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FROST HEAVE MODEL CALCULATIONS FOR THE CALGARY FROST HEAVE TEST FACILITY

L.E.C. Engineering Limited

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FROST HEAVE MODEL CALCULATIONS

for the

CALGARY FROST HEAVE TEST FACILITY

FINAL REPORT

by

L.E.C. ENGINEERING LTD.

APRIL 1985

Work on this project was conducted under the auspicies

of the Earth Physics Branch

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ABSTRACT

Frost heave calculations using the Segregation Potential (SP) model and the Incremental Ice Segregation (DISR) model are compared to the observed frost heave data from chilled pipeline sections at the Calgary Frost Heave Test Facility. Model calculations are performed with the measured temperature gradients and measured frost depths for a range of SP values (determined by laboratory tests) and a range of DISR parameters. Frost heave calculations combining the SP model with thermal gradients and frost bulb depths determined by thermal simulation models are also presented.

RÉSUMÉ

Le soulèvement dû au gel est calculé par le modèle de potentiel de ségrégation (SP) ainsi que le modèle 'Incremental Ice Segregation' (DISR) et comparé avec les soulèvements obtenus sur plusieurs sections de pipelines refroidis à l'installation d'essai de Calgary. Les calculs sont effectués en utilisant les profondeurs du front de gel et les gradients thermiques mesurés, ainsi qu'un série de valeurs de SP (déterminé par essais en laboratoire) et une série de paramètres pour le DISR. Des calculs de soulèvement qui combinent le modèle SP avec un modèle thermique simulant les gradients thermiques et les profondeurs de gel sont aussi réalisés.

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1.0 Executive Summary

Frost heave model calculations of heave at the Calgary Frost Heave Test Facility have shown that the Segregation Potential frost heave model of Konrad and Morgenstern provides a good estimate of the observed frost heave. The initial calculations in this report, using the Segregation Potential values derived from relatively simple laboratory tests, and measured temperature gradients, provide a very good estimate of the observed frost heave for the Control, Deep Burial and Gravel pipe sections. The Restrained section heave corresponds to a Segregation Potential value below the lower range of the laboratory test results.

A procedure is presented to calculate the heave at the frost front based on the pipe temperature and the frost bulb depth. This procedure allows the design engineer to carry out initial design calculations in a simple manner before calling upon expensive computer thermal simulator calculations in the final design stage.

The good agreement of these calculations with the observed heave data, plus the relatively quick and easy laboratory testing required to determine the Segregation Potential values for a given soil type should place this frost heave model high on the engineer's list of useful design tools in estimating frost heave due to the operation of buried chilled pipelines.

The Incremental Ice Segregation Ratio, DISR, model developed by C.T. Hwang of EBA Engineering Consultants and Foothills Pipe Lines in the late 1970's, was also used to calculate heave. This engineering model also provides a good estimate of the heave created when a pipeline is operated in the chilled mode.

This DISR model has the advantage over the Segregation Potential model in its simplicity of interpretation of field observations. The Incremental Ice Segregation Ratio is derived from the field or laboratory data, as the slope of a plot of frost heave against frost front penetration depth, i.e. a plot of H vs. X. A higher slope value corresponds to a more frost susceptible soil. However, the laboratory testing program required to define the DISR parameters is not as short or straight forward as the one used to determine the Segregation Potential model parameters.

Both models were used to calculate the frost heave at the Insulated Silt section over four freeze-thaw seasons. The calculations for both models compared reasonably well with the observed data for frost heave parameters similar to those found for the Restrained section. These Segregation Potential values are about 20% below the lower limit values obtained from the laboratory test program.

Model calculations were also carried out for the two test plates at the Calgary test facility. These calculations showed a difference in the relative frost heave characteristics of the soil.

The Segregation Potential model calculations found the soil to have a low frost susceptibility, similar to the Restrained section. However, the DISR model calculations placed the soil frost susceptibility at the upper end, with the Control section. The field observations, X vs H plots seen in section 2.3, show that the observed DISR for the plates is similar to that for the Restrained and Insulated Silt sections.

A computer thermal simulation of ground freezing was carried out for the Control and Deep Burial sections. The good agreement with the data is seen in Appendex 2.

The thermal simulator frost bulb depths and thermal gradients were used to carry out a Segregation Potential model frost heave calculation for the Deep Burial section (chapter 7). The calculated heave here was quite good, although it was less then that calculated in chapter 4, because the thermal simulation temperature gradient is less than the observed values after day 600.

Quasi-Static thermal simulation model frost heave calculations were carried out using the Segregation Potential frost heave model for the Deep Burial section. These calculations using the model temperature gradients predicts a heave rate which is much too strong after day 2000. However, the frost heave calculation is quite good, when this model is coupled with a modified temperature gradient, which drops off with time.

A procedure is presented for the calculation of the long term frost heave created by the operation of a buried chilled pipeline. This procedure determines the long term frost heave from a simple Quasi-Static model frost heave calculation based on a modified temperature gradient.

2.0 FIELD OBSERVATIONS

This section presents the Calgary Frost Heave Test Facility field observations of the Non-Insulated and Insulated pipe sections from Carlson et. al. [1982] and Carlson [1984] and the test plates from Nixon et. al. [1982].

2.1 NON-INSULATED SECTIONS

Plots of the frost heave time history and of the heave versus the frost penetration are presented in this section. The average pipe frost heave time history, for all four non-insulated sections, is presented in Figure 2.1-1. It is seen that during its lifetime the Control section heaved faster than the other three sections, reaching a heave of 66 cm in 1260 days [42 months]. By day 2,100 [month 70] the Deep Burial section had heaved about 65 cm, the Gravel section about 43 cm and the Restrained section about 36 cm.

The heave time histories of the Control, Deep Burial, Gravel, and Restrained sections are seen in Figures 2.1-2, 2.1-4, 2.1-6, and 2.1-8. The variation in heave measured at the heave rods (e.g. CM1, CM2 & CM3 for the Control section) gives a representation of the differential frost heave over a 9 metre length. Plots of heave versus frost penetration depth below the pipe are seen in Figures 2.1-3, 2.1-5,2.1-7 and 2.1-9. A similar plot of data from a laboratory freezing test on Calgary silt is shown in Figure 2.1-10.

2.2 INSULATED SECTIONS

The time history of the Insulated Silt section heave is seen in Figure 2.2-1 while the plots of heave versus frost penetration depth below the pipe is seen in Figures 2.2-2 and 2.2-3.

2.3 TEST PLATES

Two 0.8 metre diameter heave plates were also operated at the Calgary Test Facility. Nixon et al [1982] discuss the data obtained from one of these plates, named Plate #7, and Nixon [1982] presented frost heave data for Plates # 7 & # 8 and frost heave calculations for Plate #7. The heave time history for the first freeze cycle is seen in Figure 2.3-1 and the heave versus frost penetration depth in Figure 2.3-2.

3.0 FROST HEAVE MODELS

This section presents two emperical models for calculating the amount of frost heave which will occur under a buried chilled pipeline. The first one is the Segregation Potential model developed by Konrad and Morgenstern and the second one is the Ice Segregation Ratio model developed in the late 1970's by Dr. C.T. Hwang of EBA Engineering Consultants [Hwang, 1977a] and Foothills Pipe Lines.

3.1 THE SEGREGATION POTENTIAL MODEL

3.1.1 MODEL DESCRIPTION

Konrad and Morgenstern, in a series of papers [see Konrad and Morgenstern 1980, 1981, 1982], developed a frost heave theory based on the concept of the segregation potential in a fine grained soil. Subsequently, they applied their model to calculation of frost heave of the chilled buried pipe sections at the Calgary test facility, in Konrad and Morgenstern [1984] ([K & M 1984]). The theory is based on the well known concept that frost heave is not only caused by the freezing of "in-situ" pore water but also by water flowing from the unfrozen soil to the freezing front. This latter water flow is induced by a suction gradient that develops in the frozen soil.

This engineering theory, in its simplest form used in this report, states that for a given time interval the incremental heave, DH, is given by

[1] $$DH = DHI + DHS$$

where

$$DHI = [0.09]*[volw]*[DX]$$

volw = the volume of pore water which freezes, and

DX = the increase in frost front growth in the time interval.

0.09 = the volumetric expansion that occurs when water freezes.

$$DHS = [1.09]*[v]*[Dt]$$

v = [SP]*[grad(T)] = the velocity of arriving water

SP = the segregation potential

grad(T) = the temperature gradient just behind the frost front

Dt = the time interval.

The term volw = 0.34 is, for saturated soil, the soil porosity reduced somewhat to account for the volume of unfrozen pore water.

The segregation potential, SP, is pressure dependent. Konrad and Morgenstern [K & M 1984] showed that for Devon silt

[2] $$SP = SP[0] * \exp(-a*P)$$

where

SP[0] = the segregation potential at zero applied pressure

P = the pressure at the freezing front, and

a = a constant for Devon silt.

Nixon, in a recent report to EMR [Nixon 1983] has shown that the SP of Calgary silt from the test site also follows an exponential pressure dependence.

3.1.2 SEGREGATION POTENTIAL MODEL PARAMETERS

3.1.2.1 The in-situ pore water volume, volw

The porosity of the Calgary silt is about 0.38 and 90 % of the pore water freezes [K & M 1984]. Therefore the parameter volw has the value of about 0.34.

3.1.2.2 The Segregation Potential for Calgary silt

An extensive program of laboratory measurements of the SP for Calgary silt has been undertaken for EMR by Nixon [1984]. The results of his test program are presented in Figures 3.1-1 & 2. It is seen that the pressure dependence does follow an exponential behaviour. The average line drawn on the plot has the parameters

$$SP[0] = 0.00220 \quad [(mm*mm) / (sec*Deg\ C)] \text{ , and}$$

$$a = +0.0042 \quad [\ 1 / (kPa)] \text{ .}$$

Thus

$$SP[P] = (0.00220) * \exp\{-(0.0042) * P(kPa)\} \text{ .}$$

Upper and lower bounds for the segregation Potential, used in the calculations to follow are:

upper bound: SP[P] = (0.00300) * exp {-(0.0049) * P(kPa) } , and

lower bound: SP[P] = (0.00150) * exp {-(0.0034) * P(kPa) } .

Because the average pressure at the base of a frost bulb under a pipeline is of the order of 50 kPa, early frost heave calculations were based on the heave characteristics derived from laboratory tests run at this pressure. The Segregation Potential model calculations in this report are identified by the SP value at 50 kPa. For Calgary silt the 50 kPa values for the above curves are:

average curve:	SP[50] = 0.00178	[(mm*mm) / (sec*Deg C)]
upper bound:	SP[50] = 0.00235	[(mm*mm) / (sec*Deg C)]
lower bound:	SP[50] = 0.00126	[(mm*mm) / (sec*Deg C)]

3.1.2.3 The Pressure at the Freezing Front

The pressure at the freezing front is composed of two components; a) the dead weight of the soil above the base of the frost bulb and b) the uplift resistance to heaving of the pipe and frost bulb.

The soil density is taken to be 2,000 kg/(m*m*m) above the water table and 1,000 kgm/(m*m*m) below the water table. For the first several years of operation the average water table depth was about 1.8 metres. Thus, for the Control section the soil mass per unit area is calculated as

soil above water table	= 1.8*2,000 = 3,600	kg/(m*m)
soil below water table	= 0.2*1,000 = 200	kg/(m*m)
berm after day 440	= 1.5*2,000 = 3,000	kg/(m*m)
frost bulb growth	= DX*1,000 = 1,000*DX	kg/(m*m)

The uplift resistance of the soil above and to the side of the pipe and frost bulb should also be included in calculating the total pressure on the base of the frost bulb. This component can be calculated as the shear resistance of shear planes on both sides of the pipe. This uplift resistance,2T, is given by

[3] 2T = K0 * tan(30 deg.) * gamma * H * H * 9.8

where

KØ = Ø.5 = the coefficient of lateral soil pressure,

tan(3Ø deg.) = Ø.58,

gamma = the average soil density = 1,5ØØ kg/(m*m*m),

H = the average shear plane height, and

9.8 = changes kg/(m*m) to Newtons/(m*m) or Pascals.

This uplift resistance force is then averaged over the width of the base of the frost bulb. For the sections buried at the standard depth, the Control, Gravel and Insulated ones, the shear resistance is calculated at about 4 kPa. For the Deep Burial section it is about 8 kPa.

In the winter the surface soil freezes, thus increasing its strength. However, only about a half metre or less of soil gets as cold as -2 deg. C and it is estimated that the increase in uplift resistance varies from a negligable amount to a few times the summer value,during December, January, February and March. This additional contribution has been omitted in the current estimates, due to the approximate nature of this estimate.

The pressure at the base of the frost bulb, for each of the pipe test sections, is given in Table 3.1.

The test plates, called Plate #7 and Plate # 8, are discussed in Nixon et al.[1982] and Nixon [1982] . They are circular disks, about Ø.8 metres in diameter, buried 3 metres below the ground surface. The uplift resistance force for these plates is thus expected to be quite a bit higher than the above values due to the very different geometries of the plates and long pipe sections. This was seen to be true in pressure readings obtained using Glotzel pressure cells placed just above the test plates [Nixon 1982].

Plate # 7 was placed in a ditch excavated with a backhoe and covered with native soil. The initial pressure readings were close to the estimated soil dead weight, but when heaving started the pressure rose to more then double the overburden value.

Plate # 8, however, was placed in a small augered hole, which was backfilled with no compaction. The initial perssure readings of this plate were only about half the soil dead weight value as calculated for Plate # 7, due to soil arching effects in the small augered hole (private communication from Nixon, 1982).

The pressure time histories, used in this study, for these two plates is presented in Table 3.2.

3.1.2.4 The Temperature Gradient

In keeping with the spirit of simplicity, the temperature gradient can be calculated as the pipe temperature, Tp, (Deg. C below freezing) divided by the frost bulb thickness below the pipe. However, because the temperature profile below the pipe is curved, not a straight line, better results are obtained if a fraction of the temperature is used to calculate the temperature gradient. This is shown in calculations on the Control section. Both of these procedures lead to excessively high gradients initially, when the frost bulb depth is very small. The temperature gradient value was therefore limited in order to obtain better agreement with the observed Control section heave.

In order to obtain a better understanding of the application of the Segregation Potential model further calculations were undertaken using the observed temperature gradients from Carlson [1984].

3.1.2.5 The Frost Bulb Growth Below the Pipe

The base studies in this report were carried out using a frost bulb growth which closely follows the observed behavior. The depth of the frost bulb below the base of the pipe was parameterized using power formulae as:

[4] Depth = (A) * ([time] to the power P)

where

A and P are constants derived by fitting a power curve to the field data.

It was found, in general, that the frost bulb depth time history could be broken into three sections, represented by two power curves followed by a final constant depth. The parameters used for the various test sections are given in Tables 3.3, 3.4 and 3.5.

3.2 ICE SEGREGATION RATIO MODELS

3.2.1 MODEL DESCRIPTION

During the late 1970's Foothills Pipe Lines was developing an empirical frost heave model based on the ice-segregation ratio model. The early form of these emperical models is given in Hwang [1977a] and a more refined version in Carlson et. al. [1982].

In the ice segregation ratio model, when soil freezes

[5] Heave = [ISR] * [Frost Penetration Depth]

where

ISR = the ice segregation ratio.

The ISR is defined, for a frozen soil sample, as the total thickness of ice in the frozen sample divided by the overall thickness of the frozen soil sample. The ISR values range from 0.0 upto 1.0.

Carlson et. al. [1982] use an incremental ice segregation ratio, DISR, concept, where the heave is calculated as the sum of a series of incremental heaves. The incremental heave of a thin soil layer is calculated as

[6] DH = [DISR] * [DX].

They indicate that the incremental ice segregation ratio, for a given soil type, can be defined as a function of two parameters; firstly, the frost penetration rate, and secondly the pressure at the frost front. The total heave is now calculated as

[7] $$\text{HEAVE} = \sum [DH] = \sum [DISR(dx/dt, P)]*[DX].$$

3.2.2 DISR MODEL PARAMETERS

3.2.2.1 Frost Penetration Rate Dependence

It is necessary to know the function DISR(dx/dt, P) before a calculation can be undertaken. Figures 3.2-1 & 2 present DISR values as a function of dx/dt, as derived from the various field test sections and laboratory tests [see Carlson et al 1982]. The calculations to follow use the parameterization

[8] DISR = [A] * ([dx/dt] raised to the power B),

where A and B are constants for a given soil type. Several curves are shown on the Figure. This parameterization is somewhat arbitrary and others could be used.

3.2.2.2 Pressure Dependence

Laboratory frost heave tests have shown that the pressure dependence of the incremental ice segregation ratio can be approximated by an exponential curve. We have

[9] DISR(dx/dt, P) = [DISR(dx/dt, 0)]*[exp(-C*P)]

where

C is a constant.

This is, of course, a similar pressure dependence as for the segregation Potential of section 3.1.1.

3.2.2.3 The Frost Bulb Growth Below the Pipe

The frost bulb growth below the pipe is represented in the identical manner as described for the Segregation Potential model.

4.0 HEAVE CALCULATIONS USING THE SEGREGATION POTENTIAL MODEL

4.1 THE NONINSULATED SECTIONS

This section deals with frost heave calculations using the Segregation Potential, SP, model as described in section 3.1. The Segregation Potential values for Calgary Silt obtained in the lab tests by Nixon [1984] have been used as the basis for these calculations. These values were presented in section 3.1.2.2.

4.1.1 Calculations using the Experimental grad(T)

The first set of heave calculations uses a temperature gradient at the base of the frost bulbs which is derived from the values obtained at each test section. The procedure used to arrive at these values for the centre line of the frost bulb, i. e. directly below the pipes, from the temperature strings spaced one metre away, is discussed in Appendix 1.

The calculated heave, shown in Figures 4.1-1 to 4.1-4, is thus based on soil parameters obtained in lab tests, or from field measurements.

The heave calculations and observed heave for the Control section are seen in Figure 4.1-1. The Segregation Potential calculations use the average and upper limit values for Sp. The upper limit calculation, SP[50] = 0.00235, is seen to be in very good agreement with the observed heave data points.

For the Deep Burial section, Figure 4.1-2 shows that the observed data falls between the average and lower limit curves. A Sp value about 10% below the average value, i.e. SP[50] = 0.00160 leads to good agreement with the data points.

For the Gravel section, Figure 4.1-3 shows good agreement between the calculations using the average and lower limit curves, for the first 24 months. A Sp value about 10% below the average value,i.e. SP[50] = 0.00160 as with the Deep Burial section, leads to good agreement with the data points, during this time span. The drop off in the observed heave, after 20 months, is not predicted by the current calculations. This observed drop off in the frost heave is probably due to the seasonal fluctuations in the actual temperature gradient at the base of the frost bulb. The calculations used an average value for the temperature gradient and therefore they do not show the seasonal variations.

For the Restrained section, Figure 4.1-4 shows the lack of agreement between the calculation using the lower limit curve and the data points. The calculated values are thirty % higher than the data

point values. Indeed, the calculation using Sp[50] = 0.00090 is in good agreement with the data.

4.1.2 Calculations using grad(T) = 0.5*(Tp / X).

Data on the temperature gradients in the frost bulb will generally not be available. It is thus informative to test out Segregation Potential model calculations which use a mathematical estimate of the temperature gradient based on the pipe temperature, Tp, and the frost bulb depth,X. The simplest approach would be to set

$$grad(T) = Tp / X .$$

However, this assumption leads to temperature gradients which are very large, especially during the initial freezing period, when the frost bulb is still very small. Also, during the initial freezing period, the pipe will generally not have reached the long term temperature value, and therefore this formulae will overestimate the actual gradient. For these reasons, an upper limit is placed on the initial values of grad(T).

In order to arrive at a more representative formula, calculations were undertaken using both the Hardy Associates Limited (HAL) thermal simulator [Nixon & Halliwell 1982] and the Quasi static model [Hwang 1977b]. This study is discussed in Appendix 2. The study concluded with the assumption that

[10] $$grad(T)\ [@\ t=0.1\ C] = (0.5) * (Tp /X)$$

gives a reasonable, and easy to use value for grad(T). The effective temperature, Teff, for non-insulated pipe sections, is thus given by

[11] $$Teff = (0.5) * Tp$$

and

[12] $$grad(T)\ [@\ t=0.1\ C] = (Teff / X).$$

Control section calculations using eq 12 for grad(T) are presented in Figure 4.1-5. Both of the calculations shown used an upper limit to grad(T). The top curve is for grad(T) < 50 Deg. C per metre and the lower one for grad(T) <10 Deg. C per metre. The two calculations use Sp[50] = 0.00235, the upper limit value. The grad(T) <10 calculation is a good representation of the data points, being only about 10 % high. The model parameters used for this calculation and those for the other pipe sections are given in Table 4.1.

Similar calculations for the Deep Burial, Gravel and Restrained sections are seen in Figures 4.1-6, 4.1-7 and 4.1-8

respectively. These latter calculations, which all use the limit grad(T) < 10, are only about 10 % above the calculated heave results obtained using the observed temperature gradients. This simple approximation for grad(T), with an upper limit to it's initial values, is seen to give very reasonable frost heave results in this simple calculation of the frost heave produced by the operation of a chilled pipeline.

4.2 THE INSULATED SILT SECTION

Frost heave calculations using the Segregation Potential model have been made for the Insulated Silt test section.

4.2.1 Calculations using the Experimental grad(T)

The observed temperature gradients directly below the Insulated Silt test section are given in Appendix 1 for the 1980-81 and 1981-82 winters. These values were derived from the thermistor strings directly below the pipe.

Figure 4.2-1 shows the results of the 1980-81 season heave calculations using Sp[50] values of 0.00070 and 0.00080. These curves compare favourably to the heave data points during the last half of this 180 day heave period, but they overpredict the initial heave.

Figure 4.2-2 shows the 1981-82 season heave calculation results, again for Sp values of 0.00070 and 0.00080. These results, although slightly low for the first month, are in very good agreement with the observed heave values.

The time histories of the Insulated Silt section heave and frost penetration, as determined from the temperature measurements, are presented in Figure 4.2-3. During the 1981 summer [days 850 - 950] the frost bulb around this section thawed back completley.

The temperature readings at the base of the pipe went negative, indicating frost bulb growth, about day 940. However, although the temperature measurements indicated frost bulb growth,the pipe continued to settle slowly and did not begin to heave again until day 1020, about 80 days later.

A discussion of this seeming discrepency is in order. Due to the fact that these temperature strings were installed through the pipe [see Figure 2.4-3 of Carlson 1984], thus creating a thermal leak in the insulation coating at the position of the temperature string, the initial frost bulb growth curve may not be representative of the overall behaviour of this pipe section. With this in mind, calculations were run using the modified frost bulb growth curve,

also shown on Figure 4.2-3. The effect of reducing the temperature gradient by 33 % during the initial freezing period is seen in Figures 4.2-4 and 4.2-5. Somewhat higher Sp values of 0.00080 and 0.00100 are now required to match the data.

4.2.2 Calculations using grad(T) = (Teff / X).

For each freezing cycle, the temperature at the outside of the insulated pipe cycles from a positive or close to zero (Deg. C) value to a minimum value about two months later and then it starts to warm up slowly over the next several months. This behaviour is seen in Figure 2.6-29 of Carlson [1984]. A thermal simulator program would have to be run to estimate the ground temperature just outside the insulation.

Figures 4.2-6 and 4.2-7 show results of heave calculations for the 1980-81 and 1981-82 heave seasons. These calculations used Teff values of -2.0 and -2.5 Deg. C.

4.3 THE TEST PLATES

Data on the temperature gradients for the first freezing period, 1979-80, is presented in Apendix 1, and the frost bulb growth parameters are given in Table 3.5.

4.3.1 Calculations using the Experimental grad(T)

Plate #7 Segregation Potential model heave calculations for SP[50] values of 0.00060 and 0.00080 are seen in Figure 4.3-1. The agreement between the data and SP[50] = 0.00060 curve is very good for the whole time period. It should be noted that the flat nonheaving period about day 40 was due to a mechanical failure of the cooling system.

The Plate #8 calculation results are seen in Figure 4.3-2. These results are also for SP[50] = 0.00060 and 0.00080. Although the general magnitude of the predicted heave agrees with the data, the calculated values fall below the data during the early heave period and have too large a slope (heave rate) during the later period. The low heave rate after day 60 may be due to a local change in the soil properties as indicated by the rapid dropoff in slope of the H-X curve of Figure 2.3-3 for X > 40 cm.

4.3.2 Calculations using grad(T) = (Teff / X).

An analysis of the plate and ground temperature profiles lead to the assumption that the effective temperature in the grad(T)

formulae be approximated as:

[13] $$Teff = (0.8) * Tp ;$$

thus,

[14] $$grad(T) = (0.8) * (Tp / X).$$

The multiplying factor in eq. 13 for the circular test plates is 60 % higher than the corresponding factor in eq. 11 for a long pipe section.

Calculations were run for the plates. Plate # 7 had an effective temperature, Teff, between -3.5 to -4 Deg. C, while for Plate # 8 Teff varied between -3 and -3.5 Deg. C. Average values were chosen for the runs, giving Teff = 3.0 for Plate # 7 and Teff = 2.6 for Plate # 8. Results of these calculations are seen in Figures 4.3-3 and 4.3-4.

5.0 HEAVE CALCULATIONS USING THE ICE SEGREGATION RATIO MODEL

An incremental ice segregation ratio, DISR, function was discussed in section 3.2.2, and the functional form was given in eq. 8. as

DISR = [C3] * ([dx/dt] raised to the power -[C4]).

This section discusses the results of the DISR calculations for the pipe and plate sections. The calculations cover the parameter C3 range from 50 downto 20.

5.1 THE NON-INSULATED SECTIONS

Control section results for parameter values of C3 = 50, 45 and 40, and C4 = 0.4, 0.5 and 0.6 are presented in Figures 5.1-1a and 5.1-1b. The parameter range which gives good agreement to the data is discussed in section 6.

Deep Burial section results for parameter values of C3 = 45 and 40, and C4 = 0.4, 0.5 and 0.6 are presented in Figures 5.1-2. The parameter range which gives good agreement to the data is discussed in section 6.

Gravel section results for parameter values of C3 = 35 and 30, and C4 = 0.4, 0.5 and 0.6 are presented in Figures 5.1.3. The parameter range which gives good agreement to the data is discussed in section 6.

Restrained section results for parameter values of C3 = 30, 25 and 20, and C4 = 0.4, 0.5 and 0.6 are presented in Figures 5.1-4. The parameter range which gives good agreement to the data is discussed in section 6.

5.2 THE INSULATED SILT SECTION

DISR model calculations are presented in Figures 5.2-1 to 5.2-4 for the heave seasons 1978-79, 1979-80, 1980-81 and 1981-82. For the first three heave-thaw cycles, C3 parameters of 20 to 25 % give reasonable agreement with the heave data, but for the 1981-82 cycle which followed the complete thawback of this section, 5 % higher values of 25 to 30 % are required to match the data. A C4 = 0.5 value was used for these calculations.

5.3 THE TEST PLATES

DISR model calculations for the two test plates are presented in Figures 5.3-1 and 5.3-2. The Plate # 7 calculation used the parameter values C3 = 40 % and 45 %, and C4 = 0.05, and that for Plate # 8 used the slightly higher values of C3 = 45 % and 50 %, along with C4 = 0.5.

6.0 SUMMARY OF THE HEAVE CALCULATIONS

Table 6.1 presents the range of SP[50] values for all of the test sections.

For the non-insulated sections, the soil at the Control section is the most frost susceptible followed sequentially by the Deep Burial, Gravel and Restrained sections. The Insulated Silt section SP[50] value is similar to the Restrained section value. The SP[50] values for the two plates are also at the low end of the frost susceptability range, similar to the Insulated Silt and Restrained section values.

A plot of the DISR model parameter range which gave good agreement with the Non-insulated section heave data is seen in Figure 6.1-1. The ranges of C3 values, with C4 = 0.5, are also presented in Table 6.1, along with the corresponding C3 values for the Insulated Silt and Plate sections.

The relative frost susceptibility of the Non-insulated sections, in this DISR model, is similar to that for the Segregation Potential model. Also, as in the SP model, the Insulated Silt section C3 value is at the low end, similar to that for the Restrained and Gravel sections. However, the C3 value for the Plates is at the higher end with the Control section. In the SP model calculations, the plates were grouped at the low frost susceptibility end, with the Restrained and Insulated Silt sections. The field observations, X vs H plots seen in section 2.3, show that the observed DISR for the plates is similar to that for the Restrained and Insulated Silt sections.

The calculations discussed so far have all used a parameterization of the observed frost bulb growth curve. Calculations presented in the next two chapters will use thermal model predictions of the frost bulb growth in combination with the Segregation Potential frost heave theory.

7.0 COUPLED GEOTHERMAL SIMULATIONS AND FROST HEAVE CALCULATIONS

7.1 THE HAL THERMAL SIMULATOR

Nixon [1982] in his paper " Field frost heave using the segregation potential concept " has carried out a frost heave calculation for the Calgary test plate #7, using the Konrad-Morgenstern theory of frost heave. He also used his Hardy Assosiates Limited , HAL, thermal simulator to calculate the frost bulb growth. The thermal simulator computer program is discussed in Nixon and Halliwell [1982].

Recently, Nixon carried out thermal simulations, for this project, for the Control and Deep Burial sections. The results for the frost bulb growth are presented in Appendix 2. The calculated depths agree very well with the data values up to about day 2000, when the efficiency of the chilled air cooling system began to fall due to water leaking into the air duct and pipe system, leading to a gradual thaw back of the frost bulb.

The corresponding frost heave calculations, based on the Tg=5 Deg. C frost bulb growth and thermal gradient calculation, are presented in Figure 7.1-1. The calculated heave using the upper limit Sp values is in very good agreement with the data, while the average Sp value calculation is about 15 % low.

The analysis of section 4.1 showed the best agreement with the heave data for SP values slightly below the avarage value. The discrepency between that result and the current preference of the HAL calculation for the upper limit SP values stems from the difference in the long term thermal gradient values in the two calculations. After day 500, the HAL thermal simulator temperature gradients fall well below the observed values as can be seen in the plots of Appendix 1.

A procedure to extrapolate the calculated heave to determine the maximum heave at an infinite time will be presented in chapter 8.

7.2 QUASI-STATIC FROST HEAVE MODEL CALCULATIONS

The application of the Quasi-Static, Q-S, model to the calculation of the frost bulb growth is discussed in Appendix 3. In addition, the Q-S model gives an estimate of the thermal gradient at the base of the frost bulb. Using this estimate of the thermal gradient, a frost heave calculation using the Segregation Potential model can be undertaken. It is also possible to use a calculated temperature gradient, grad(T) = (Teff/X), as was done in section 4.2.2. Calculations have been carried out using both procedures.

Figure 7.2-1 shows the heave data for the Deep Burial section, as well as the calculated heave using the two procedures outlined above. The heave calculated using the Q-S temperature gradient is higher then that calculated using the formulae grad(T)=Tp/2X, for the first 3,000 days.

Both of the above calculated heave curves have slopes, or heave rates, which are much too high after day 2,000. The heave rate can be reduced by using an effective pipe temperature which decreases with time in the calculation of the temperature gradient. A calculation which uses

$$Teff(days) = Tp * \{0.5 - Time(days)/10,000\}$$

to calculate grad(T)=Teff/X , is seen in Figure 7.2-2. This calculation is in very good agreement with the data up to about day 2,500 when the frost bulb began to thaw back. It is also close to the HAL upper limit SP calculation of section 7.1 up to day 4,000.

A discussion of the extrapolation of the calculated heave to an infinite time is presented in chapter 8.

8.0 LONG TERM HEAVE PREDICTIONS

8.1 A HYPERBOLIC CURVE APPROXIMATION

It is known that a hyperbolic curve of the form

[15] $$H = [Time * Hinf] / [Time + K]$$

where
Hinf = the long term (infinite) heave, and
K = a constant

provides a reasonable fit to the intermediate and long term heave in fixed end-temperature laboratory frost heave tests. This chapter will discuss the application of eq. 15 to predict, in conjunction with the Quasi-static frost heave calculations of chapter 7, the long term frost heave produced by the operation of a buried chilled gas pipeline.

Eq. 15 can be rearranged as

[16] $$[Time/H] = [1/Hinf]*[Time + K].$$

It is seen in eq. 16 that a plot of [Time/H] versus Time will produce a straight line with a slope of [1/Hinf], and an intercept of [K/Hinf]. This property of eq. 16 will be used in the next section.

8.2 DETERMINATION OF LONG TERM FROST HEAVE

Before proceding with the extrapolation of the Quasi-Static model heave calculation of section 7.2, the applicability of this hyperbolic curve to model the observed field data will be assessed. This is best tested by plotting the ratio of the time over the observed frost heave, i.e. [Time/H], against the observed time. This plot, seen in Figure 8.2-1, shows that the data points between days 600 to 2300 do indeed lie in a straight line; therefore the data in this time region can indeed be represented by a hyperbolic curve. The dominent rise in this curve after day 2500 reflects the rapid settlement of the test section following the air duct blockages, as discussed in Carlson [1984]. It is concluded that the hyperbolic curve does fit the observed data after the initial ground freezing period of about two years. A straight line least squares fit to the data resulted in the parameters Hinf = 98.5 cm and K = 1037 days.

Now, the ratio [Time/H] is seen plotted against Time for the Quasi-Static frost heave calculation of section 7.2, in Figure 8.2-2. It is seen that the [Time/H] versus Time curve is linear between days 1,500 and 4,000 and then curves upwards after day 4,000. The least

squares fit shown has the parameters Hinf = 112 cm and K = 1485 days. This long term frost heave value compares very well with the similar value of Hinf = 98.5 for the observed data.

The good agreement between the frost heave as calculated by the Quasi-Static model with a modified time dependent temperature gradient and by the hyperbolic curve derived above is seen in Figure 8.2-3.

A procedure for determining the magnitude of long term frost heave due to the operation of a buried chilled gas pipeline follows from the above calculations.

Firstly, carry out a Quasi-Static thermal model frost heave calculation, which uses a modified time dependent temperature gradient as described in section 7.2. This calculation should go for 4,000 days.

Secondly, plot the calculated values of [Time/H] versus Time and fit a straight line to the latter portion of this curve. The curve should be approximately a straight line beyond day 1,500.

Thirdly, the value of the long term frost heave is determined as the inverse of the slope of the fitted straight line.

9.0 CONCLUSIONS

Frost heave model calculations, presented in chapter 4, of heave at the Calgary Frost Heave Test Facility have shown that the Segregation Potential frost heave model of Konrad and Morgensterm provides a good estimate of the observed frost heave. The initial calculations in this report, using the Segregation Potential values derived from relatively simple laboratory tests, and measured temperature gradients and frost bulb depths, provide a very good estimate of the observed frost heave for the Control, Deep Burial and Gravel pipe sections. The Restrained section heave corresponds to a Segregation Potential value below the lower range of the laboratory test results.

A procedure is presented to calculate the temperature gradient at the frost front, and thus the heave, based on the pipe temperature and the frost bulb depth. This procedure allows the design engineer to carry out initial design calculations in a simple manner before calling upon expensive computer thermal simulator calculations in the final design stage.

The Incremental Ice Segregation Ratio, DISR, model was also used to calculate heave. This engineering model also provides a good estimate of the heave created when a pipeline is operated in the chilled mode. This DISR model has an advantage over the Segregation Potential model in its simplicity of interpretation of field observations.

A computer thermal simulation of ground freezing was carried out for the Control and Deep Burial sections. The good agreement with the data is seen in Appendex 2.

The thermal simulator frost bulb depths and thermal gradient were used to carry out a Segregation Potential model frost heave calculation for the Deep Burial section. The calculated heave here was quite good, but it is less then that calculated in chapter 4, because the thermal simulation temperature gradient is less than the observed values after day 600.

Quasi-Static thermal simulation model frost heave calculations were carried out using the SP frost heave model for the Deep Burial section. These calculations using the model temperature gradients predicts a heave rate which is much too strong after day 2000. However, the frost heave calculation is quite good, when this model is coupled with a modified temperature gradient, which drops off with time.

A procedure is presented for the calculation of the long term frost heave created by the operation of a buried chilled pipeline. This procedure determines the long term frost heave from a simple Quasi-Static model frost heave calculation based on a modified temperature gradient.

10.0 BIBLIOGRAPHY

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TABLES

component of total		CONTROL SECTION	DEEP BURIAL SECTION	GRAVEL SECTION	* RESTRAINED SECTION	INSULATED SECTION
SOIL ABOVE WATER TABLE	[kPa]	36	36	36	-	36
SOIL BELOW WATER TABLE	[kPa]	2	12	2	-	2
SHEAR RESISTANCE	[kPa]	4	8	4	-	4
subtotal		42	56	42	-	42
BERM [after day 440]	[kPa]	30	30	0	-	0
PRESSURE AT BASE OF PIPE	[kPa]	72	86	42	45	42
PRESSURE INCREASE WITH DEPTH	[kPa/m]	10	10	10	28	10

* TAKEN FROM SLUSARCHUK ET AL. 1978

TABLE 3.1 PRESSURE at the FROST FRONT - PIPE SECTIONS

component of total		* PLATE # 7	* PLATE # 8
SOIL ABOVE WATER TABLE	[kPa]	---	---
SOIL BELOW WATER TABLE	[kPa]	---	---
SHEAR RESISTANCE	[kPa]	---	---
subtotal		---	---
BERM [after day 440]	[kPa]	---	---
PRESSURE AT BASE OF PIPE	[kPa]	60	25
PRESSURE INCREASE WITH DEPTH	[kPa/m]	180	110

* BASED ON NIXON 1982

TABLE 3.2 PRESSURE at the FROST FRONT - TEST PLATES

	CONTROL SECTION	DEEP BURIAL SECTION	GRAVEL SECTION	RESTRAINED SECTION
STAGE # 1				
START TIME [MON]	0	0	0	0
END TIME [MON]	1.30	5.00	3.00	3.50
PARAMETER C3	0.52	0.24	0.52	0.52
PARAMETER C4	1.00	0.94	0.67	0.685
STAGE # 2				
START TIME [MON]	1.30	5.00	3.00	3.50
END TIME [MON]	25.1	35	26	22
PARAMETER C3	0.60	0.53	0.71	0.73
PARAMETER C4	0.43	0.45	0.39	0.416
STAGE # 3				
START TIME [MON]	25.1	35	26	22
DEPTH [METRES]	2.40	2.66	2.60	2.65

DEPTH = [C3] * ([MONTHS] to the power [C4])

TABLE 3.3 FROST BULB DEPTH EQUATION PARAMETERS

NON-INSULATED SECTIONS

	INSULATED SILT SECTION 1978-79	INSULATED SILT SECTION 1979-80	INSULATED SILT SECTION 1980-81	INSULATED SILT SECTION 1981 - 82
STAGE # 1				
START TIME [DAYS]	0	0	0	0
END TIME [DAYS]	90	48	140	260
PARAMETER C3	0.336	0.315	0.256	0.154
PARAMETER C4	0.56	0.08	0.677	0.828
STAGE # 2				
START TIME [DAYS]	---	48	---	---
END TIME [DAYS]	---	200	---	---
PARAMETER C3	---	0.247	---	---
PARAMETER C4	---	0.62	---	---
STAGE # 3				
START TIME [DAYS]	90	200	140	260
DEPTH [CM]	62	80	73	91.5

DEPTH = [C3] * ([MONTHS] to the power [C4])

TABLE 3.4 FROST BULB DEPTH EQUATION PARAMETERS

INSULATED SECTIONS

	PLATE # 7	PLATE # 8
STAGE # 1		
START TIME [DAYS]	0	0
END TIME [DAYS]	10	3
PARAMETER C3	0.335	1.575
PARAMETER C4	0.29	1.08
STAGE # 2		
START TIME [DAYS]	10	3
END TIME [DAYS]	110	110
PARAMETER C3	0.305	0.255
PARAMETER C4	0.2	0.29
STAGE # 3		
START TIME [DAYS]	---	---
DEPTH [CM]	---	---

DEPTH = [C3] * ([MONTHS] to the power [C4])

TABLE 3.5 FROST BULB DEPTH EQUATION PARAMETERS

PLATES # 7 & # 8

FIGURE #	SECTION	SP[50]	Teff	grad(T)
4.1-1	CONTROL	UL AVG	-----	OBSERVED FIELD DATA
4.1-2	DEEP BURIAL	AVG 160 LL	-----	OBSERVED FIELD DATA
4.1-3	GRAVEL	AVG 160 LL	-----	OBSERVED FIELD DATA
4.1-4	RESTRAINED	LL 90	-----	OBSERVED FIELD DATA
4.1-5	CONTROL	UL UL	-4.75 -4.75	<50 <10
4.1-6	DEEP BURIAL	160	-4.75	<10
4.1-7	GRAVEL	160	-4.75	<10
4.1-8	RESTRAINED	90	-4.75	<10

UL SP[50] = 235 (0.000 01*mm*mm) / (sec*Deg C)
AVG SP[50] = 178 (0.000 01*mm*mm) / (sec*Deg C)
LL SP[50] = 126 (0.000 01*mm*mm) / (sec*Deg C)

TABLE 4.1 SEGREGATION POTENTIAL MODEL PARAMETERS
NON-INSULATED PIPE SECTIONS

FIGURE #	SECTION	SP[50]	Teff	grad(T)
4.2-1	INSULATED SILT 1980-81	70-80	-----	OBSERVED FIELD DATA
4.2-2	INSULATED SILT 1981-82	70-80	-----	OBSERVED FIELD DATA
4.2-3	INSULATED SILT 1980-81	80-100	-----	REDUCED FIELD DATA
4.2-4	INSULATED SILT 1981-82	80-100	-----	REDUCED FIELD DATA
4.2-5	INSULATED SILT 1980-81	70	-2.0	<10
4.2-6	INSULATED SILT 1981-82	70	-2.0 -2.5	<10

TABLE 4.2 SEGREGATION POTENTIAL MODEL PARAMETERS
INSULATED PIPE SECTIONS

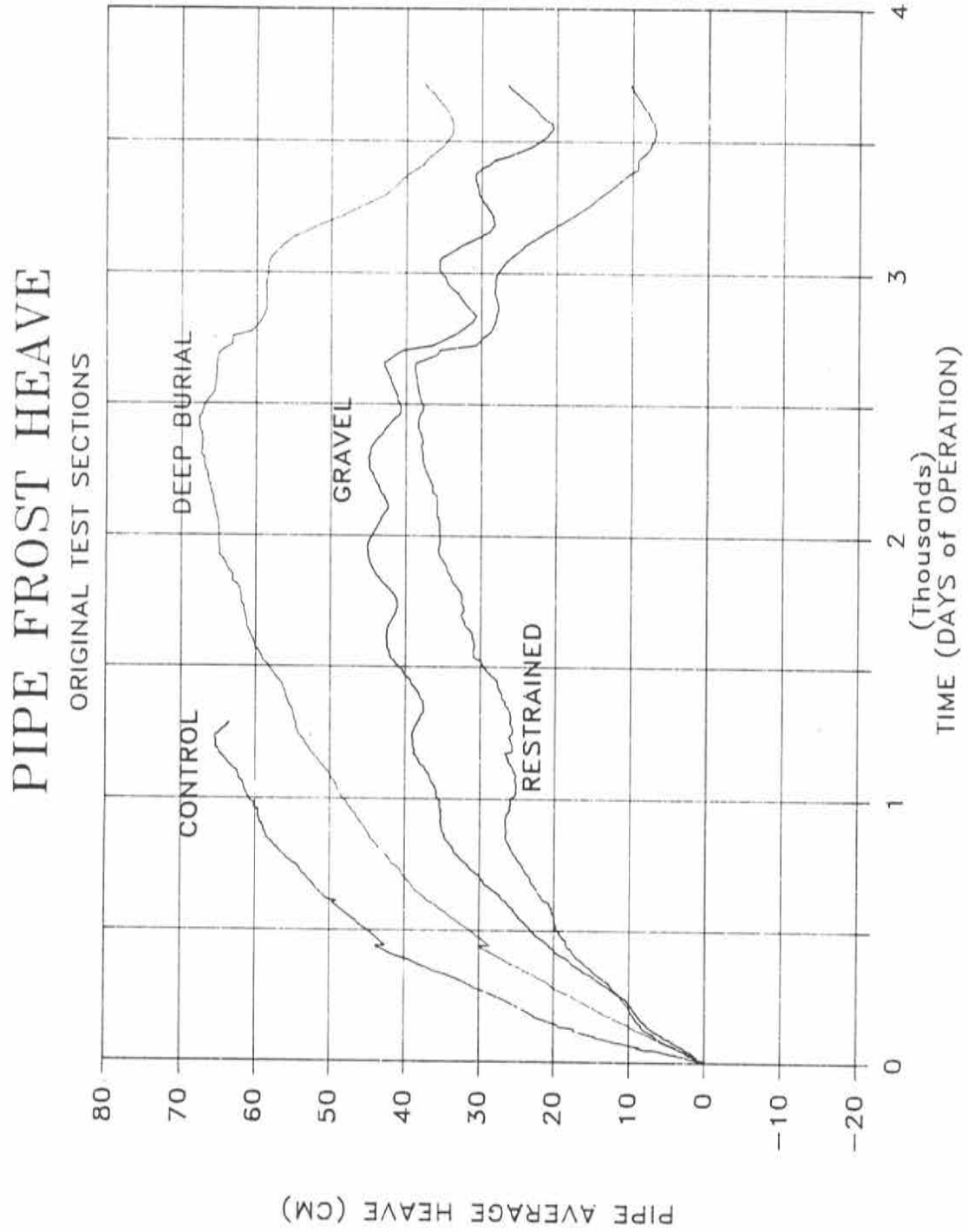
FIGURE #	SECTION	SP[50]	Teff	grad(T)
4.3-1	PLATE #7	60-80	----	OBSERVED FIELD DATA
4.3-2	PLATE #8	60-80	----	OBSERVED FIELD DATA
4.3-3	PLATE #7	60-80	-3.0	<40
4.3-4	PLATE #8	60-80	-2.6	<40

