The project as a whole is supervised by a scientific committee and members affiliations indicate the institutions which are involved in the Memorandum of Agreement:

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I. EXPERIMENTAL DESIGN

1.1 General

This report presents a summary of the results of the third year (1 January 1984, 31 December 1984) of an experiment monitoring deformation and stresses in a chilled pipeline buried in soils undergoing periods of freezing and thawing conditions. The study is part of a joint Canada-France pipeline-ground freezing research project located in a large temperature controlled facility in Caen, France.

The progression of a freezing front due to a buried chilled pipeline leads to heaving of the surrounding soil depending on its frost susceptibility. When a chilled pipeline crosses a transition zone between two initially unfrozen soils of contrasting frost susceptibilities differential heaving of the soils occurs. This leads to deformation of the buried pipeline and to related stresses and strains. In practise the complex interaction between the heaving soil and a buried pipeline present unique design problems.

A complex system of instrumentation monitoring the soil and pipeline at the test facility in Caen provides the data required for a comprehensive analysis. To some degree, the behaviour of freezing soil and the resulting displacements of the pipeline must be studied separately. An understanding of heaving characteristics is required to predict the behaviour of freezing soils beneath the chilled pipeline. A knowledge of the pipeline displacements and related strains can be used to determine the state of stress in the pipeline as the

freezing of the ground progresses. In a fuller consideration, the behaviour of the pipe as frost heave occurs is seen to be modified by the already-frozen material around the pipe. In turn the pipe and annulus of frozen soil modify the frost-heave behaviour.

The project in Caen is a multi-disciplinary study involving many aspects of soil freezing/thawing and of the effects associated with a chilled buried pipeline. The main feature of the project is the undertaking of a large-scale experiment with precise control of the physical, thermal and hydrologic variables. The experiment attempts to produce the type of conditions necessary for a fundamental study of each of a number of factors relating to frost heave and chilled buried pipelines. The contract being reported on concerns the reaction of the pipeline to frost heave phenomena.

Table 1 shows the timetable of events since the start of the project.

TIMETABLE OF EVENTS

Date	Event
31 Dec. 1981	Memorandum of agreement signed
21 Sept. 1982	completion of construction

	Date		Operating Conditions	
	From	To	Air/ground surface temp., °C	Pipe temp. °C
First Freeze Period	21 Sept/82	8 June/83	-0.75	-2
Surface Thaw Period	8 June/83	17 Oct./83	+4	-2
Second Freeze Period	17 Oct/83	Summer/85?	-0.75	-5

II EXPERIMENTAL CONDITIONS

2.1 Test Facility

The experiment is located at the "Station de Gel" at the Centre de Geomorphologie du CNRS, Caen, France. The reader is referred to an earlier report by Burgess et al. (1982) for a detailed description of the test facility and initial set-up of the experiment.

The facility consists of a refrigerated hall 18m long by 8m wide with adjacent rooms to accommodate instrumentation and mechanical equipment. The base or trough of the hall has been specially prepared for the experiment in order to isolate the thermal and hydraulic regime and to carefully control experimental conditions. As shown on Figures 2.1 and 2.2 two different soil types, a non-frost susceptible sand and a frost susceptible silt, have been placed on each half of the trough. A 18m long, 273mm diameter steel pipeline with an independent refrigeration system was buried in the soils with 30 cm of cover.

2.2 Instrumentation

The experiment is heavily instrumented and a large number of readings are taken on a regular schedule (see Geotechnical Science Laboratories, 1982, 1983, 1984a,b). Table 2 presents an outline of the main types of instruments and a summary of the frequency of readings. Included are thermocouples and heat flux meters monitored automatically with a data acquisition unit. Also, regular measurements are taken manually of thermistors, water levels, surface levelling, tensiometers, pressure cells, telescopic heave tubes, frost depth tubes, TDR moisture

Table 2 Instrumentation Scheme

Regime	Type of Sensor or Measurement	Number	Frequency of Readings	Comments
Thermal	Thermocouples (Iron/ Constantan)	Approx. 160	every 4 hours	Read automatically by Solartron Orion data-logging system.
	Heat Flux Plates	5	every 4 hours	Read by same system as thermocouples.
	Thermistors	25	3 times/week	
	Frost Tubes	5	3 times/week	Indicate frost depth by colour change of organic dye.
Hydrologic	Piezometers	12	every day	Periodically supplemented by readings in 6 control wells.
	Tensiometers	20	3 times/week	
	Addition/removal of water		every day	Collected and measured defrost water from each of the three room ventilators and the pipe. Also recorded volume of water added at or pumped from base of pit.
	Time Domain Reflectometry (TDR)	28 horizontal 6 vertical	once/week	Electromagnetic measurement of volumetric unfrozen water content.
Pipe Deformation	Levelling (rods on pipe)	29 rods	once/week	Optical surveying
	Rotation (rods on pipe)	29 rods	once/week	Angle measurement

.../2

Table 2 continued

	Curvature (rods on pipe)	24 points (3 rods each)	once/week	"curvature gauge" using finite difference approximation
	Strain gauges	22 pairs (half-bridge) 2 rosettes (3 gauges each)	2 times/week	Half bridge measures flexural strain only. Rosettes measure all strain components.
Physical Soil Parameters	Levelling (points on surface)	226 points	Axis and 2 cross-sections once per week. All points once per month.	All points referenced to fixed outside datum.
	Telescoping Tubes (Soil Heave)	38 in 4 sets	Once/week	Nested tubes of various length, indicate relative movement of soil layers.
	Magnetic Heave Device	2 access tubes 14 magnets	Once/week	Movement of magnets buried in soil indicates relative movement of soil.
	Glotzl Earth Pressure Cells	15	3 times/week	
	Gamma Ray Probes	8 profiles in 2 cross-sections	Approx. every 4 months	Gives profiles of total soil density. Buried PVC discs provide markers for soil heave estimation.

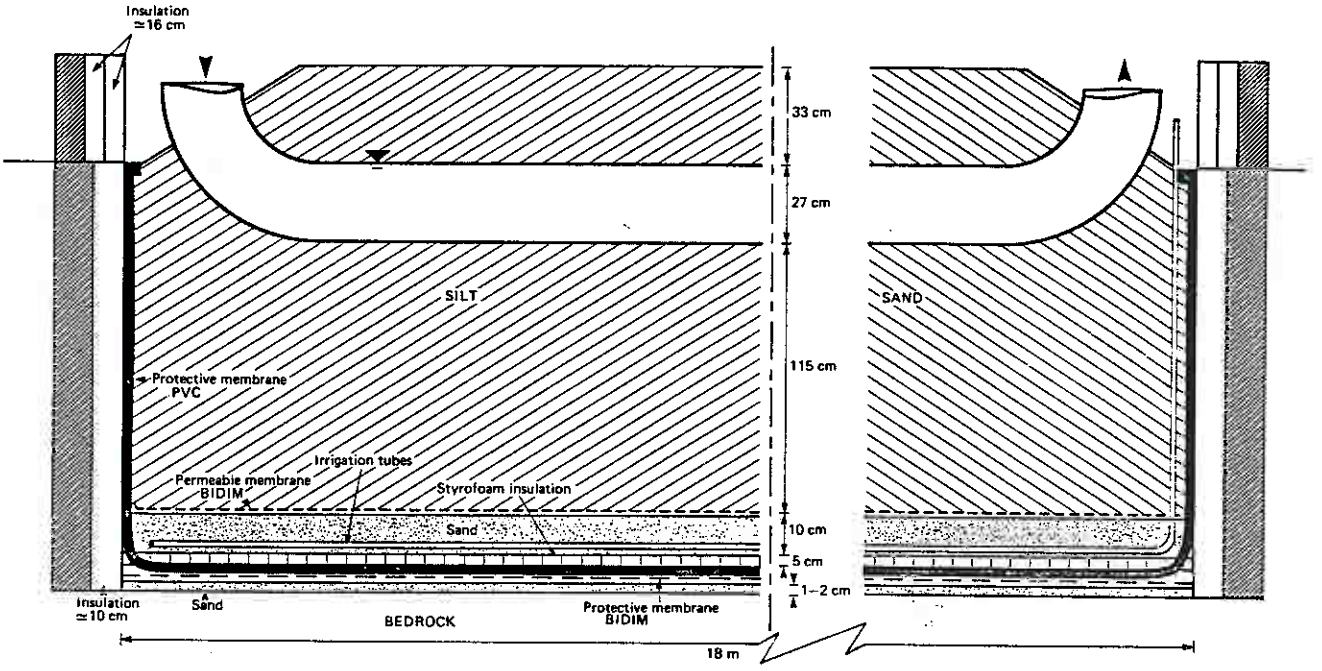

Figure 2.1 Longitudinal section of trough

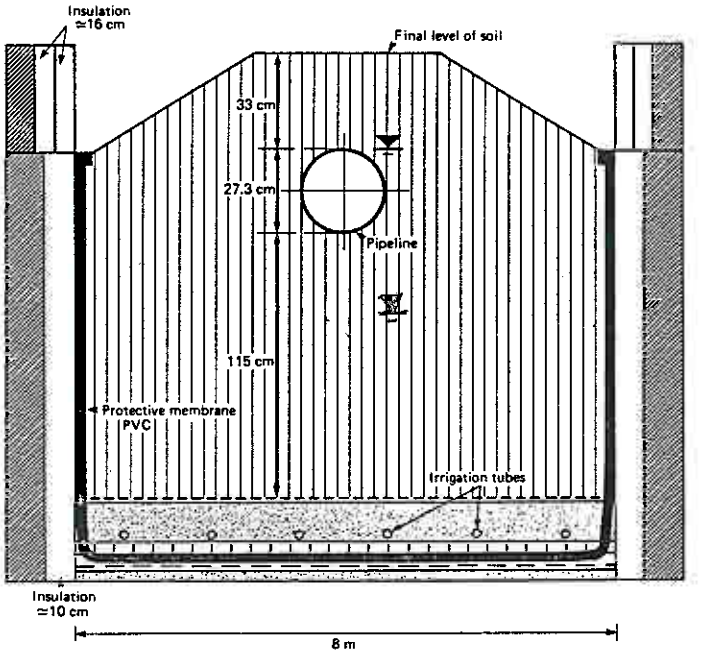

Figure 2.2 Cross-section of trough

content probes, pipe deflection, pipe curvature and pipe strain. Periodic measurements not shown on Table 2 include temperature soundings, soil density profiling and gravimetric water content determinations. Where possible all data is entered into a micro-computer on site. It is then transferred onto a magnetic tape which is sent to Canada for detailed analysis.