TABLE 4.3 SEGREGATION POTENTIAL MODEL PARAMETERS
PLATES #7 & #8

SECTION	SP MODEL SP[50]	DISR MODEL C3
CONTROL	230-240	43-53
DEEP BURIAL	150-170	41-42
GRAVEL	140-160	28-33
RESTRAINED	80-100	24-28
INSULATED SILT	70-100	20-30
PLATES #7 & #8	60- 80	40-50

TABLE 6.1 FROST HEAVE MODEL PARAMETER RANGE

FIGURES



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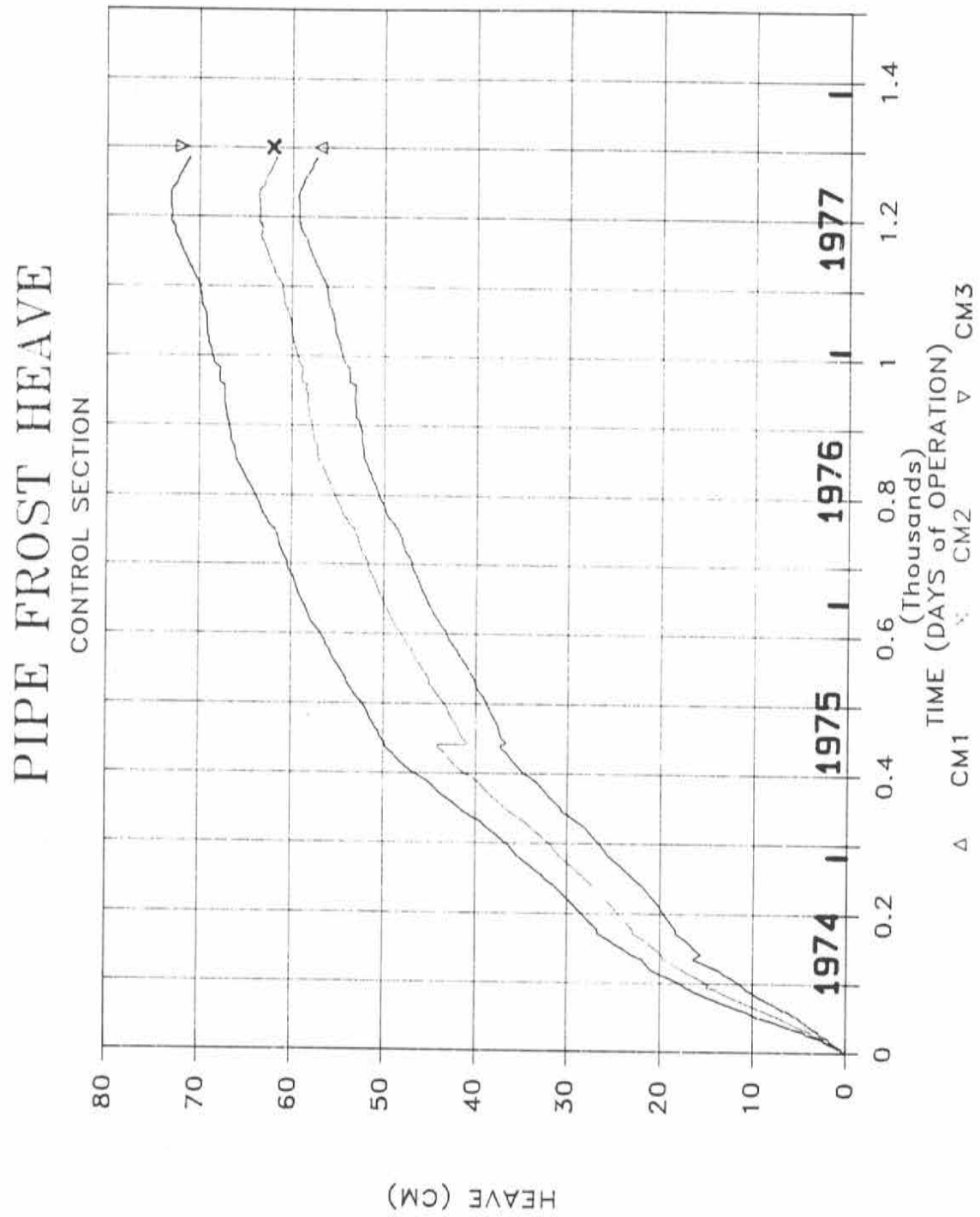
CALGARY FROST HEAVE TEST FACILITY

PIPE FROST HEAVE

CONTROL, DEEP BURIAL, GRAVEL and RESTRAINED SECTIONS

FIGURE 2.1-1



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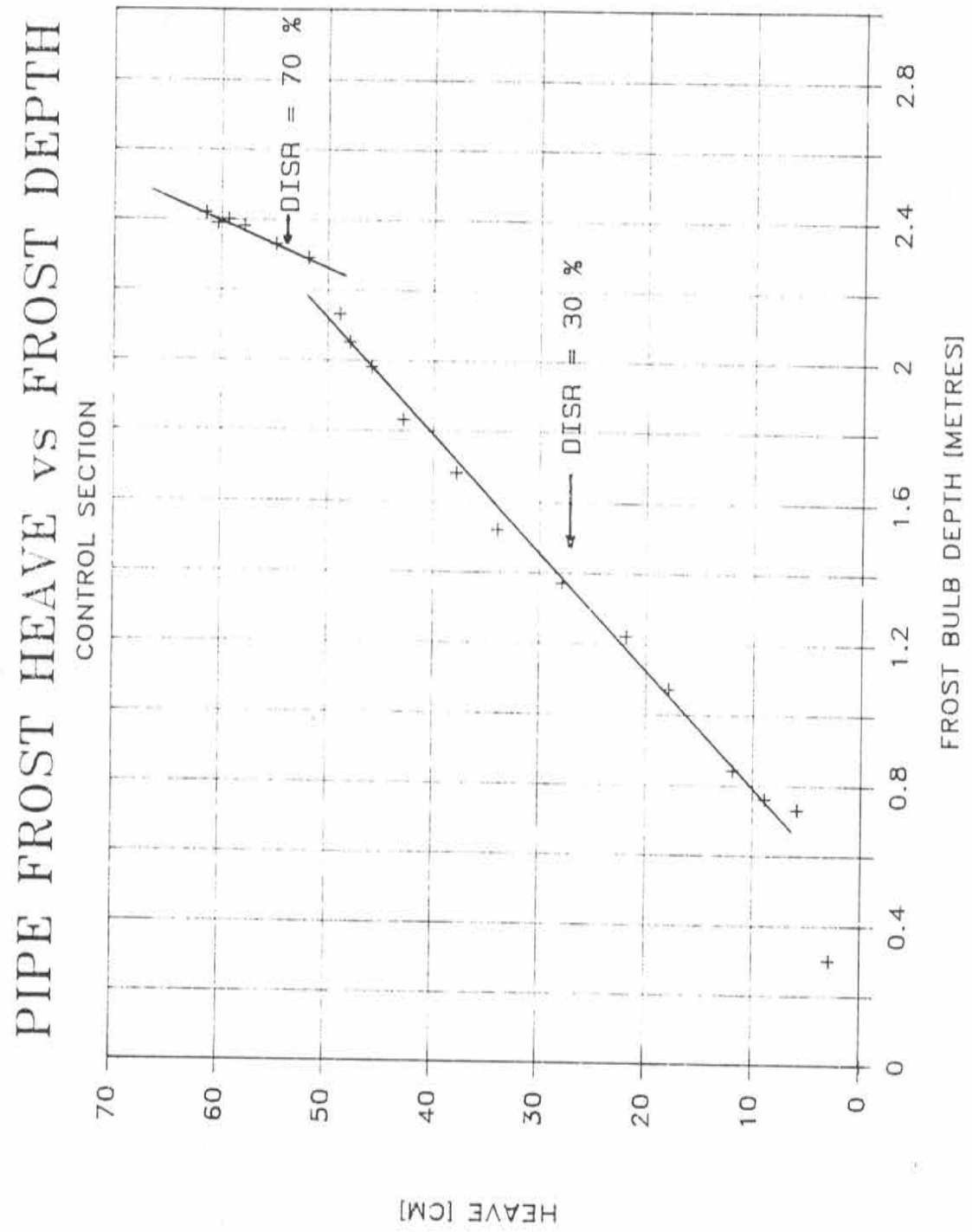
CONTROL SECTION

PIPE FROST HEAVE

FIGURE 2.1-2



after CARLSON et. al. [1982]

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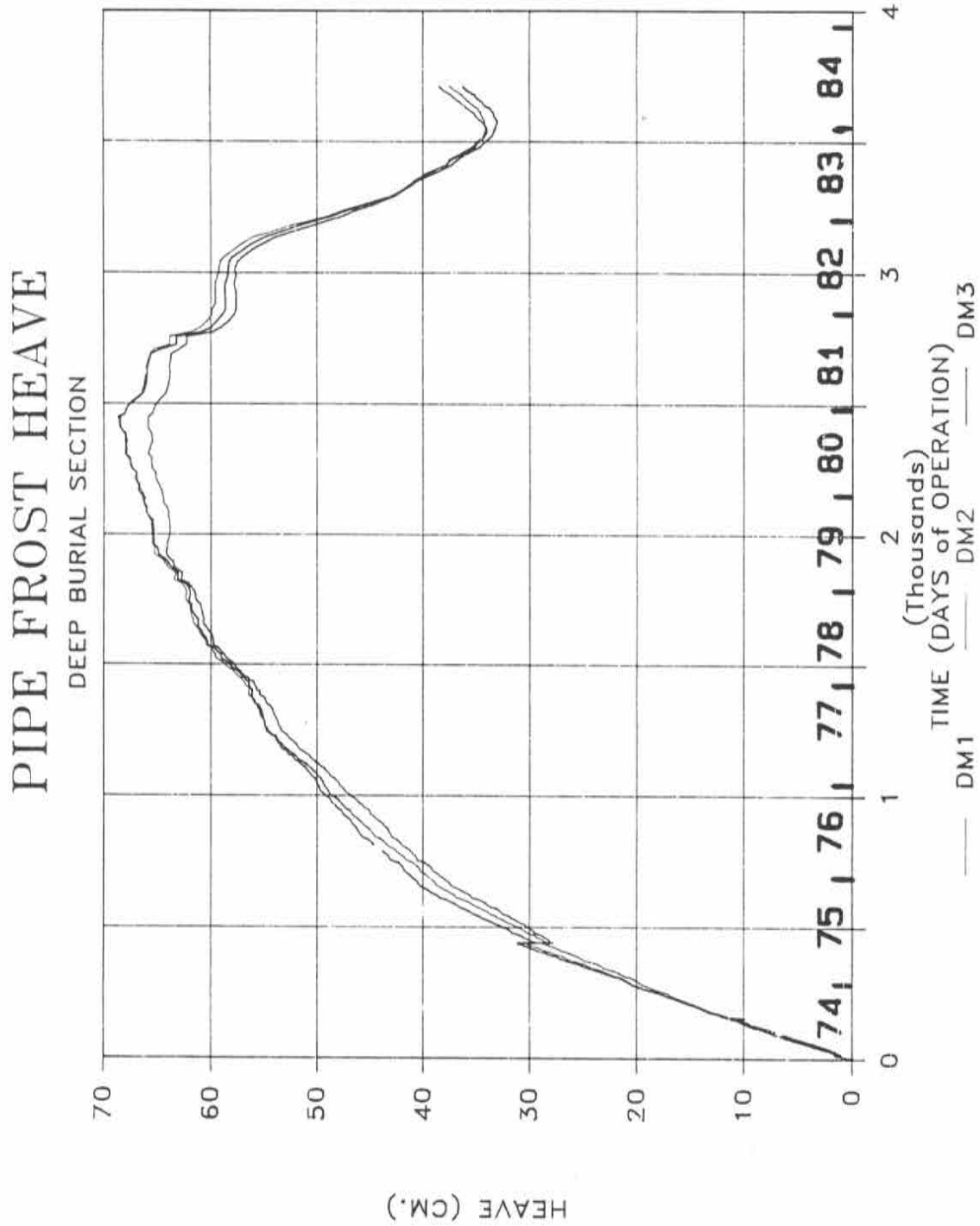
CONTROL SECTION

PIPE FROST HEAVE

VS

FROST BULB DEPTH

FIGURE 2.1-3



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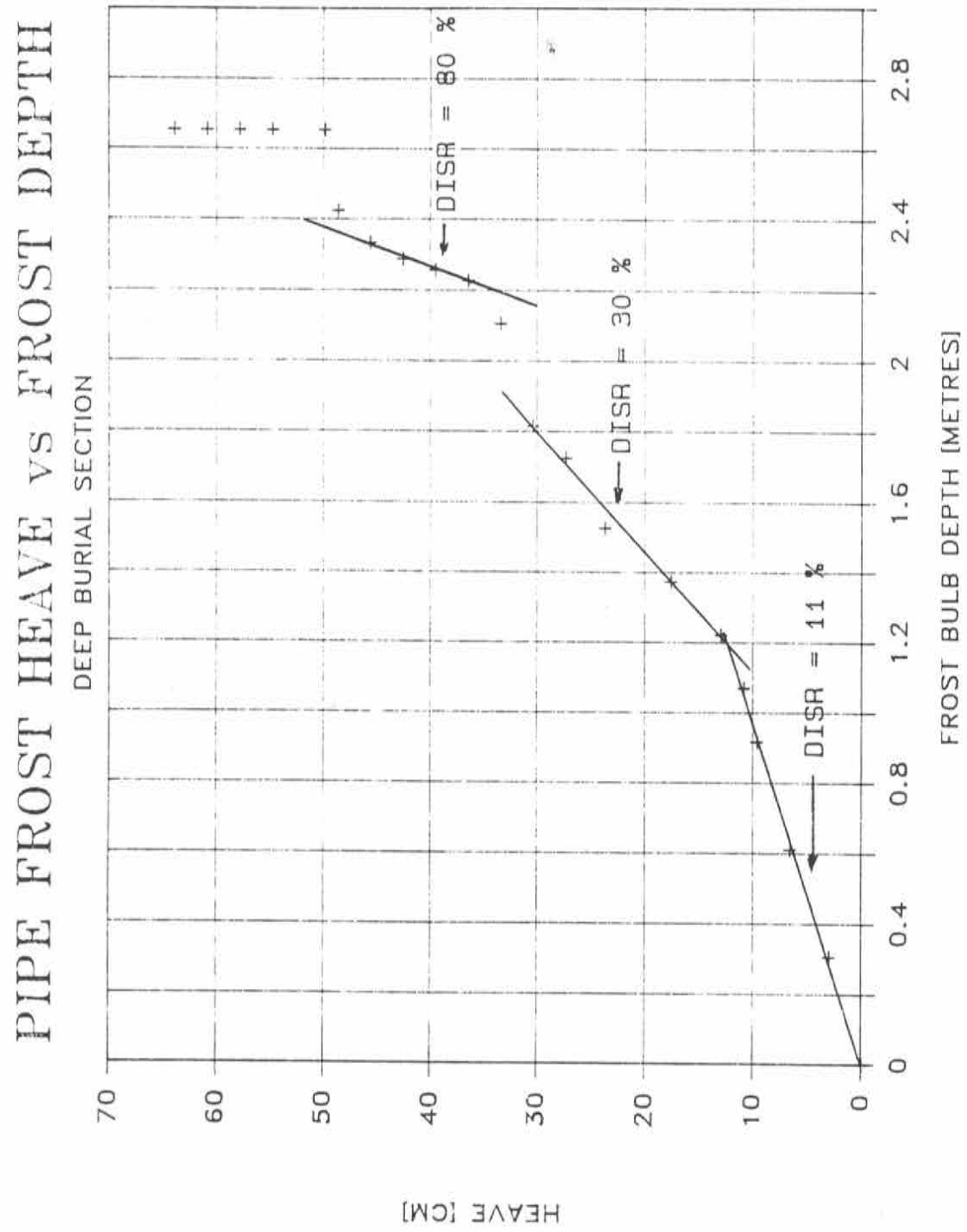
DEEP BURIAL SECTION

PIPE FROST HEAVE

FIGURE 2.1-4



after CARLSON et. al. [1982]

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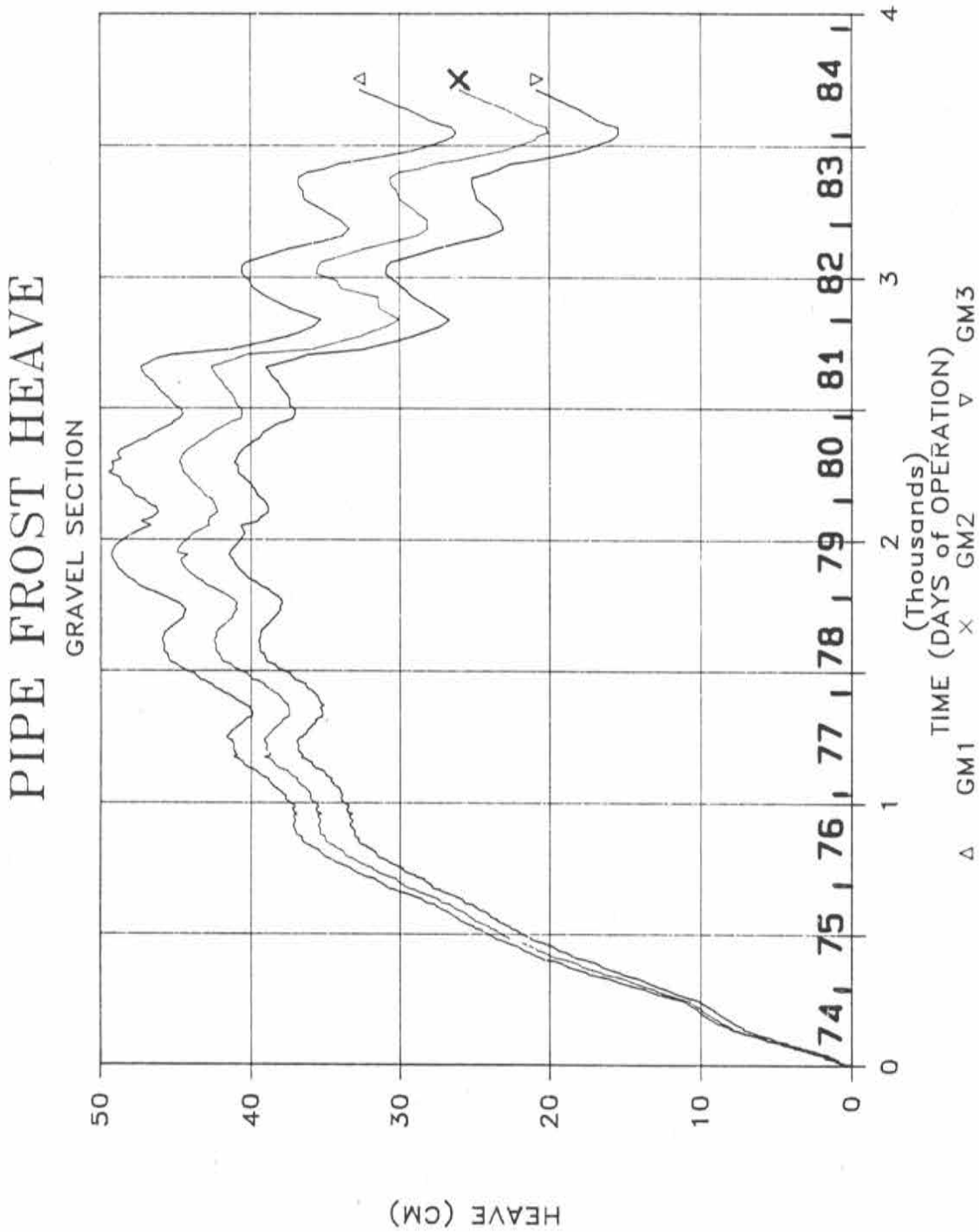
DEEP BURIAL SECTION

PIPE FROST HEAVE

VS

FROST BULB DEPTH

FIGURE 2.1-5



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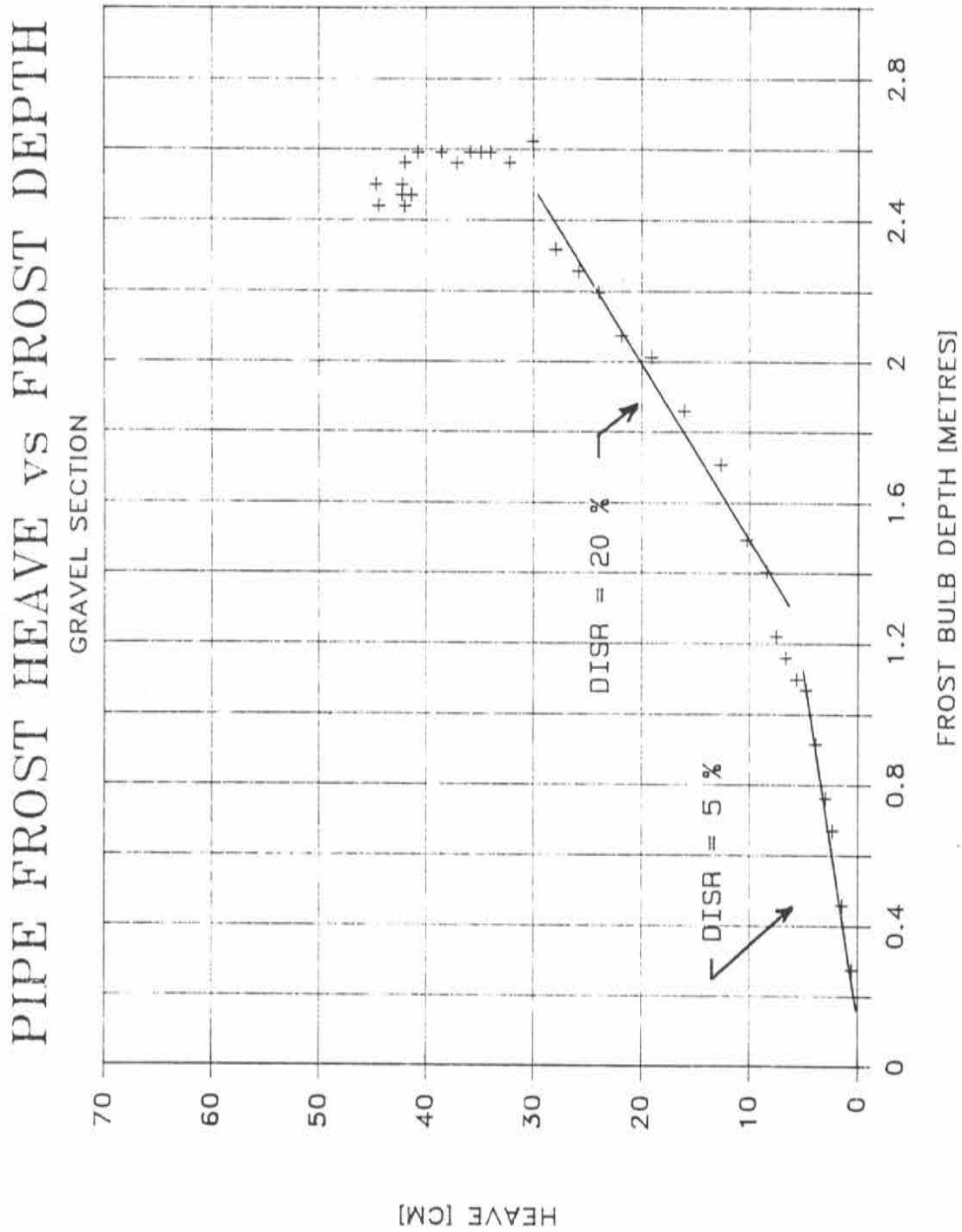
GRAVEL SECTION

PIPE FROST HEAVE

FIGURE 2.1-6



after CARLSON et. al. [1982]

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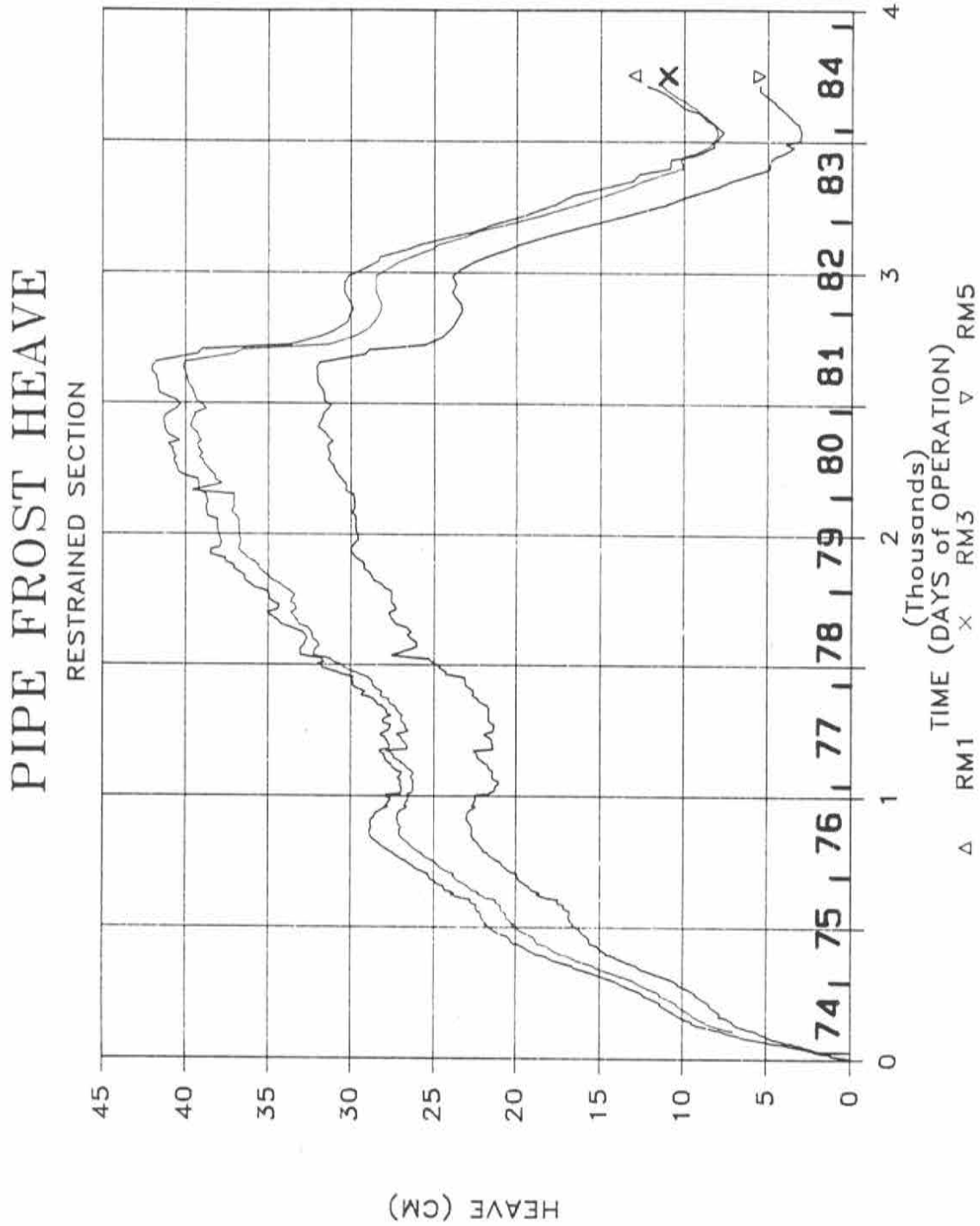
GRAVEL SECTION

PIPE FROST HEAVE

vs

FROST BULB DEPTH

FIGURE 2.1-7



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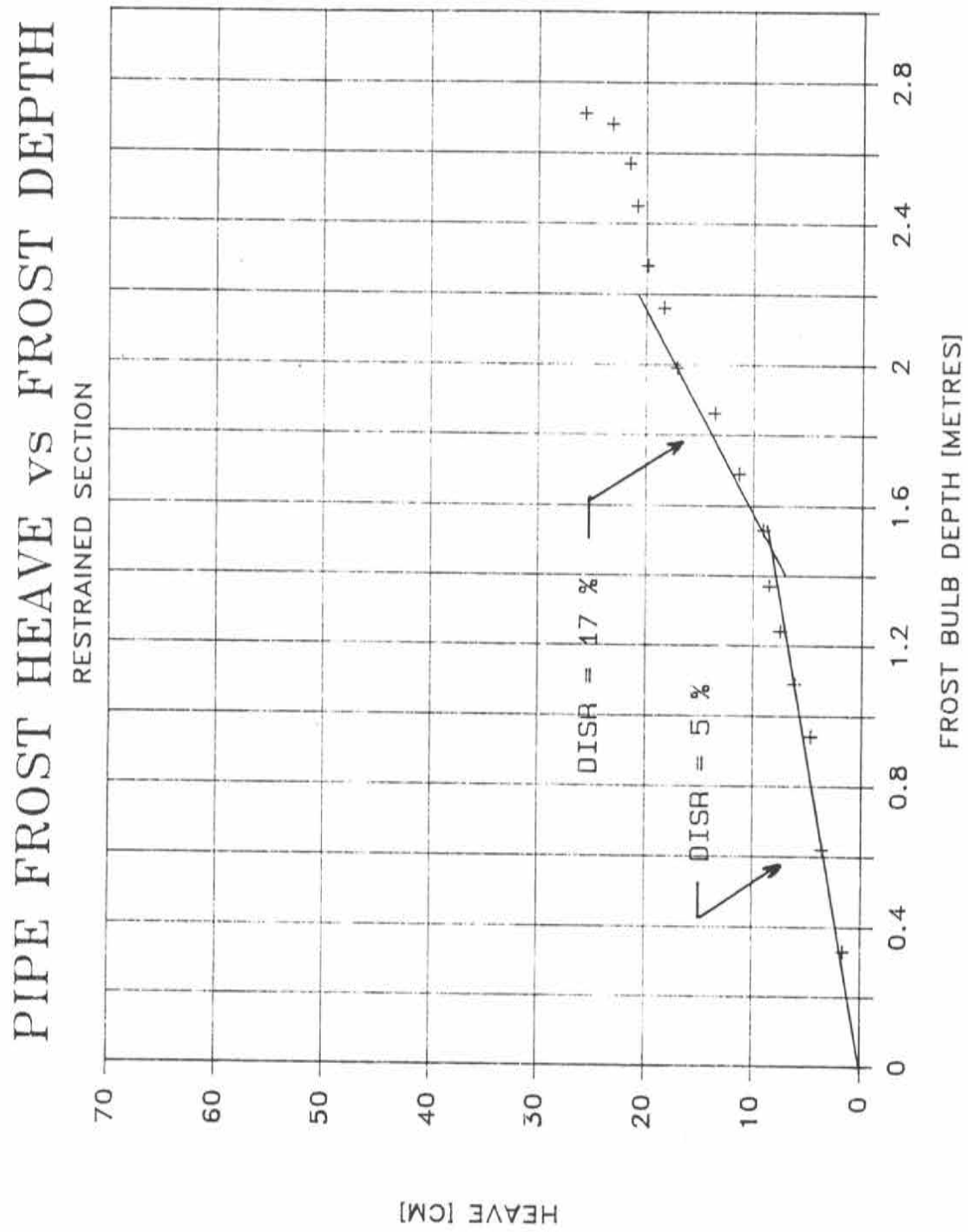
RESTRAINED SECTION

PIPE FROST HEAVE

FIGURE 2.1-8



after CARLSON et. al. [1982]

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CALGARY FROST HEAVE TEST FACILITY

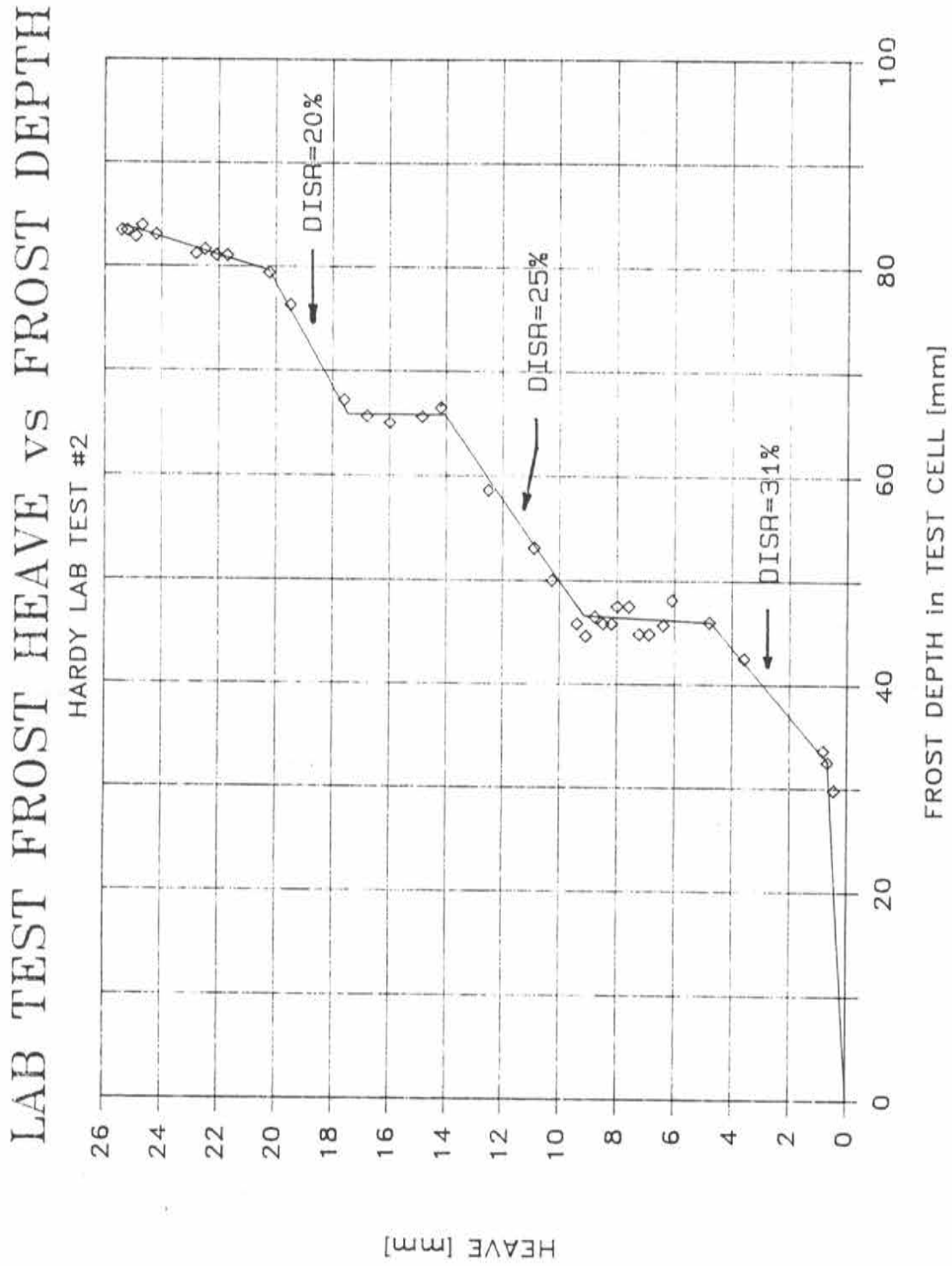
RESTRAINED SECTION

PIPE FROST HEAVE

VS

FROST BULB DEPTH

FIGURE 2.1-9



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CALGARY FROST HEAVE TEST FACILITY

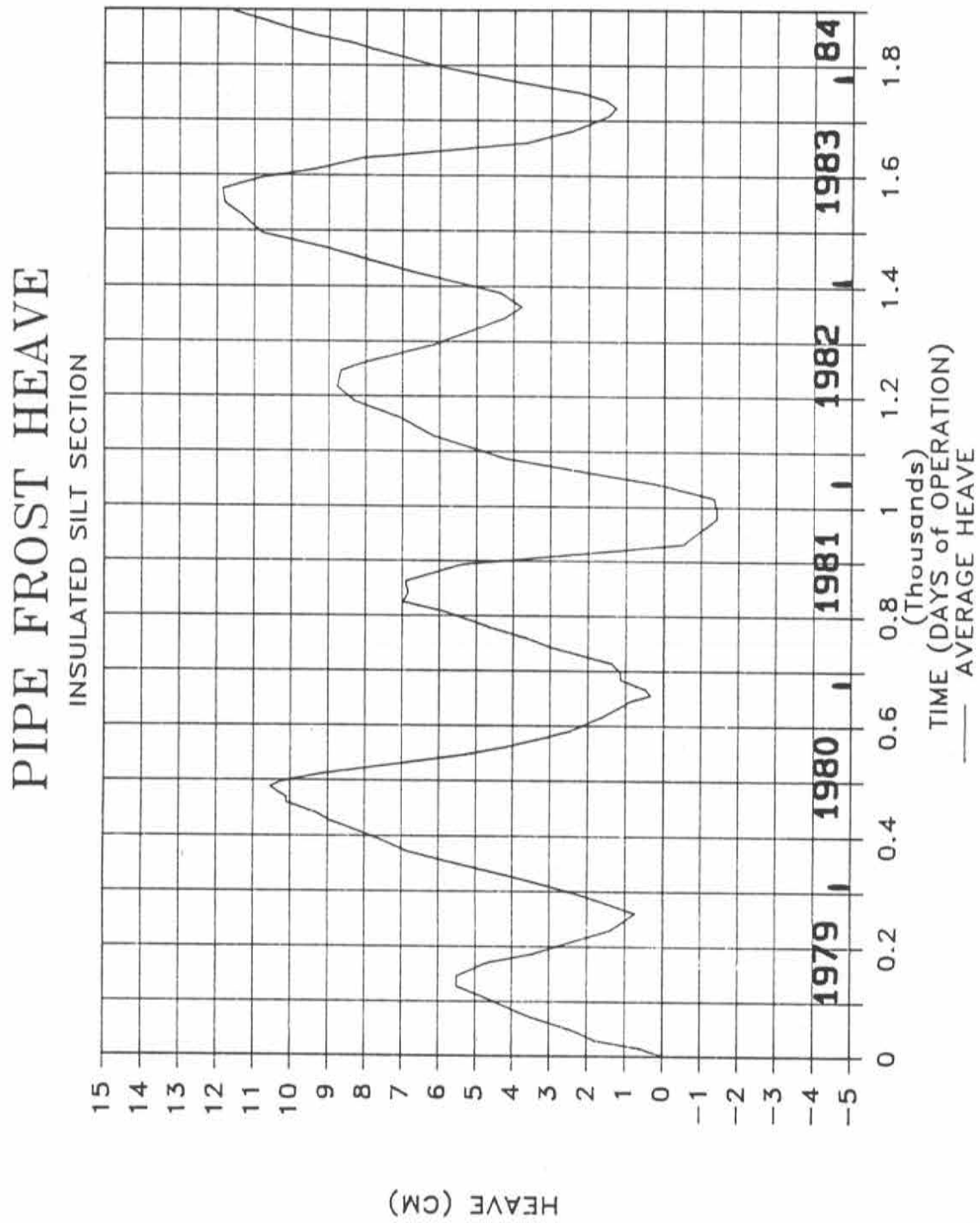
LABORATORY TEST #2

HEAVE

VS

FROST DEPTH

FIGURE 2.1-10



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CALGARY FROST HEAVE TEST FACILITY

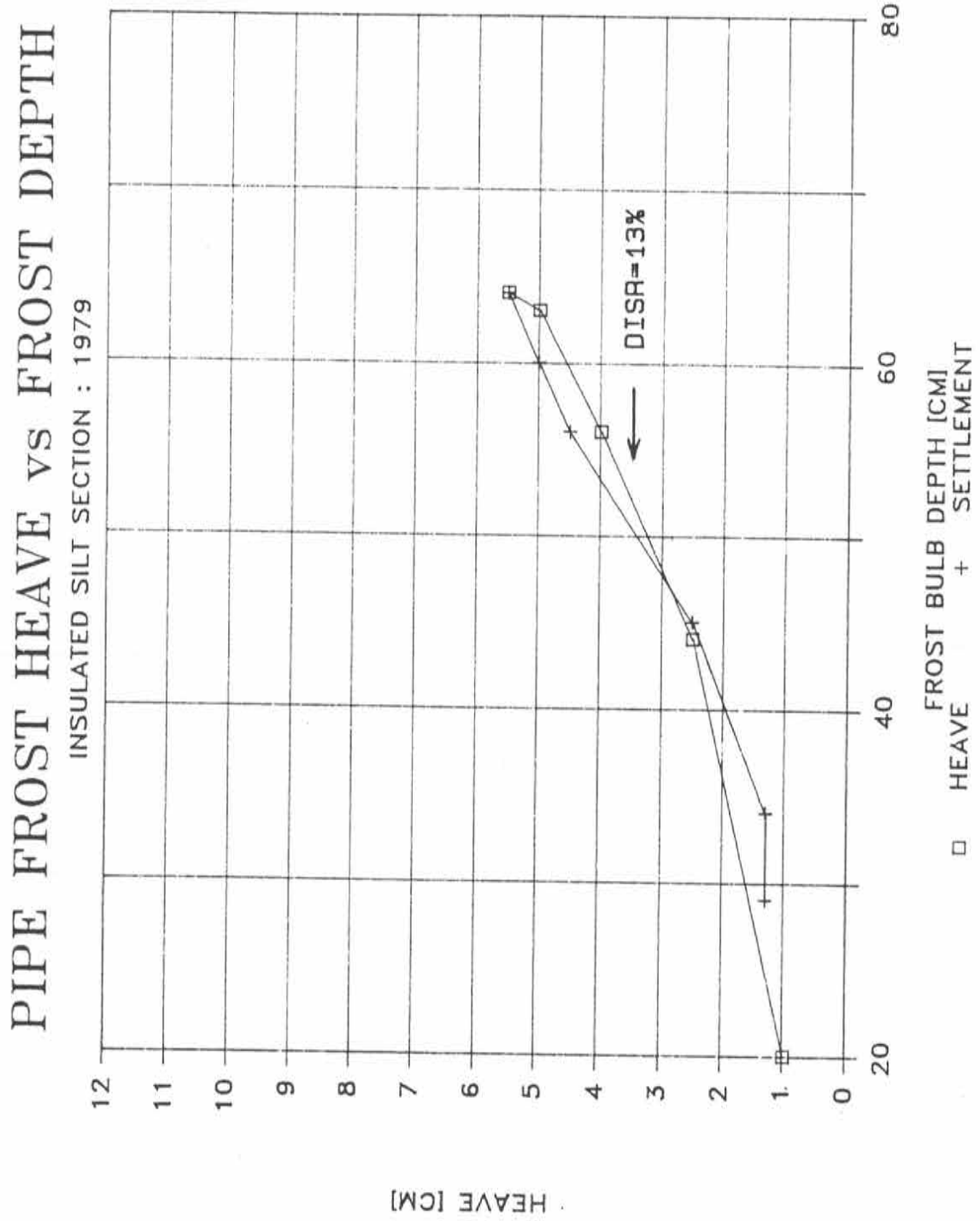
INSULATED SILT SECTION

PIPE FROST HEAVE

VS

FROST DEPTH

FIGURE 2.2-1



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CALGARY FROST HEAVE TEST FACILITY

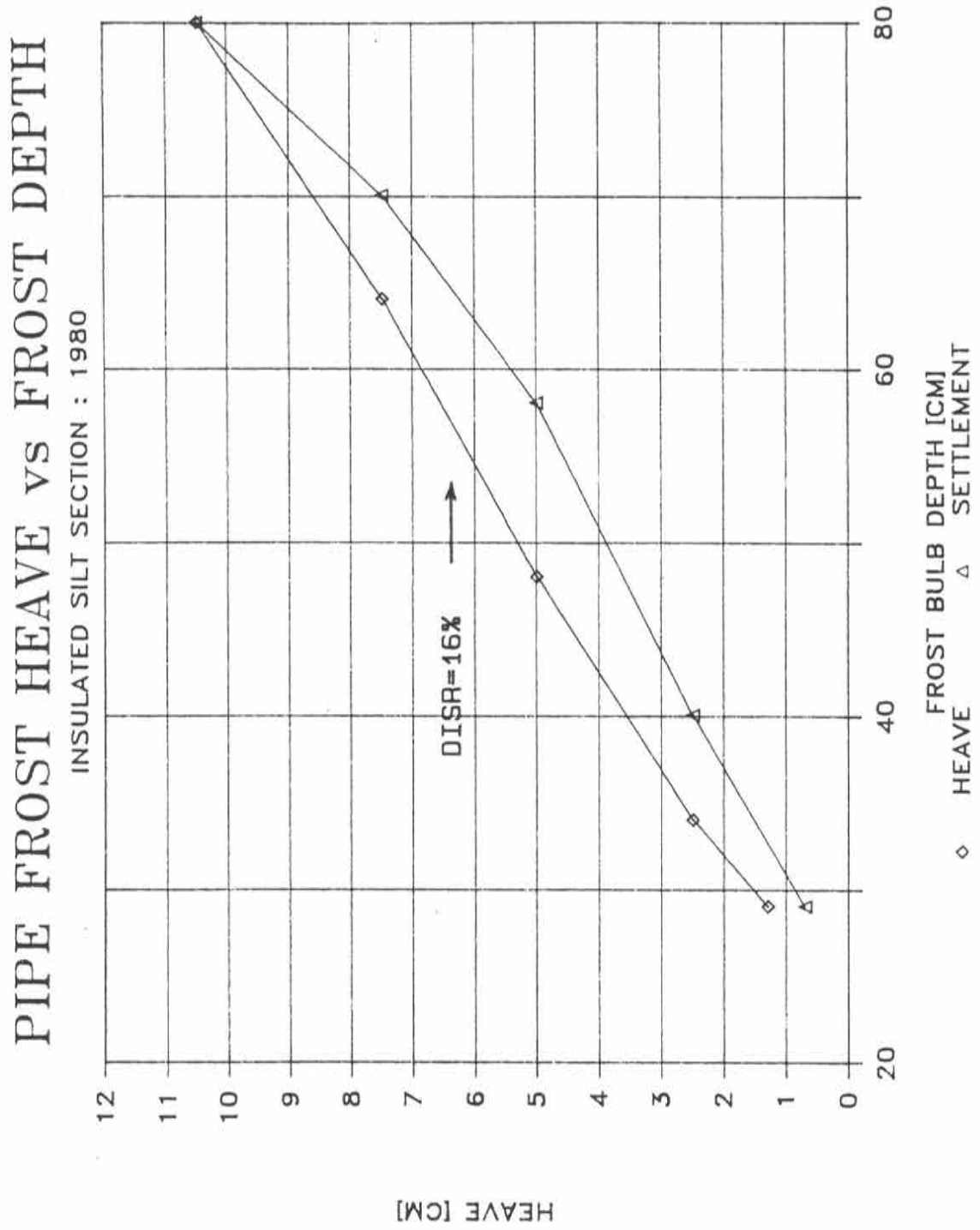
INSULATED SILT SECTION

1979 PIPE HEAVE

VS

FROST BULB DEPTH

FIGURE 2.2-2



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CALGARY FROST HEAVE TEST FACILITY

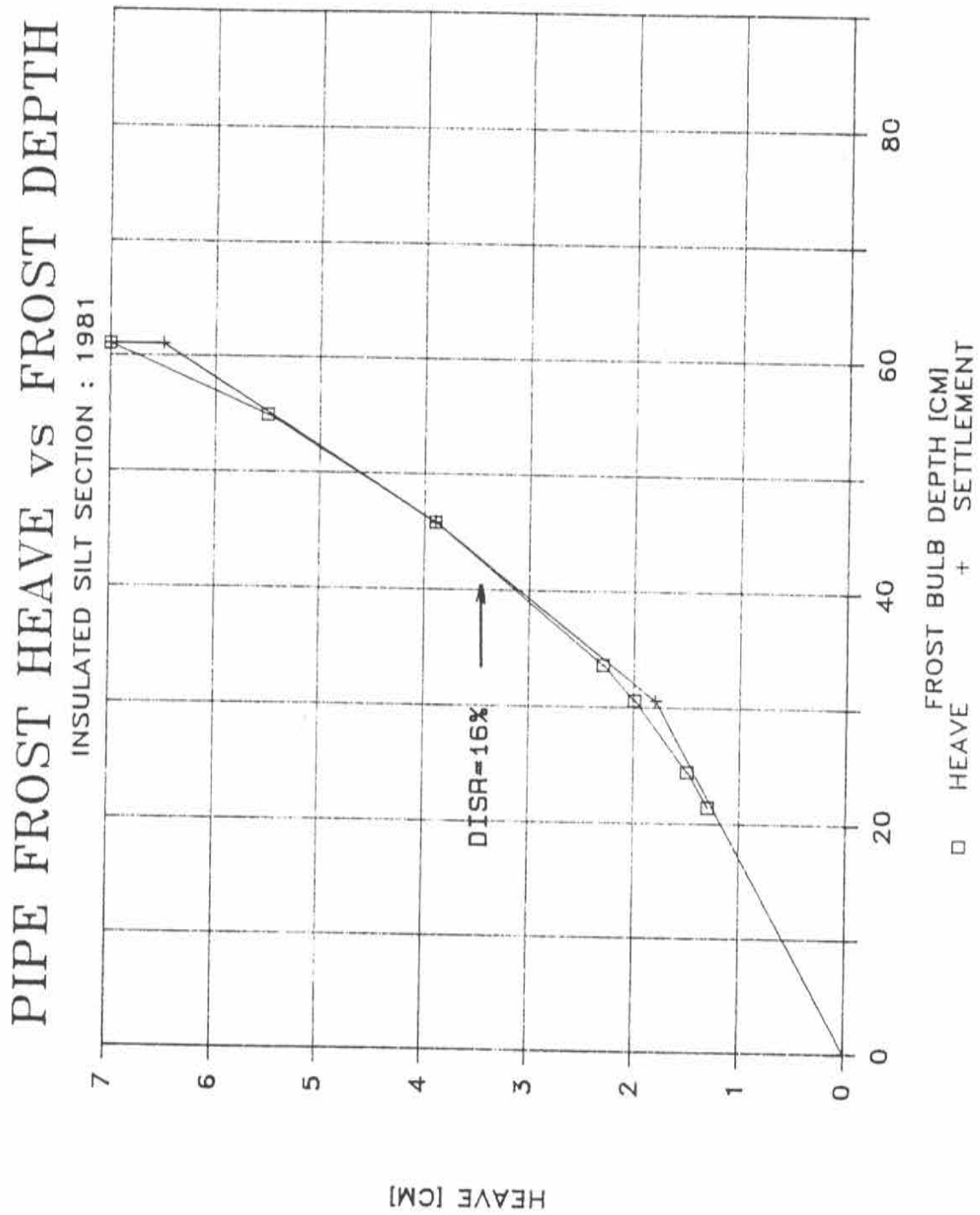
INSULATED SILT SECTION

1980 PIPE HEAVE

VS

FROST BULB DEPTH

FIGURE 2.2-3



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CALGARY FROST HEAVE TEST FACILITY

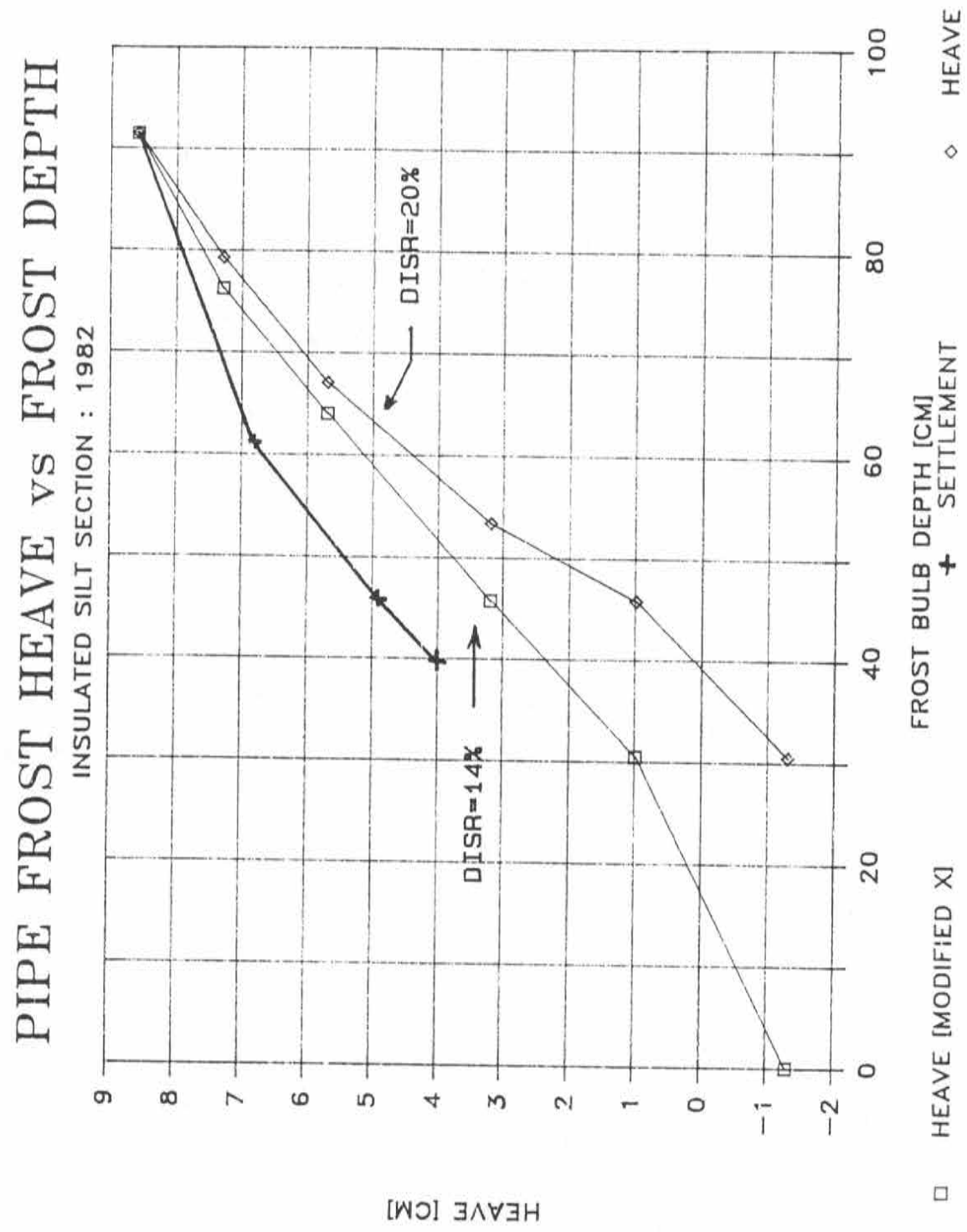
INSULATED SILT SECTION

1981 PIPE HEAVE

VS

FROST BULB DEPTH

FIGURE 2.2-4



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CALGARY FROST HEAVE TEST FACILITY

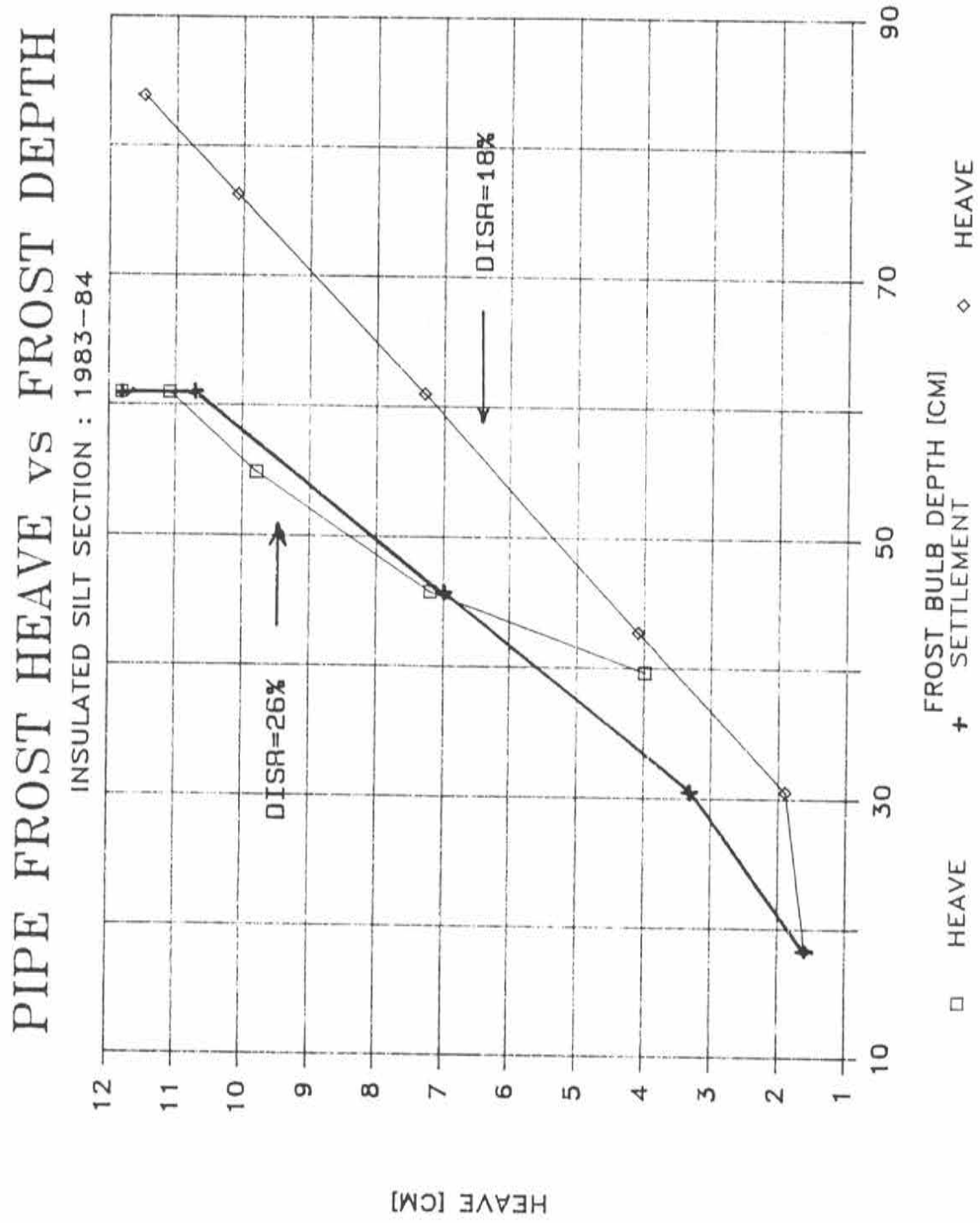
INSULATED SILT SECTION

1982 PIPE HEAVE

VS

FROST BULB DEPTH

FIGURE 2.2-5



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CALGARY FROST HEAVE TEST FACILITY

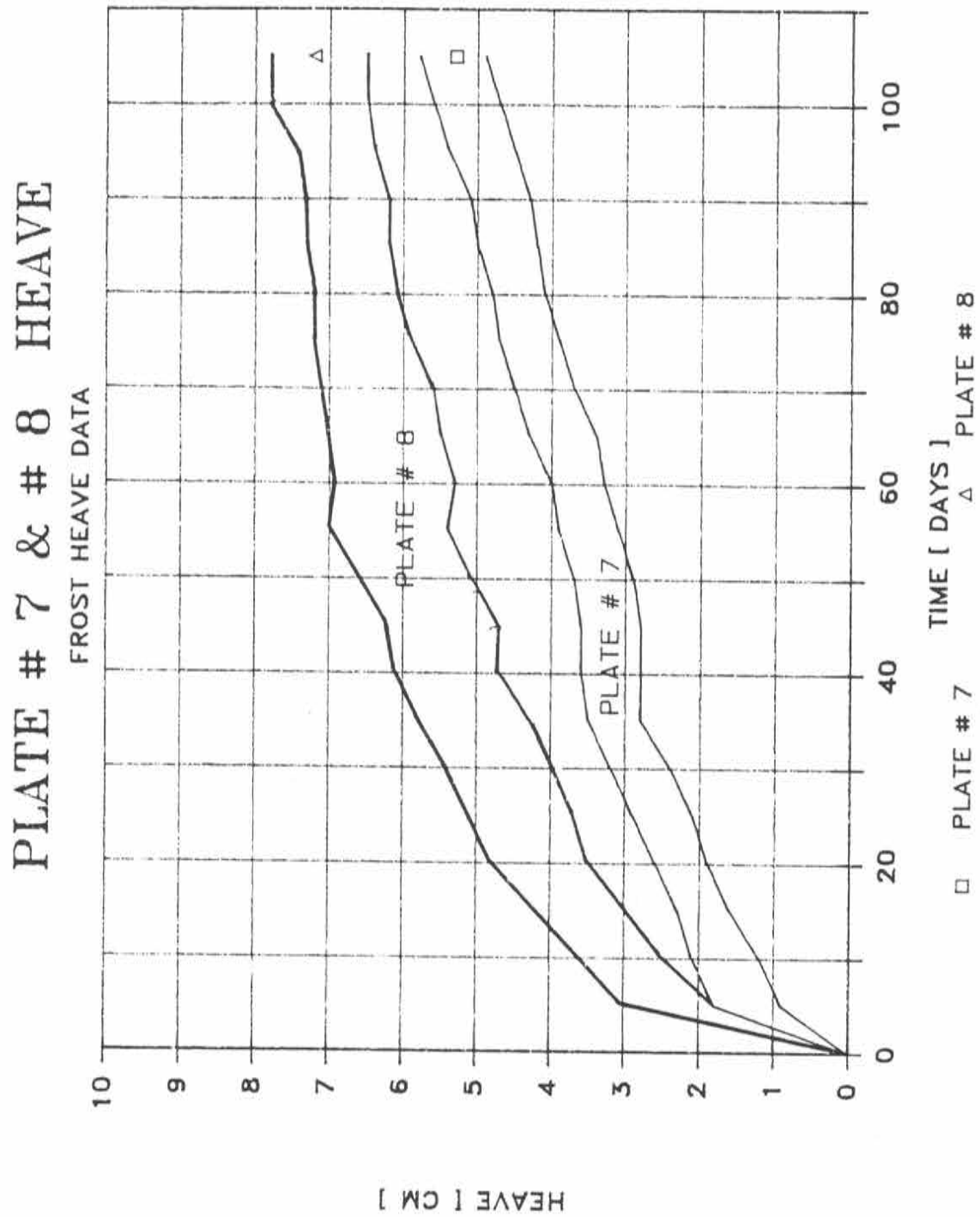
INSULATED SILT SECTION

1983-84 PIPE HEAVE

VS

FROST BULB DEPTH

FIGURE 2.2-6



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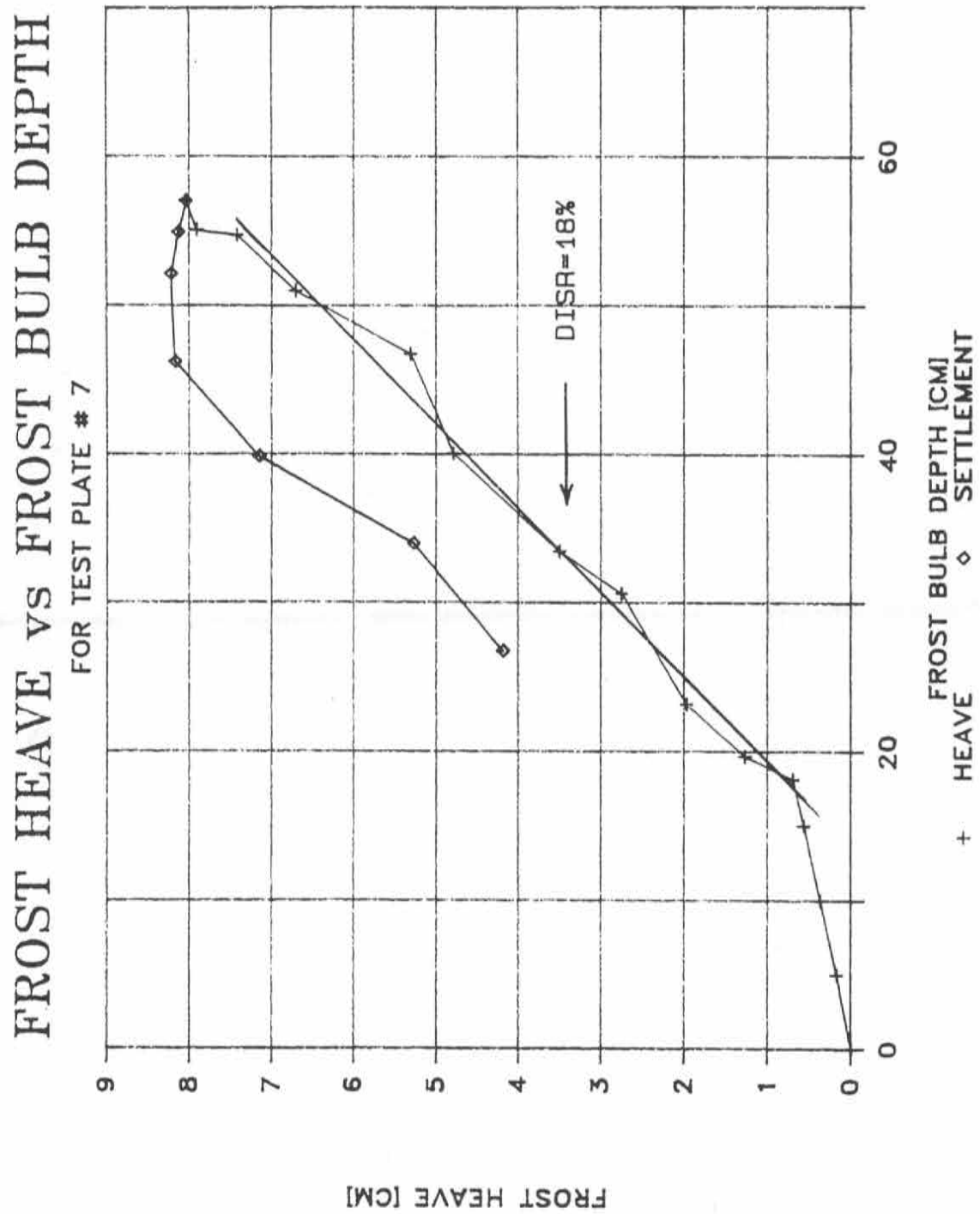
CALGARY FROST HEAVE TEST FACILITY

PLATES #7 & #8

PLATE FROST HEAVE

FIGURE 2.3-1



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CALGARY FROST HEAVE TEST FACILITY

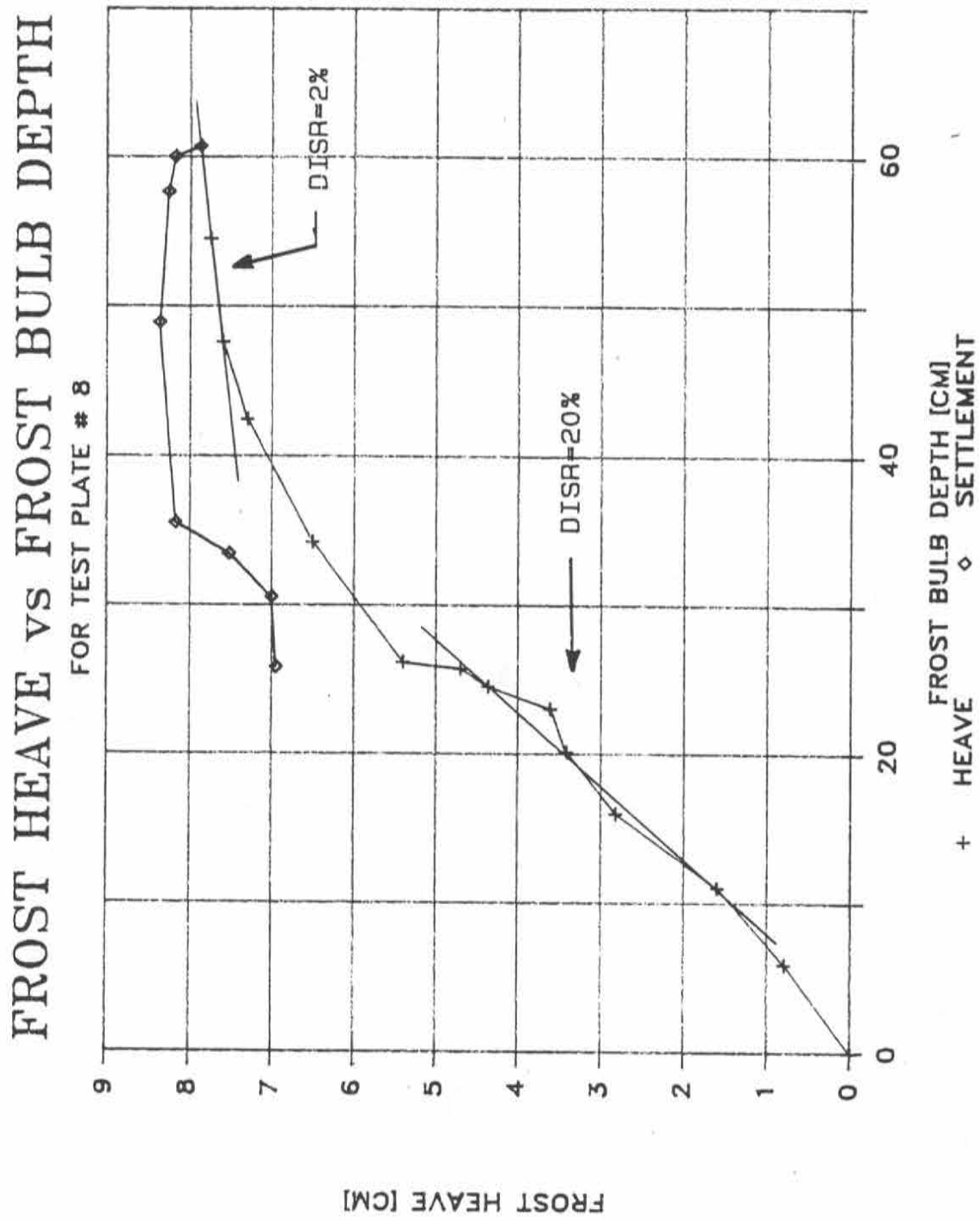
PLATE #7

FROST HEAVE

VS

FROST BULB DEPTH

FIGURE 2.3-2



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CALGARY FROST HEAVE TEST FACILITY

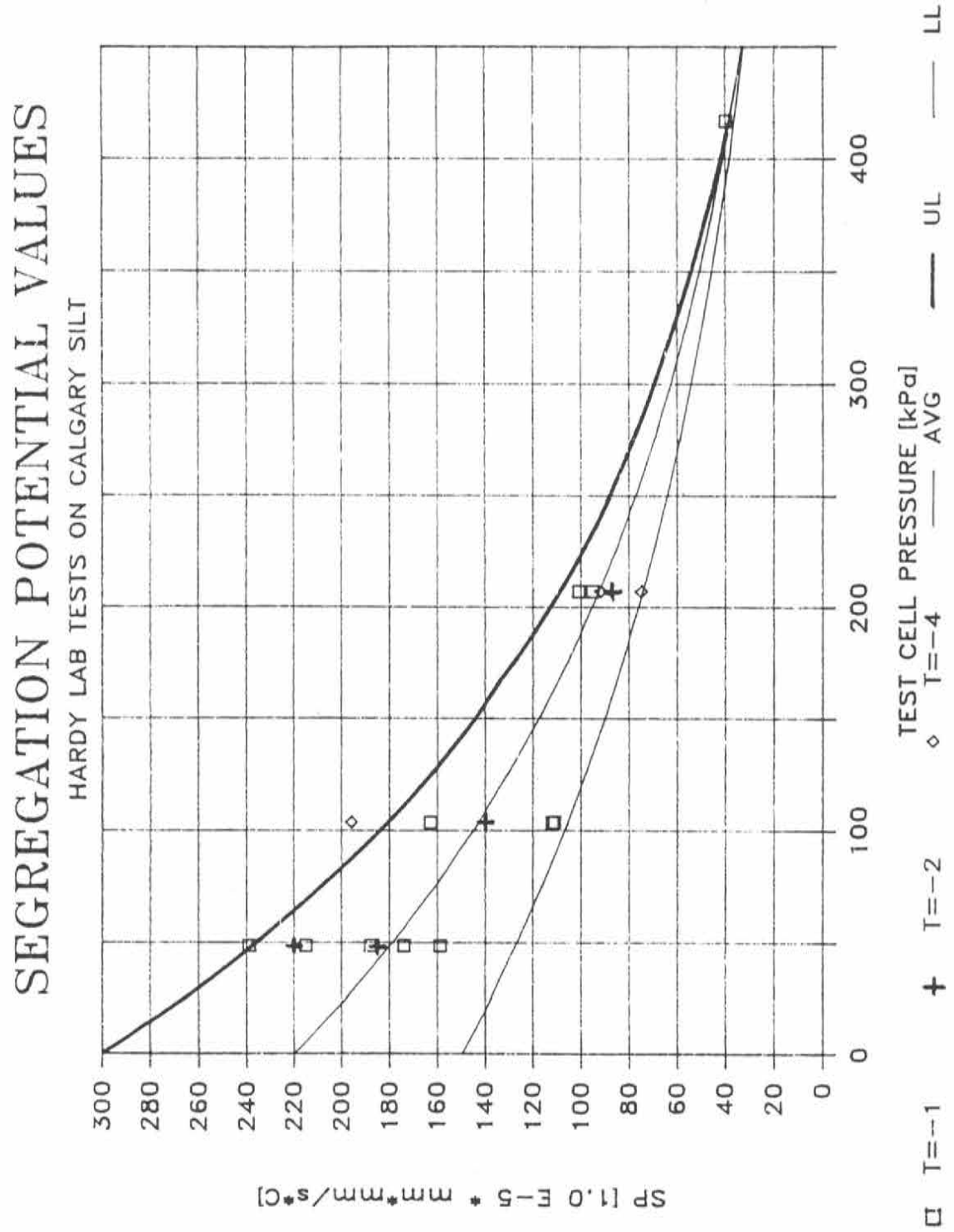
PLATE #8

FROST HEAVE

VS

FROST BULB DEPTH

FIGURE 2.3-3



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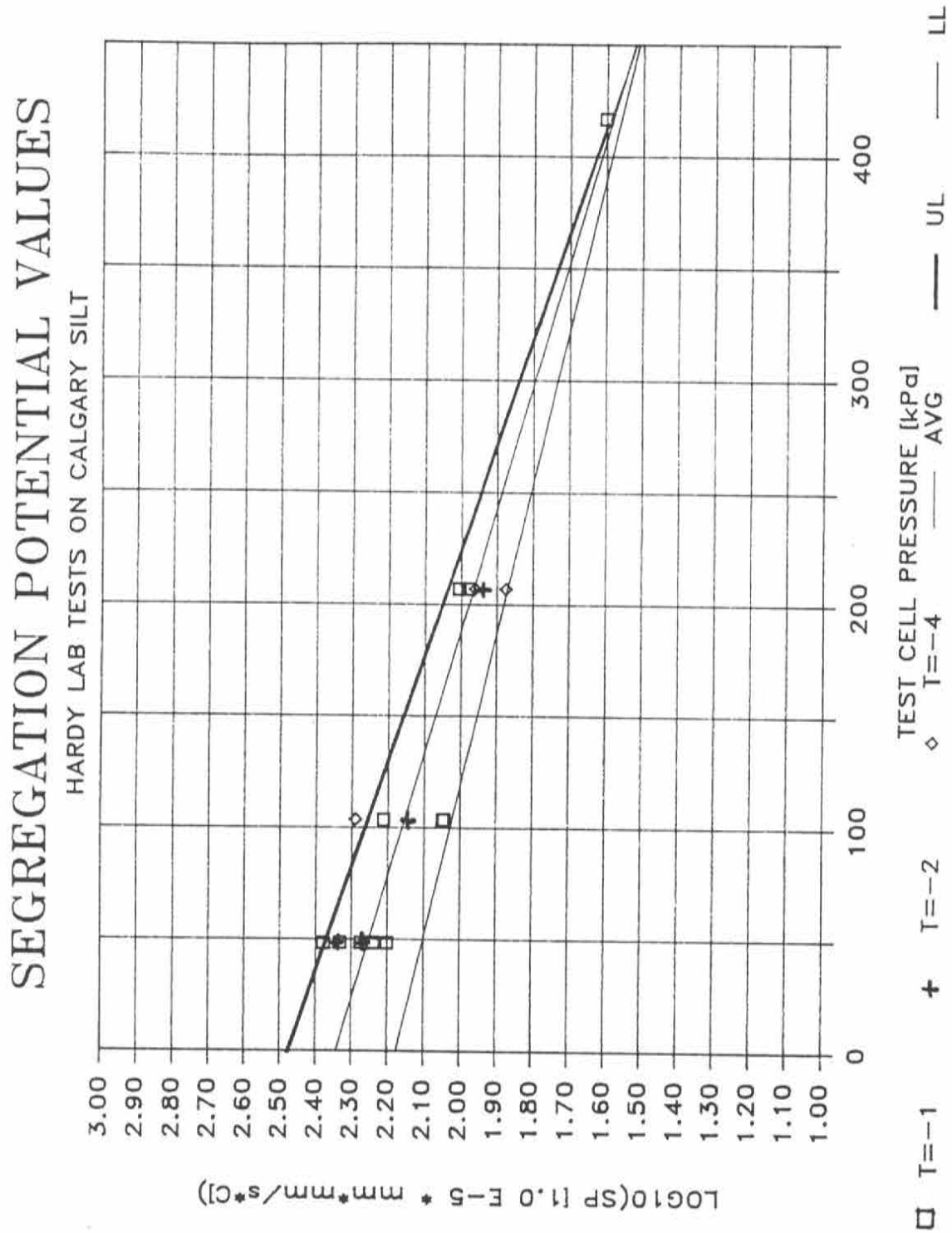
CALGARY FROST HEAVE TEST FACILITY

SEGREGATION POTENTIAL

TEST RESULTS

FIGURE 3.1-1



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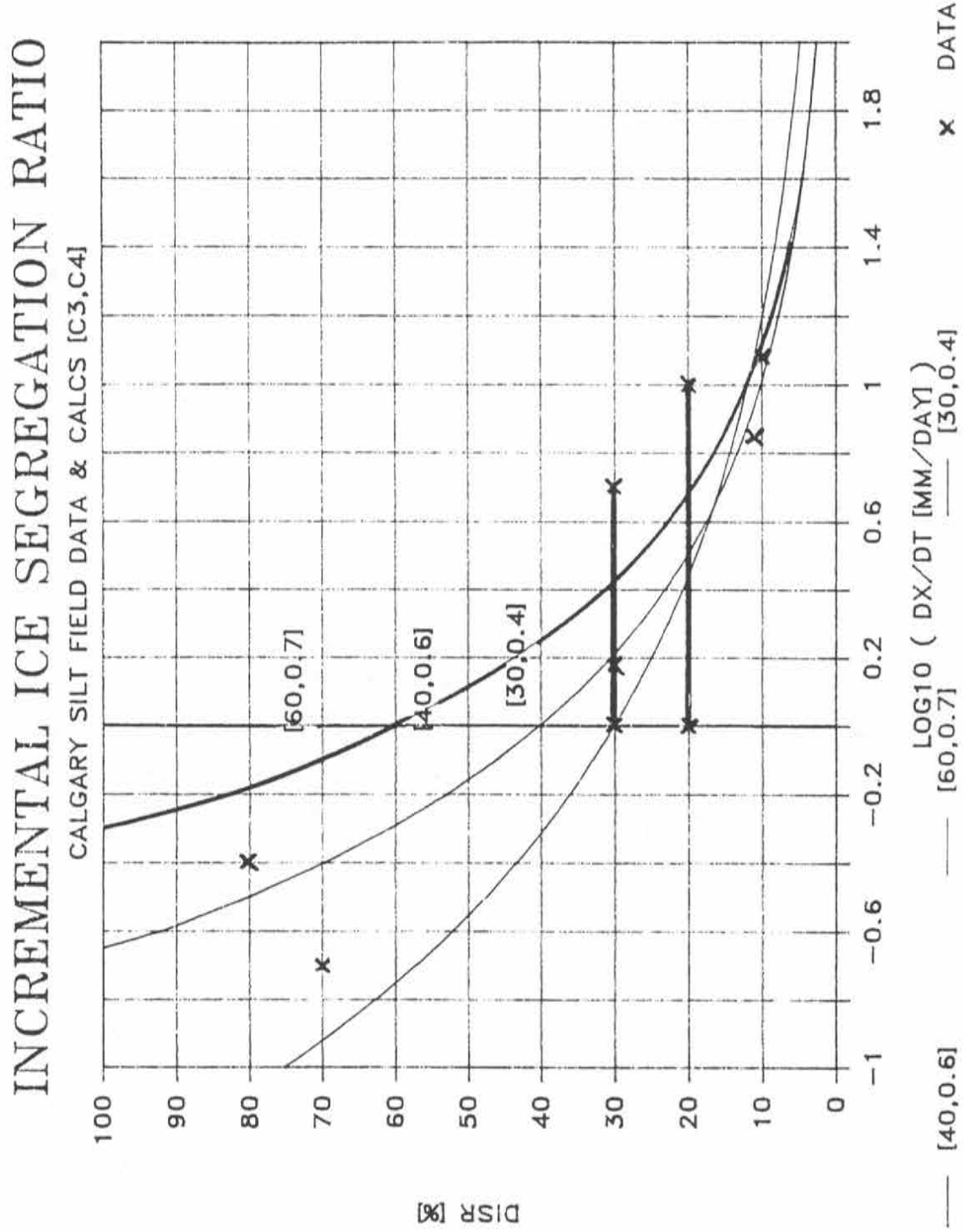
CALGARY FROST HEAVE TEST FACILITY

SEGREGATION POTENTIAL

TEST RESULTS
LOG VERSION

FIGURE 3.1-2



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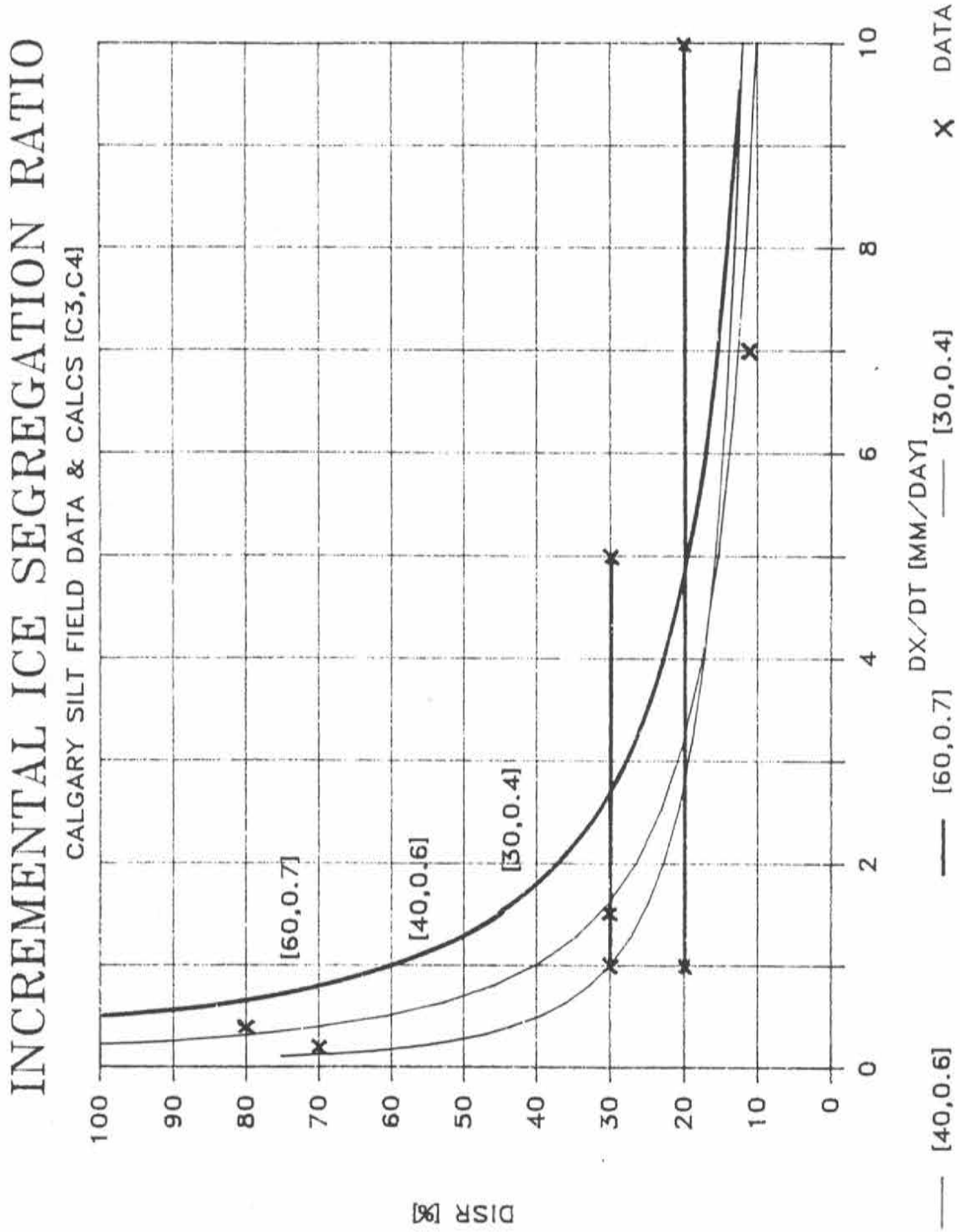
CALGARY FROST HEAVE TEST FACILITY