2.3 Operating Conditions

The operating conditions during this report period (January 1984 to December 1984) represent those of the second freeze period which began on 17 October 1983. The average temperature of the pipe is -5°C and the air temperature of the hall is at -0.75°C. The ground water table is maintained at an average of 30 cm. below the ground surface.

III EXPERIMENTAL OBSERVATIONS, SECOND FREEZE PERIOD, AND ANCILLARY STUDIES

3.1 General

Results up to Dec. 30 1984 are presented. Some information from an earlier stage of the experiment is included for comparison.

3.2 Thermal Regime

The temperature profiles beneath the pipe in the silt and sand are shown in Figures 3.1 and 3.2 respectively. The frost line has penetrated by December 15, 1984 to a depth of 75 cm in the silt and through the sand with the rate of penetration being greater in the sand

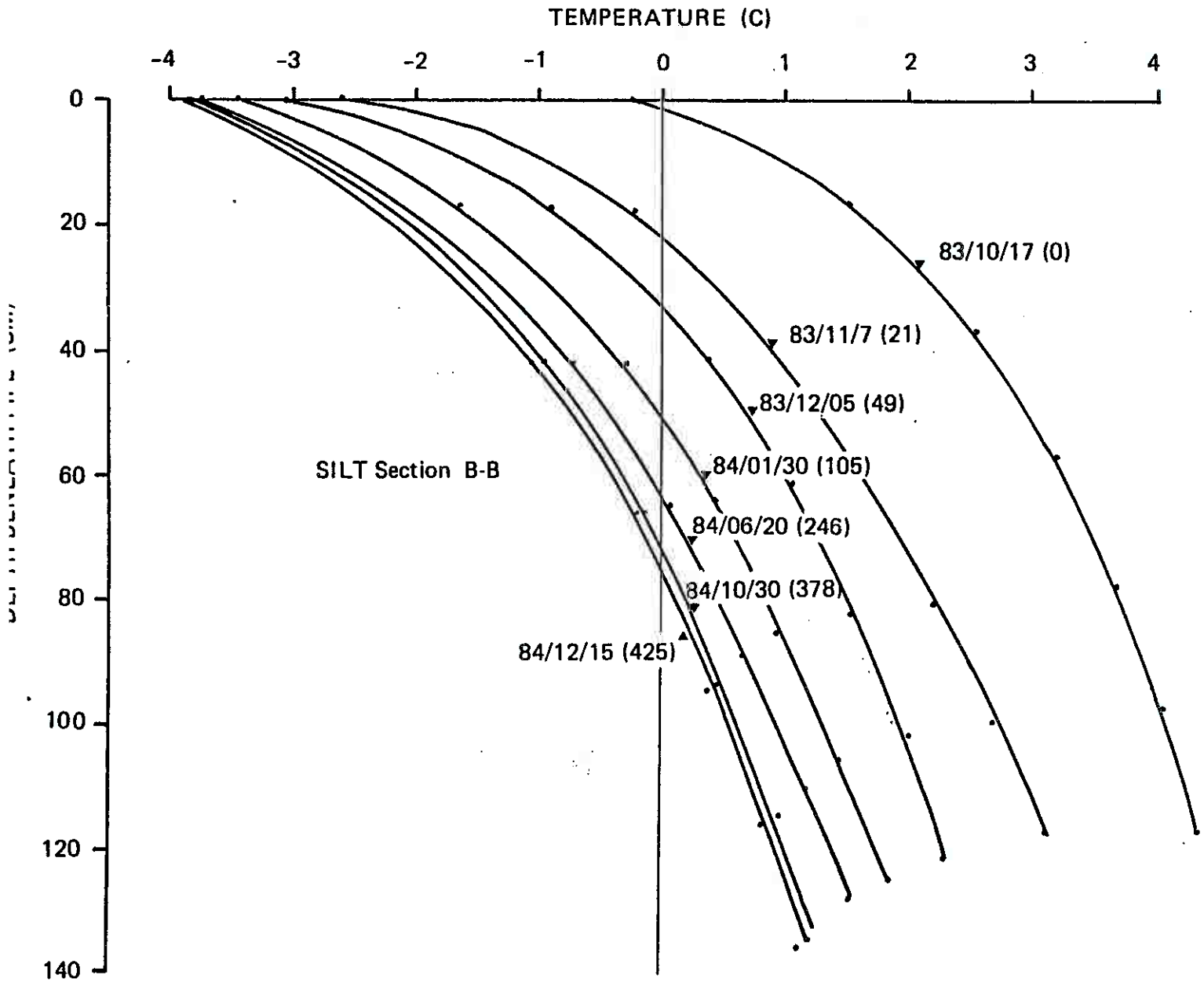

Figure 3.1 Temperatures below pipeline on various dates, silt section

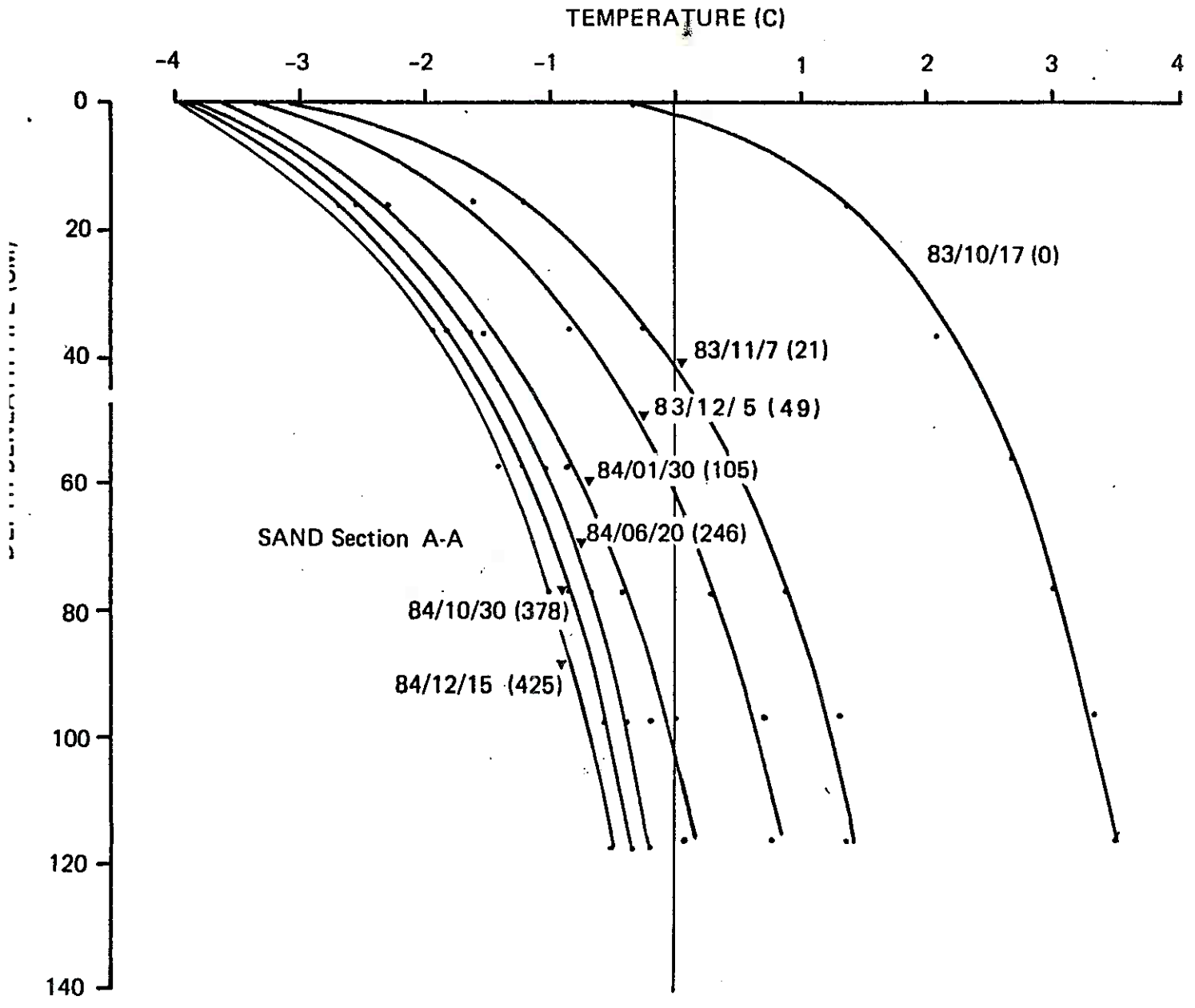

Figure 3.2 Temperatures below pipeline on various dates, sand section

than the silt as expected.

3.3 Pipe Deformation

Since a buried pipeline is not readily accessible for direct displacement measurement vertical rods are welded to the pipe at regular intervals. Each rod extends above the ground surface through a plastic access tube serving to isolate the rod from the surrounding soil. When the pipe is displaced due to frost heave forces, the rods are displaced by an equal amount. By running a weekly survey with a level of the rod-ends during the experiment a series of displacement profiles can be determined as heaving progresses. Figure 3.3 shows the profiles of the pipe plotted at various times during the experiment. The shape of the pipeline profile as the freezing front progresses is clearly illustrated. The relative displacement of the two ends is 16.86 cm since the beginning of the experiment. Most of this follows from heave of the silt soil which is several times that in the SNEC soil.