INCREMENTAL

ICE SEGREGATION RATIO VALUES

LOG VERSION

FIGURE 3.2-1



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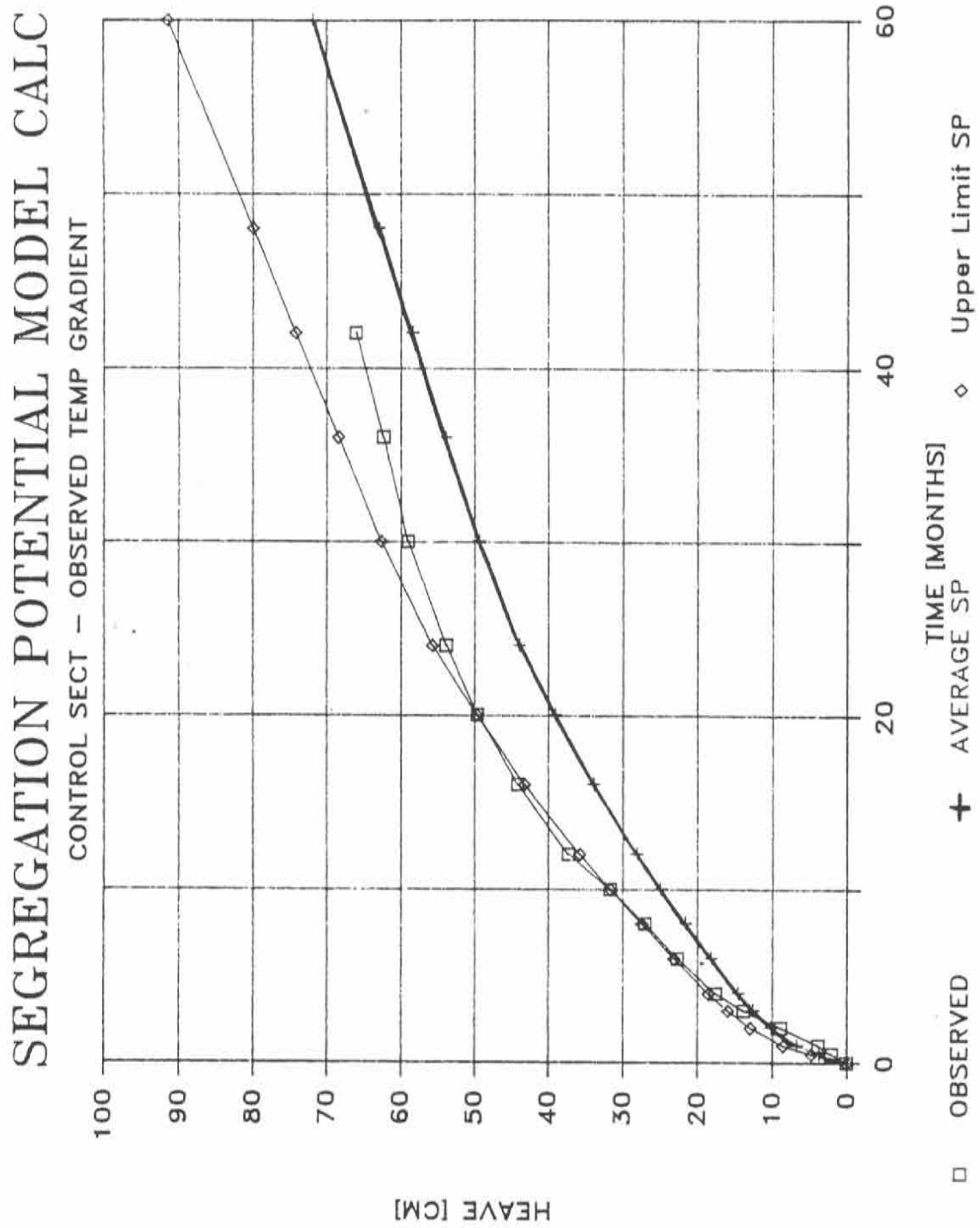
CALGARY FROST HEAVE TEST FACILITY

INCREMENTAL

ICE SEGREGATION RATIO VALUES

FIGURE 3.2-2



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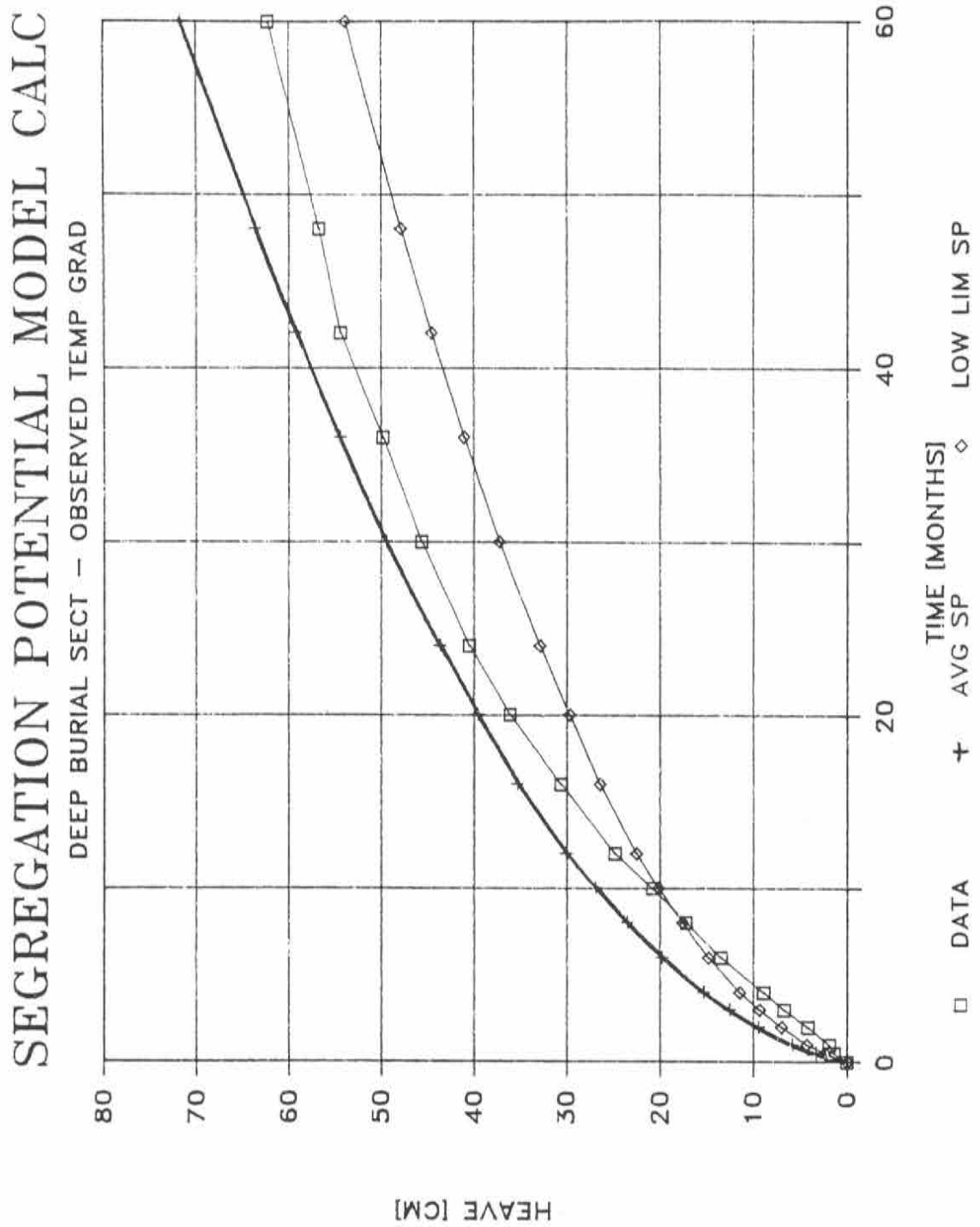
CALGARY FROST HEAVE TEST FACILITY

CONTROL SECTION

SEGREGATION POTENTIAL
MODEL CALCULATIONS
OBSERVED TEMPERATURE GRADIENT

FIGURE 4.1-1



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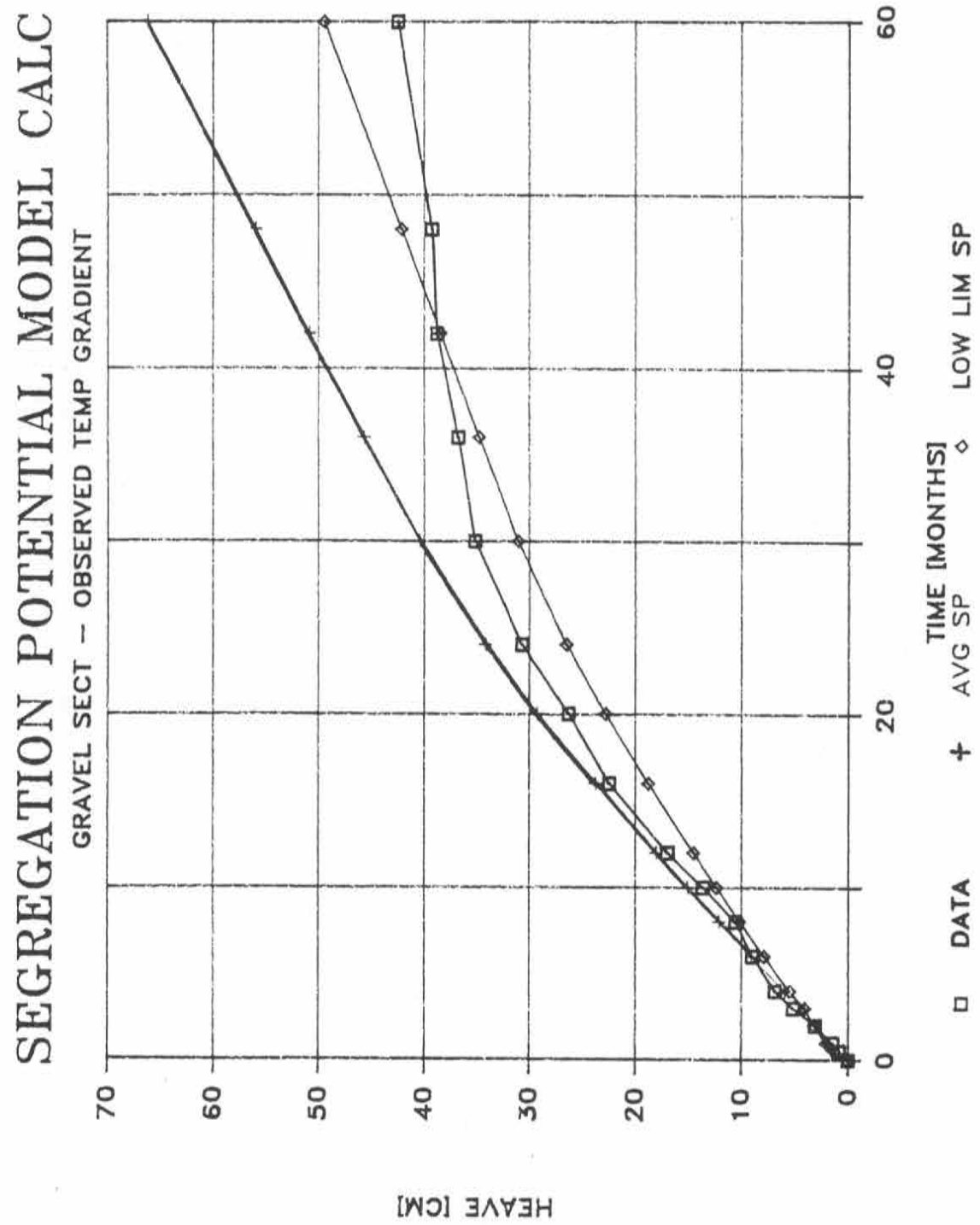
CALGARY FROST HEAVE TEST FACILITY

DEEP BURIAL SECTION

SEGREGATION POTENTIAL
MODEL CALCULATIONS
OBSERVED TEMPERATURE GRADIENT

FIGURE 4.1-2



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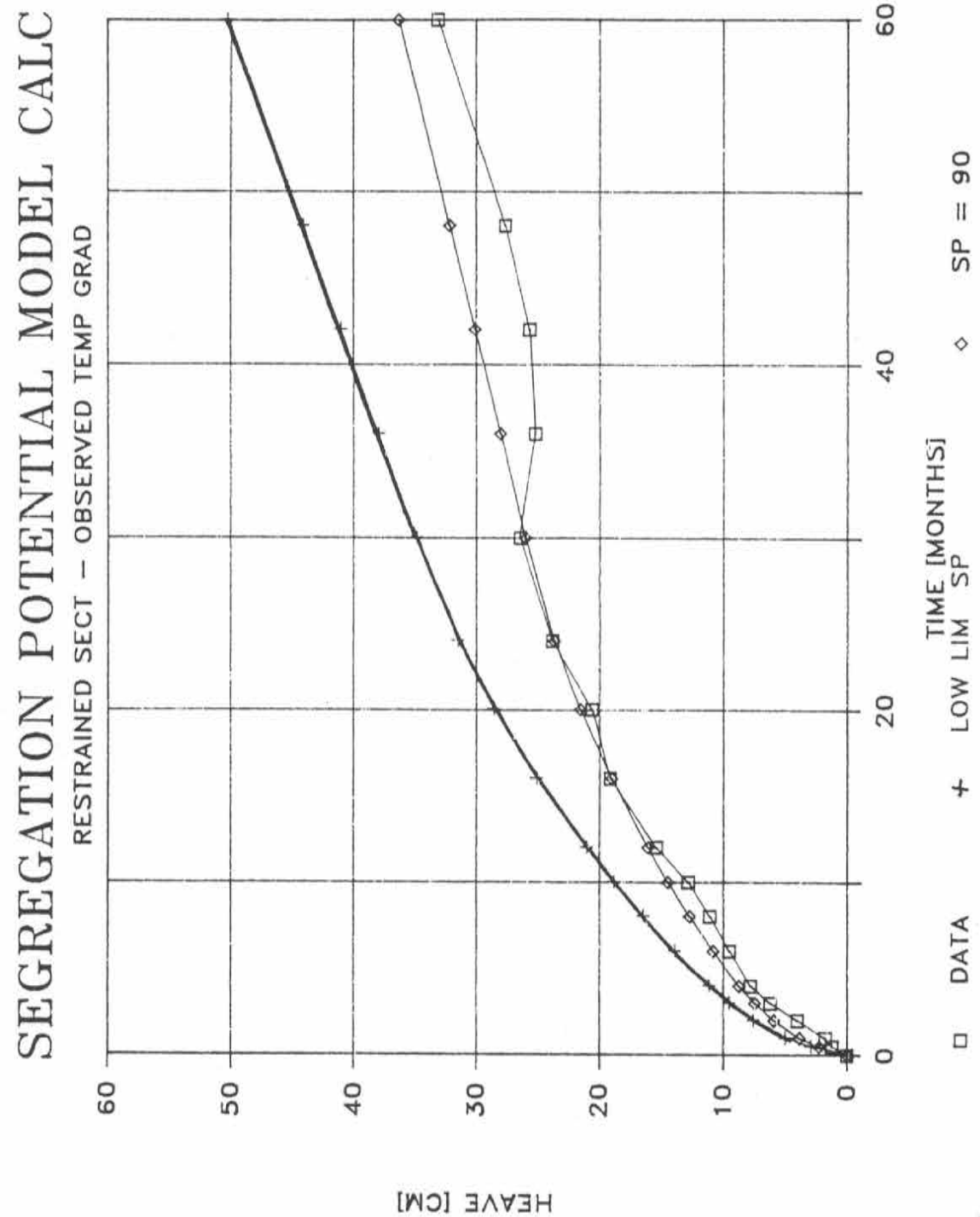
CALGARY FROST HEAVE TEST FACILITY

GRAVEL SECTION

SEGREGATION POTENTIAL
MODEL CALCULATIONS
OBSERVED TEMPERATURE GRADIENT

FIGURE 4.1-3



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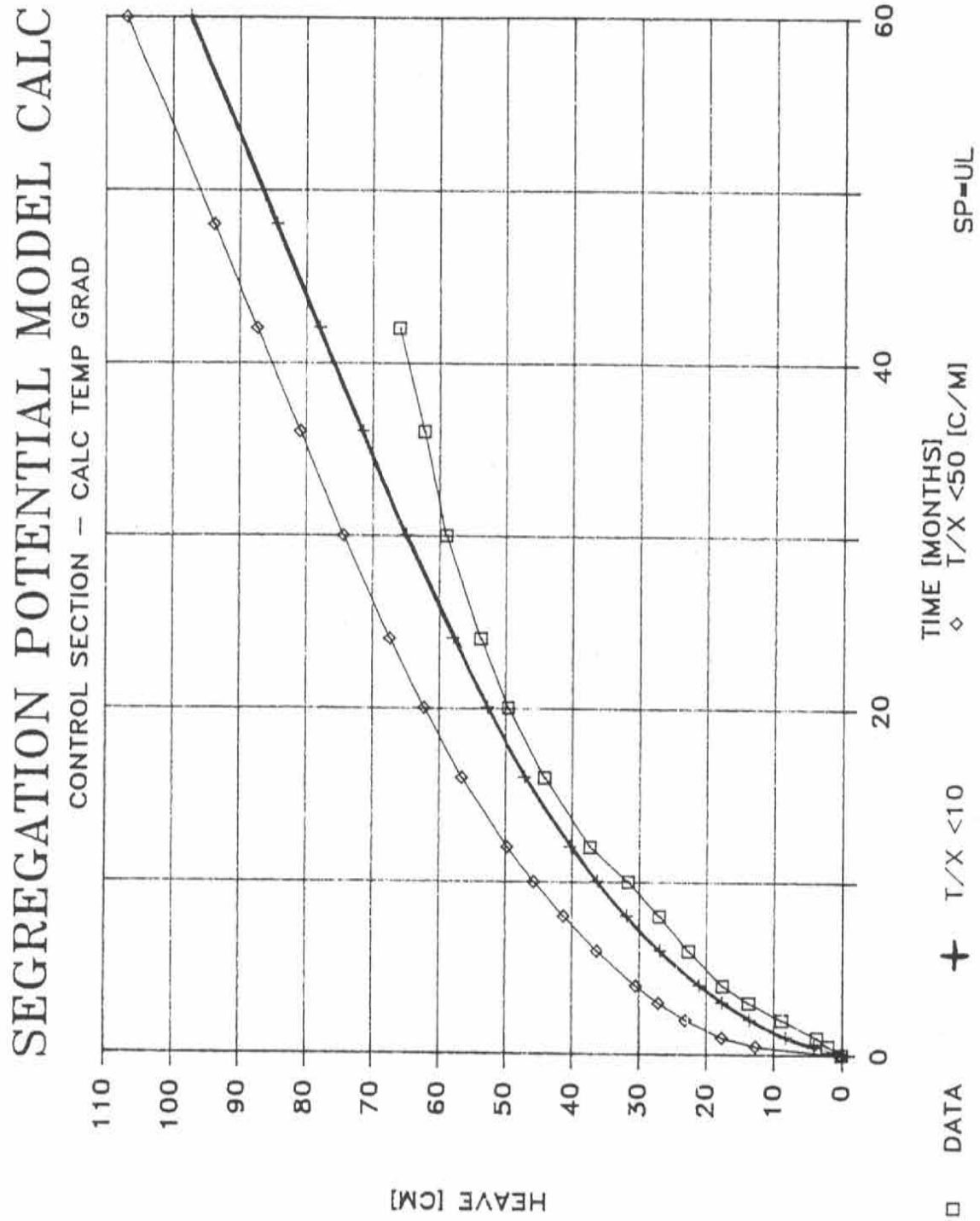
CALGARY FROST HEAVE TEST FACILITY

RESTRAINED SECTION

SEGREGATION POTENTIAL
MODEL CALCULATIONS
OBSERVED TEMPERATURE GRADIENT

FIGURE 4.1-4



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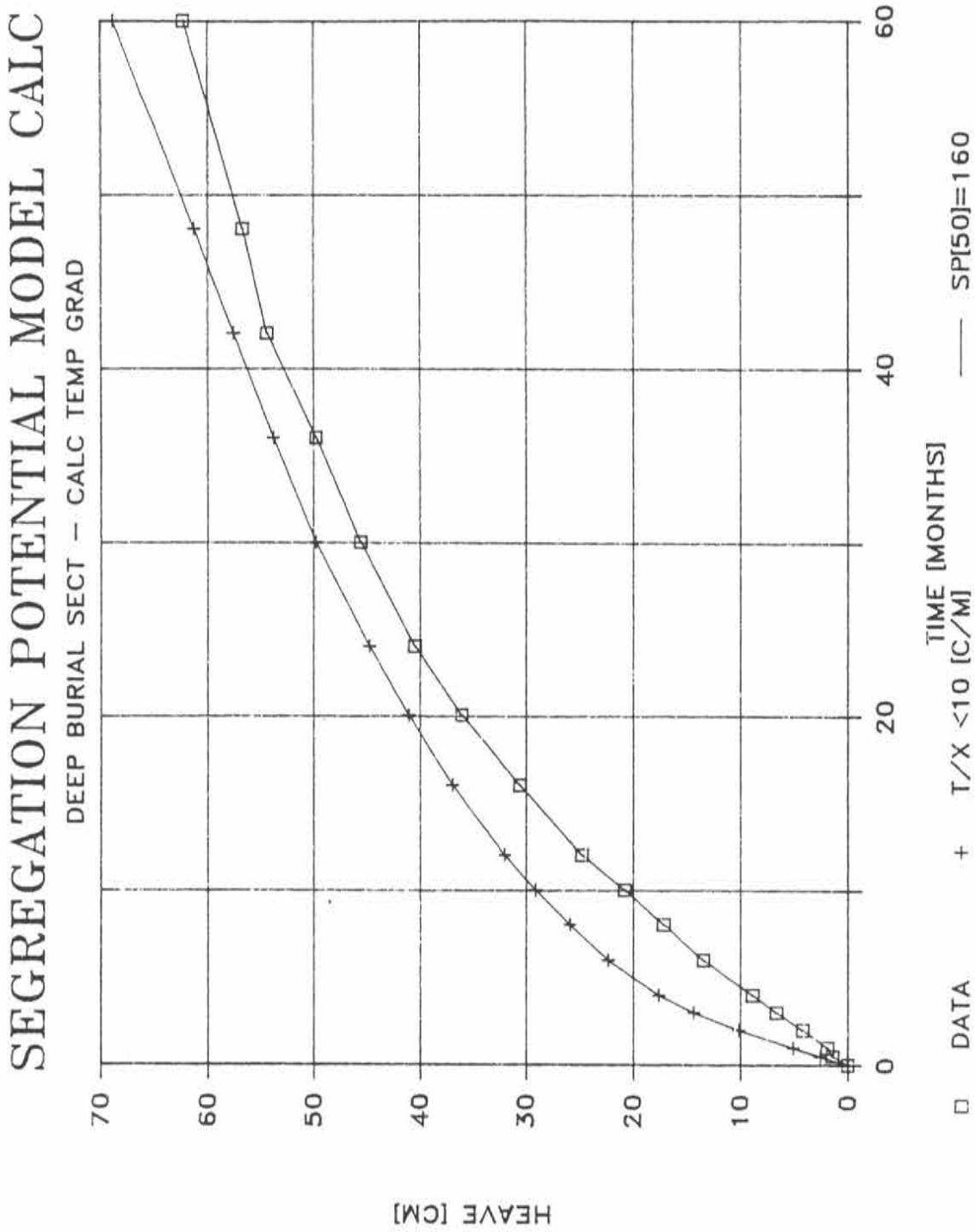
CALGARY FROST HEAVE TEST FACILITY

CONTROL SECTION

SEGREGATION POTENTIAL
MODEL CALCULATIONS
CALCULATED TEMP GRADIENT

FIGURE 4.1-5



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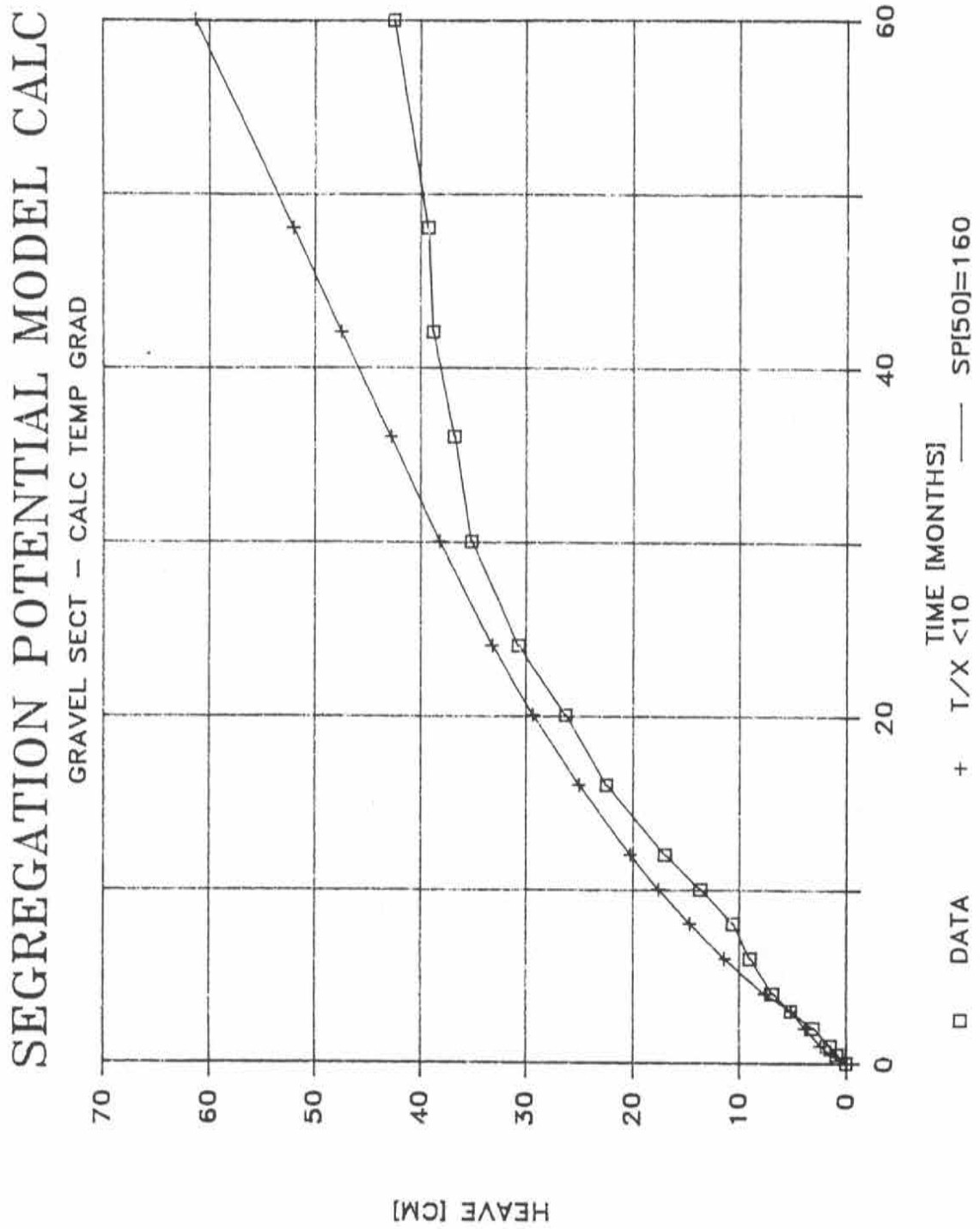
CALGARY FROST HEAVE TEST FACILITY

DEEP BURIAL SECTION

SEGREGATION POTENTIAL
MODEL CALCULATIONS
CALCULATED TEMP GRADIENT

FIGURE 4.1-6



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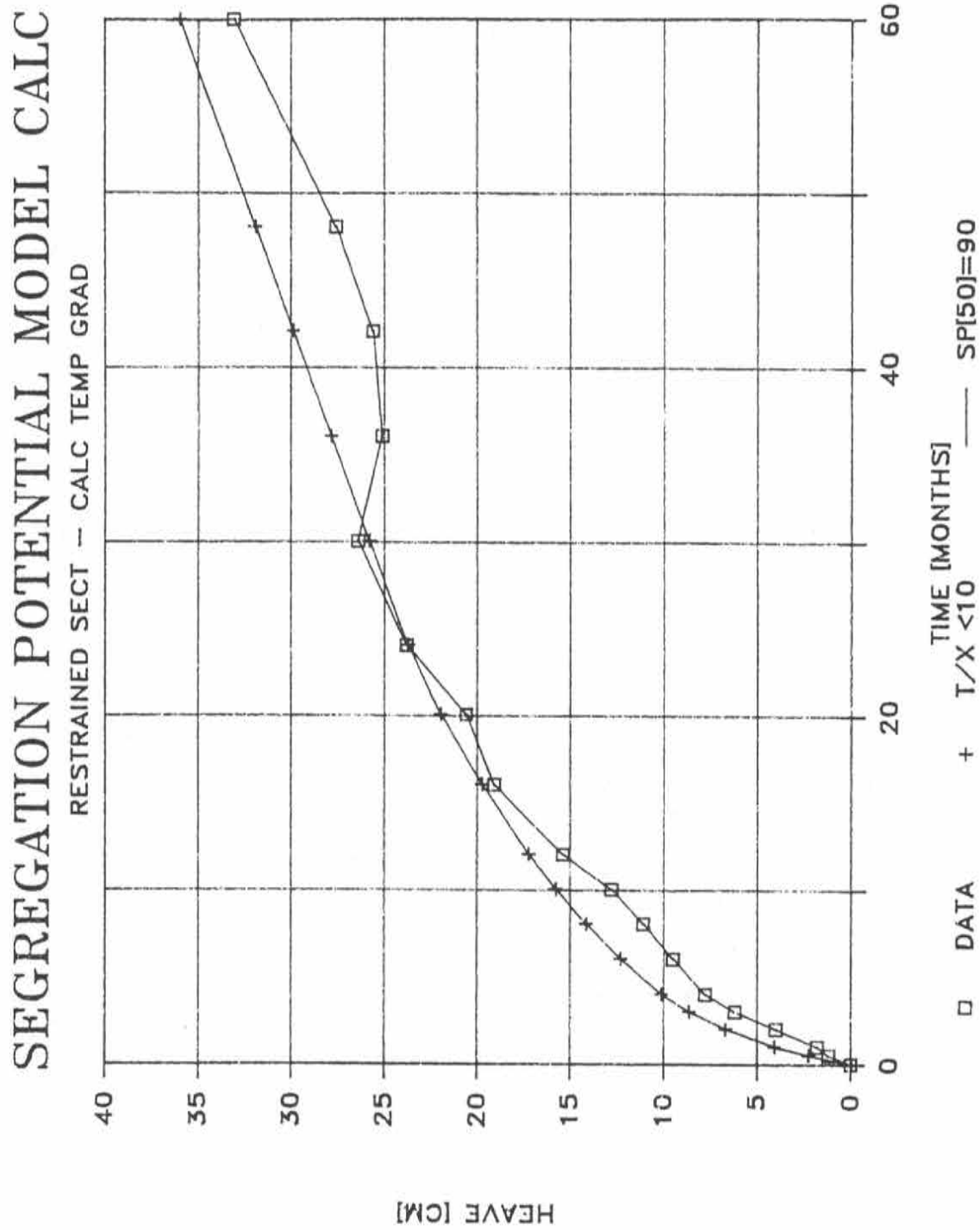
CALGARY FROST HEAVE TEST FACILITY

GRAVEL SECTION

SEGREGATION POTENTIAL
MODEL CALCULATIONS
CALCULATED TEMP GRADIENT

FIGURE 4.1-7



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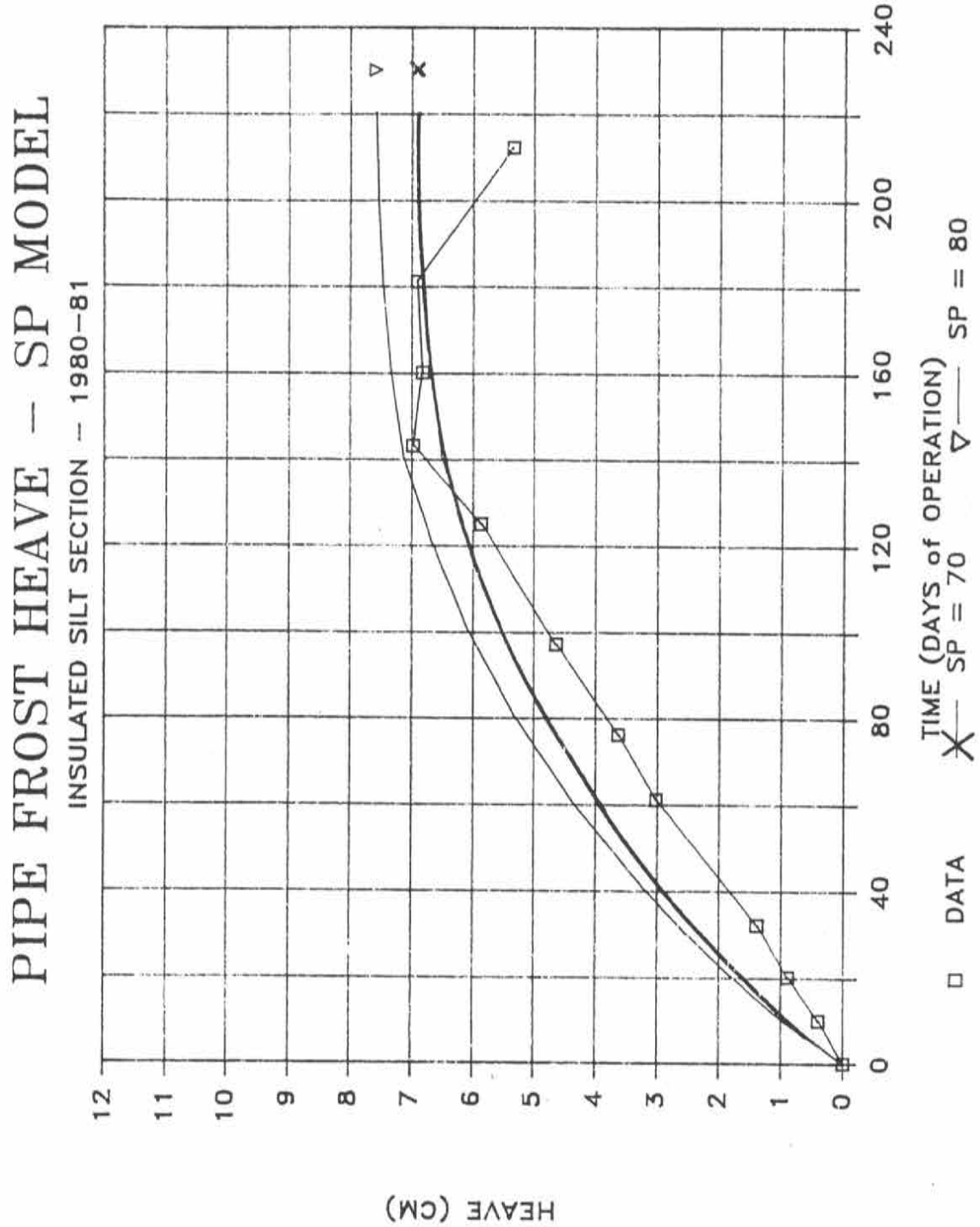
CALGARY FROST HEAVE TEST FACILITY

RESTRAINED SECTION

SEGREGATION POTENTIAL
MODEL CALCULATIONS
CALCULATED TEMP GRADIENT

FIGURE 4.1-8



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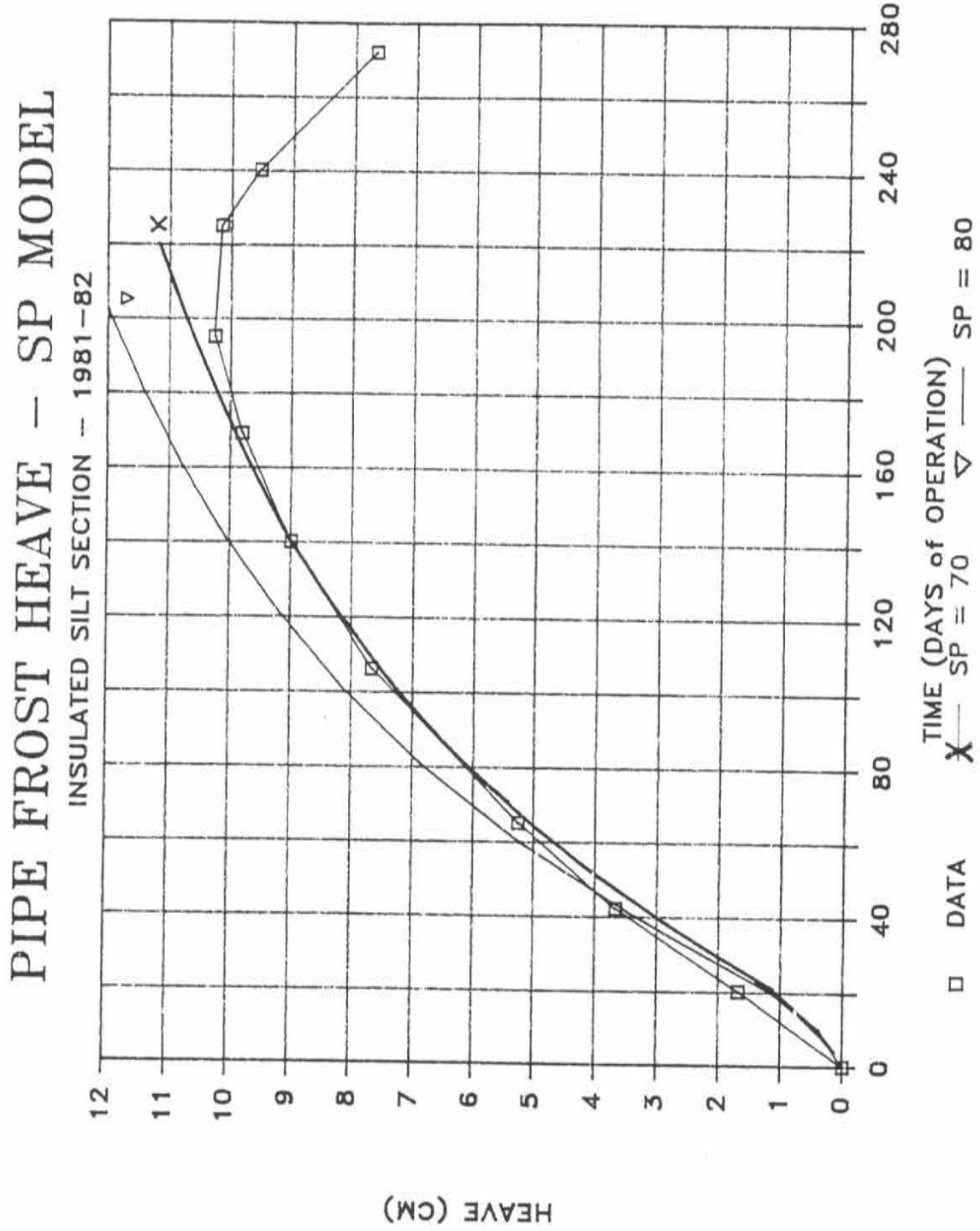
CALGARY FROST HEAVE TEST FACILITY

INSULATED SILT SECTION

SEGREGATION POTENTIAL
80-81 MODEL CALCULATIONS
OBSERVED TEMP GRADIENT

FIGURE 4.2-1



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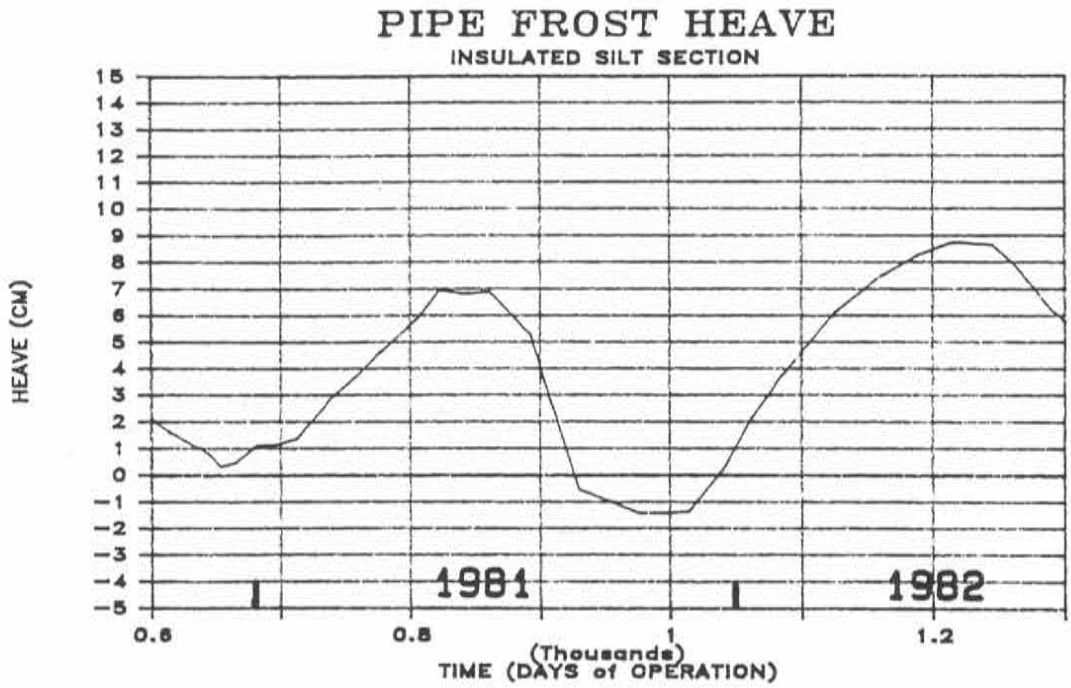
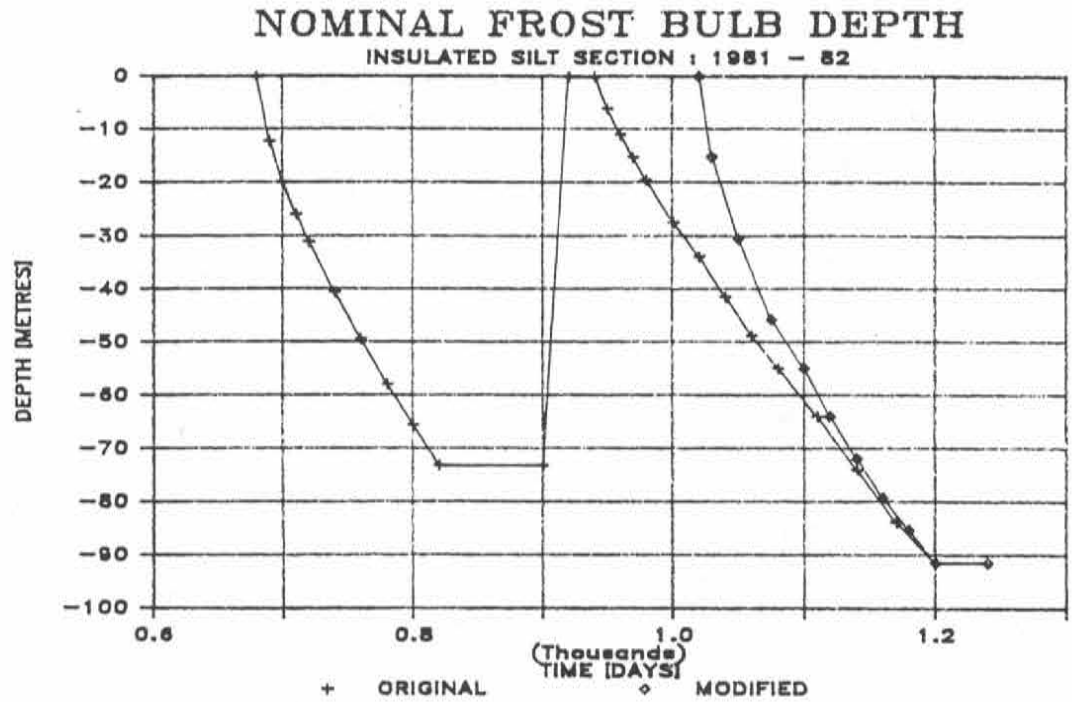
INSULATED SILT SECTION

SEGREGATION POTENTIAL
81-82 MODEL CALCULATIONS
OBSERVED TEMP GRADIENT

FIGURE 4.2-2





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CALGARY FROST HEAVE TEST FACILITY

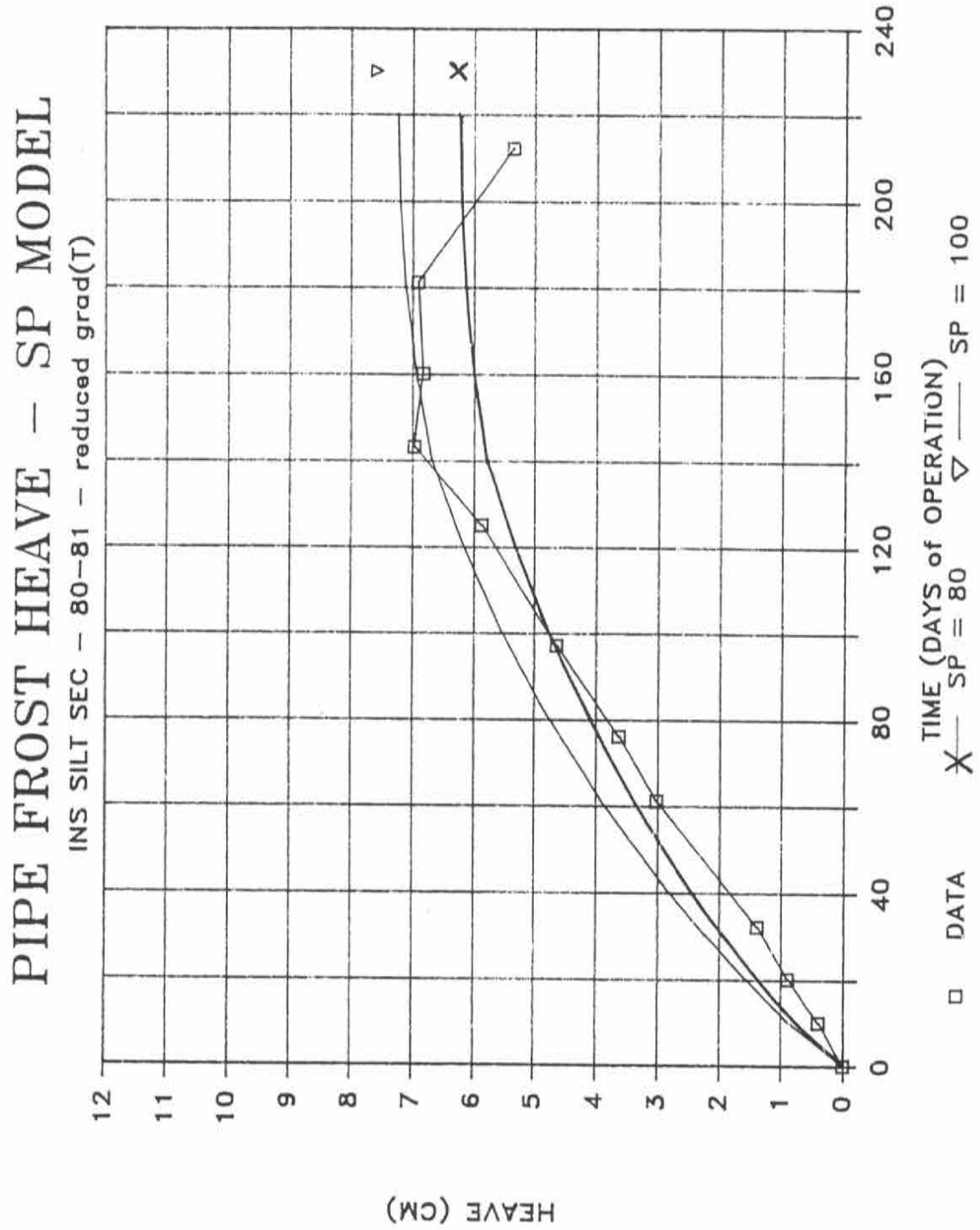
INSULATED SILT SECTION

FROST HEAVE

and

NOMINAL FROST BULB DEPTH

FIGURE 4.2- 3



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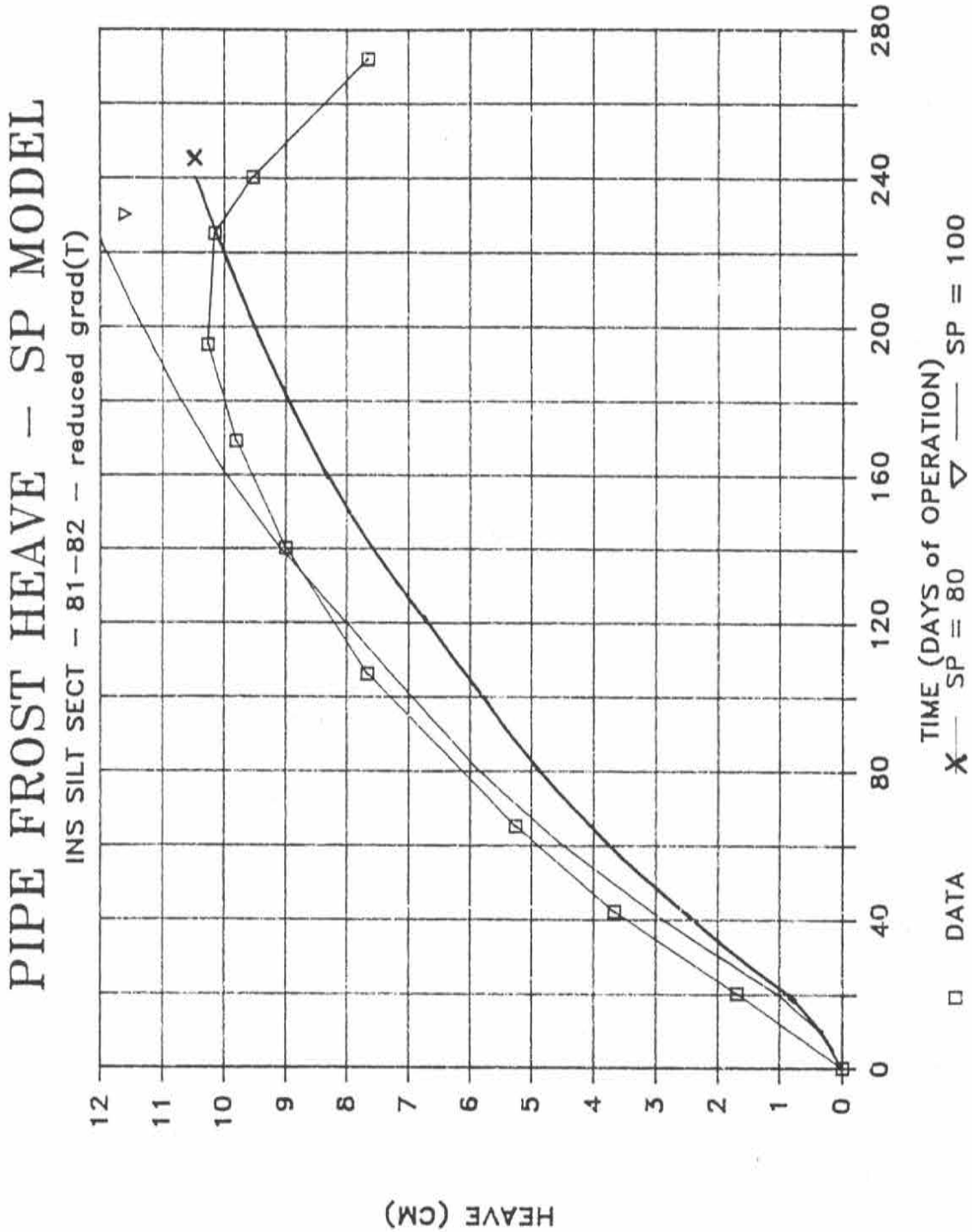
CALGARY FROST HEAVE TEST FACILITY

INSULATED SILT SECTION

SEGREGATION POTENTIAL
80-81 MODEL CALCULATIONS
REDUCED TEMP GRADIENT

FIGURE 4.2-4



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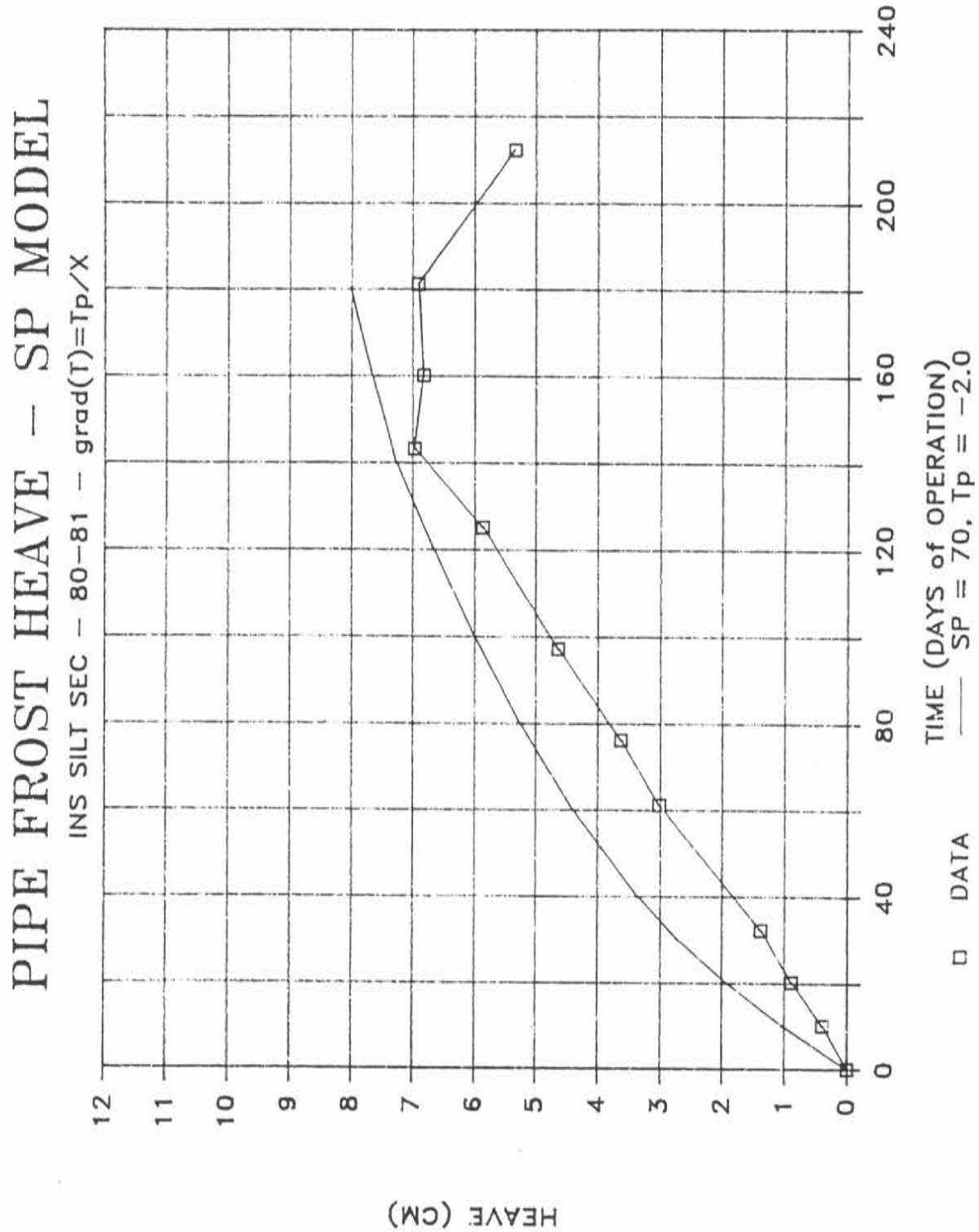
INSULATED SILT SECTION

SEGREGATION POTENTIAL
81-82 MODEL CALCULATIONS
REDUCED TEMP GRADIENT

FIGURE 4.2- 5



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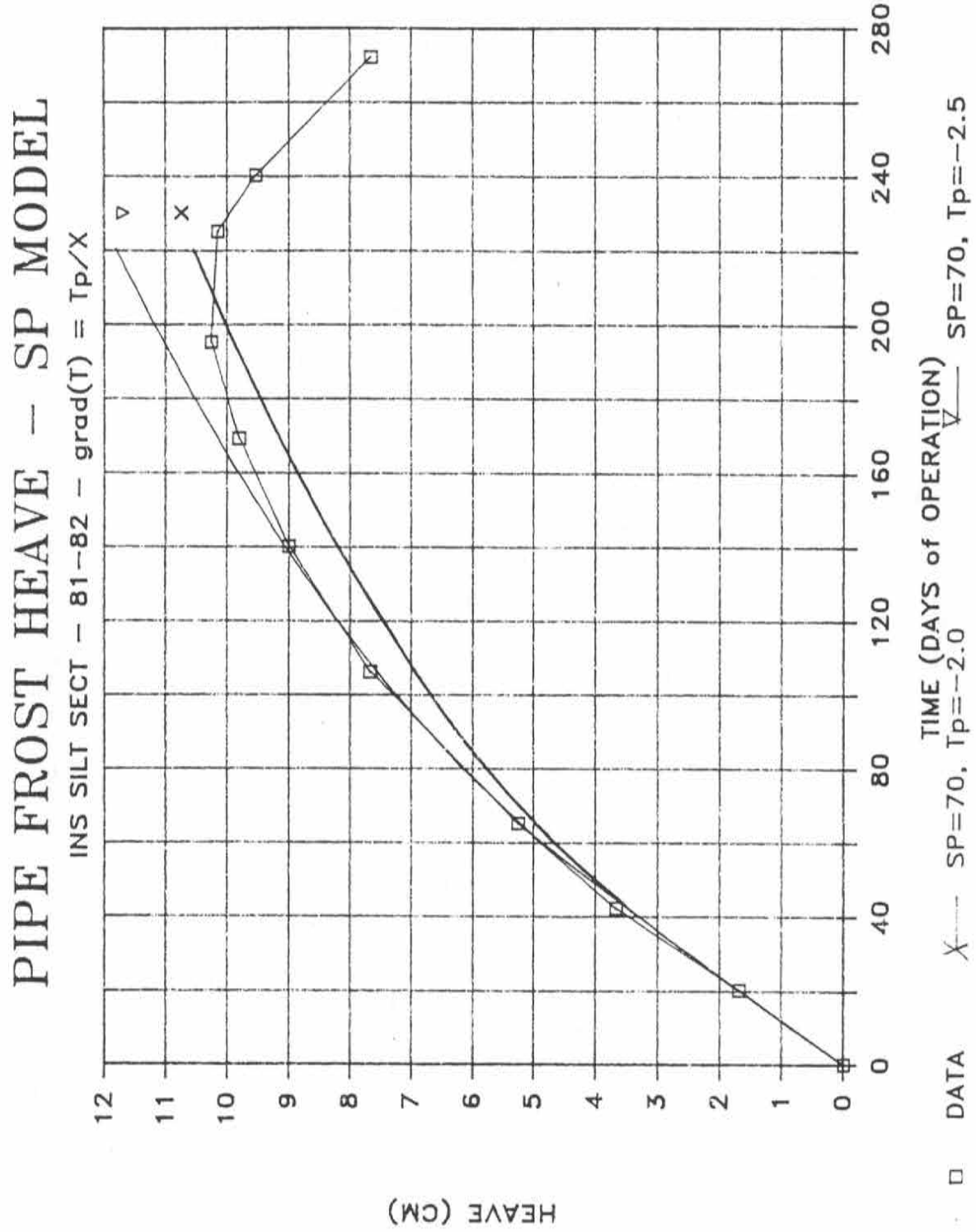
CALGARY FROST HEAVE TEST FACILITY

INSULATED SILT SECTION

SEGREGATION POTENTIAL
80-81 MODEL CALCULATION
CALCULATED TEMP GRADIENT

FIGURE 4.2-6



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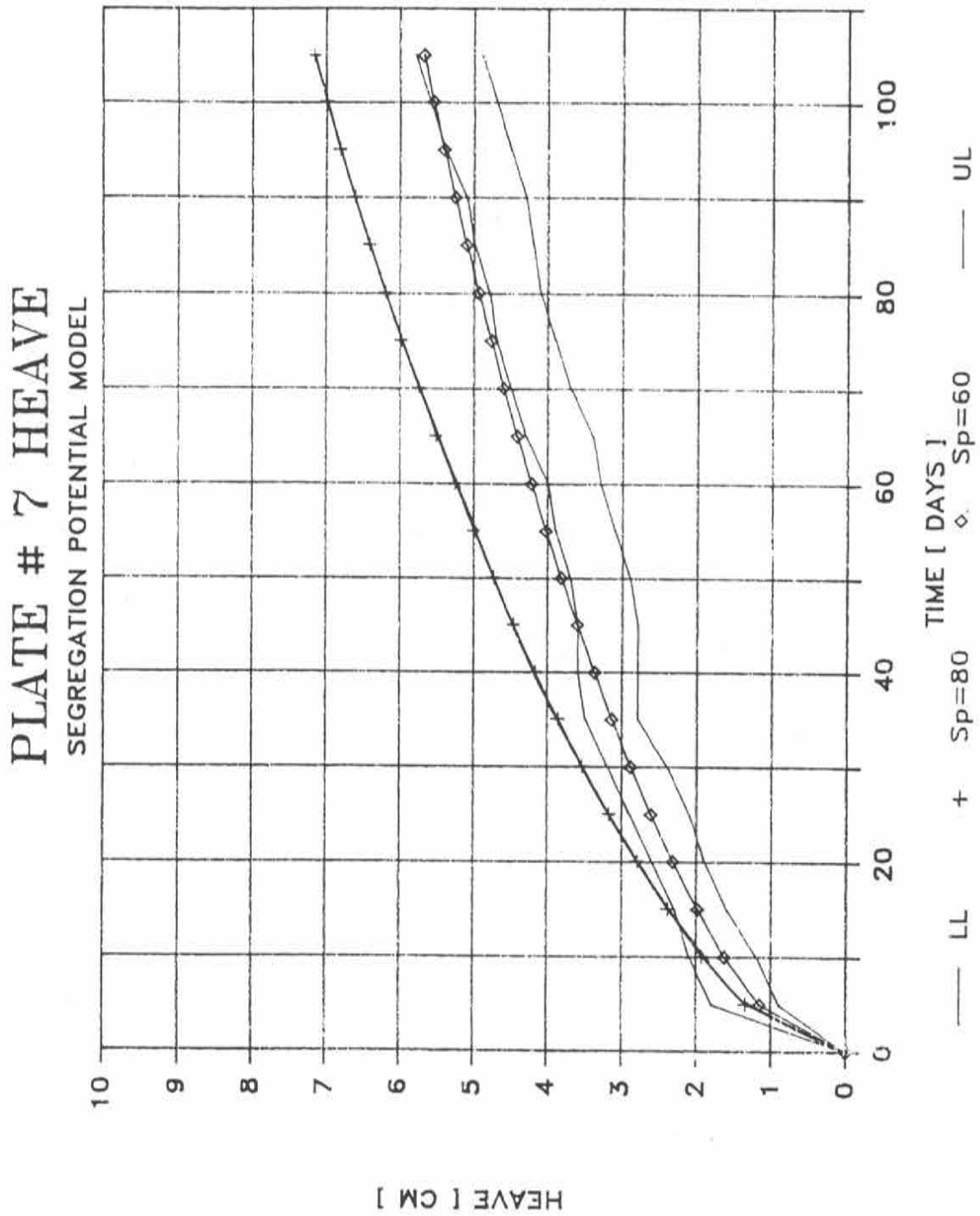
CALGARY FROST HEAVE TEST FACILITY

INSULATED SILT SECTION

SEGREGATION POTENTIAL
81-82 MODEL CALCULATIONS
CALCULATED TEMP GRADIENT

FIGURE 4.2-7



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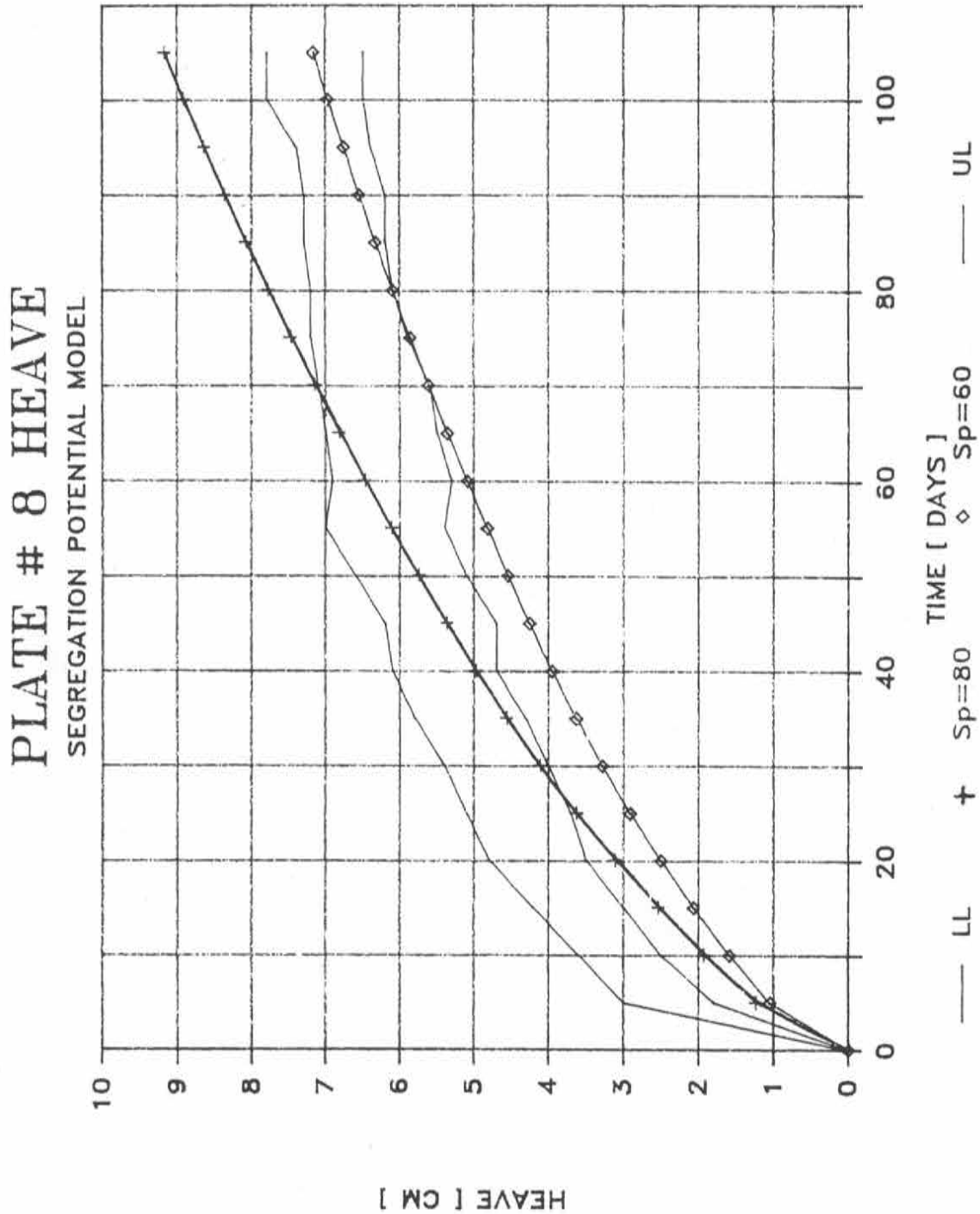
CALGARY FROST HEAVE TEST FACILITY

PLATE #7

SEGREGATION POTENTIAL
MODEL CALCULATIONS
OBSERVED TEMP GRADIENT

FIGURE 4.3-1



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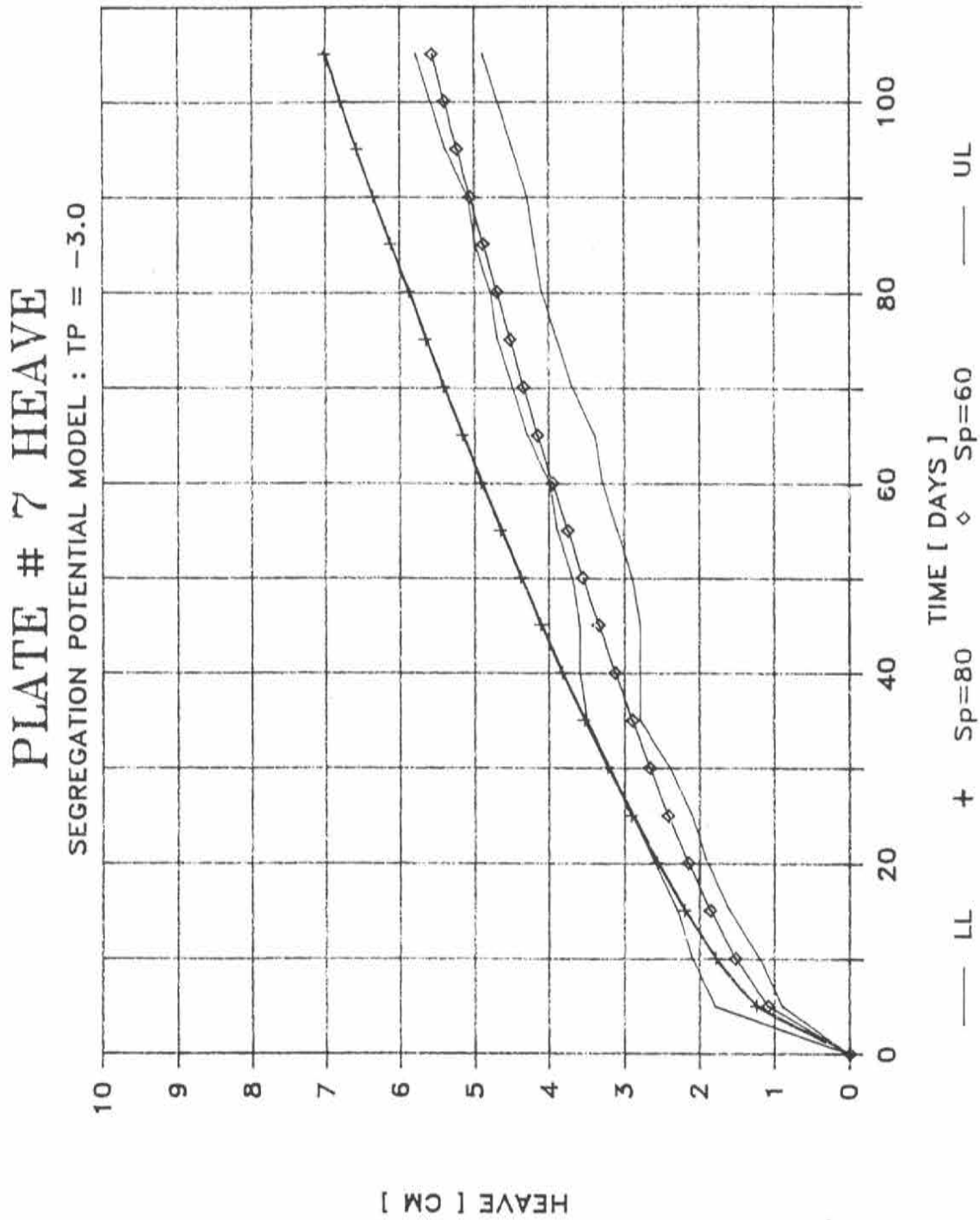
CALGARY FROST HEAVE TEST FACILITY

PLATE #8

SEGREGATION POTENTIAL
MODEL CALCULATIONS
OBSERVED TEMP GRADIENT

FIGURE 4.3-2



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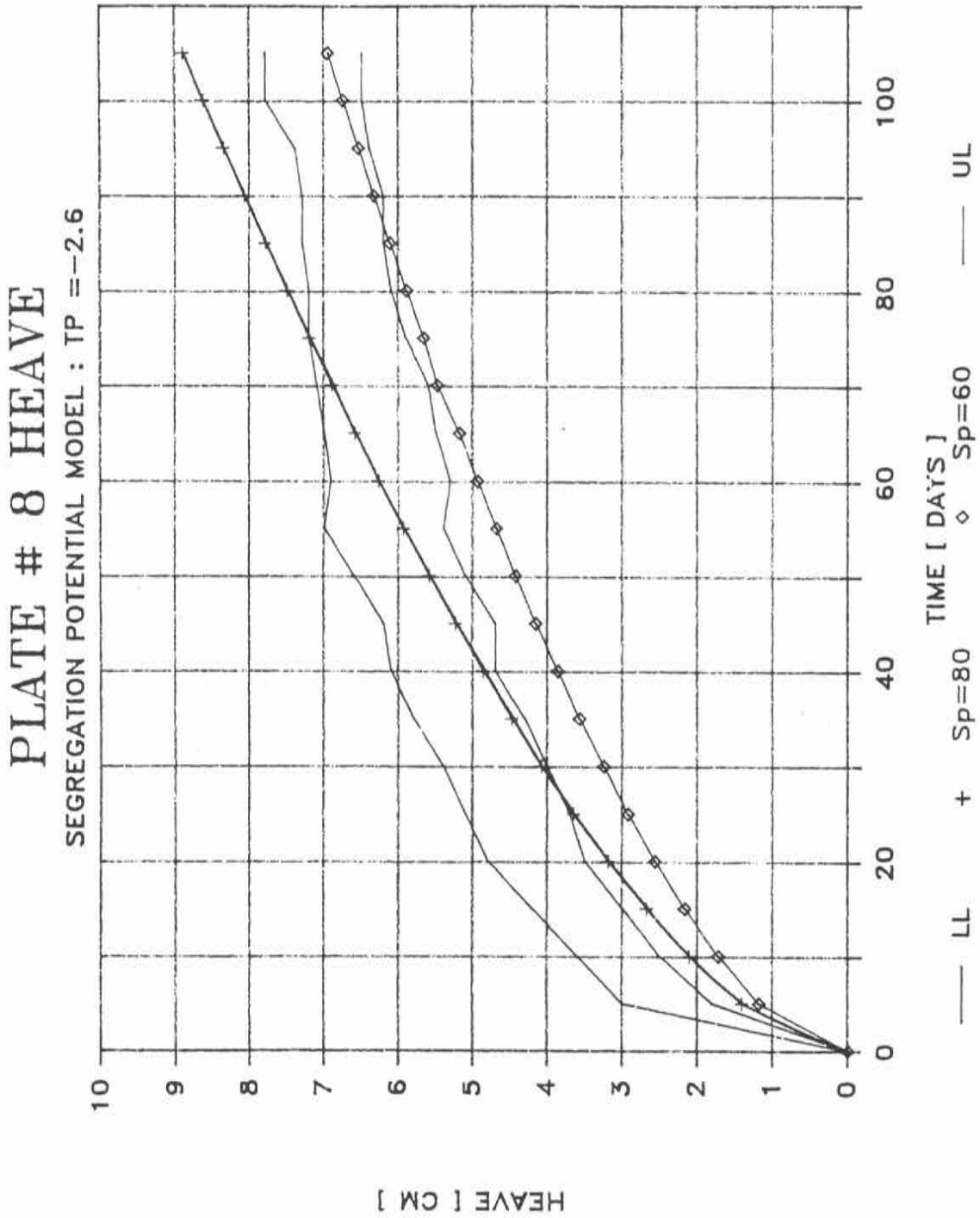
CALGARY FROST HEAVE TEST FACILITY

PLATE #7

SEGREGATION POTENTIAL
MODEL CALCULATIONS
CALCULATED TEMP GRADIENT

FIGURE 4.2-3



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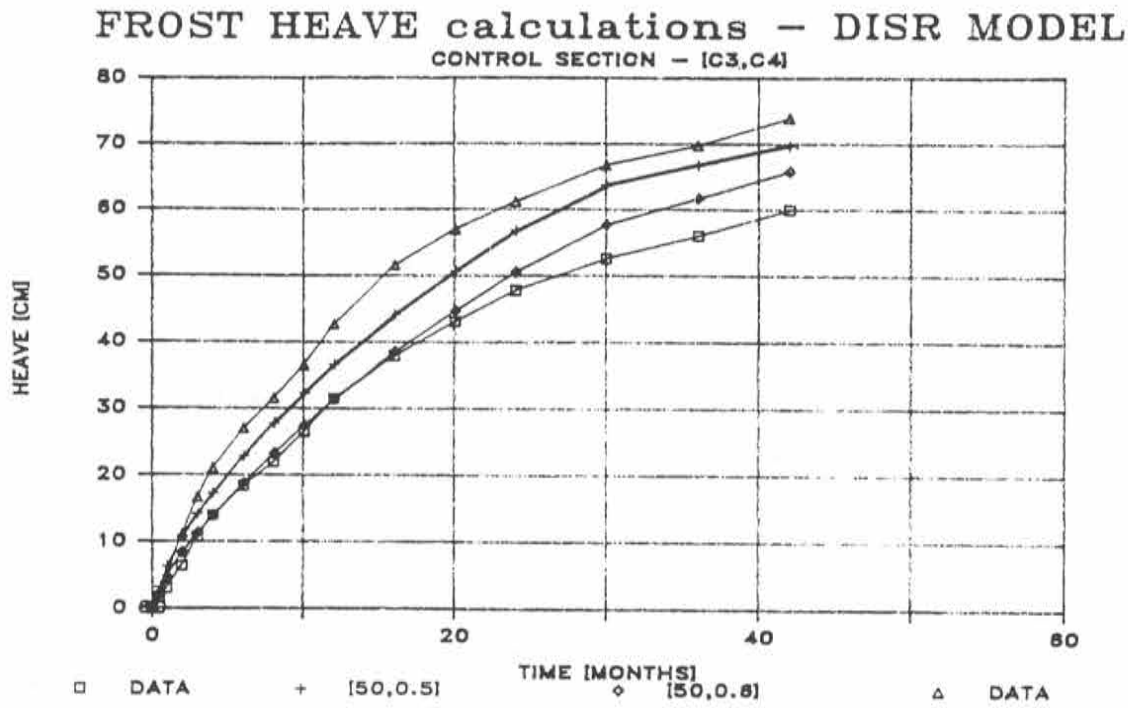
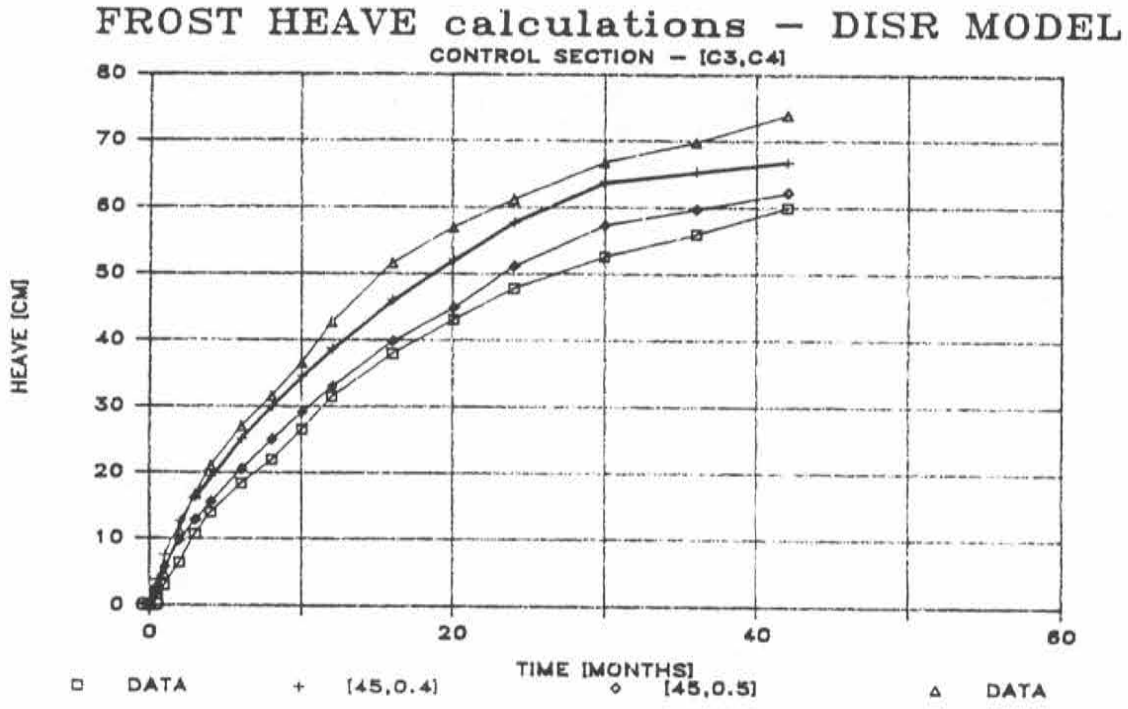
CALGARY FROST HEAVE TEST FACILITY

PLATE #8

SEGREGATION POTENTIAL
MODEL CALCULATIONS
CALCULATED TEMP GRADIENT

FIGURE 4.3-4





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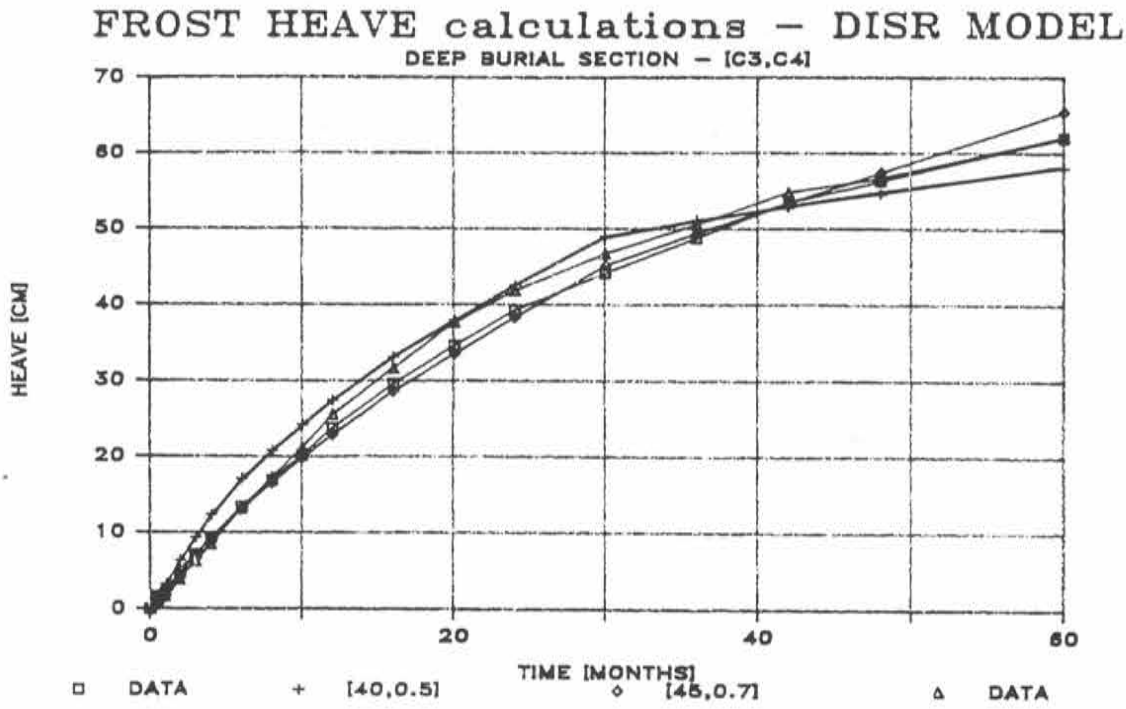
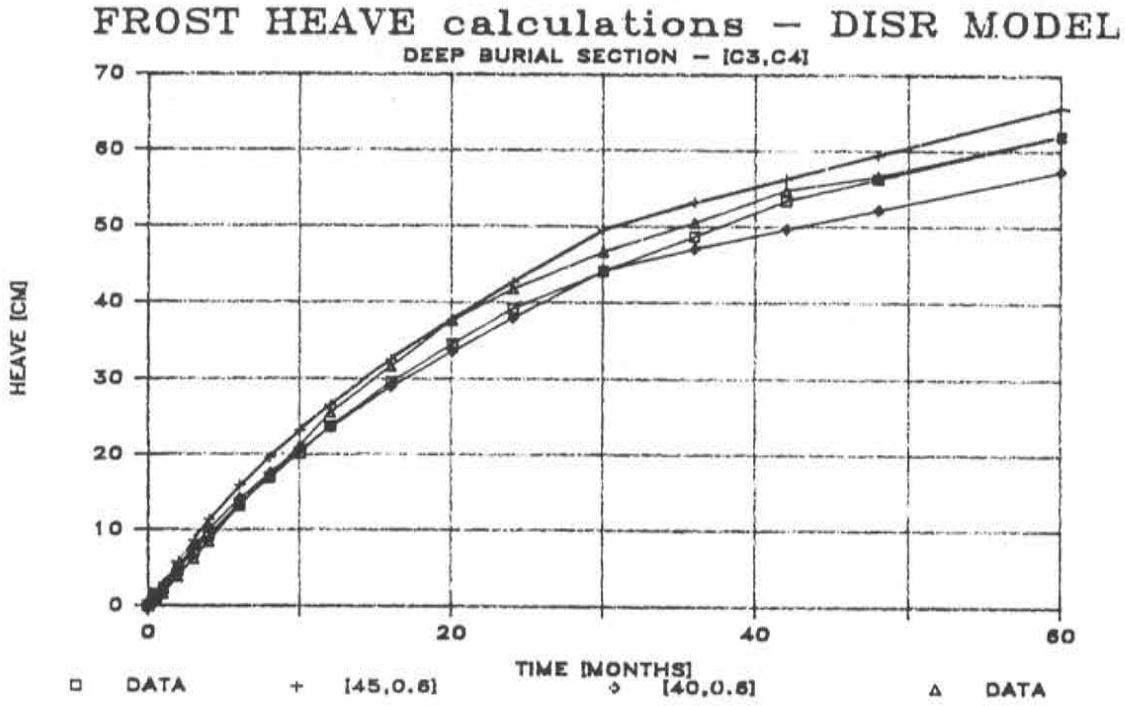
CALGARY FROST HEAVE TEST FACILITY

CONTROL SECTION

ICE SEGREGATION RATIO
MODEL CALCULATIONS

FIGURE 5.1-1





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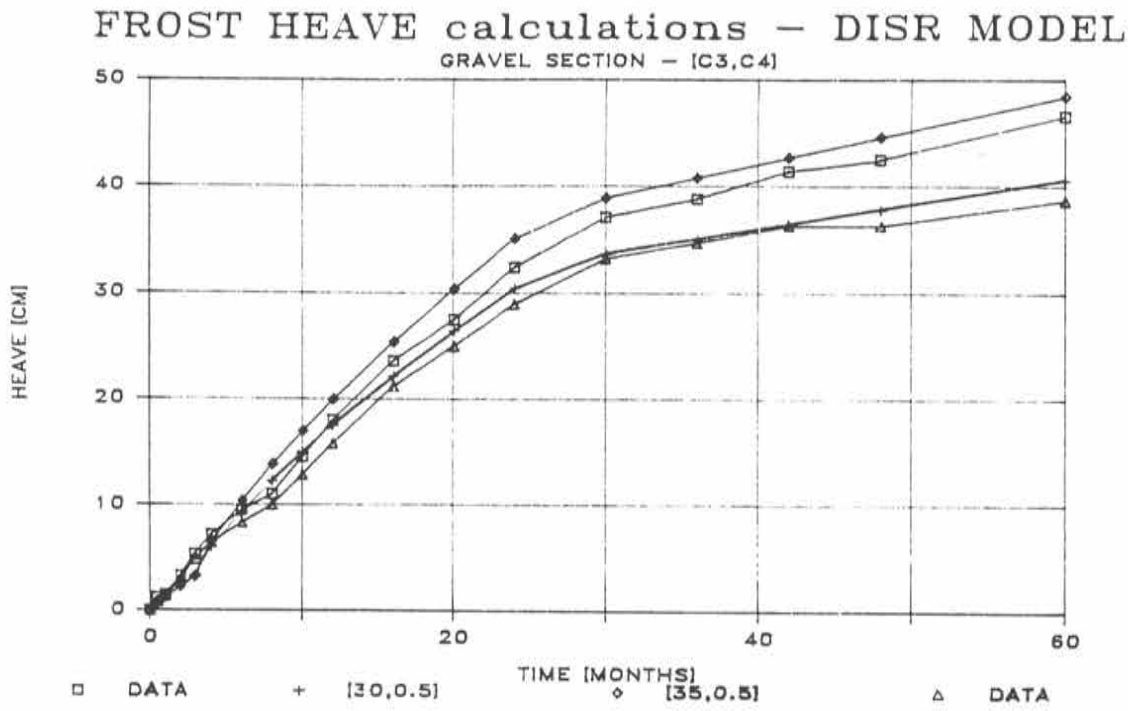
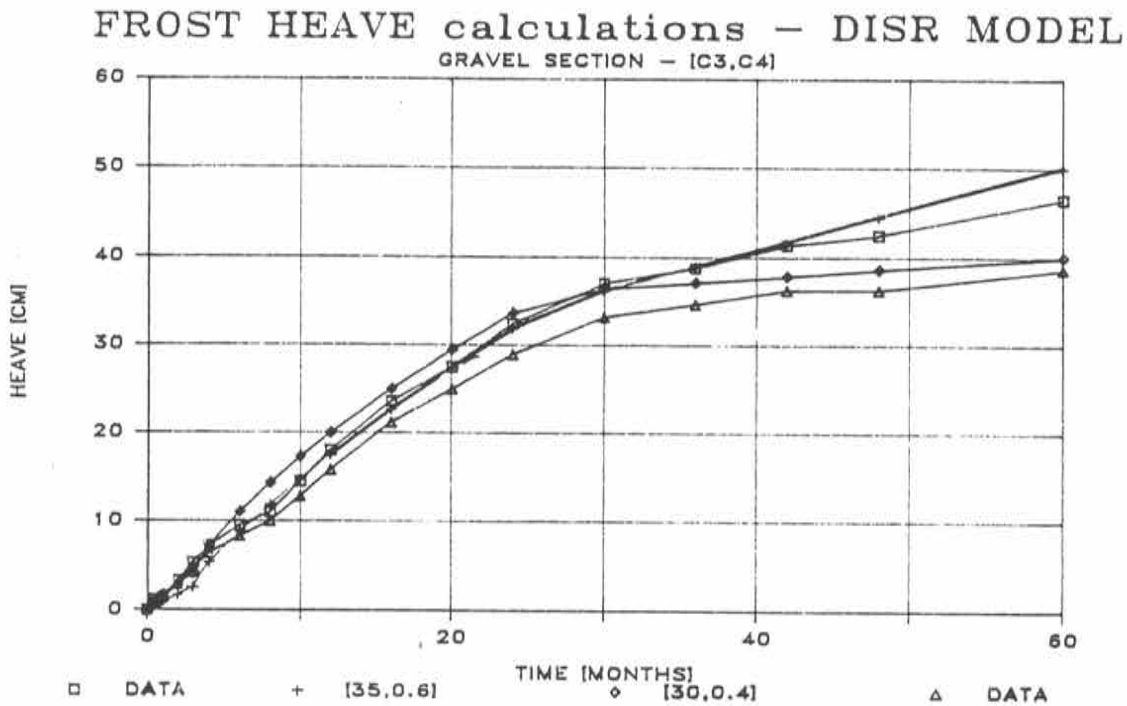
CALGARY FROST HEAVE TEST FACILITY