The deformation of the pipe is observed by four methods: levelling (as described); by observations of the tilt of special plates attached to the same rods; by use of a specially designed instrument measuring the relative movement of a rod relative to its neighbours (Bowes 1985); and by interpretation of electrical resistance strain gauges attached to the pipe. Good agreement occurs between several methods (Geotechnical Science Laboratories 1983). The strain gauge readings have been used to calculate stress in the pipe, for this report (fig. 3.4 and section 3.9 below).

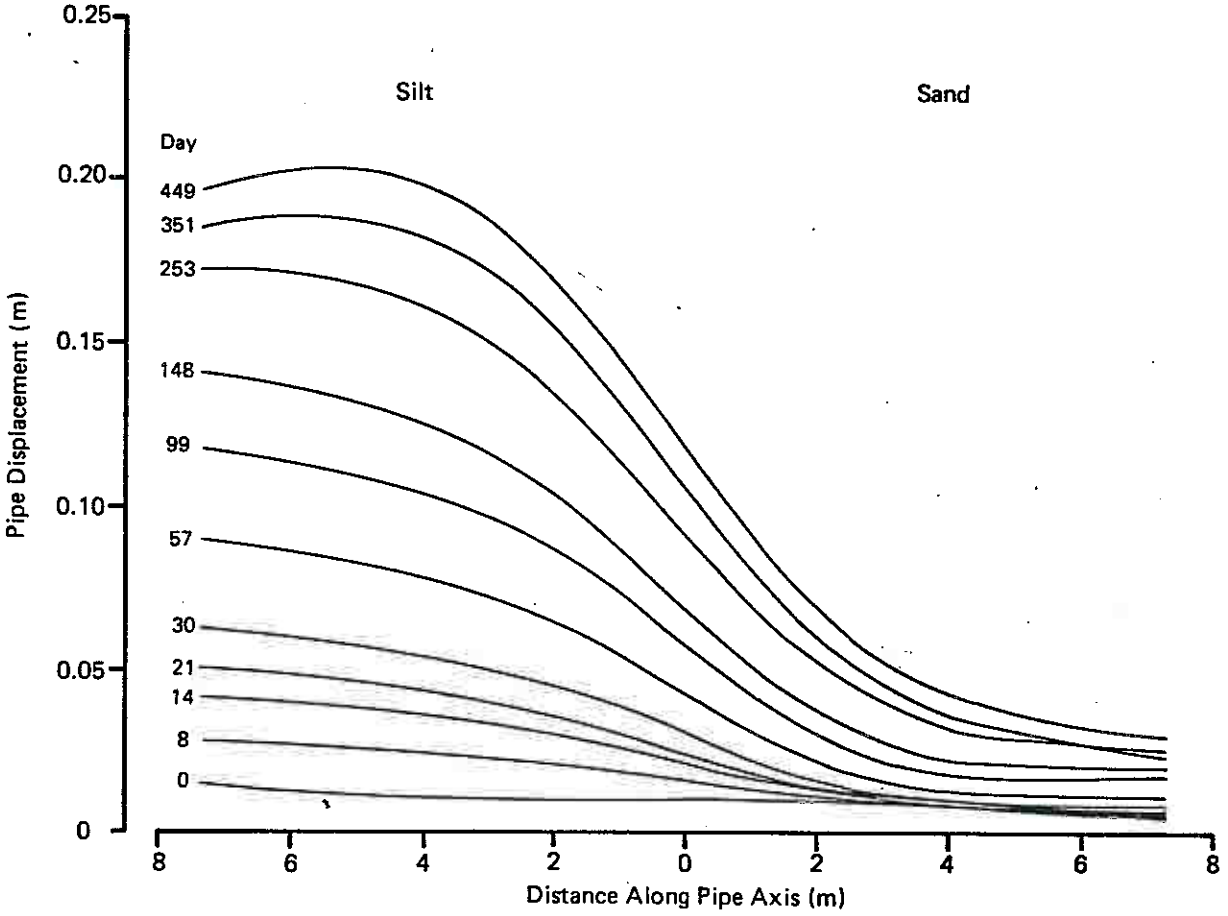

Figure 3.3 Deformation of pipeline

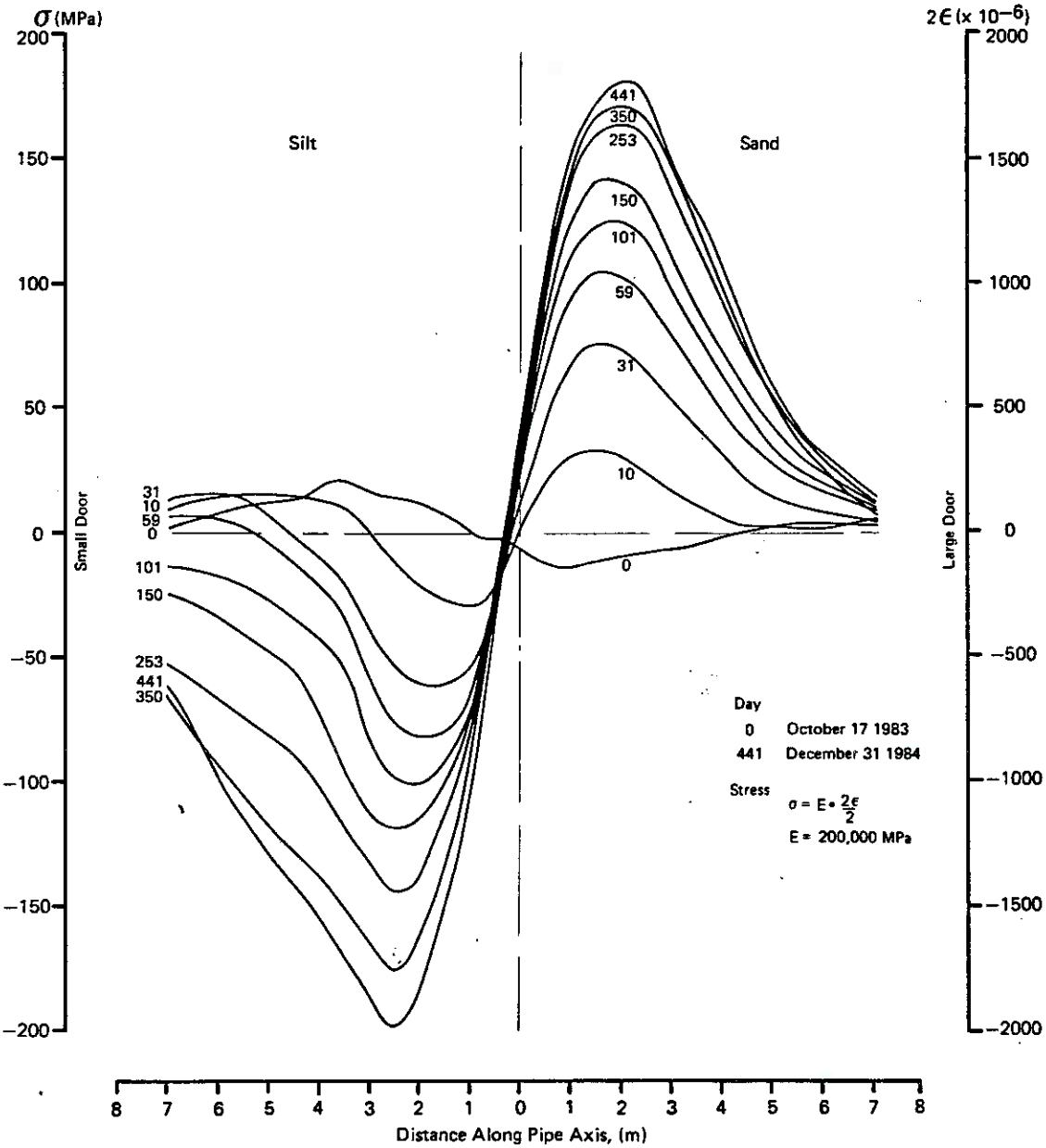

Figure 3.4 Stress and strain along pipe during second freeze

3.4 Surface expression of frost heave

The ground surface elevations at 3 monthly intervals are shown in figs. 3.5a, 3.5b, 3.5c and 3.5d. Above the pipe the heave quite closely follows that of the pipe itself. However there are no survey markers on the surface directly above the pipe so that exact comparison is difficult. Such comparison should reveal whether there is a 'thinning' of the frozen material above the pipe by lateral creep. Accordingly, markers are being placed on the surface above the pipe axis, for observation during the remainder of the operating period. Figs. 3.6 and 3.7 show surface heave for two profiles across the pipe.

3.5 Stresses developed within frozen ground

Studies have been carried out, concurrently, at the Geotechnical Science Laboratories' facilities in Ottawa, of the fundamental nature of freezing in porous media. These studies (largely financed under other contracts) have centred on the appropriate form of the Clausius-Clapeyron equation to describe freezing in confined spaces (the soil pores).