DEEP BURIAL SECTION

ICE SEGREGATION RATIO
MODEL CALCULATIONS

FIGURE 5.1-2





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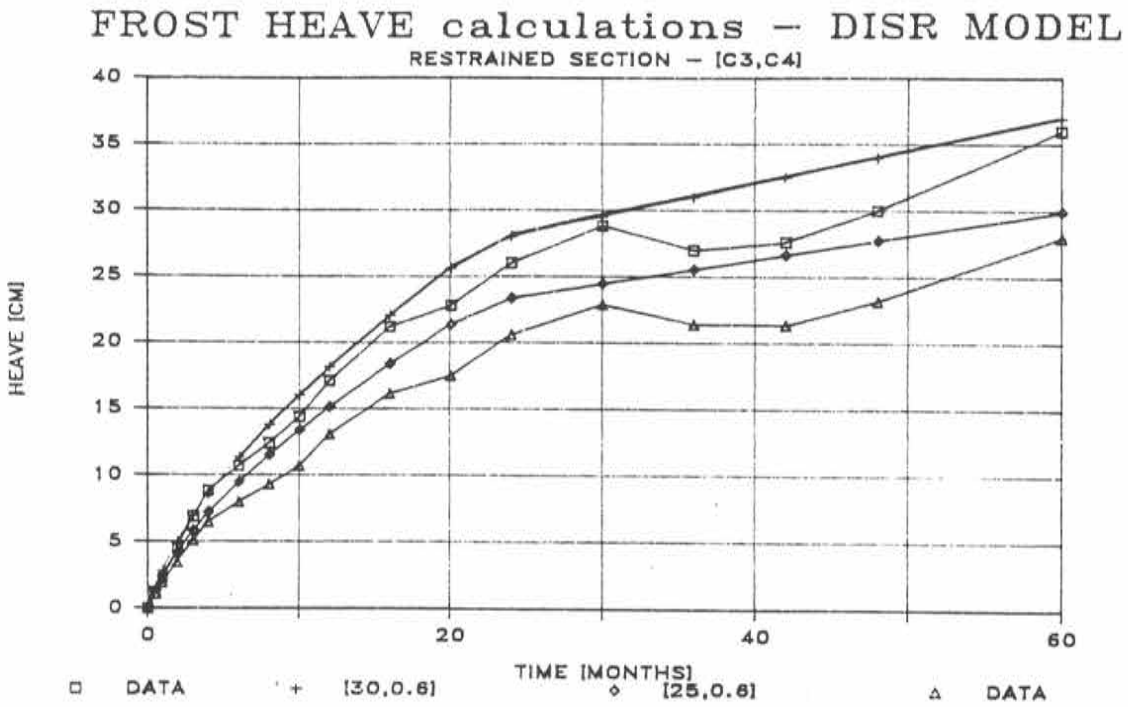
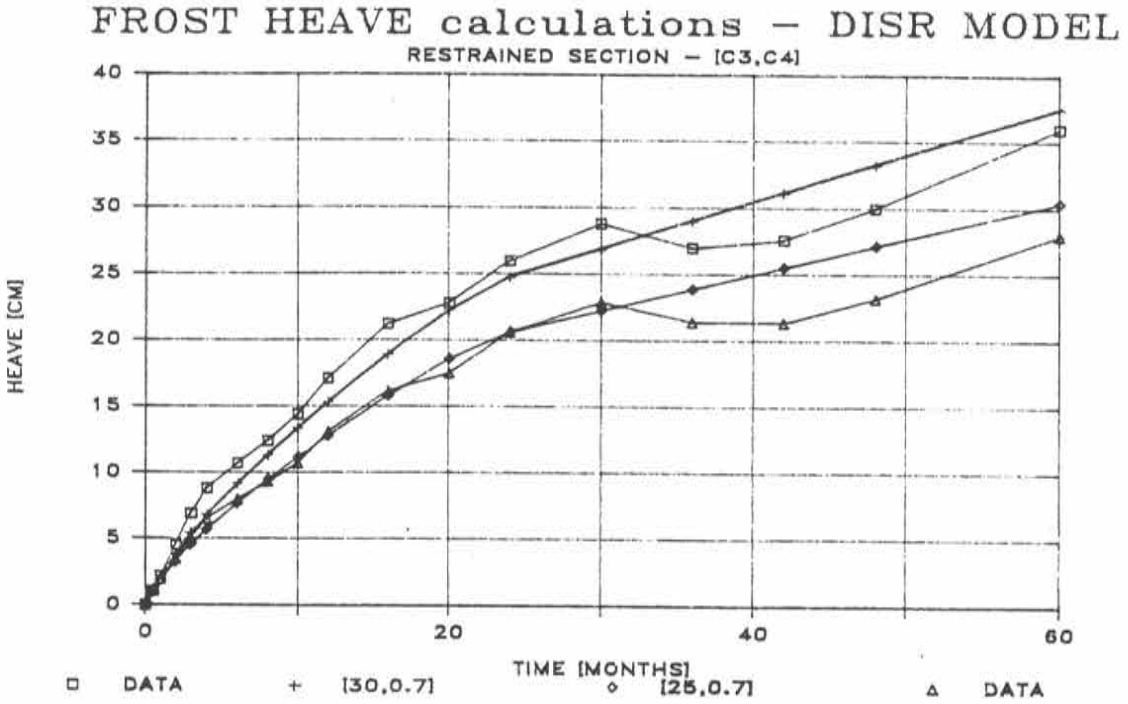
CALGARY FROST HEAVE TEST FACILITY

GRAVEL SECTION

ICE SEGREGATION RATIO
MODEL CALCULATIONS

FIGURE 5.1-3





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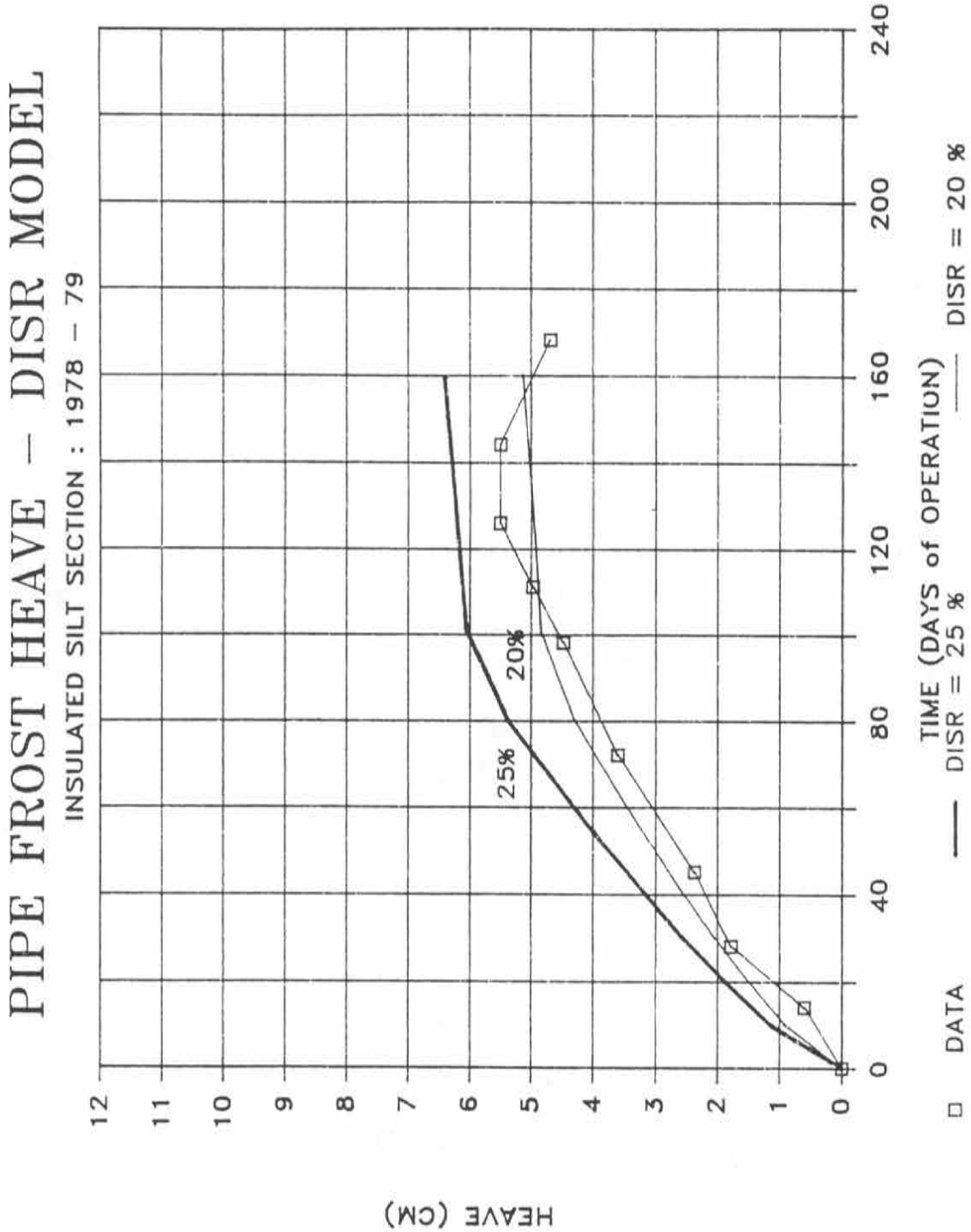
CALGARY FROST HEAVE TEST FACILITY

RESTRAINED SECTION

ICE SEGREGATION RATIO
MODEL CALCULATIONS

FIGURE 5.1-4



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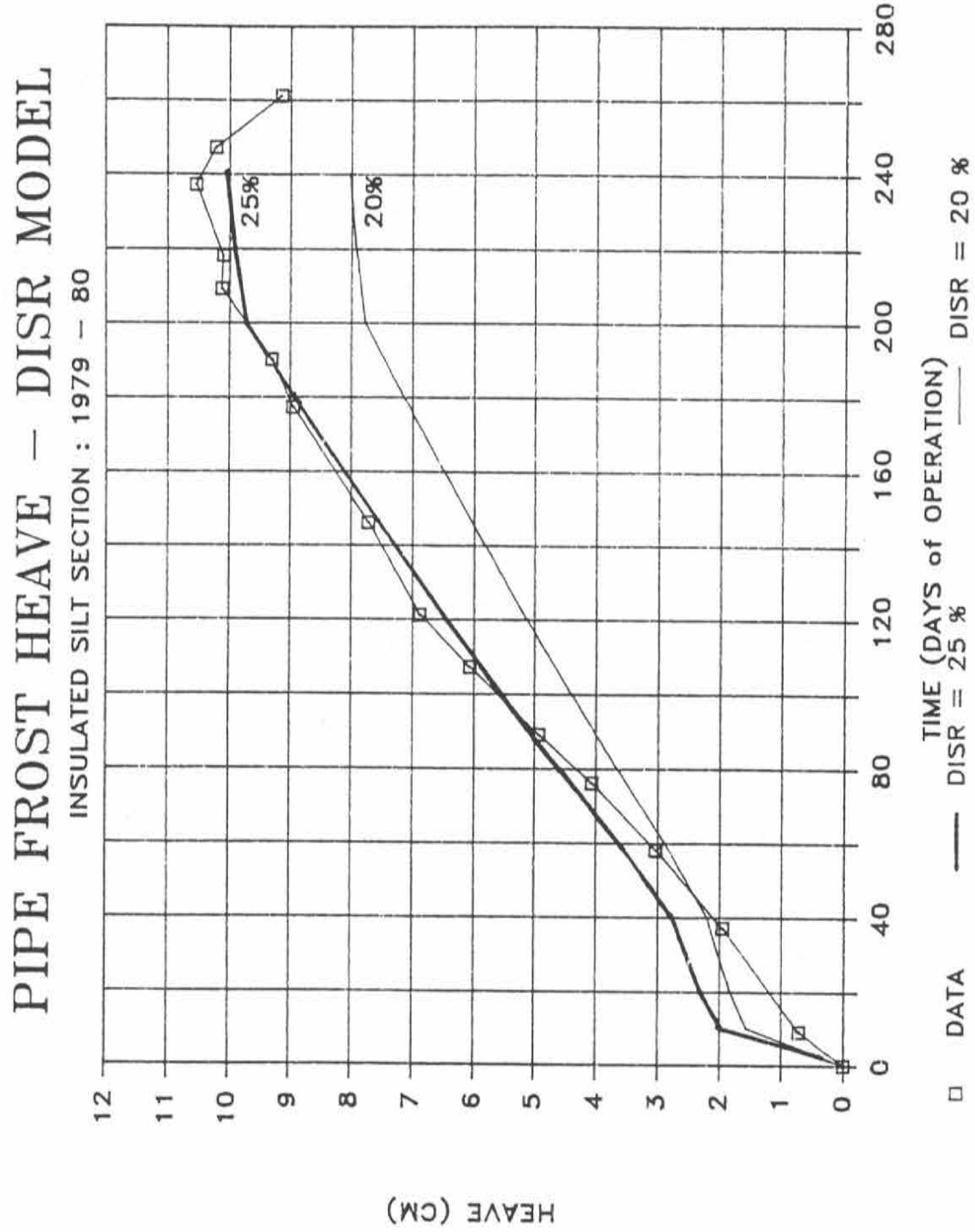
CALGARY FROST HEAVE TEST FACILITY

INSULATED SILT SECTION

1978-79 INCREMENTAL
ICE SEGREGATION RATIO
MODEL CALCULATIONS

FIGURE 5.2-1



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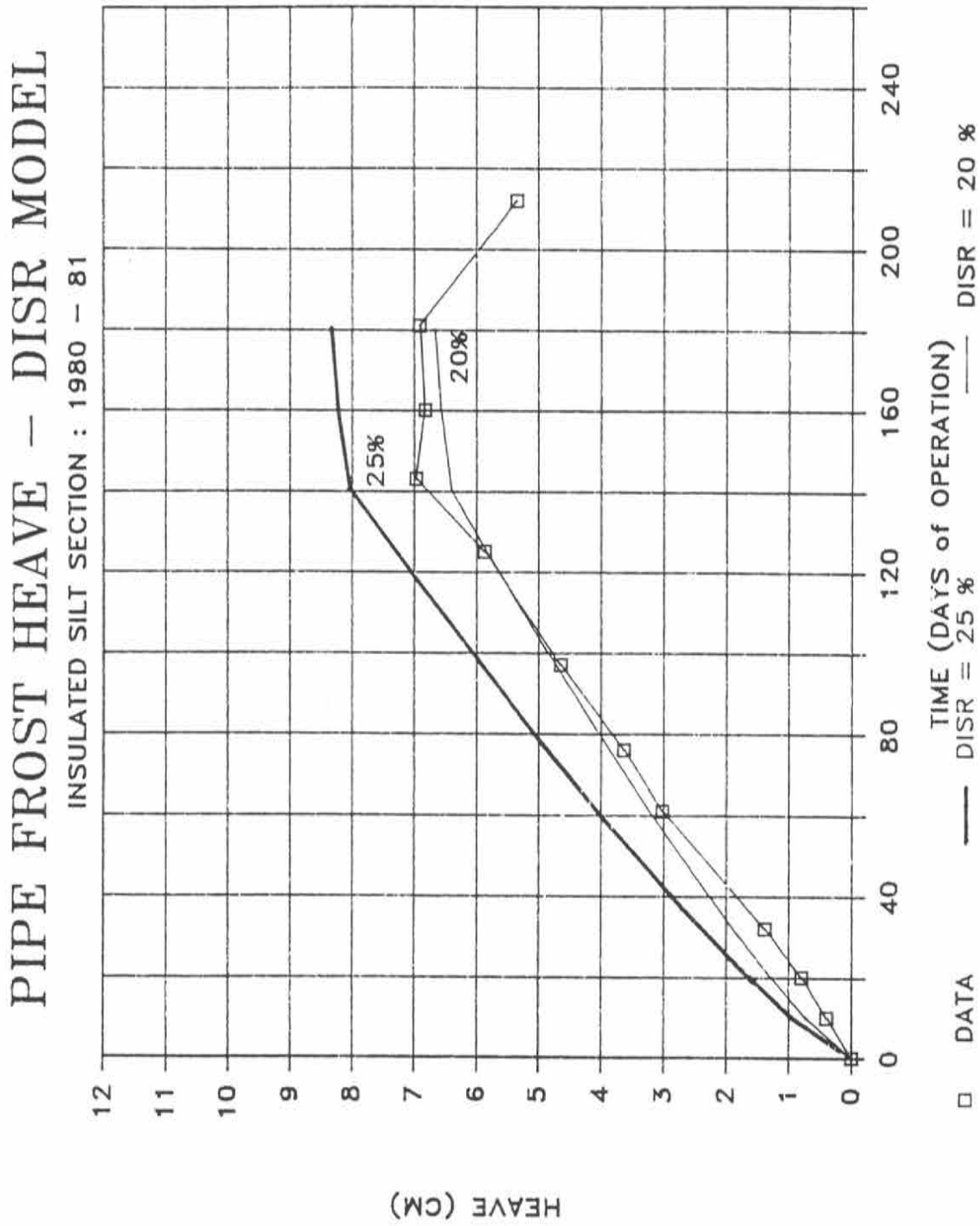
INSULATED SILT SECTION

1979-80 INCREMENTAL
ICE SEGREGATION RATIO
MODEL CALCULATIONS

FIGURE 5.2-2



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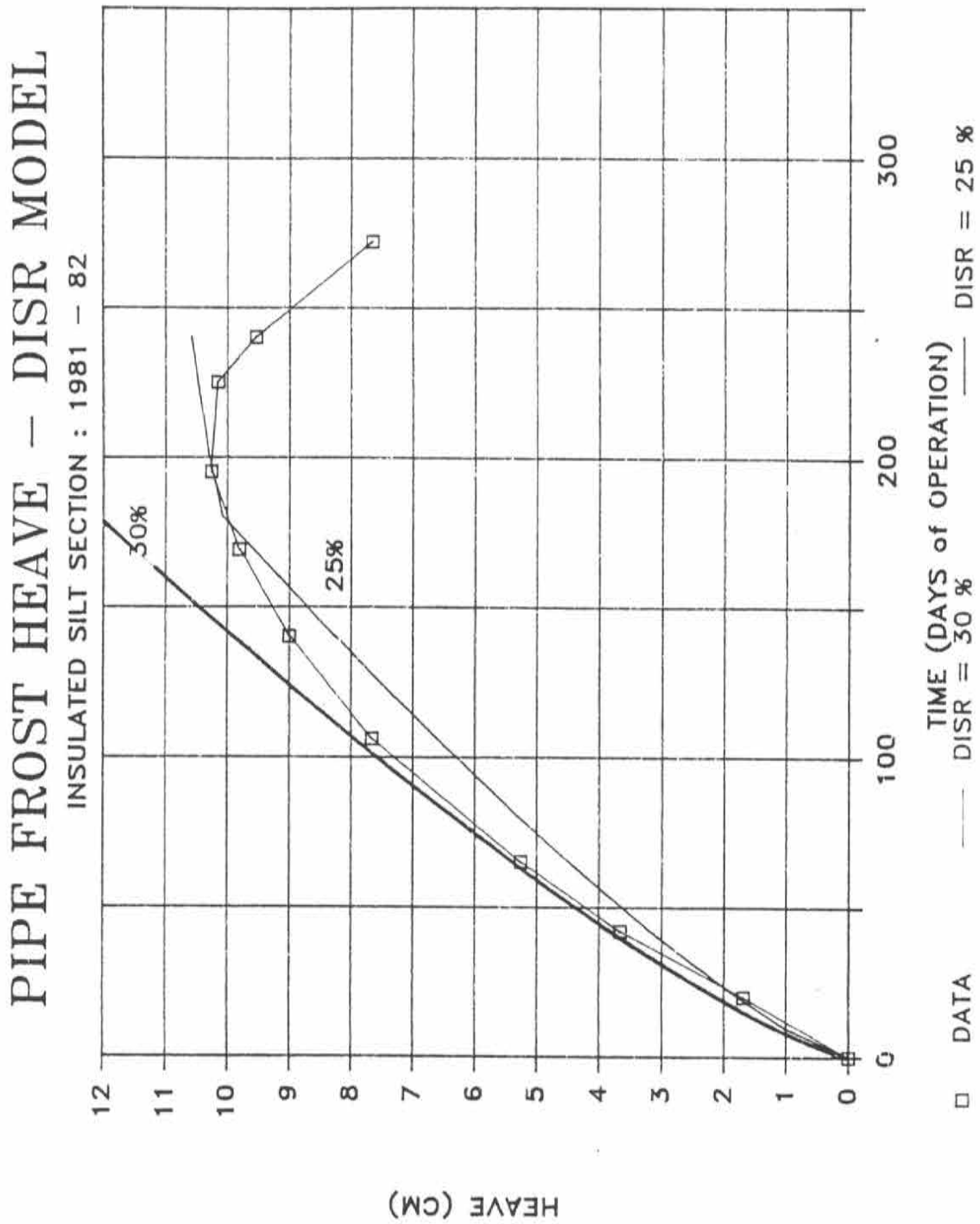
INSULATED SILT SECTION

1980-81 INCREMENTAL
ICE SEGREGATION RATIO
MODEL CALCULATIONS

FIGURE 5.2-3



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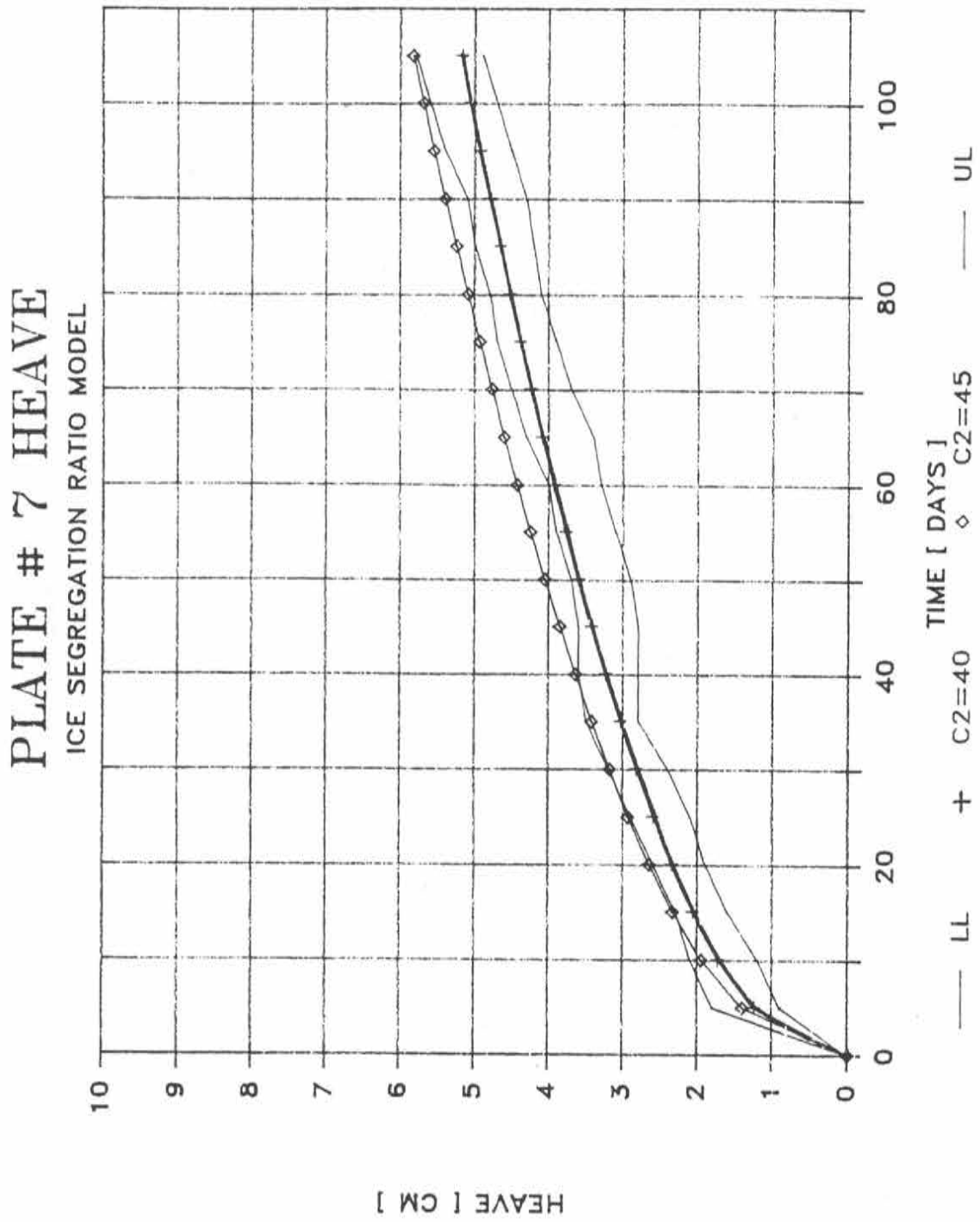
INSULATED SILT SECTION

1981-82 INCREMENTAL
ICE SEGREGATION RATIO
MODEL CALCULATIONS

FIGURE 5.2-4



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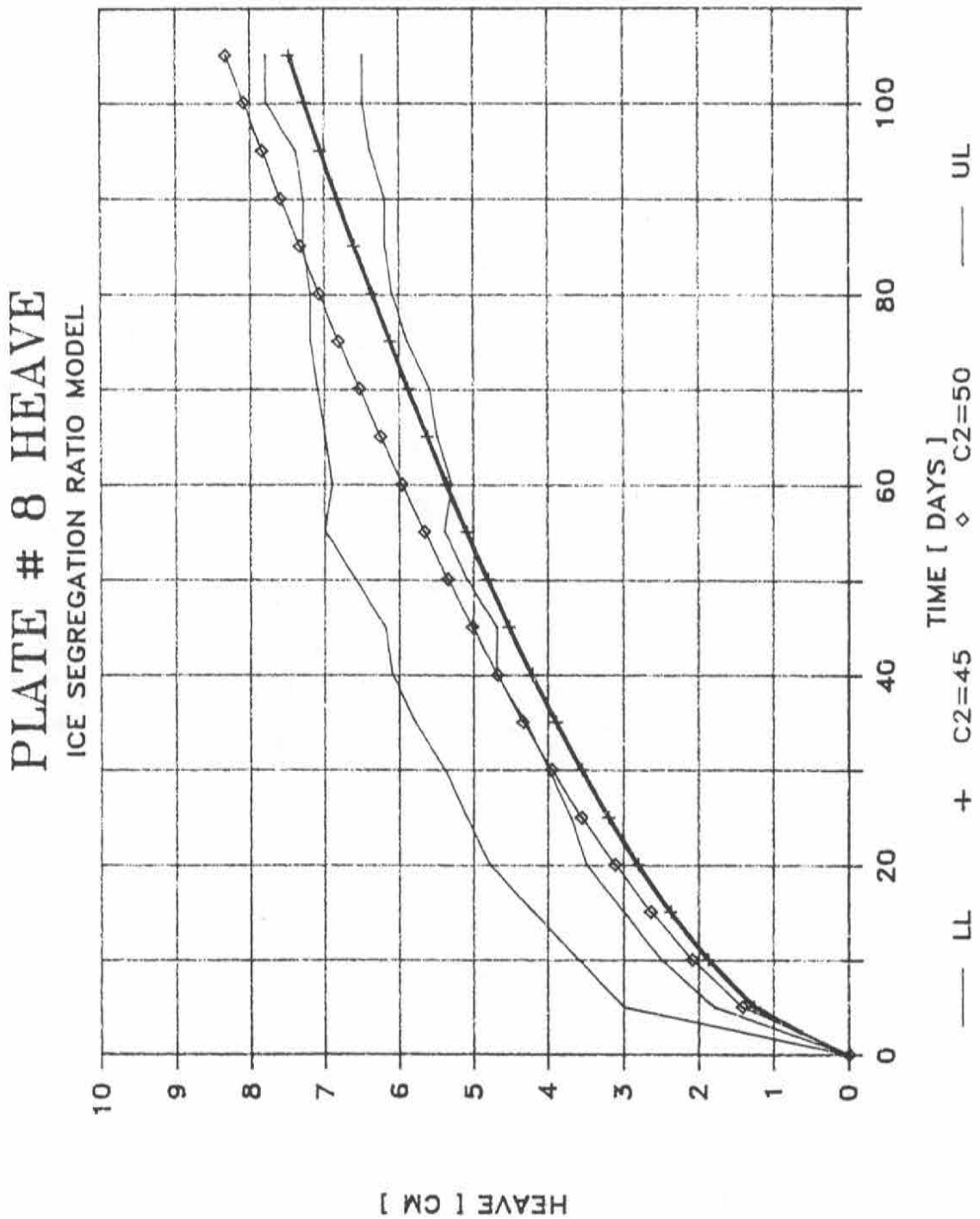
CALGARY FROST HEAVE TEST FACILITY

PLATE #7

INCREMENTAL
ICE SEGREGATION RATIO
MODEL CALCULATIONS

FIGURE 5.3-1



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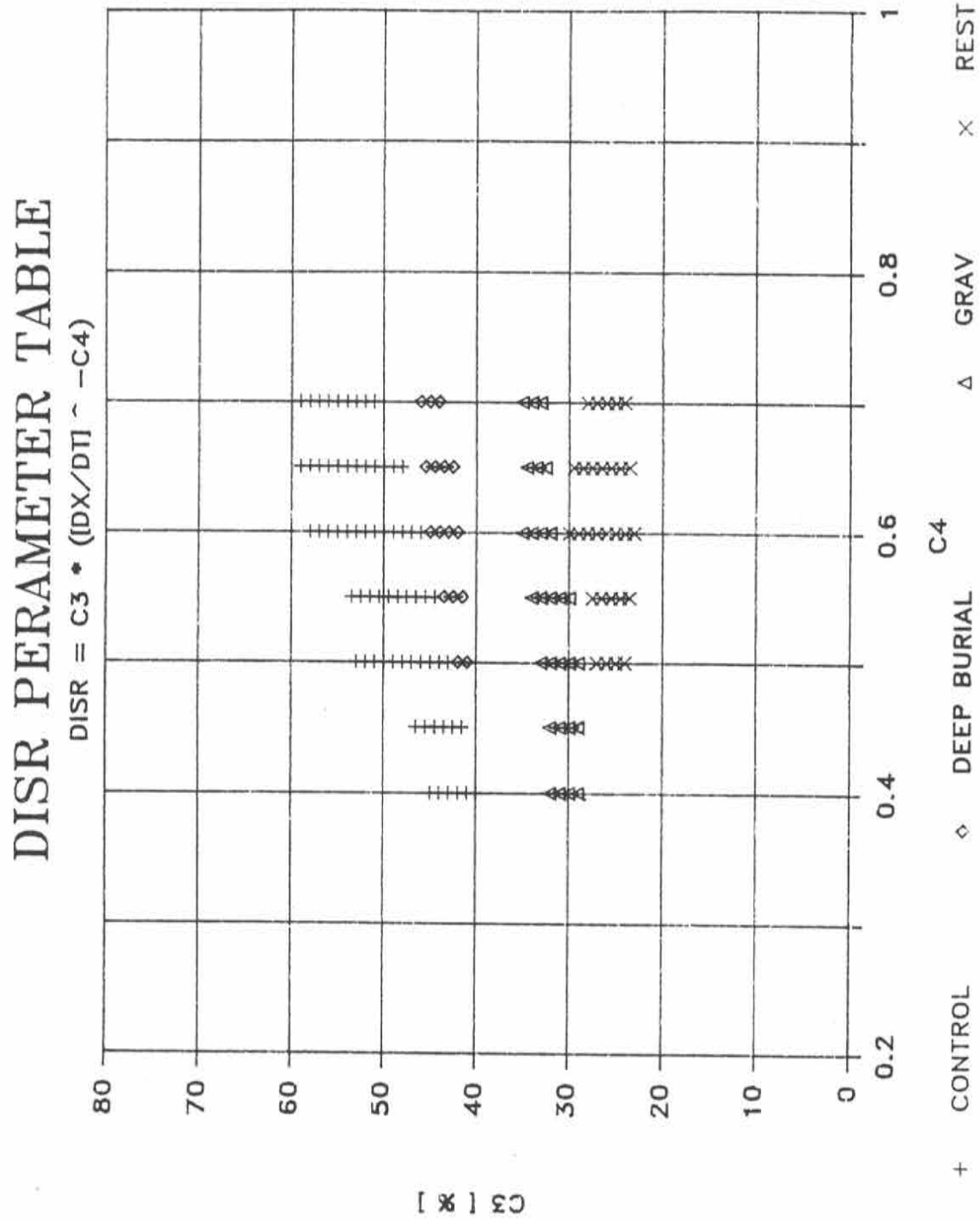
CALGARY FROST HEAVE TEST FACILITY

PLATE #8

INCREMENTAL
ICE SEGREGATION RATIO
MODEL CALCULATIONS

FIGURE 5.3-2



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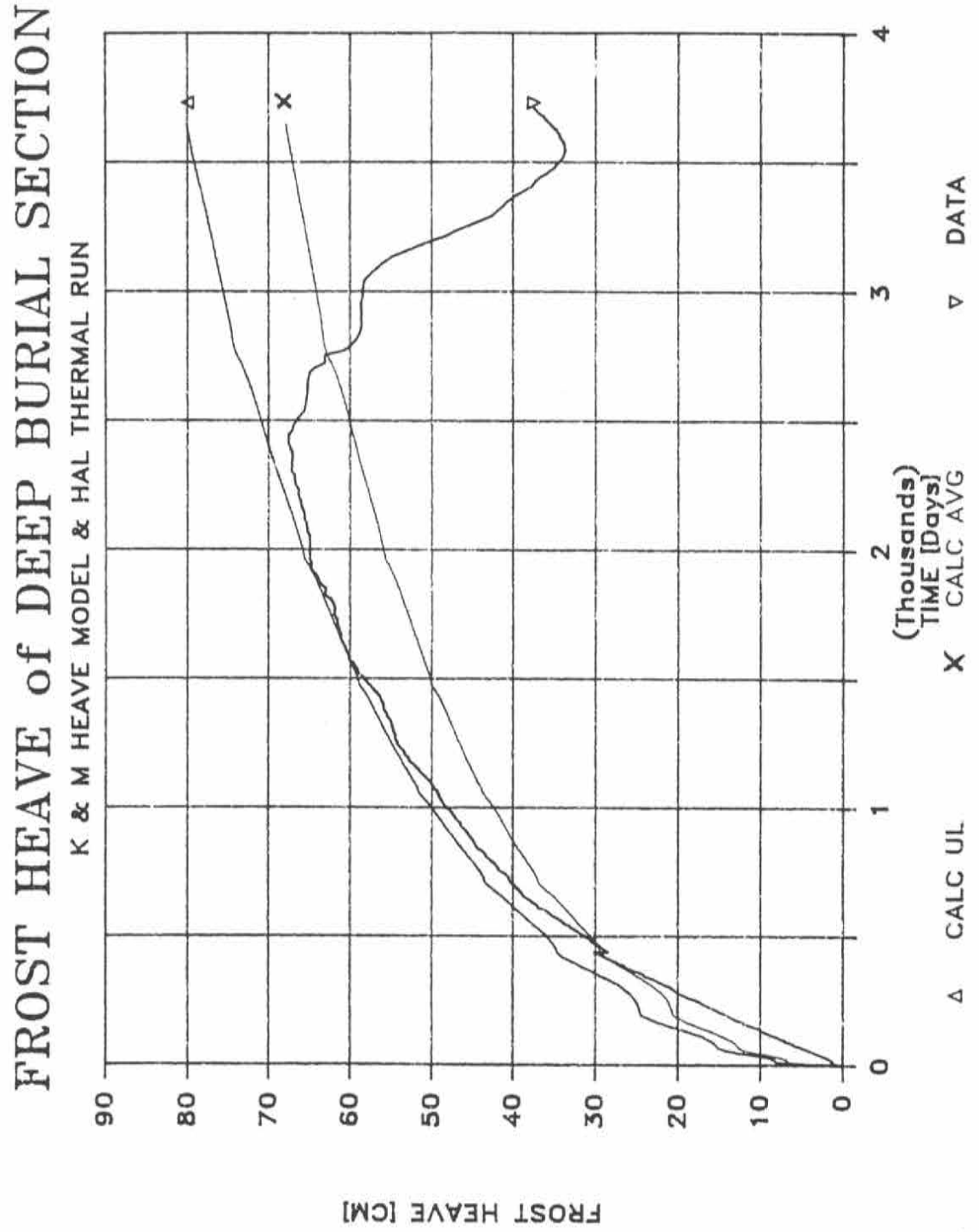
PARAMETER TABLE

INCREMENTAL
ICE SEGREGATION RATIO
MODEL CALCULATIONS

FIGURE 6.1-1



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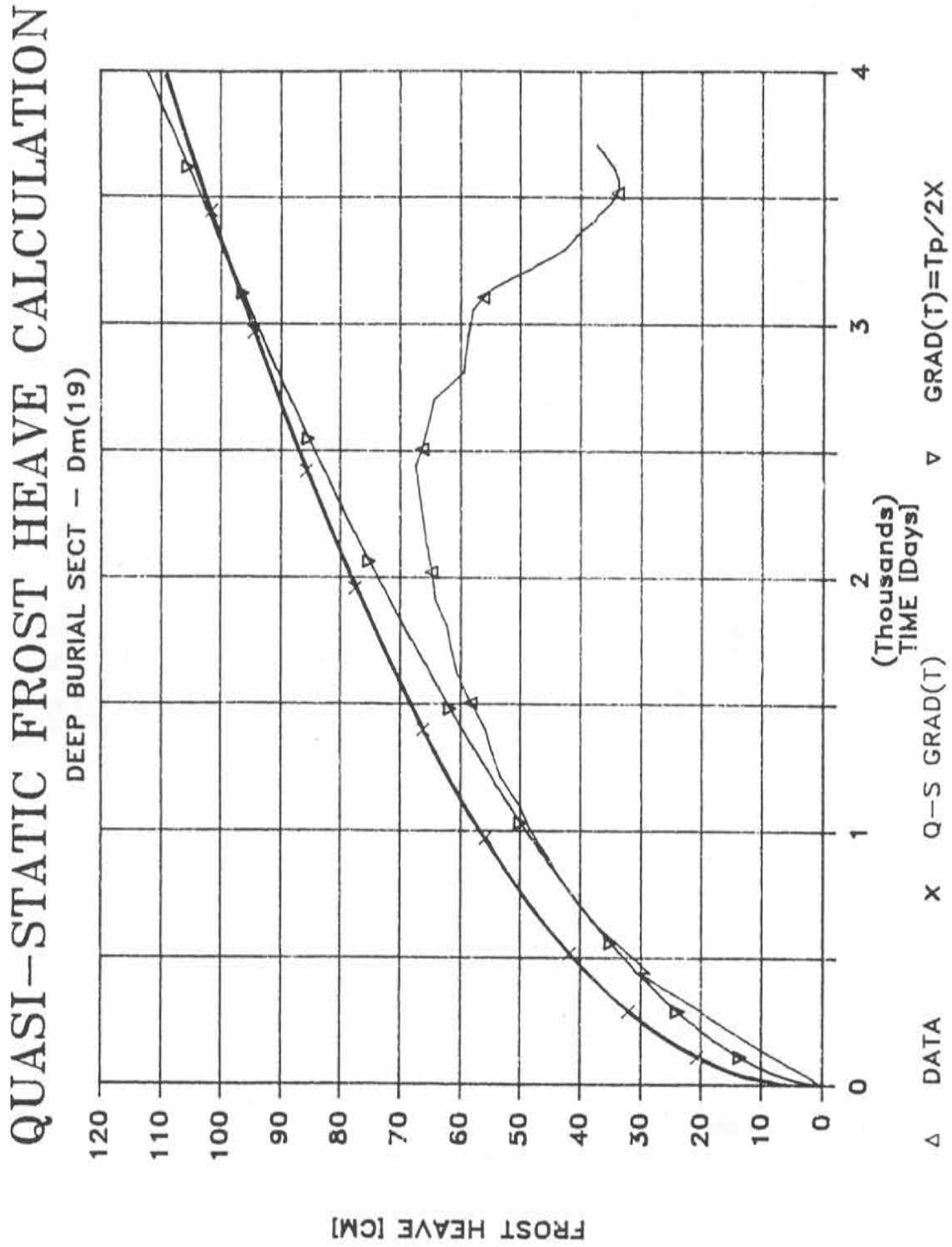
CALGARY FROST HEAVE TEST FACILITY

S P FROST HEAVE CALC

HAL THERMAL SIMULATION
DEEP BURIAL SECTION

FIGURE 7.1-1



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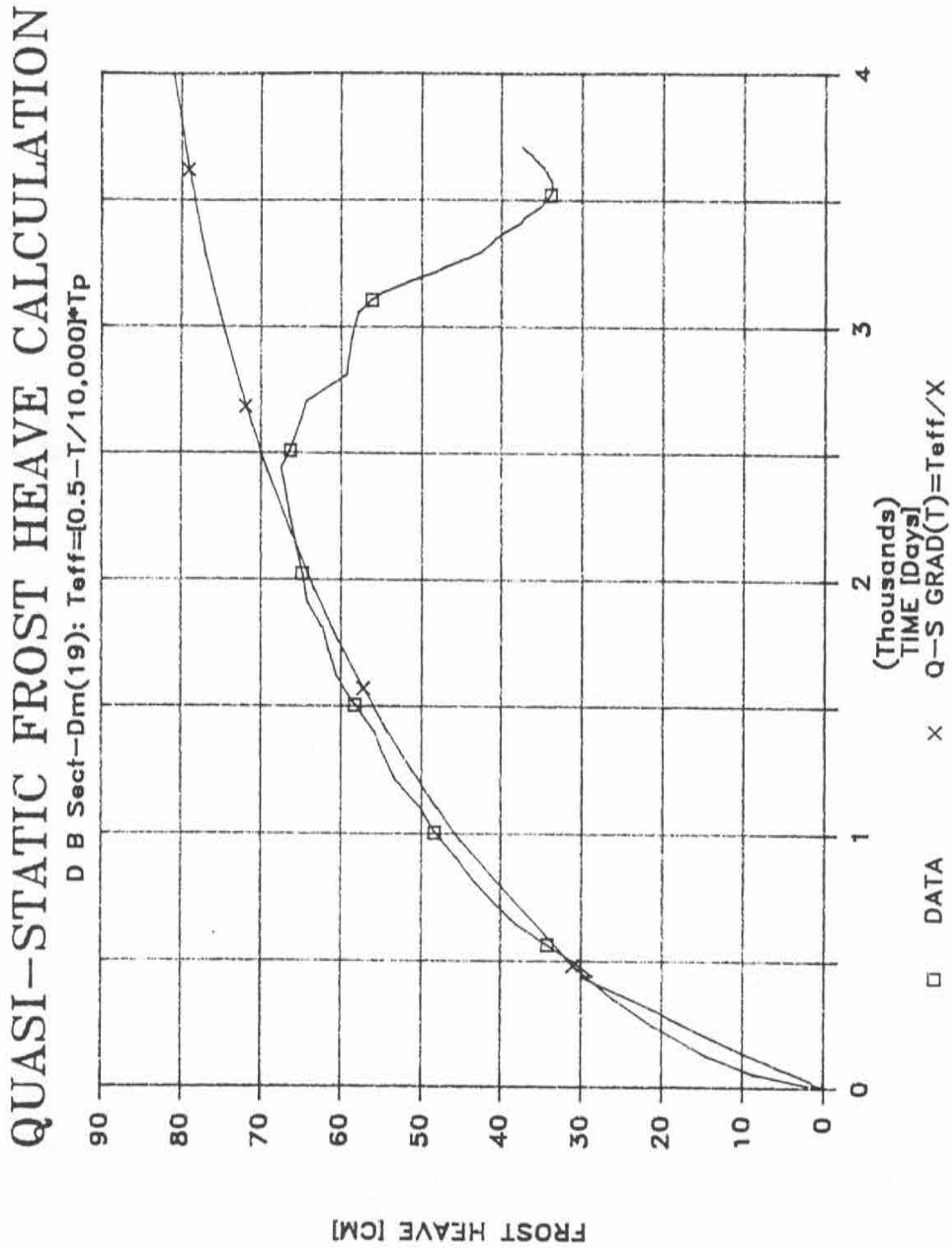
S P FROST HEAVE CALC