There is general agreement amongst soil physicists that an equation of the form:

$$dT = \frac{(dP_w\ V_w - dP_i\ V_i)T}{\ell} \qquad 3.1$$

describes the process, P_i being the pressure in the ice phase, P_w, the

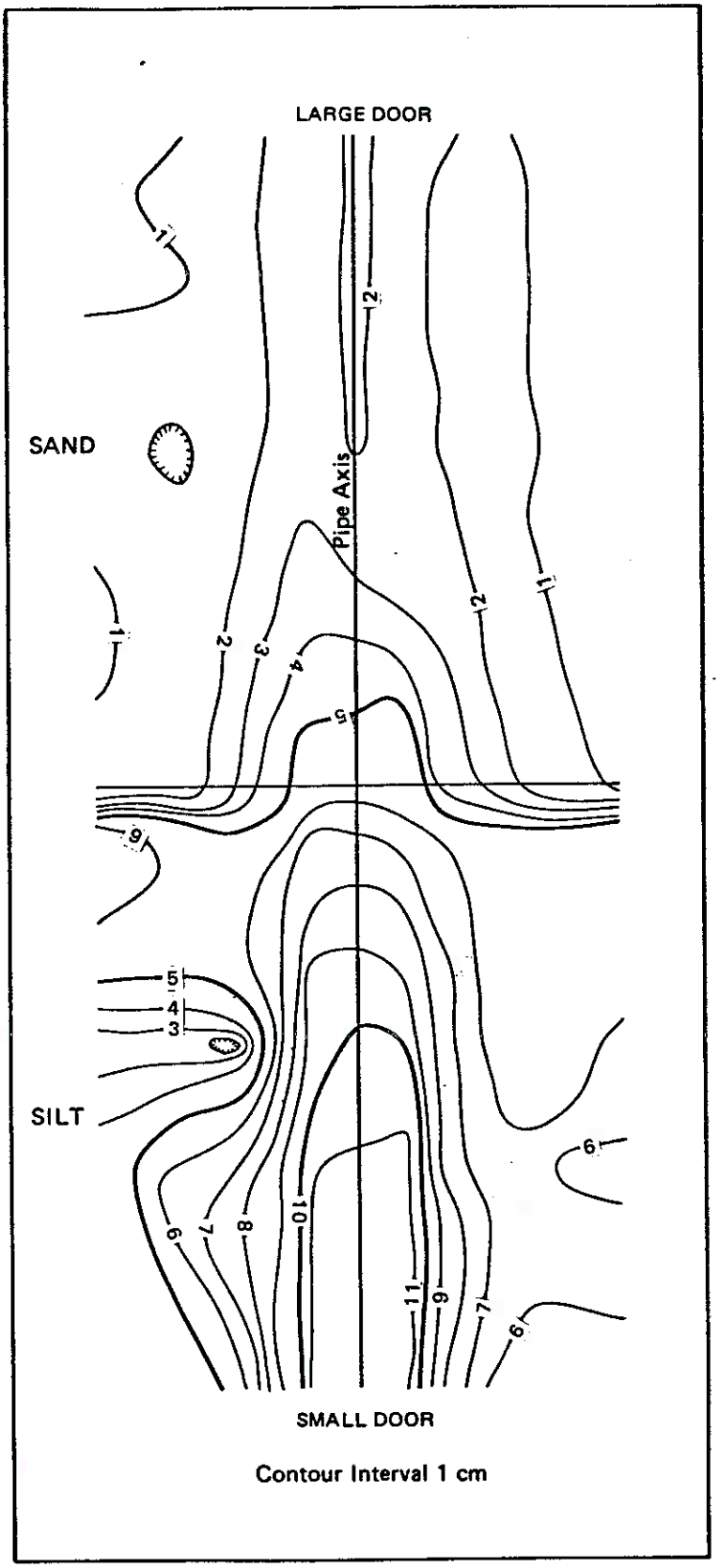

Figure 3.5a Ground surface elevations, day 107

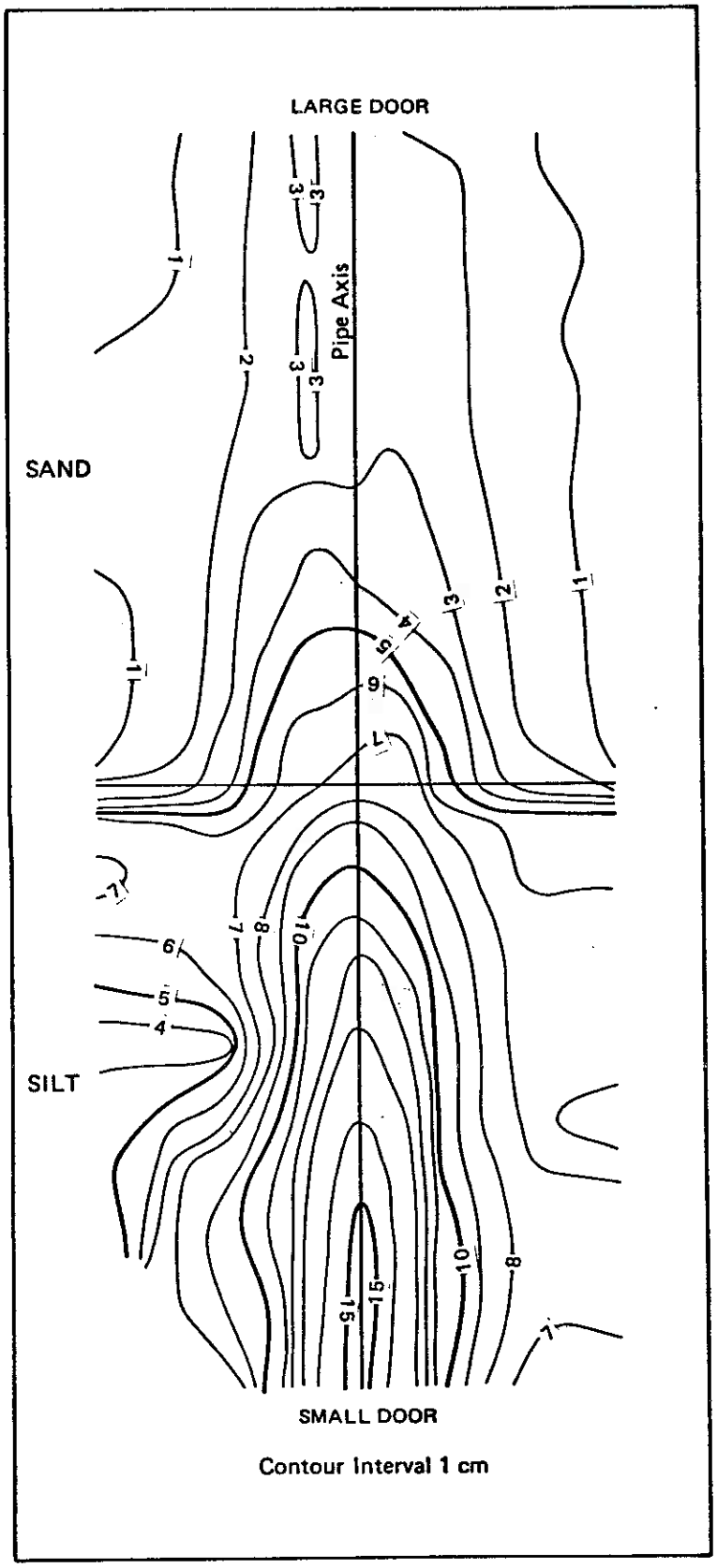

Figure 3.5b Ground surface elevations, day 200

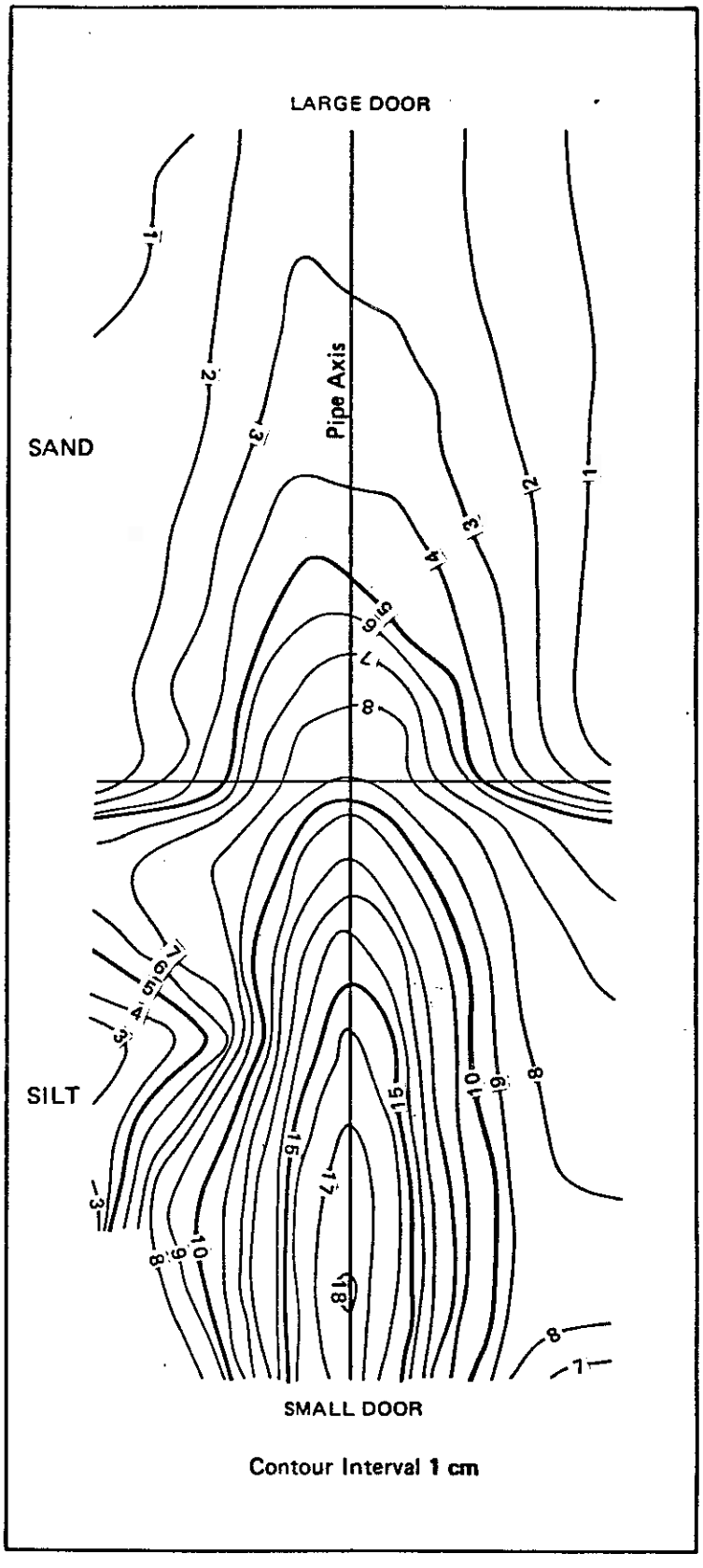

Figure 3.5a. Ground surface elevations, day 300

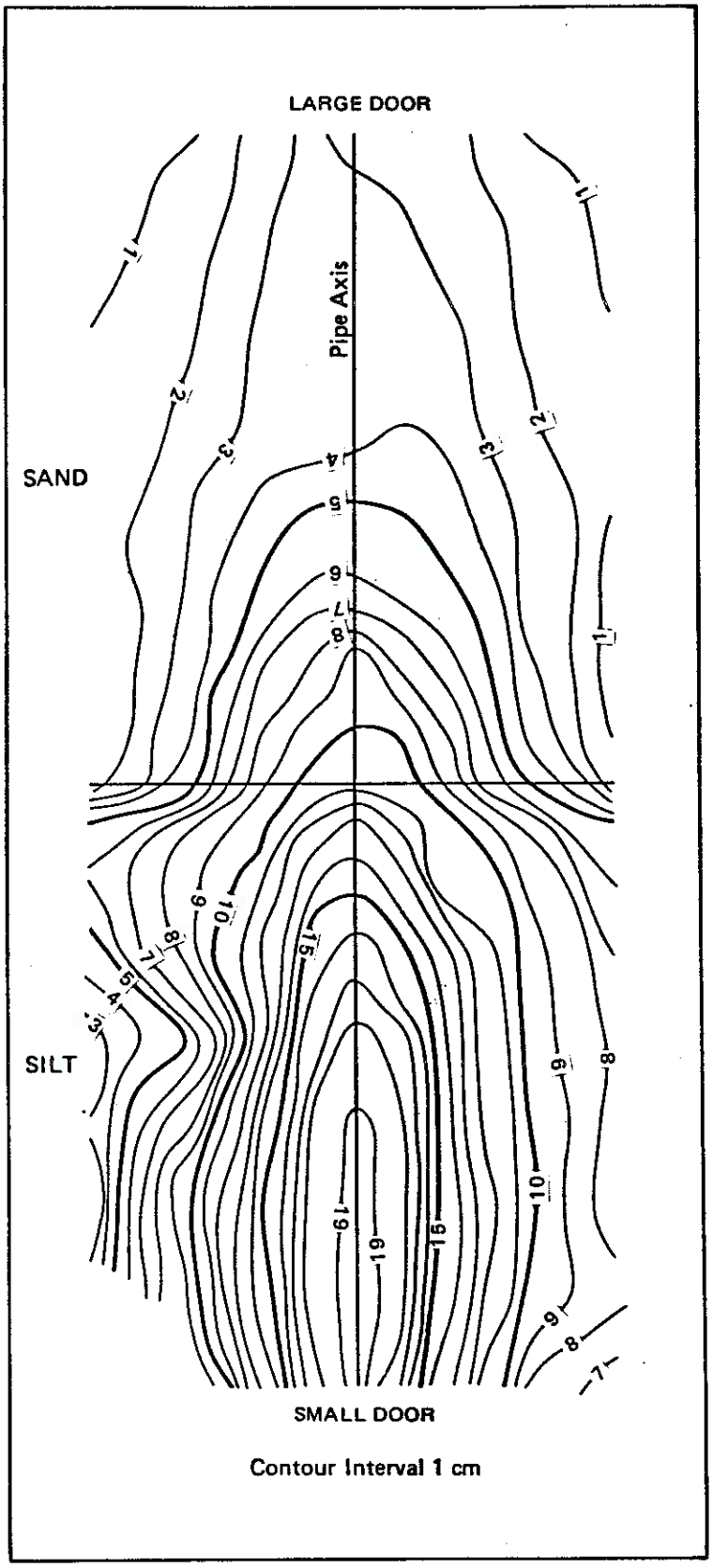

Figure 3.5d Ground surface elevations, day 423

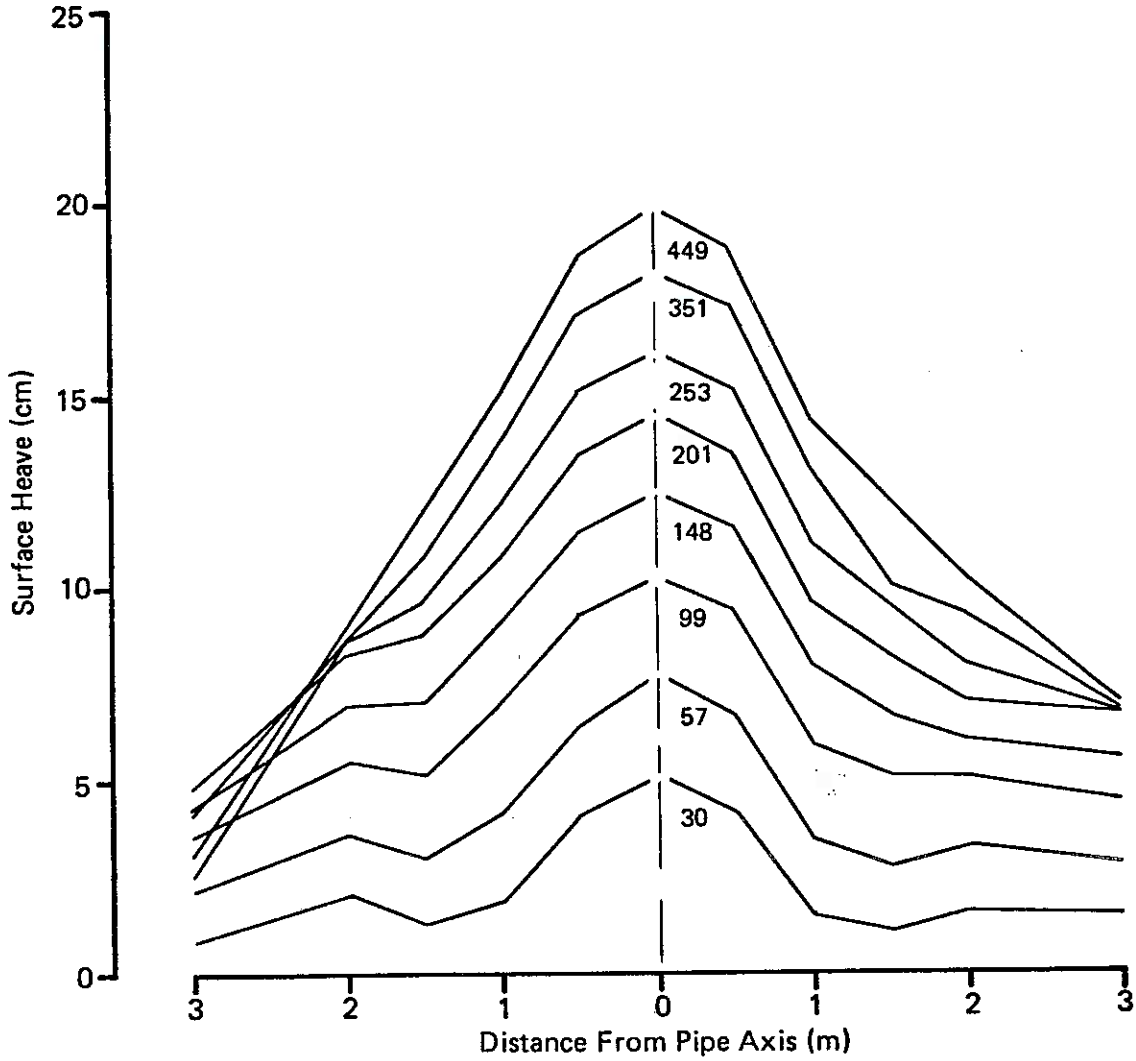

Figure 3.6 Surface relief along section B-B, silt, transverse to pipe

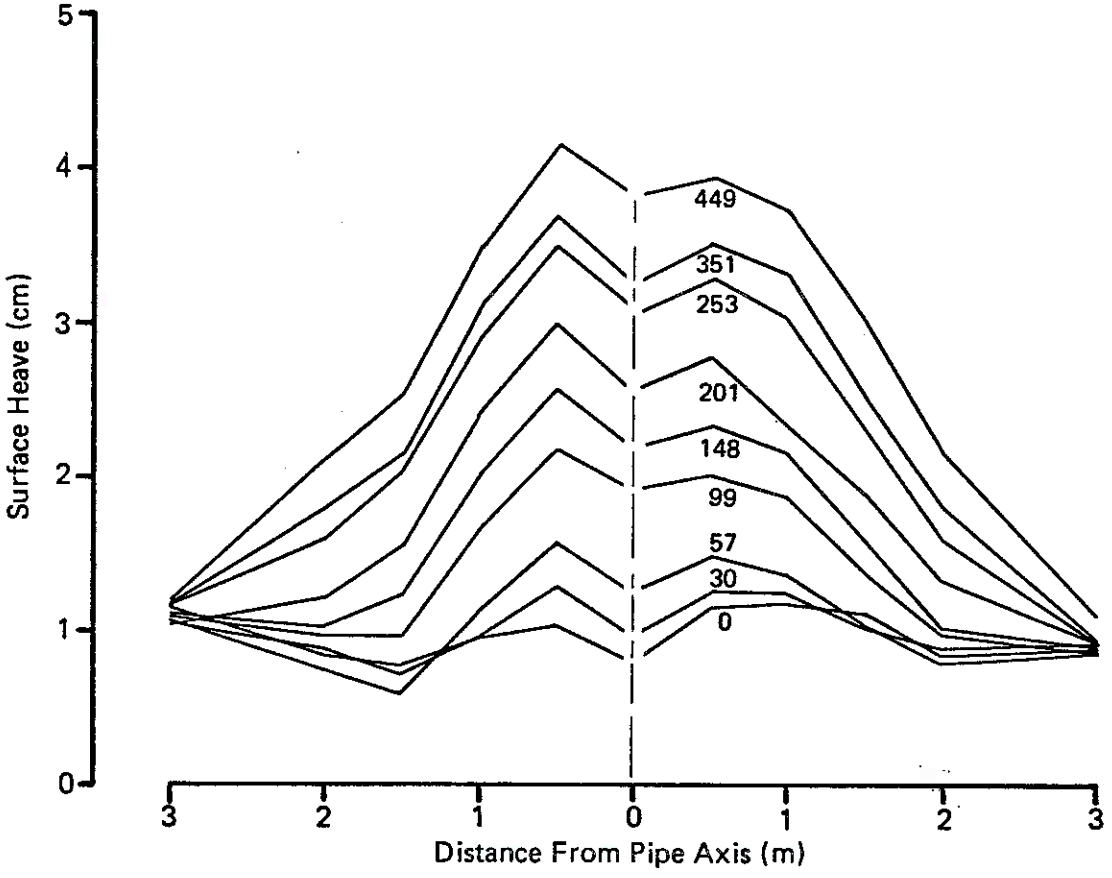

Figure 3.7 Surface relief for various days along section A-A, sand, transverse to pipe