QUASI-STATIC MODEL
DEEP BURIAL SECTION

FIGURE 7.2-1



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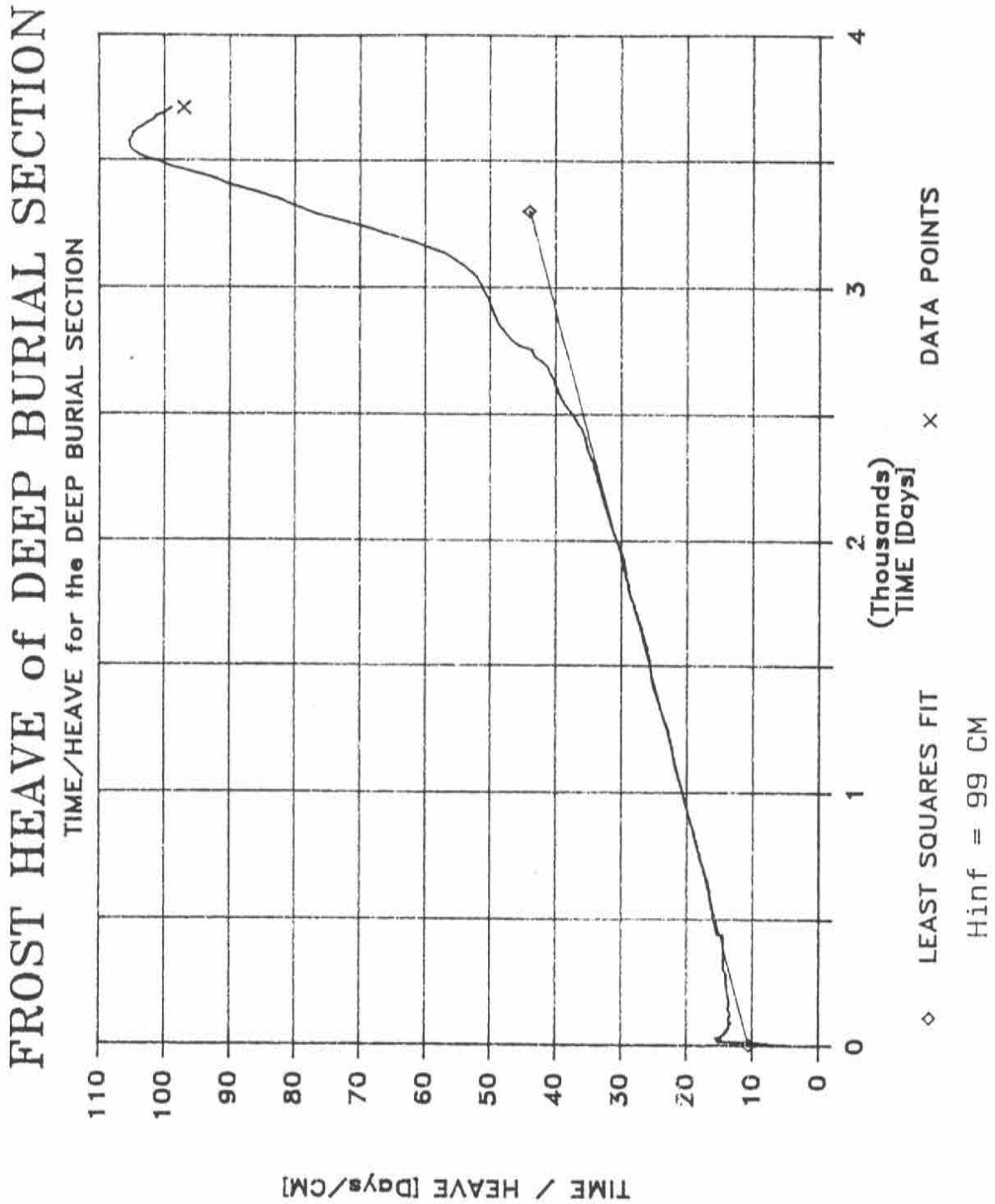
CALGARY FROST HEAVE TEST FACILITY

S P FROST HEAVE CALC

QUASI-STATIC MODEL
MODIFIED TEMP GRADIENT
DEEP BURIAL SECTION

FIGURE 7.2-2



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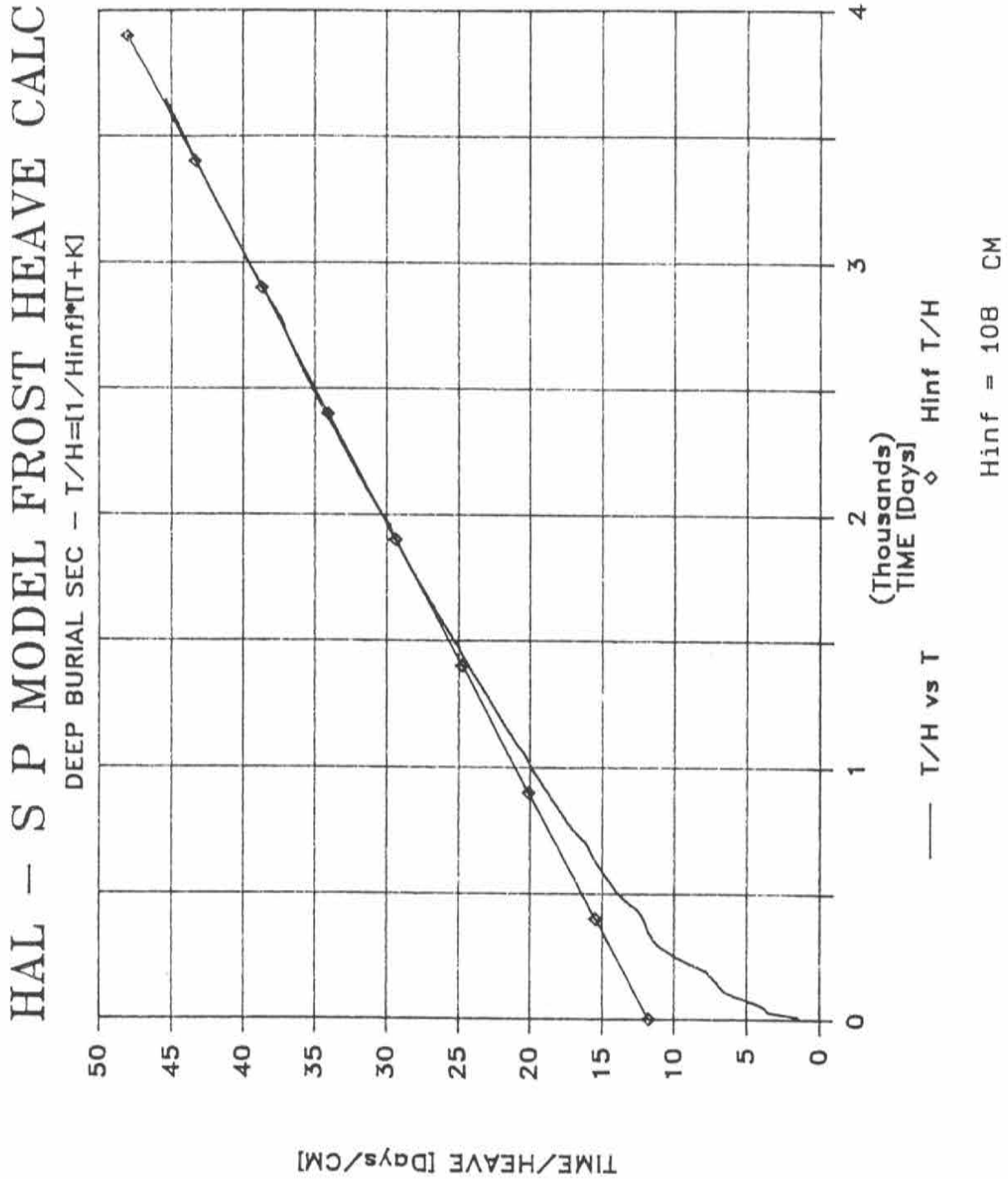
TIME/HEAVE vs TIME

FIELD DATA
DEEP BURIAL SECTION

FIGURE 8.2-1



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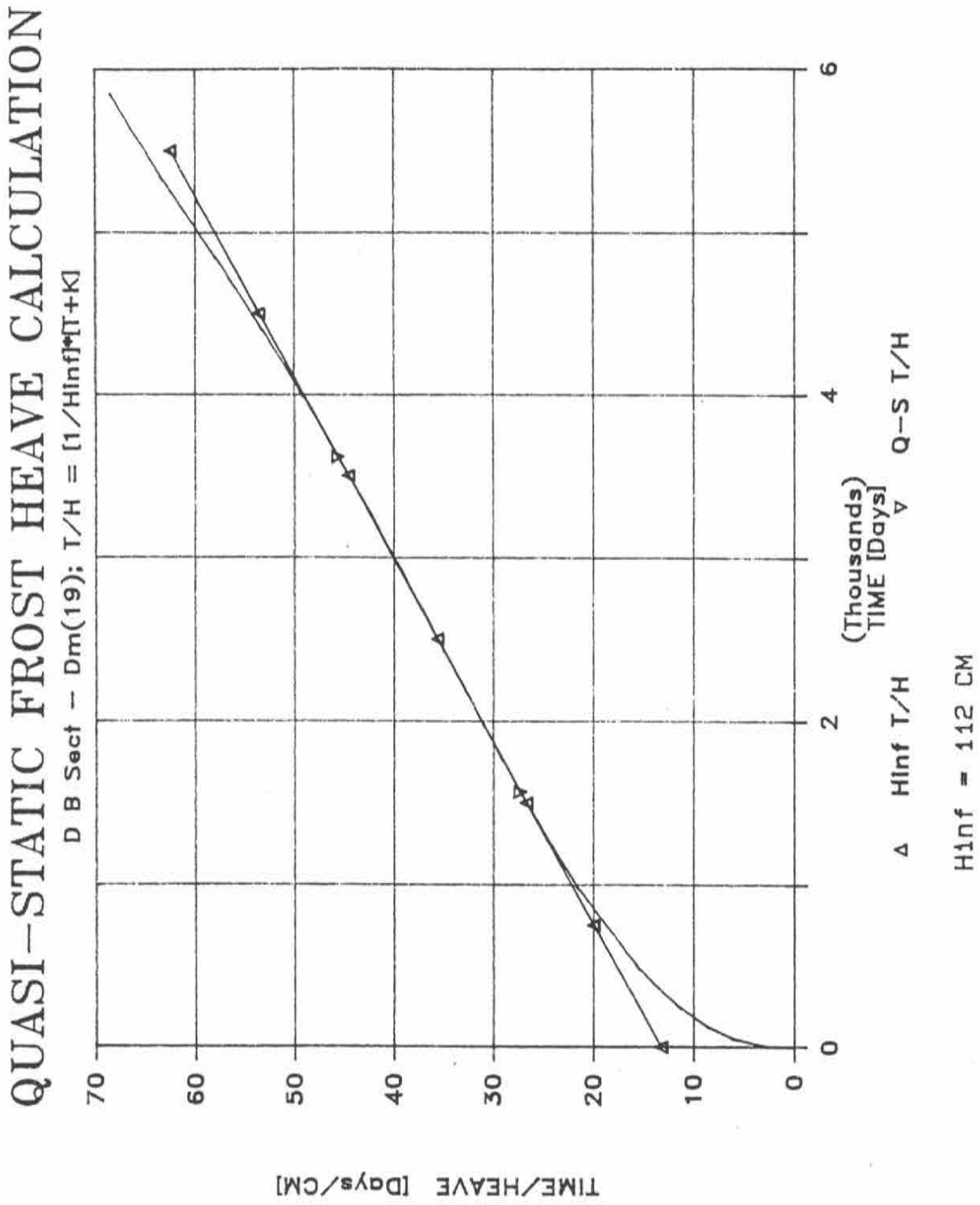
CALGARY FROST HEAVE TEST FACILITY

TIME/HEAVE vs TIME

HAL & HYPERBOLIC CALCULATIONS
DEEP BURIAL SECTION

FIGURE 8.2-2



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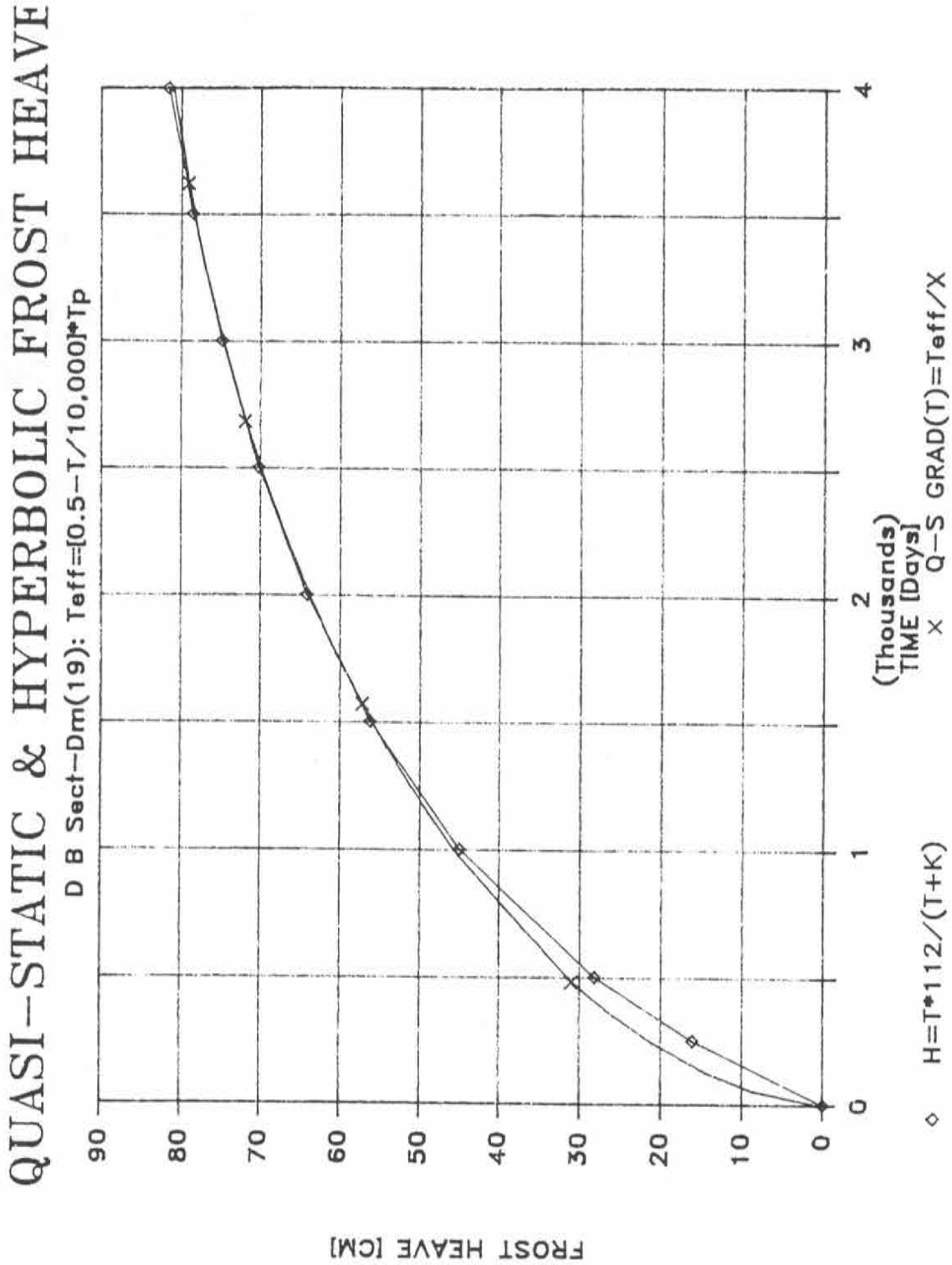
CALGARY FROST HEAVE TEST FACILITY

TIME/HEAVE vs TIME

QUASI-STATIC &
HYPERBOLIC CALC
DEEP BURIAL SECTION

FIGURE 8.2-3



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CALGARY FROST HEAVE TEST FACILITY

CALCULATED HEAVE

QUASI-STATIC &
HYPERBOLIC MODELS

FIGURE 8.2-4

APPENDIX 1

APPENDIX 1

TEMPERATURE GRADIENTS AT THE FROST FRONT

In order to carry out a frost heave calculation using the Segregation Potential model, it is necessary to know both the segregation potential values, SP, and the temperature gradient, grad(T), at the frost front. The SP values can be obtained from relatively simple lab tests, while the grad(T) values have usually been obtained from computer thermal simulations. For the first set of calculations in section 4.1.1, grad(T) was taken from the observed ground temperatures. Since the temperature strings are offset from the pipe centreline by one metre, the observed values had to be converted to equivalent values directly under the pipe.

The measured grad(T) values, at the position of the temperature strings, are given in Figure A1-1 for the Control section. This data is from Carlson [1984]. Similar data for the Deep Burial, Gravel and Restrained sections is seen in Figures A1-2,3 & 4.

Now, thermal simulations, using the HAL Thermal Simulator [Nixon and Halliwel 1982], were run in order to determine a relationship between the grad(T) values directly below the pipe and at a one metre offset. Results of these calculations for the Control and Deep Burial sections are seen in Figures A1-5 and A1-6. It is seen that after the first 100 days the grad(T) values for these two locations are very similar. The HAL calculation temperature gradient values are presented along with the observed data, for the Control section, in Figure A1-7. The agreement is quite good. A similar plot for the Deep Burial section is seen in Figure A1-8. In this case however, after day 600, the HAL calculation values drop down to only one half the data values.

Using the HAL calculations as a guide, equations for grad(T) based on the observed values were formulated for used in section 4.1.1 to calculate the frost heave at the Non-insulated sections.

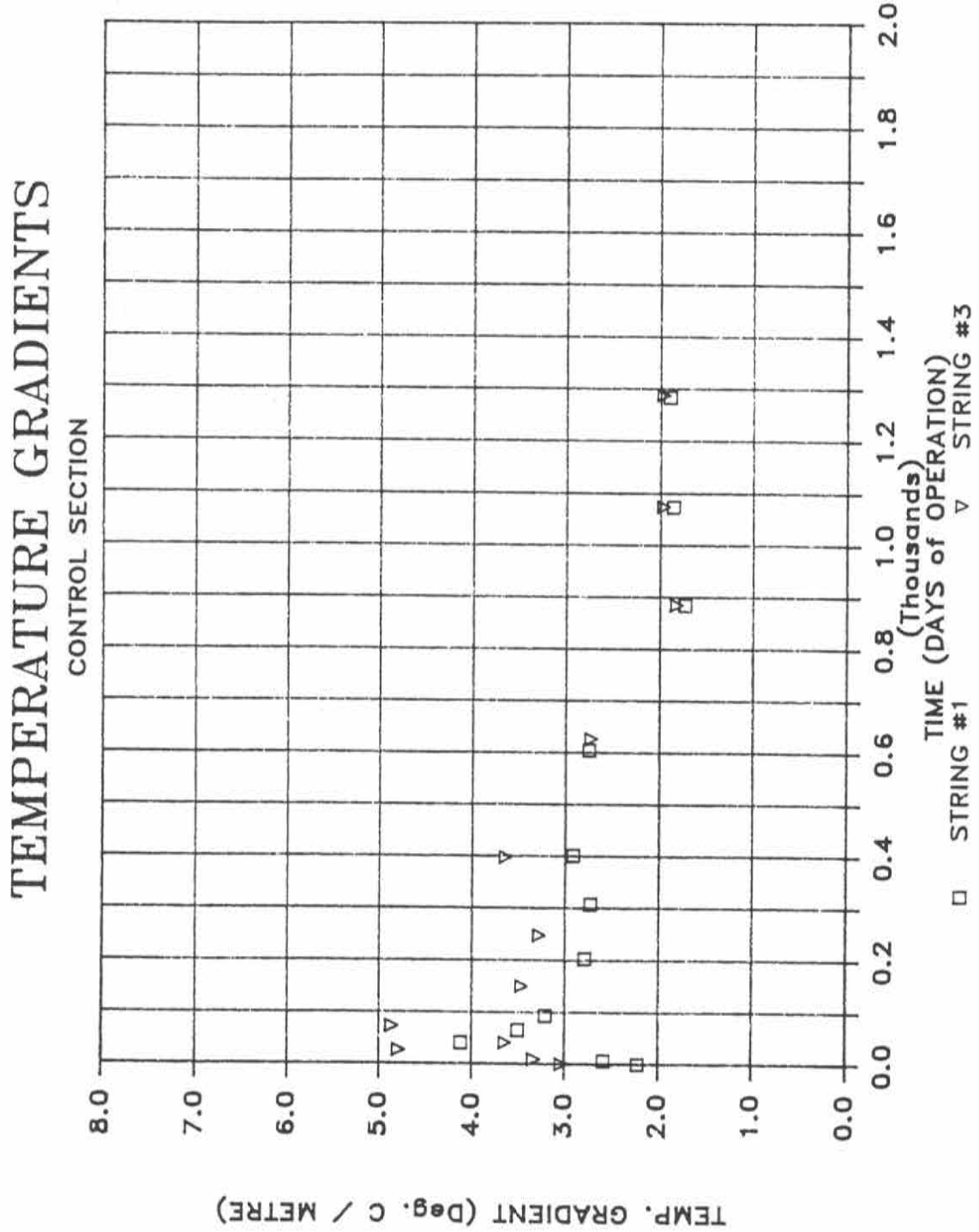
For the insulated pipe section, Figure A1-9 shows the temperature gradient directly under the centre of the pipe section. These values are derived from the thermistor strings installed through the pipe about day 700 (January 1981). The grad(T) values cycle from zero to a maximum value quite quickly and then drop off slowly back to or close to zero. The data in the figure covers the 1981 and 1982 winters.

The grad(T) values at the frost fronts under Plate #7 and Plate # 8 are presented in Figure A1-10 for the first 120 days of operation of these sections. The values for the two sections are almost identical. Also, the grad(T) values here are about double the values for the Insulated pipe section.

The use of the Segregation Potential frost heave model would be more expedient if we had a simple means of determining the grad(T) values and were not forced to carry out costly time consuming thermal simulations. To this end, the HAL thermal simulation data was analyzed to obtain the ratio of the grad(T) at a soil temperature of 0.1 Deg. C to the average frost bulb grad(T) value. The average frost bulb grad(T) value is calculated as the pipe temperature divided by the frost bulb depth below the pipe. This ratio is seen in Figure A1-11 for the Deep Burial section. An average value, for the ratio, of 0.5 is representative of the calculated value for the first two years and somewhat conservative for succeeding years. Data points from the Quasi Static model (discussed in Appendix 3) are also shown on the figure. The approximation

$$\text{grad}(T) = [0.5] \quad [Tp / X]$$

has been used in the heave calculations of section 4.1.2. With a limitation on the maximum value of 10 Deg. C per metre , calculated when X is very small, these calculations show very good agreement with the data.



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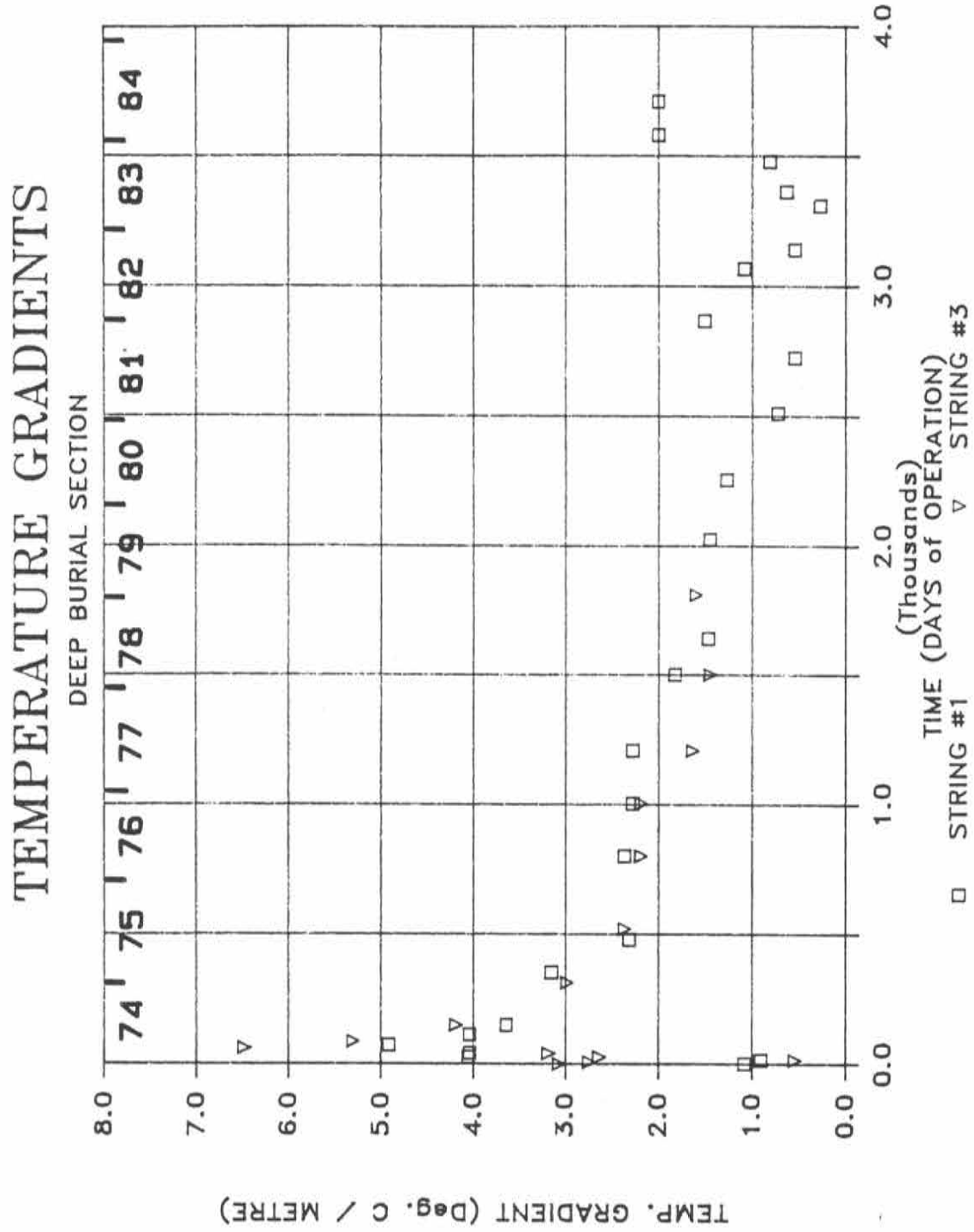
CALGARY FROST HEAVE TEST FACILITY

MEASURED

TEMPERATURE GRADIENTS
CONTROL SECTION

FIGURE A1-1



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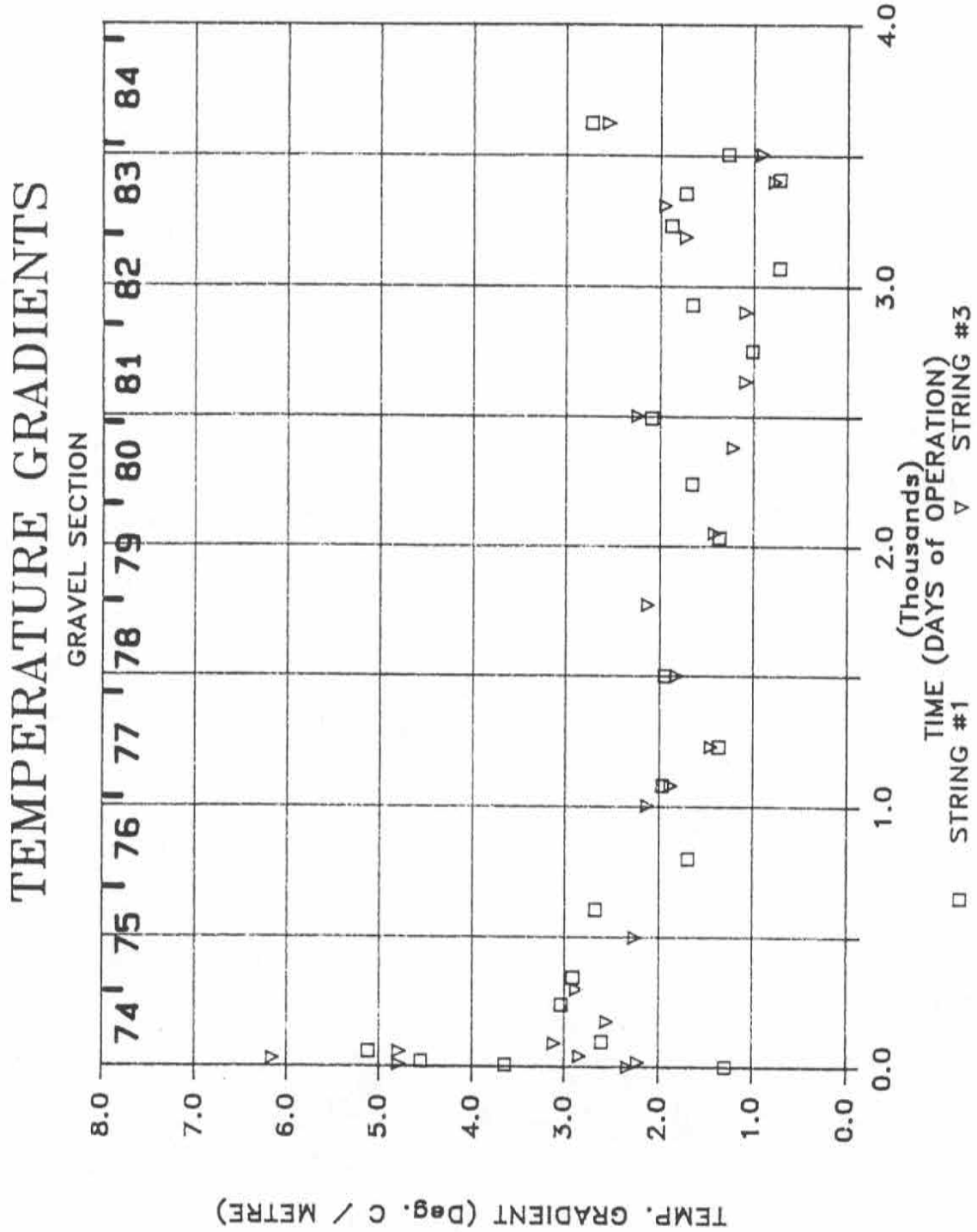
MEASURED

TEMPERATURE GRADIENTS
DEEP BURIAL SECTION

FIGURE A1-2



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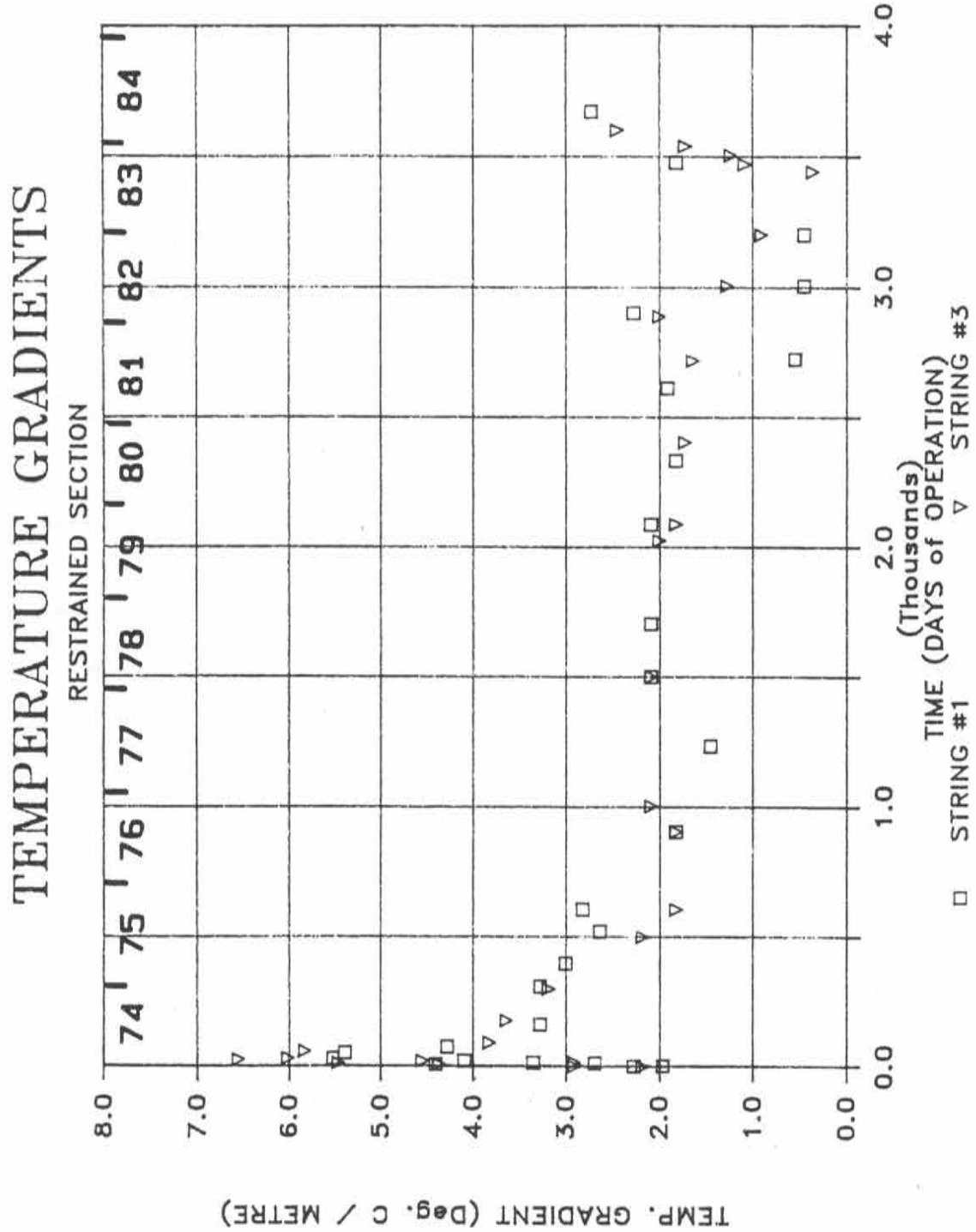
MEASURED

TEMPERATURE GRADIENTS
GRAVEL SECTION

FIGURE A1-3



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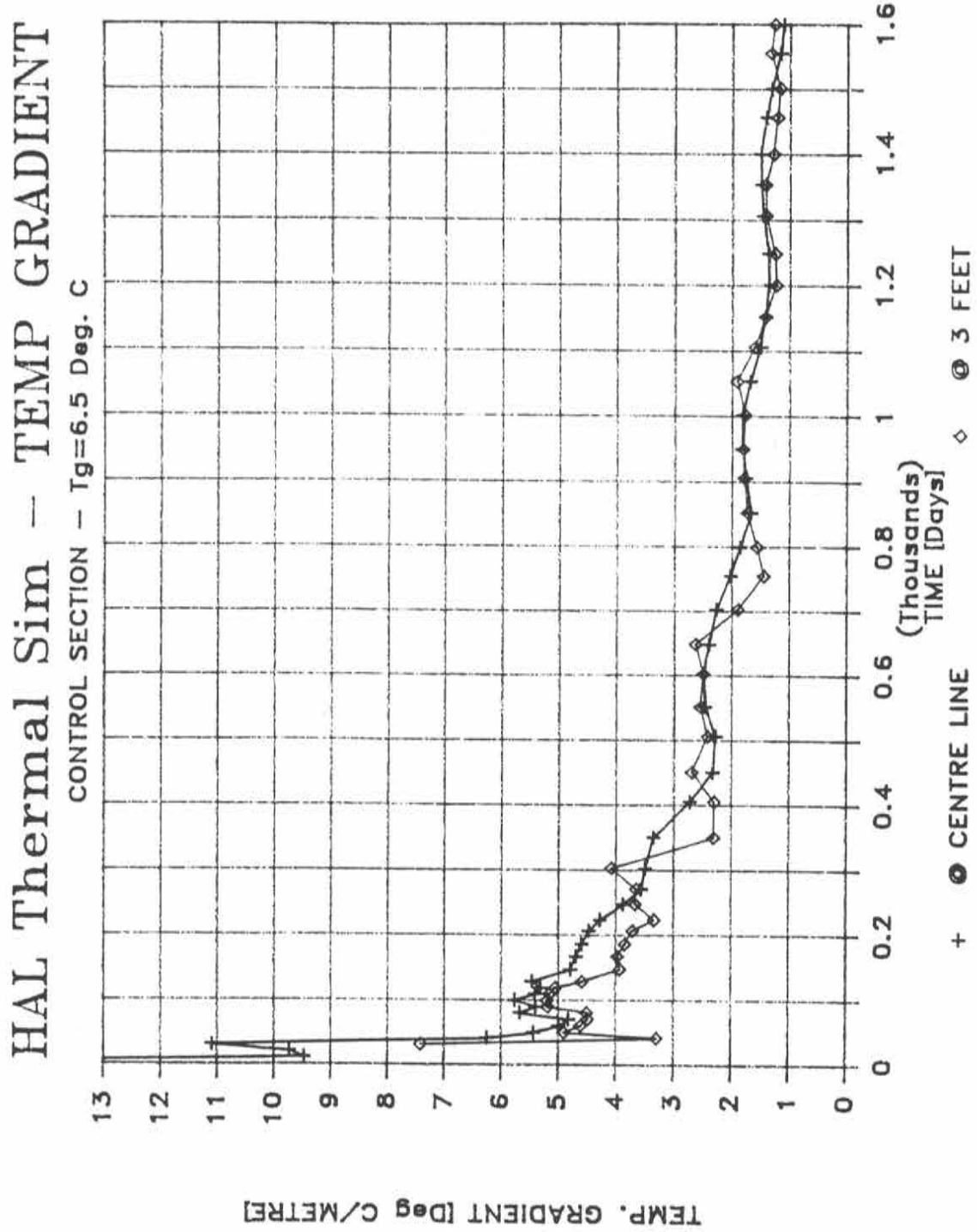
CALGARY FROST HEAVE TEST FACILITY

MEASURED

TEMPERATURE GRADIENTS
RESTRAINED SECTION

FIGURE A1-4



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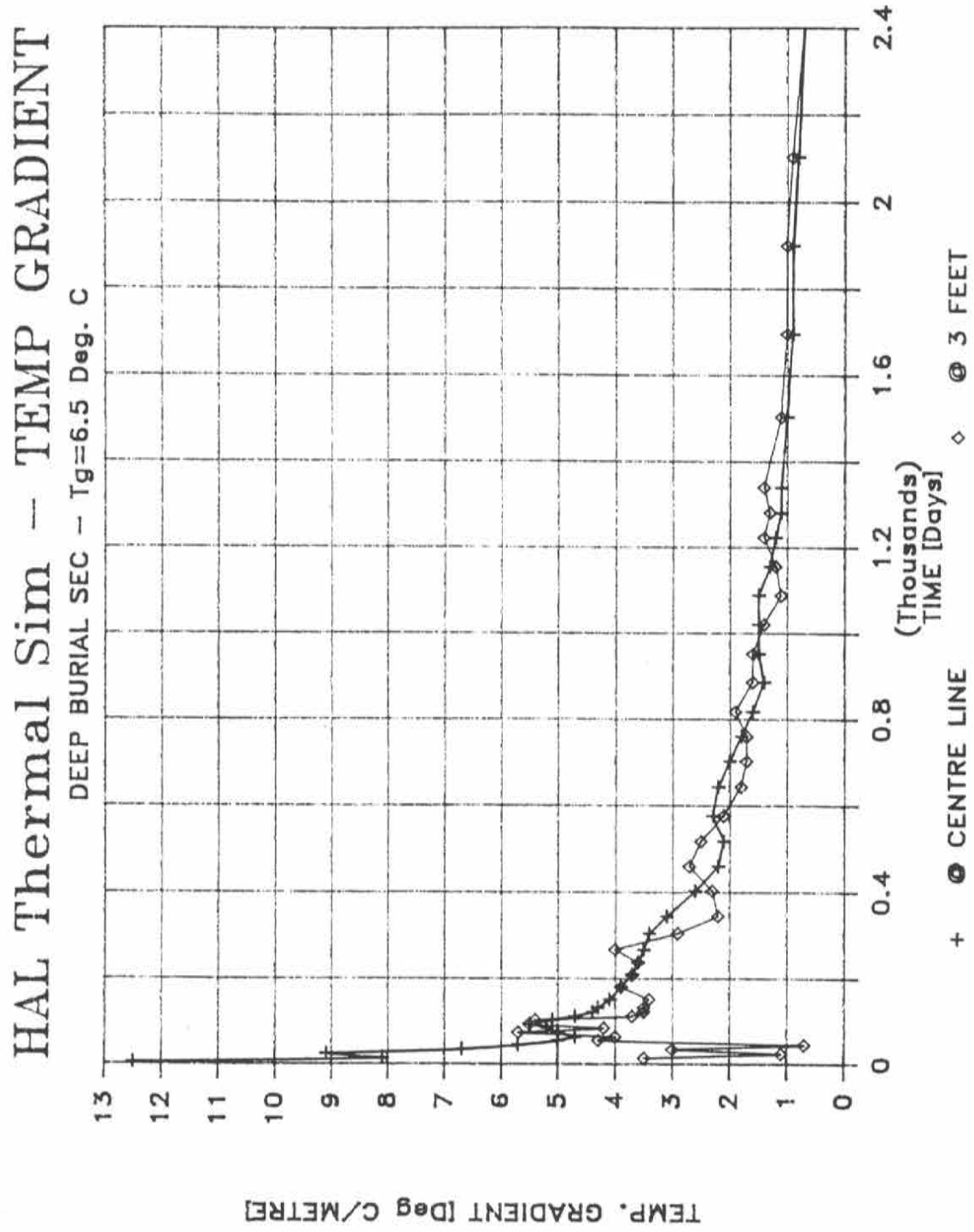
CALGARY FROST HEAVE TEST FACILITY