pressure in the water phase, T, the absolute temperature, dT, the temperature below the normal freezing point of water, V_w and V_i the specific volumes of water and ice respectively and ℓ, the latent heat of fusion. The pressures of ice and water, in equilibrium, are not equal, when interfaces are confined as in soil pores. The difference in pressures, which increases with dT, according to eqn. 3.1, is accommodated either by a fall in pressure of the water or by an increase of ice pressure, or a combination of both. The fall in water pressure (or potential) constitutes the suction causing water to move to, and within, the frozen zone. The rise in ice pressure is the source of frost heave pressure. The partitioning, however, is usually uncertain, such that prediction of frost heave rates or of pressures is difficult.

The laboratory tests in Ottawa have demonstrated that the pressure of the ice within the soil is related to the resistance of the soil matrix to deformation (Williams and Wood 1985). The finding greatly assists application of eqn. 3.1. It demonstrates, too, that the externally effective heaving pressure (i.e. that acting where the soil exerts stress against a pipe or other structure) will be the temperature-dependent pressure developed at sites within the soil, less the stress carried by the soil-ice matrix. Eqn. 3.1 shows that the highest pressures will be developed in the coldest parts of the soil, but that the external effects will be modified by the creep resistance of the particular soil which increases with colder temperatures. The implications of this work are that the full analysis of the heave and heave pressures, and of the deformation and stresses in the pipe,

will be complex, and require a variety of tests on the specific soil(s). The thermodynamic conditions, and laws governing phase change have to be satisfied as well as those governing the mechanical (creep) behaviour of the soil and pipe. The relation of pipe deformation to soil deformation behaviour has been examined by Ladanyi and Lemaire (1984). Laboratory analyses of the creep properties of the Caen silt and SNEC soils will be reported soon, under contract OSU83-00157.

3.6 Stress within annulus of frozen soil

Glotzl cells for measuring ground pressures, are placed below the pipe at several depths. The observations obtained are of particular significance and importance and relate to the work described in the previous paragraph.

The observations obtained from 3 cells placed one below another at depths of 10, 46 and 86 cm. below the pipe are shown in fig. 3.8. In each case the stress corresponds approximately to the weight of overlying soil and pipe, until the frozen ground envelopes the cell. At that point the stress rises. Cell no. 4 (fig. 3.8) showed this first as it is adjacent to the small annulus remaining frozen from the previous freeze-thaw cycle. It is noteworthy that the elevated pressures are not transmitted to the unfrozen soil beneath, even in the silt side of the transition zone where the pipe is exerting a downward stress. In other words the stresses which are the ultimate source of the heaving pressure deforming the pipe, are absorbed by the annulus and pipe. The implication is that the reactive stress for deformation and uplift is not to be found in underlying ground but in the layer (that is, outer)

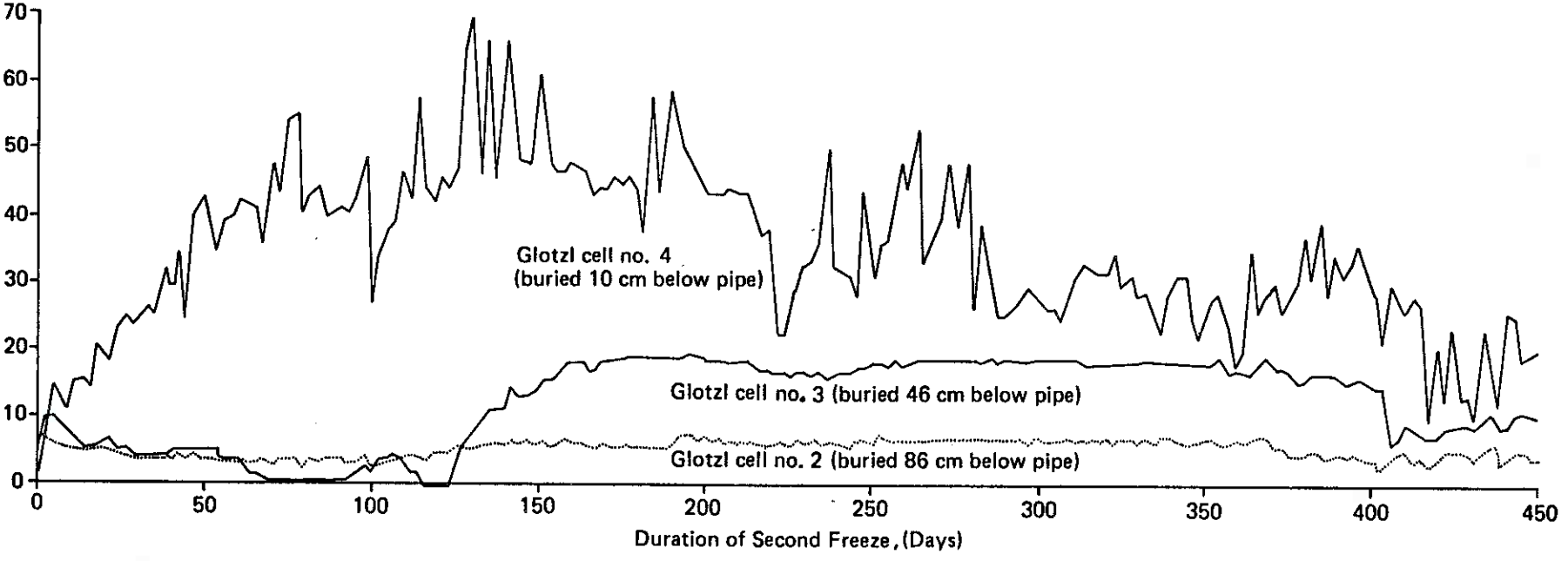

Figure 3.8 Total stress at three depths below pipe, in silt (at section B-B)

parts of the annulus of frozen ground around the pipe. A further implication is that pipes enclosed in an annulus of frozen ground are exposed to stresses tending to crush the pipe.

3.7 Strain of frozen ground by secondary frost heave

Although it used to be thought that the frost heave of soil occurred at the time of first freezing it is now known that frozen soil continues to expand (heave) slowly, after it has become firmly frozen. Migrations of unfrozen ('film') water are responsible for this, the 'secondary' frost heave. Rather little is known about the rates of this heave which, because of the high pressures developed in association with it, may be of great significance for the long-term deformation of an operating pipeline.

Several methods are being employed to measure secondary frost heave, and the observations will be reported fully under the provisions of contract OSU83-00157. Fig. 3.9 shows the progress of heave as freezing occurs in successively deeper layers, as recorded by telescoping tubes (Mackay 1981, Smith 1985). In principle, the continuation of heave in one layer, after heave has commenced in the next lower one, is evidence of secondary frost heave although care is required in interpretation. Fig. 3.10 shows the cumulative heave, calculated from the same observations, at the base of the pipe. The figures agree well with the direct observations of pipe movement.

3.8 Cracking of ground, lateral to pipe

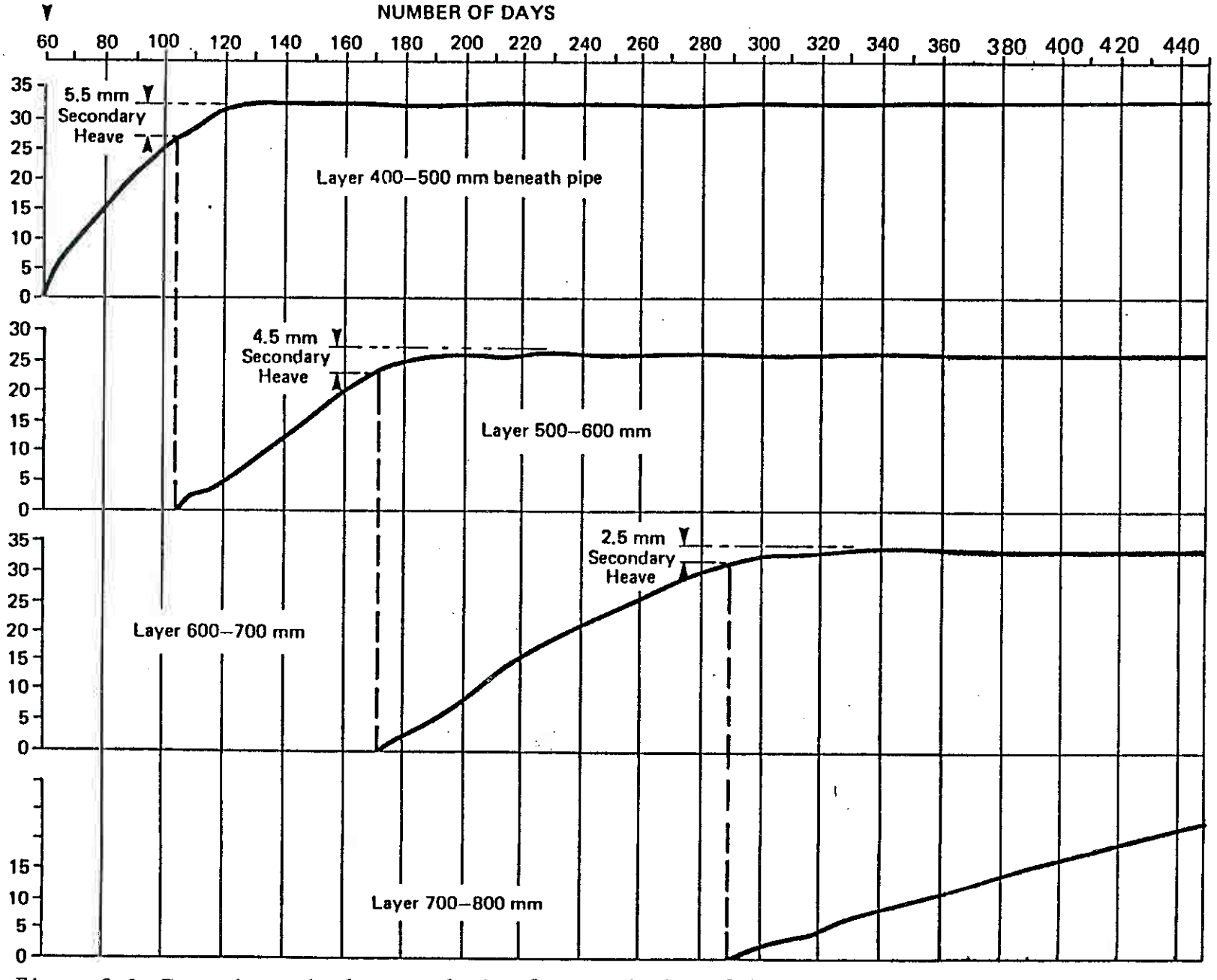

Figure 3.9 Frost heave by layer and time for vertical profile

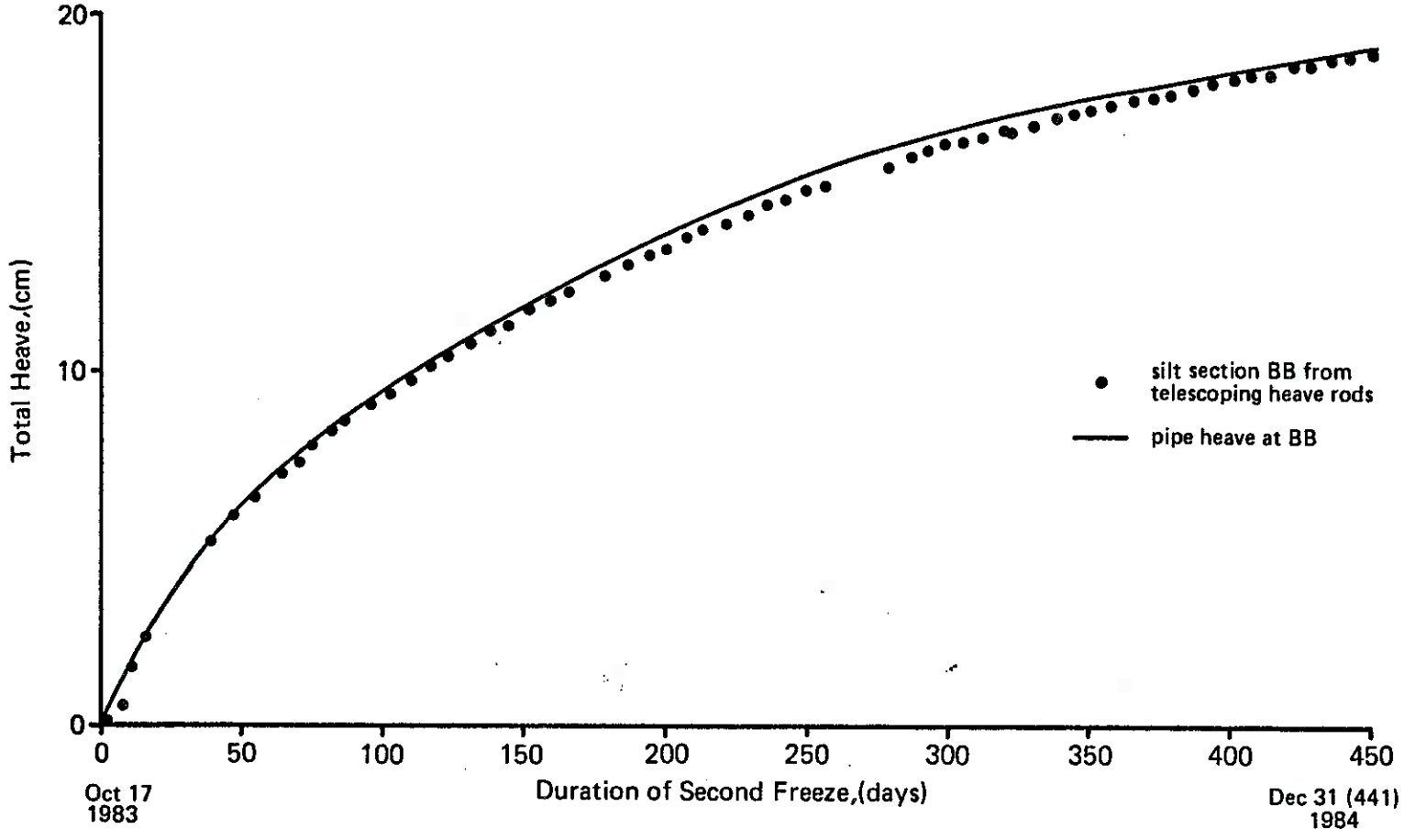

Figure 3.10 Total heave below pipe from observations with telescopic rods (points) compared with pipe displacement (line).

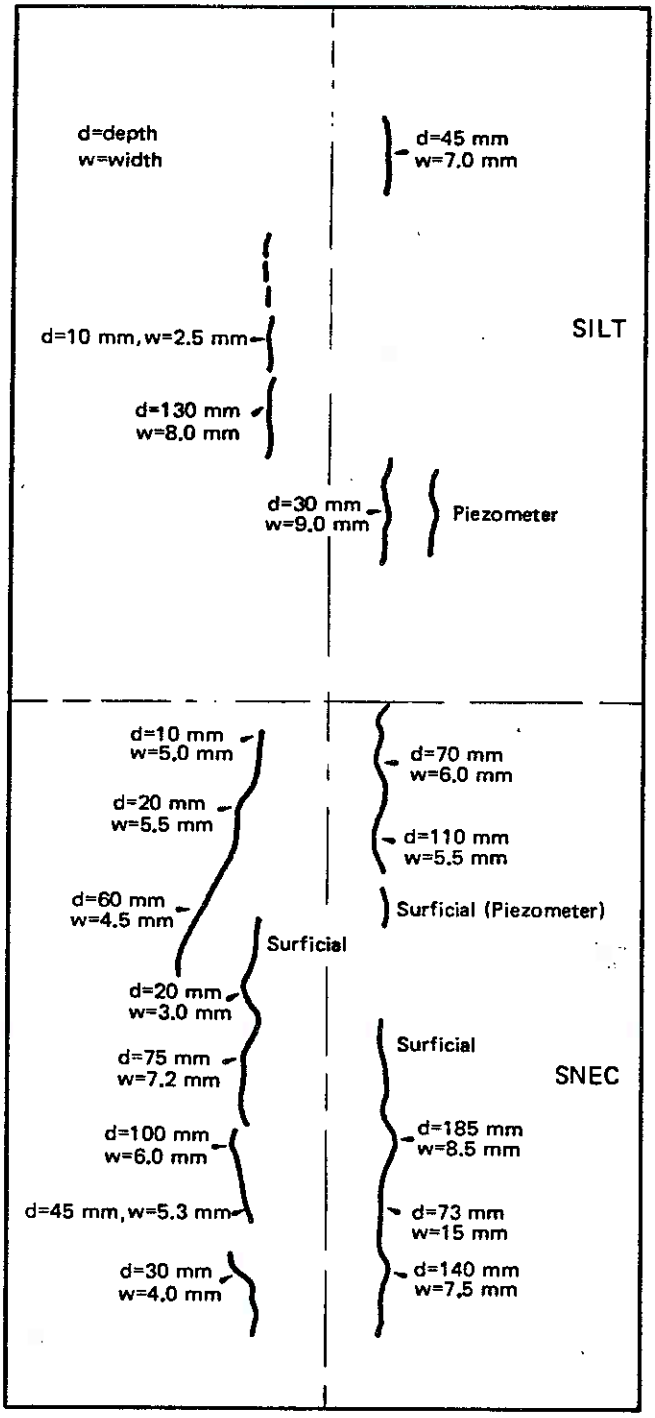

Figure 3.11 Plan of cracks at soil surface. D = depth, W = width (see text).

the ground, roughly parallel to, and on either side of the line of the pipe (fig. 3.11). The values of depth and width of a crack were obtained using a wedge device which is inserted into the crack. It measures average, not, therefore, maximum values. The cracks appear from the surface to 'lean' slightly from the vertical and away from the pipe.

The cracks may be significant in relation to the proposal of Sayles (1985) that shear separators be placed lateral to a pipe, so as to reduce the stresses inflicted upon the otherwise restrained pipe by frost heave.