CALCULATED

TEMPERATURE GRADIENTS
CONTROL SECTION

FIGURE A1-5



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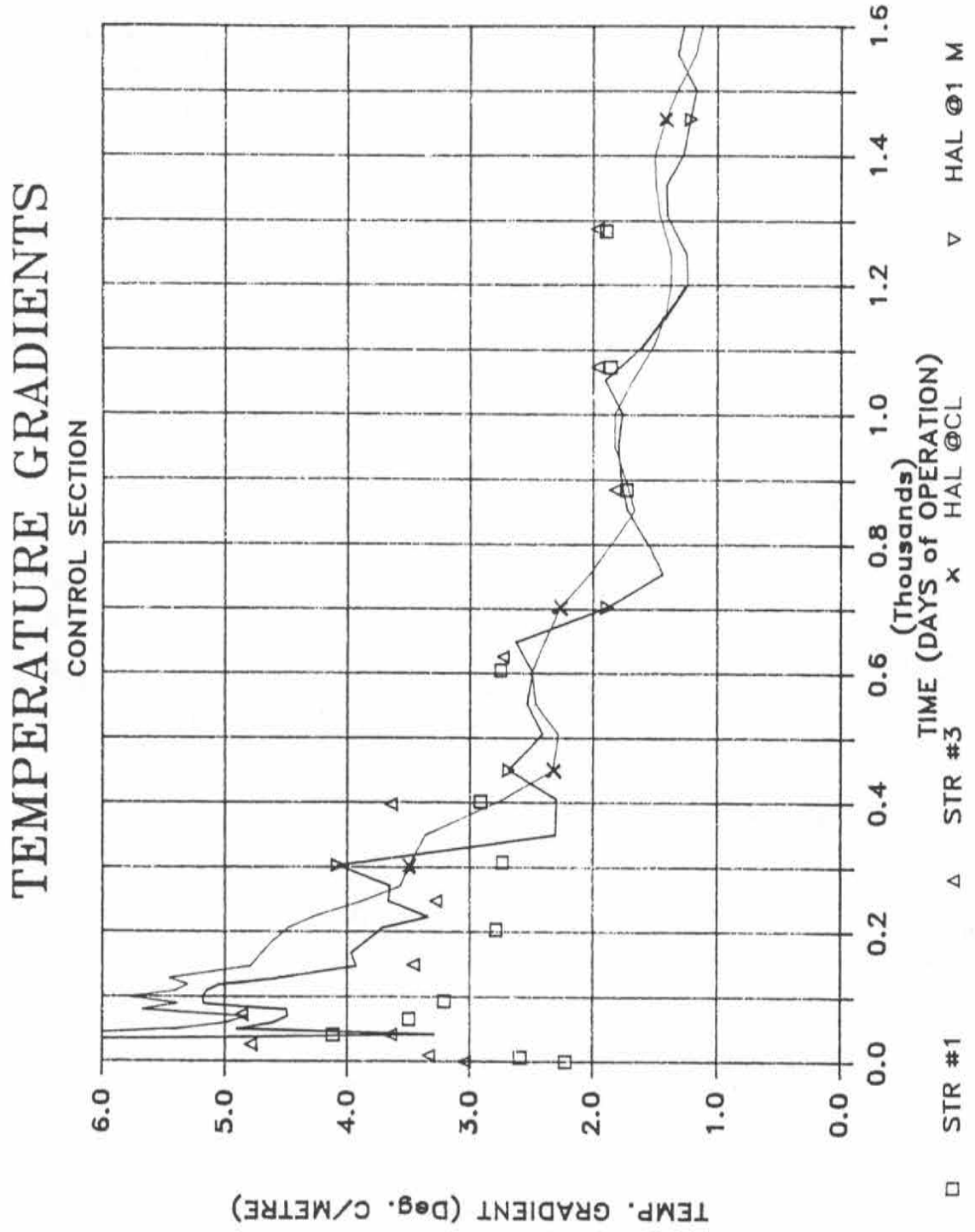
CALGARY FROST HEAVE TEST FACILITY

CALCULATED

TEMPERATURE GRADIENTS
DEEP BURIAL SECTION

FIGURE A1-6



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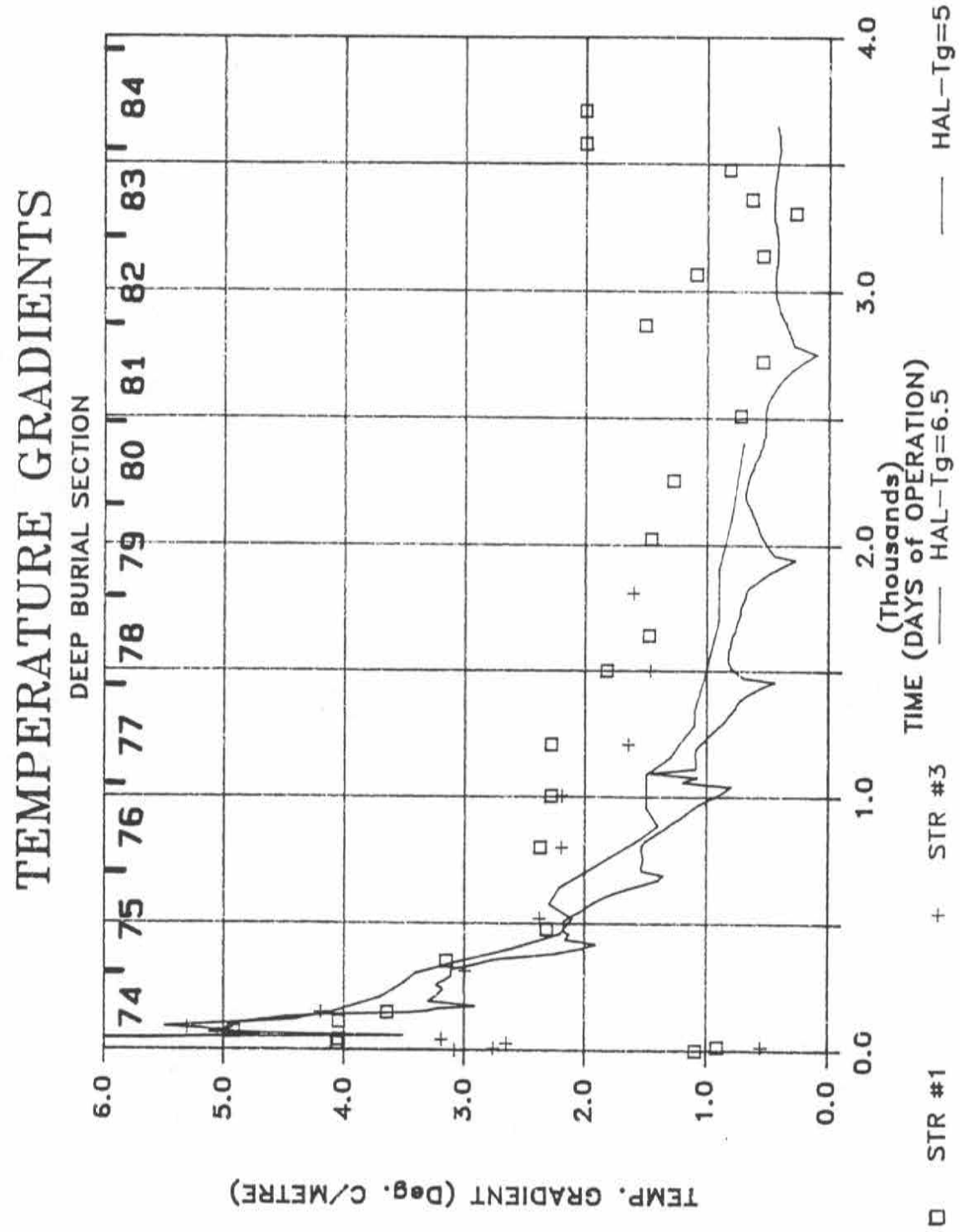
CALGARY FROST HEAVE TEST FACILITY

MEASURED & CALCULATED

TEMPERATURE GRADIENTS
CONTROL SECTION

FIGURE A1-7



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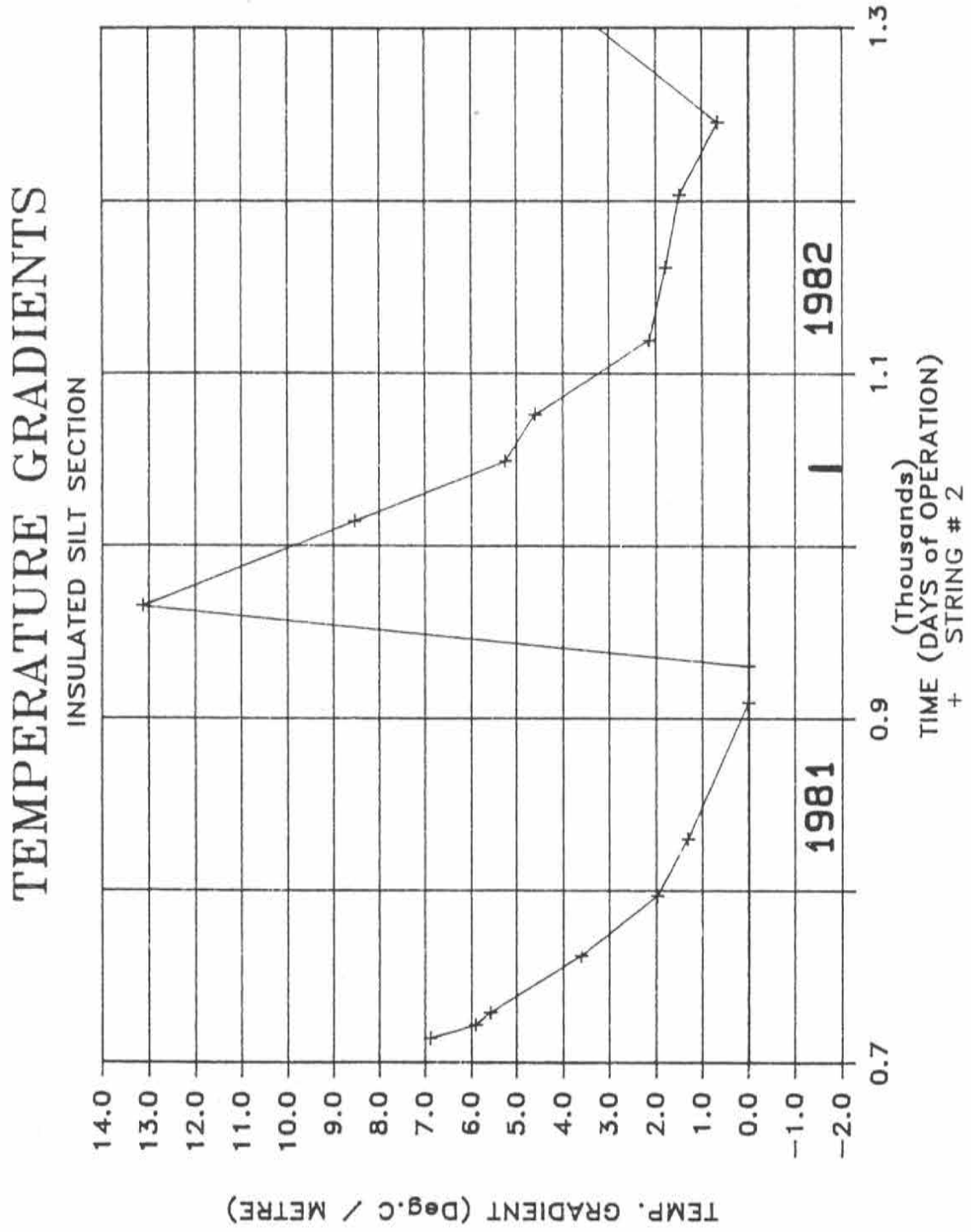
CALGARY FROST HEAVE TEST FACILITY

MEASURED & CALCULATED

TEMPERATURE GRADIENTS
DEEP BURIAL SECTION

FIGURE A1-8



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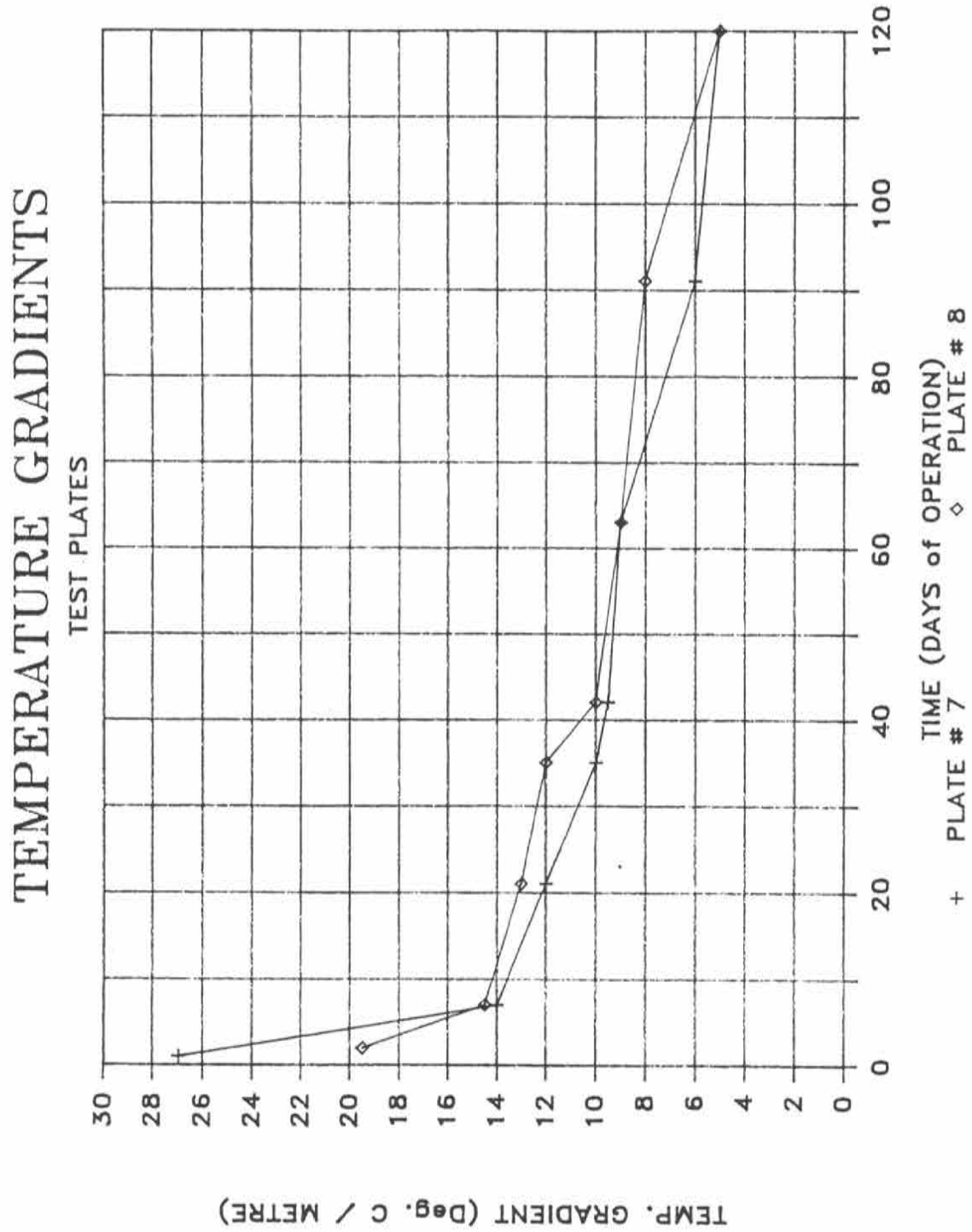
CALGARY FROST HEAVE TEST FACILITY

MEASURED

TEMPERATURE GRADIENTS
1981-82 INSULATED SILT
SECTION

FIGURE A1-9



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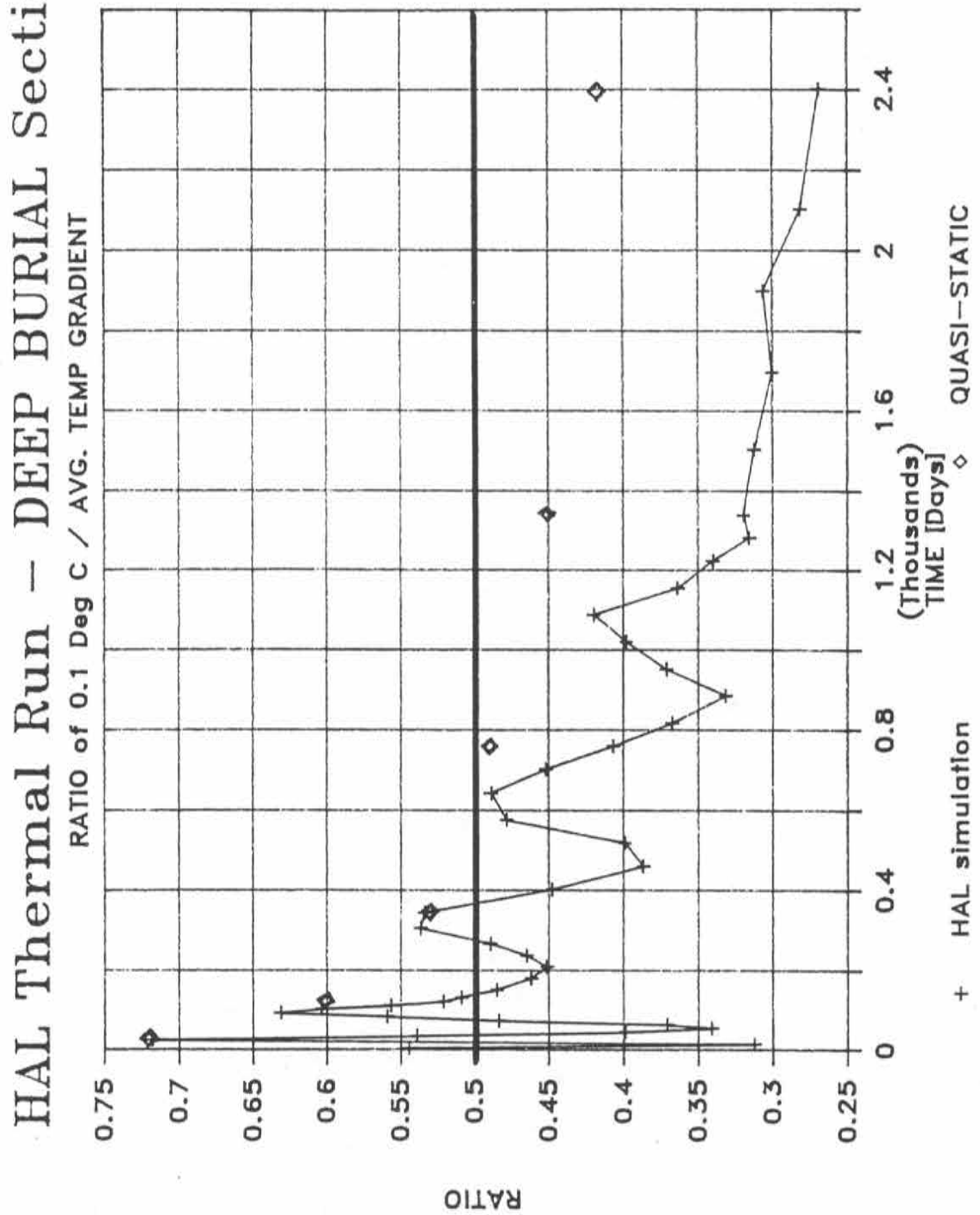
CALGARY FROST HEAVE TEST FACILITY

MEASURED

TEMPERATURE GRADIENTS
TEST PLATES

FIGURE A1-10



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CALGARY FROST HEAVE TEST FACILITY

RATIO of TEMP GRADIENT

at FROST FRONT to
AVERAGE TEMP GRADIENT

FIGURE A1-11

APPENDIX 2

APPENDIX 2

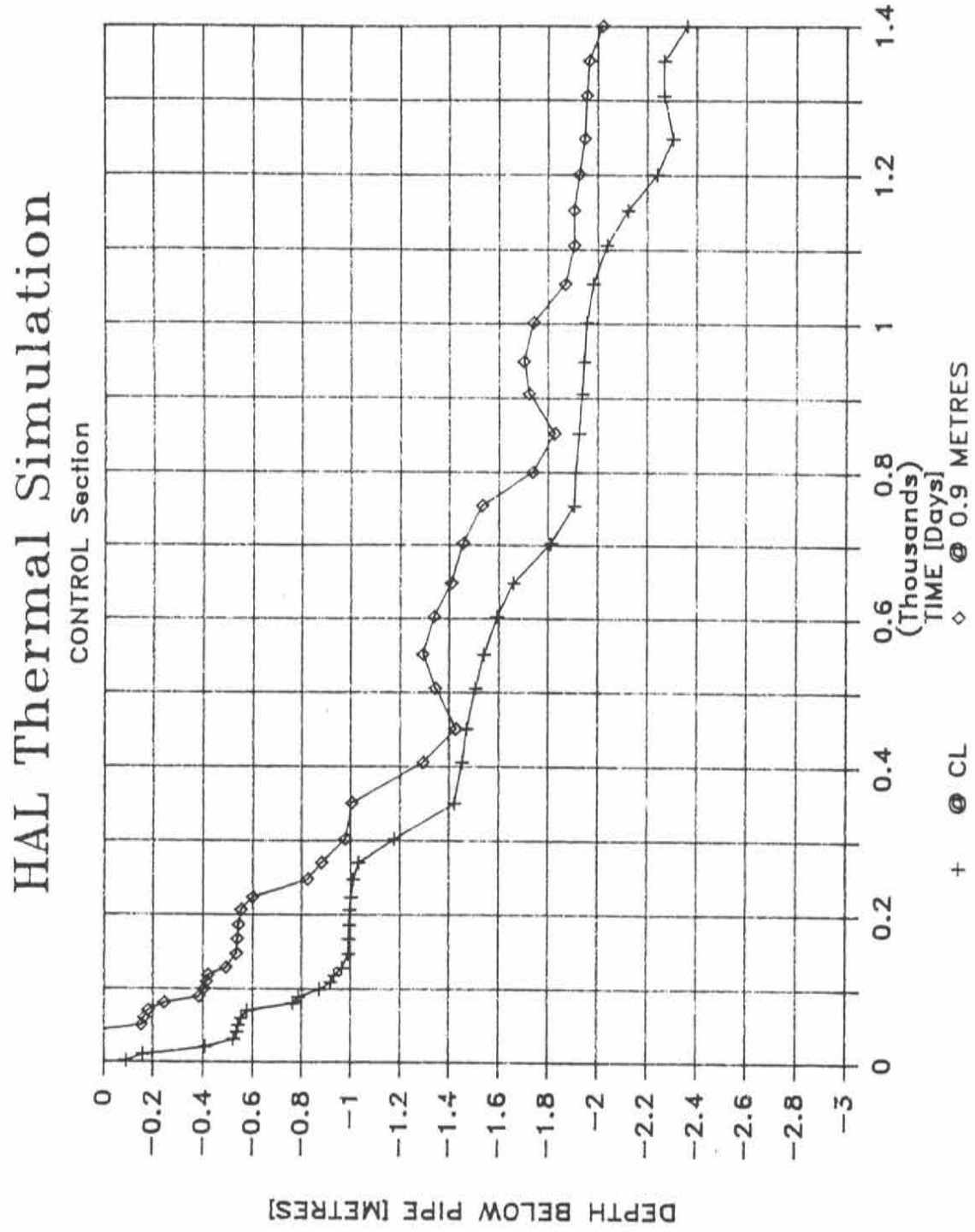
HAL THERMAL SIMULATION OF THE FROST BULB DEPTH

HAL Thermal Simulator results for the frost bulb depth below the Control and Deep Burial pipe sections are presented in Figures A2-1 & 2. The Control section and top two curves of the Deep Burial section plot were calculated using the parameters, pipe temperature, Tp = -8.5 Deg. C and ground temperature, Tg = 6.5 Deg. C [from Konrad & Morgenstern, 1984]. The top curve is the frost front position at a one metre offset from the pipe centreline and the second curve gives the value below the pipe. On the average, there is a 0.1 m to 0.3 m difference in the two curves; i.e. the frost front position directly under the pipe is about 0.2 m deeper than the value at the temperature strings.

The lower curve on Figure A2-2 for the Deep Burial section gives the calculated frost bulb depth below the pipe for the parameters Tp = -9.5 Deg C and Tg = +5 Deg. C [based on Carlson 1984]. This curve is compared to the string #1 and #3 data in Figure A2-3. Remembering the 0.2 m difference between the centreline and one metre offset position, the calculated depth is very good for string #1 and only slightly high compared to the string #3 data points.

About day 2000 the data points indicate that the frost bulb stopped growing, whereas in the HAL simulation the frost bulb continues to grow. This is likely due to the reduction in chilling caused by the ice blockage of the pipe,following water leakage into the air duct system.

This HAL Thermal Simulation is compared to a Quasi-Static model calculation in Appendix 3.



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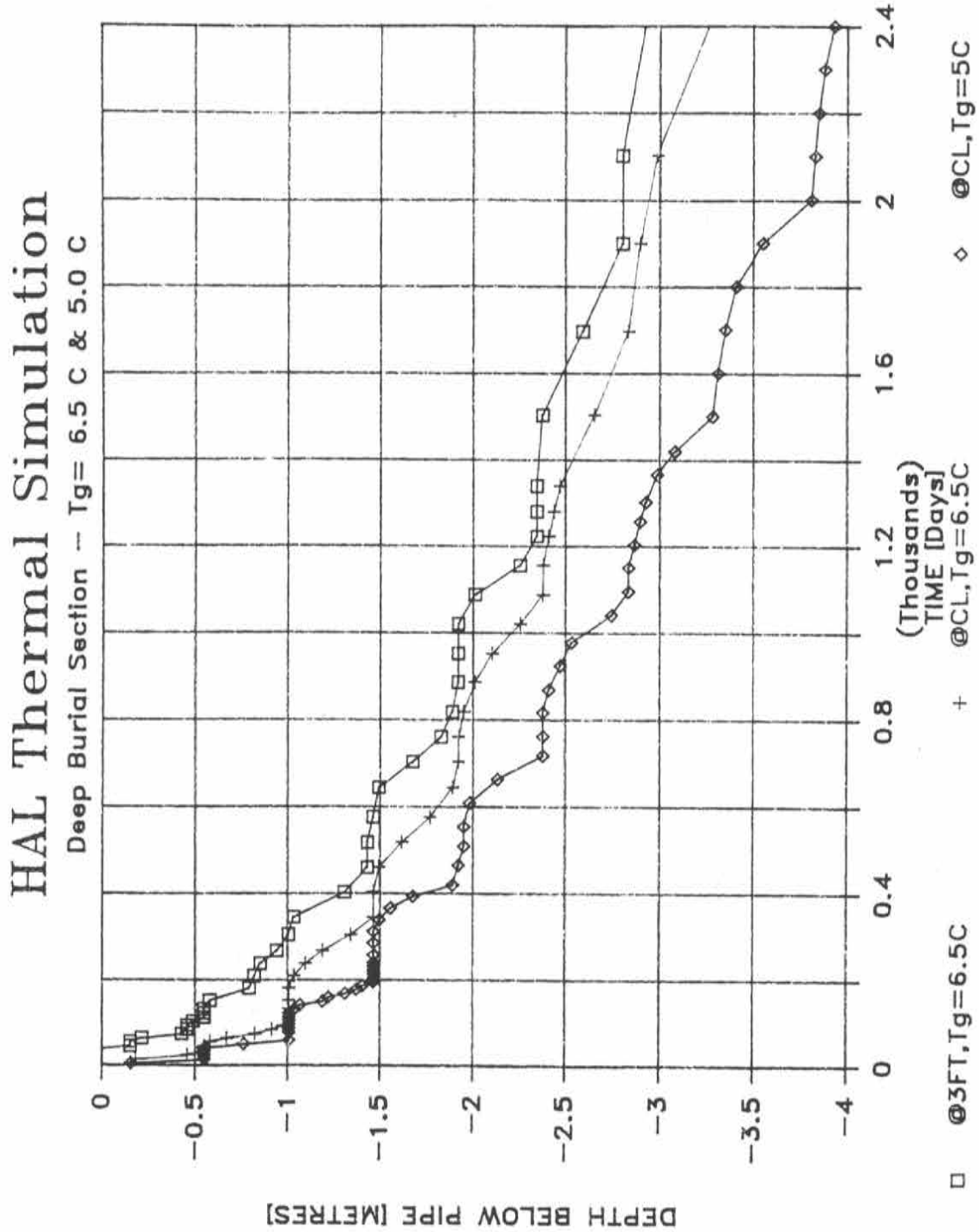
HAL THERMAL SIMULATION

CONTROL SECTION

FIGURE A2-1



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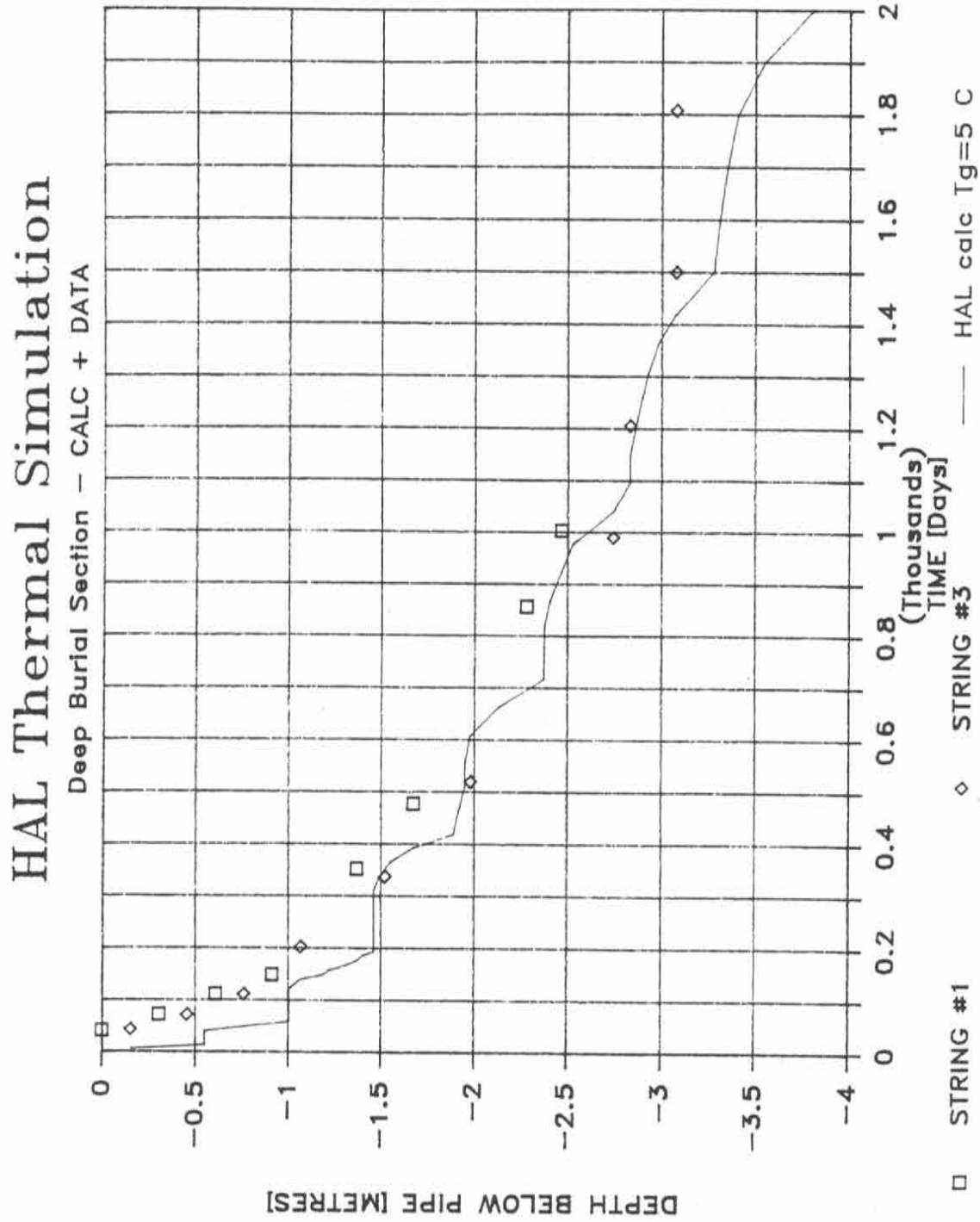
HAL THERMAL SIMULATION

DEEP BURIAL SECTION

FIGURE A2-2



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HAL THERMAL SIMULATION

& DATA

DEEP BURIAL SECTION

FIGURE A2-3

APPENDIX 3

APPENDIX 3

THE QUASI-STATIC MODEL - FROST BULB DEPTH

The previous Appendix showed that the HAL Thermal Simulation for Tg = 5 Deg. C agrees well with the observed frost bulb depth up to about day 2000. This Appendix starts out by comparing the Quasi-Static model [see Hwang 1977] calculation to that of the HAL Thermal Simulation [Nixon and Halliwell 1982]. The Quasi-Static model calculations are then compared to the data for the Control and Deep Burial sections.

Hwang [1977], in his paper " On quasi-static solutions for buried pipes in permafrost ", gives the equations to calculate the frost bulb depth, D(burial depth), as a function of the burial depth of the pipe. The burial depth used in the figures is a dimensionless one defined as

u = burial depth to centre of pipe / radius of pipe.

Hwang goes on to state that a better approximation of the frost bulb depth is obtained by using a modified depth, Dm(u'), given by

$$Dm(u') = [1/2] * [D(u) + D(ibd)].$$

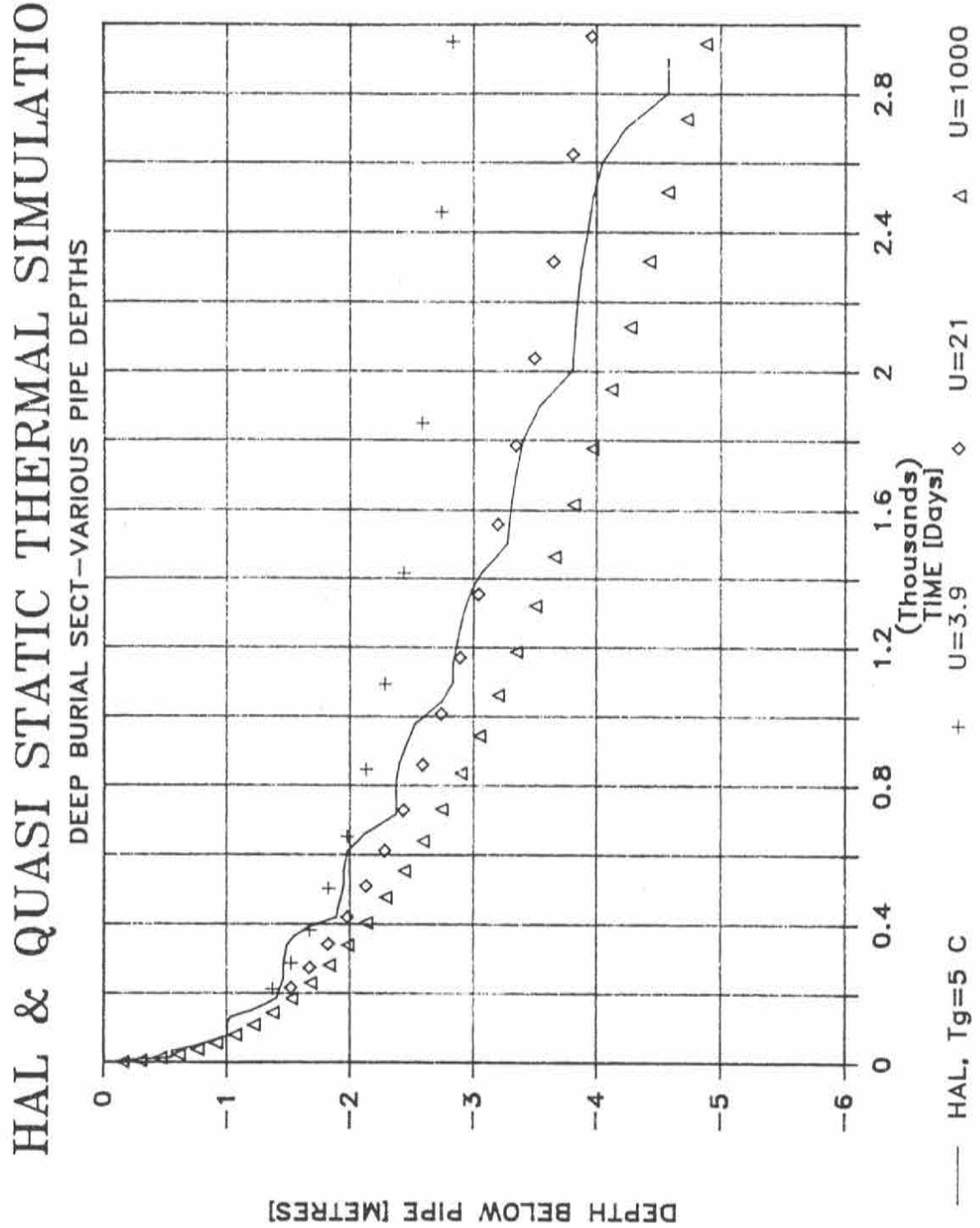
where ibd = infinite burial depth, say u = 1000.

Burial depths of 2 m and 3 m were used for the Control and Deep Burial sections respectively in these Quasi-Static calculations.

The Deep Burial section HAL Thermal Simulator calculation for Tg = 5 Deg. C, along with the Quasi-Static, model calculations for D(u), Dm(u) and D(ibd) are presented in Figure A3-1. As stated by Hwang, the calculation for D(u) is above and that for D(ibd) below the HAL Thermal Simulation. The Dm(u'=21) value agrees very well with the HAL values up to day 2600, where the HAL values drop below these Quasi-Static model values.

Control section Quasi-Static model calculations are compared to the data in Figure A3-2. As with the comparison to the HAL calculation, the modified Quasi-Static values, Dm(u'=10), provide a good estimate of the frost bulb depth (remember that the observed frost depth under the pipe is about 0.2 m below the string #1 & #3 data points).

Deep Burial section Quasi-Static calculations are compared to the data points in Figure A3-3. Again, the modified depth, Dm(u'=21), provides a good estimate of the frost bulb depth, up to day 2000, when the frost bulb began to thaw back.



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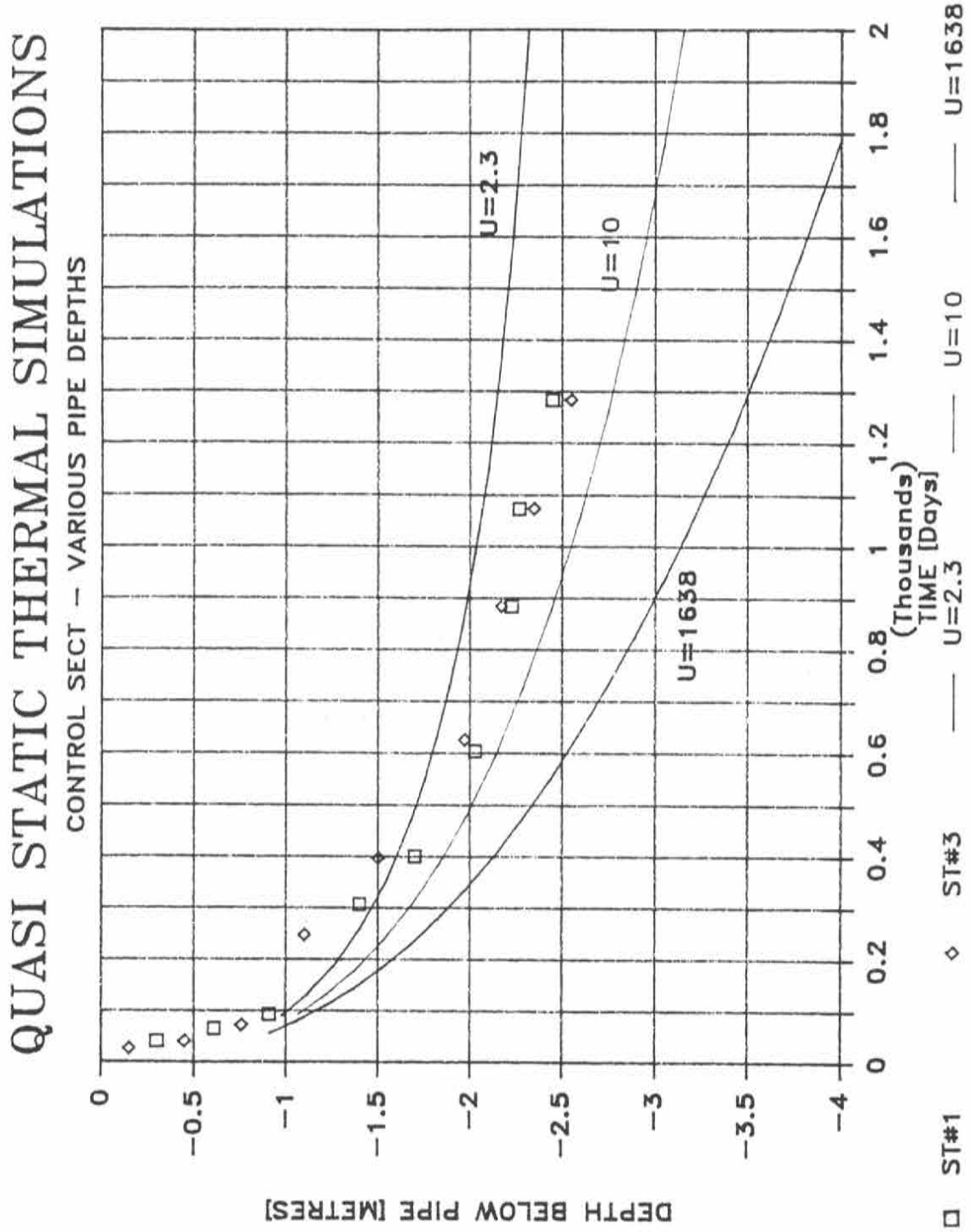
HAL & QUASI-STATIC

THERMAL SIMULATION
DEEP BURIAL SECTION

FIGURE A3-1



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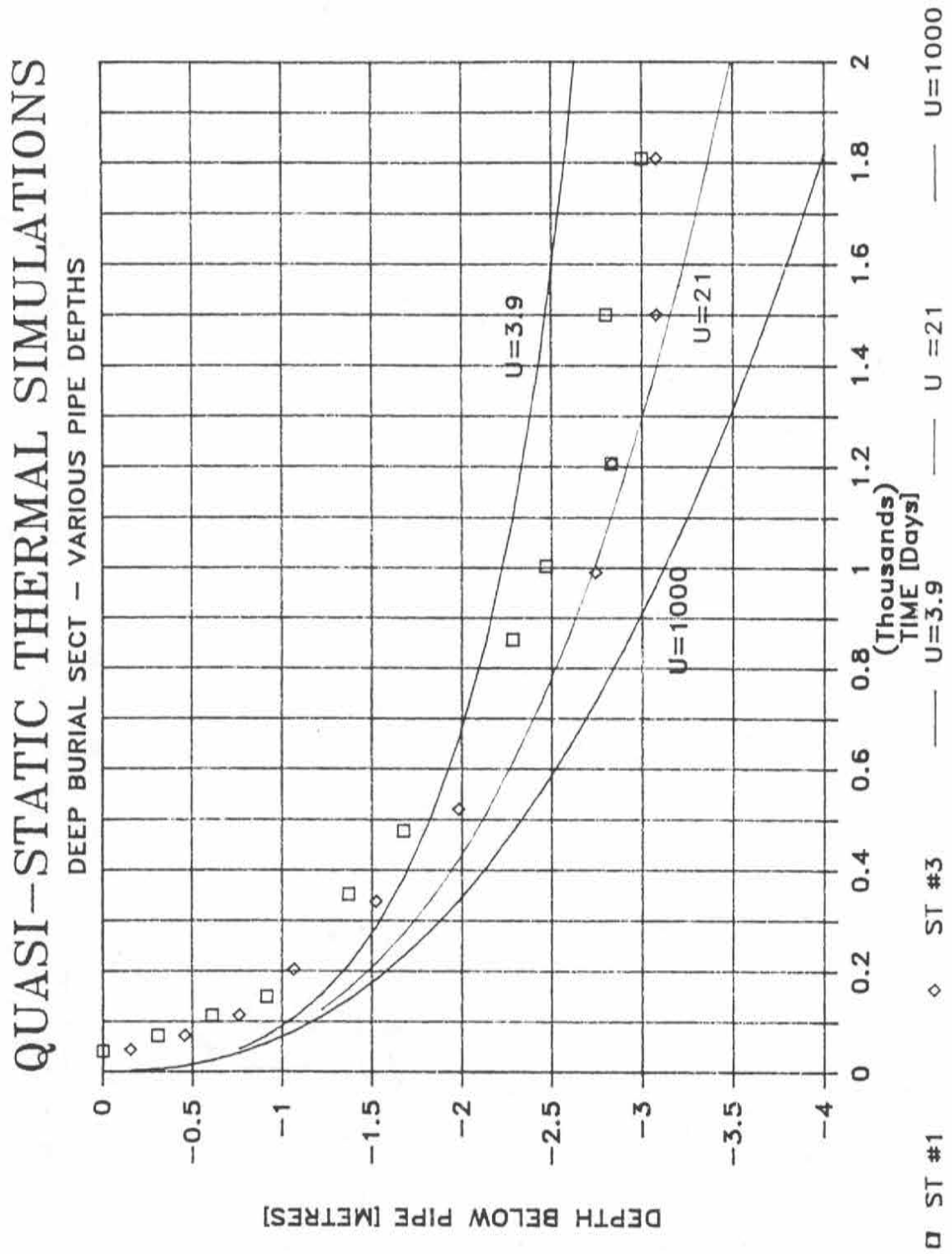
QUASI-STATIC

THERMAL SIMULATION
& DATA
CONTROL SECTION

FIGURE A3-2



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QUASI-STATIC

THERMAL SIMULATION

& DATA

DEEP BURIAL SECTION

FIGURE A3-3