3.9 Numerical modelling

The approach taken in the project has been the comparison of laboratory and theoretical studies of the thermodynamic behaviour of the freezing soils, with the experimental results obtained from the pipeline experiment. The contribution of Laboratoire Centrale des Ponts et Chaussées in Paris, to the France-Canada project, includes the development and application of numerical models of the heat flows and moisture migrations. These models, which require the input of data on soil thermal and hydraulic properties determined in the Geotechnical Science Laboratories, represent a powerful tool for prediction of frost penetration and heave provided sufficient is known of the material properties. The approach is described in Blanchard and Frémond (1984), and Blanchard, Frémond and Williams (1984) and will be more fully reported under contract OSU83-00157.

IV DISCUSSION OF FINDINGS

4.1 Significance of ground conditions

The aim of the study is to obtain sufficient understanding of the pipe-ground interaction to predict those conditions which will expose operating pipeline to damaging stresses. A significant length of a northern gas pipeline may have to be built above ground or in other manner isolated from the effects of ground freezing. Such procedures will be expensive and it will be very important to determine the extent to which soil and other conditions make such procedures necessary.

Analysis of the data obtained under the present contract, as well as of that obtained under contracts relating especially to the behaviour of the freezing soils, makes clear the complexity of the problem of prediction (Dallimore 1985, Kettle 1985). The variability of natural conditions of soils and microclimate, even over short distances, let alone the lengths of trunk pipelines, means that the frost heave effects will also vary greatly. The conditions at the test site, however, lie well within the range that will be met in the field. At this time it is possible only to outline the relationships of pipe deformation to soil conditions, illustrated by the experiment, and to draw attention to those aspects requiring continued study.

1. The frost heave of the soil depends on the local conditions: soil lithology, heat flow and moisture availability are important. The two latter are modified by the presence of a pipe. Perhaps even more

restraining stresses. These are determined by the pipe and its surrounding annulus of frozen ground. As demonstrated by the laboratory studies the resistance due to the soil will be a complex function of the rate of strain, temperature and other factors which require detailed study of the creep behaviour.

2. The differential heave of the pipe and the ensuing deformation involves lengths being impressed, and withdrawn, through the frozen annulus in a manner also dependent on the mechanical properties of the frozen material. The stresses in the pipe will depend on this behaviour in soil 'transition' zones (Lemaire 1983).

3. The pressure within the frozen annulus shown by Glotzl cells is apparently the result of pressures developed by the movement of moisture and growth of ice layers. This 'secondary heaving' is detected by the telescopic heaving tubes, which record strains of the frozen ground. It appears the internal pressures control rates of secondary heaving, in accordance with the Clausius-Clapeyron equation relating temperature pressure and water potentials. Their significance with respect to the 'crushing' effect which an annulus of frozen ground will have on the enclosed pipe requires study.

4.2 Pipe stresses

The differential displacement causes stresses to be induced in the pipeline. These stresses have been calculated from the reading of strain gauges placed at regular intervals along the pipe and are ch

in Figure 3.4. The maximum stress in the pipeline was 200 MPa (84-12-17) representing approximately 85% of the theoretical yield strength of the steel pipeline.

During the experiment, the gas pressure inside the pipe was substantially zero, and the only significant stress was the longitudinal stress resulting from bending. The maximum stress did not exceed the yield stress and, consequently, the pipe suffered no permanent strain. It might then appear that an operating pipeline could be safely subjected to the same deformation. This false conclusion ignores the effect of pressure stress which is invariably present in an operating pipeline. The pressure stress has a longitudinal component which, when combined with the longitudinal bending stress, may pose a threat to the integrity of the pipe.

When internal gas pressure is applied to a pipe the material in the pipe wall is subjected to circumferential stress. This stress usually controls the design and dictates the limiting value of pressure for a safe pipeline. The pressure also produces longitudinal stress which is approximately one-half the value of the circumferential stress. Because it is smaller, the longitudinal stress does not usually influence the design. However, when a pipe is subjected to bending, the bending stress is also longitudinal and must be superimposed on that caused by the gas pressure. In this way a pipe that is capable of safely carrying a given pressure load may be rendered unsafe if it is simultaneously subjected to frost heave. Thus, an operating pipeline that had been designed and built to safely contain gas at a certain pressure, could be

such a pipeline it would be necessary to reduce the gas pressure in order to restore the line to a safe condition.

In order to illustrate the significance of the frost-heave stresses encountered in the present experiment, a calculation has been made of the effect of these stresses on the reduction in gas pressure that would be required to maintain a safe pipe in accordance with the requirements of the Canadian Standards Association standard CSA Z184-M1983.

For the dimensions and material properties of the test pipe, the pipe could safely transmit gas at a pressure of 7068 kPa provided that there were no other loads.

When such a pipe is subjected to small deformations there is no need to reduce the gas pressure. In the Caen experiment, the displacements were such that the pipe could have safely carried full gas pressure for the first 15 days of the second freeze period. After that time the stress due to frost-heave reached a level that would have made it necessary to reduce pressure; the safe pressure dropping to 4240 kPa, which is 60% of its initial value, at about 31 days into the second freeze period. At 200 days the heave-stress would equal the allowable longitudinal stress and the pressure would have to be reduced to zero.

This means that under the conditions encountered at Caen, a transmission pipeline could operate at full pressure for 15 days and then would be required to operate at a reducing pressure and be taken out of service after a life of only 200 days.

V STATUS OF CANADA-FRANCE PROJECT

In October 1984 substantial modifications were made in federal

government financing of energy-related research. In addition to termination of a number of projects there have been changes of funding for continuing projects, following an assessment of priorities. The Canada-France ground freezing project will, it is now intended, continue for a further two to three years. The Canadian involvement is primarily paid for through two contracts, which provide for (a) the utilization of the test facility and the studies into the behaviour of the freezing soils, and, (b) studies of the behaviour of the gas pipe itself - the subject of the present report. As a result of the changes it was not possible to continue the latter aspect of the work under further contracts, beyond 1984, as had been planned. Consequently in this and the next section findings concerning the pipe behaviour during the period of the contract now terminating, as well as over the course of the Canada-France project, will be reviewed.

In the course of the current contract there have been positive developments around the study. During the visit of the Prime Minister, M. Fabius, and other French Ministers to Canada, in October 1984, a proposal was made to the Canadian government that there be an extension of the current program of co-operative research into geotechnical and scientific questions relating to freezing soils. French interest in these matters relates to foundations for highways and railways and the high standards now required for these, especially for highspeed trains, - as well as to ground freezing in relation to pipelines, and other questions. A detailed proposal is currently being prepared on the French side, for submission to the Canadian government.

(National Academy of Sciences, 1985) points out the great economic significance of ground freezing and defines, in detail, the need for increased research into basic questions of the thermodynamics and physics of freezing soils.

Thus there are indications that worldwide the fundamental geotechnical, scientific questions will receive increasing attention. In Canada, the application and interpretation of such research for the purposes of gas pipeline design or other industrial purposes will, it seems, only occur if private industry is prepared to assume much of the cost of such research. The importance of the findings in the France-Canada project with respect to the industrial development of gas pipelines in freezing or frozen ground are briefly discussed in this report. Clearly, engineers and others professionally experienced in pipeline design and construction should be involved in such interpretation.

VI GENERAL CONCLUSIONS

1. Unprotected pipelines buried in initially unfrozen soil, operating at temperatures below 0°C, are liable to displacements due to frost heave which, in only a few years and possibly less, will deform the pipe beyond acceptable limits for operation. The experiment models a condition which occurs repeatedly in nature: the variation of soil type. Under natural conditions there will be other variations of thermal and hydrological conditions which can also produce differential frost heave.

The design of mitigative measures will

of the nature and extent of the frost heave phenomenon.

2. A pipeline deformed by a period of freezing, yet without being stressed beyond acceptable limits, does not return exactly to its original position following thawing. A second freeze-thaw cycle results in further jacking, a cumulative deformation. Thus thawing periods, whether naturally or artificially induced, will not necessarily overcome the problem of frost heave of the pipe.
3. The observations demonstrate slow heave of already-frozen ground, and the development of stresses locally within the frozen annulus. These observations are in keeping with recent experimental work elsewhere on the nature of the frost heave process. They increase our understanding of the fundamental thermodynamic relations for the freezing of water in soils and other porous media (see Geotechnical Science Laboratories 1984). The observations are of importance with respect to the understanding of geotechnical properties and design values, especially the amount of long-term or 'secondary' heave.
4. The results support the view that the creep properties of the frozen ground (which themselves are highly variable and dependent on temperature, soil composition and other factors) are a major controlling factor on the rate of heave and generated frost heave pressures, and thus on pipe deformation.

A final comment on the significance of the findings with respect to pipeline design is appropriate. Methods have been proposed by others for the prediction of frost heave effects on pipelines, which involve relatively simple tests in the laboratory and calculations

methods have a role in illustrating the general magnitude and extent of the effects, the present experiments show that precise prediction of the frost heave is currently impossible (see also Dallimore 1985). In contrast to other foundation problems where standard geotechnical tests usually allow the extent of difficult terrain to be defined, the sensitivity of the frost heave effect to the innumerable variations of natural thermal, hydrological, climatological and lithological conditions, and the great length of right-of-way mean that attention will have to be given to delineating sections or regions where protection against frost heave will be generally required. This requires geostatistical studies supported by research in the laboratory and field, in order to establish extreme or limiting values for various factors.

It appears that the problem of deformation of pipes by frost heave will, for significant lengths of pipelines in permafrost or near-near-permafrost regions (Williams 1979), only be overcome by effectively isolating the pipe from the frost heaving ground. This may take the form of rigid or semi-rigid enclosing berms, or the replacement of substantial amounts of soil by materials not subject to heaving. Other procedures may be developed. It will be important to define the distances for which such procedures are required. In addition further knowledge of the basic nature of the thermal, thermodynamic and mechanical properties of naturally-frozen ground will be required in order to meet the inevitable special situations where difficulties arise during, or subsequent to construction.

In the absence of further studies construction of pipelines in cold

regions will be fraught with uncertainty and the likelihood of subsequent large expenditures on maintenance.

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