Soil Freezing Around a Buried Pipeline: Design of an Experiment in a Controlled Environment Facility

M. Burgess[1], G. Lemaire[2], and A. Dupas[3]

Crustal Studies Section
Gravity, Geothermics and Geodynamics Division
Earth Physics Branch
Energy, Mines and Resources

1983

Internal Report 83-8

1. Earth Physics Branch, EMR
2. Ecole Polytechnique de Montréal
3. Laboratoire Central des Ponts et Chaussées, France

ABSTRACT

This paper discusses the design, installation and instrumentation of a joint France-Canada project to study in detail freezing around a refrigerated pipeline buried in the controlled environment facility at the Centre de Géomorphologie of the Centre National de la Recherche Scientifique, Caen, France. A 273 mm diameter pipe is buried at a depth of 30 cm in a 18 m long x 8 m wide x 2 m deep pit. Half of the excavation (lengthwise) is filled with a non frost-susceptible sand and half with a frost-susceptible silt. The water table is positioned at the top of the pipe and is maintained by supplying additional water to the base. A refrigeration system maintains the ambient temperature of the chamber at slightly below 0°C, and the temperature of the pipe at -2°C. A network of sensors is installed in each soil to monitor the thermal regime (thermistors, thermocouples, frost tubes), the moisture regime (TDR probes, tensiometres, piezometres), ground heave (telescoping heave tubes, "doubles sondes") and pipe deformation and displacement (strain gauges, rods welded to pipe). An automatic data acquisition system is dedicated to temperature measurements although all other instruments require manual observations.

FOREWORD

A natural scale experiment to model the performance of a chilled gas pipeline, buried in warm permafrost terrain that is susceptible to frost heave, is being jointly conducted by Canada and France. The research is underway in the freezing chamber of the Centre National de la Recherche Scientifique (CNRS) at their Centre de Géomorphologie in Caen, France. The project is directed by the following scientific committee:

Dr. Jaime Aquirre-Puente, Laboratoire d'Aérothermique, Centre National de la Recherche Scientifique, France.

Dr. Lucien Faugères, Director, Centre de Géomorphologie du CNRS, Caen, France.

Dr. Michel Frémond, Laboratoire Central des Ponts et Chaussées, et l'Ecole Nationale des Ponts et Chaussées, France.

Dr. Alan Judge, Earth Physics Branch, Energy, Mines and Resources, Canada.

Dr. Ch. Parey, Laboratoire Central des Ponts et Chaussées, France

Dr. A. Philippe, Laboratoire Central des Ponts et Chaussées, France.

Dr. M.W. Smith, Geotechnical Science Laboratories, Carleton University, Canada.

Dr. P.J. Williams, Geotechnical Science Laboratories, Carleton University, Canada.

Participants in the project include personnel from the above mentioned institutes as well as members of the Centre d'Ingénierie Nordique de l'Ecole Polytechnique (Montréal, Canada) and the Centre d'Etude Technique de l'Equipement (CETE, Rouen, France).

INTRODUCTION

Adequate design and assessment of structures in the north require a good understanding of the thermal, thermodynamic, hydraulic and mechanical properties of frozen soils. Future northern pipelines pose unique geotechnical problems requiring in addition a knowledge of stress fields, of behaviour of materials and of soil-pipe interaction in the northern environment.

Information relative to the prediction of the effects of soil freezing around a buried pipe, e.g. of the maximum heaving pressures and of displacements which may take place, has come mainly from small scale laboratory experiments or from field testing with pipe sections in natural ground. The desire to conduct an experiment unaffected by problems of scale and extraneous factors such as the meter by meter variations in natural soil conditions and surface microclimate, led to the design of a buried pipeline experiment in the test facility in Caen, France.

This paper describes the selection of the experimental model and the set-up of the experimental conditions in the test facility. The instrumentation installed to monitor soil and pipe behaviour is outlined in detail. Finally, pre-start up progress of the experiment is briefly discussed.

PREPARATION OF TEST FACILITY AND SET UP OF EXPERIMENTAL CONDITIONS

The controlled environment test facility of the CNRS in Caen was built in the 1960's to investigate the effects of freezing on highway test sections (Philippe et al., 1973). Chamber refrigeration is achieved by two compressors (10 HP and 6 HP). For the pipeline experiment, an additional 2 HP refrigeration system was installed to circulate refrigerated air through the pipe. The new system is capable of automatically reversing the direction of flow through the pipe at regular intervals, in order to maintain temperature uniformity along the pipe.

The chamber walls are lined with 16 cm of polystyrene insulation, the pit walls with 10 cm. Preparation of the test facility began in January 1982 with removal of the soil from previous experiments and minor repairs to the insulation. The base of the pit was then prepared as shown in Figures 1a and 1b. This procedure involved several steps. The bedrock was first covered with sand to even out irregularities and then covered with a geotextile layer to protect the overlying impermeable PVC membrance from perforations. A five cm layer of styrofoam insulation was then laid down to reduce heat flow through the base. A water distribution system, consisting of 6 perforated tubes (4 cm in diameters) was placed along the length of the pit on top of the insulation. The tubes were coated with geotextile to prevent their clogging up by soil grains and embedded in a 10 cm sand layer to facilitate water distribution. A final layer of geotextile separates the sand from the overlying soil. These basal layers total 20 cm in thickness, leaving some 180 cm for soil above with the top of the pipe to be buried at a depth of 30 cm.

The pit was filled in successive layers of 30 cm and compacted to mean dry densities of 1.85 Mgm^{-3} (sand) and 1.65 Mgm^{-3} (silt). The soils were first treated at the CETE in Rouen to disaggregate large clumps, remove large boulders, and control initial water content. Compaction was thus facilitated and made more uniform. Instrumentation was either installed as the soil layers were built up or in holes dug or drilled from the surface. These procedures are outlined in Burgess et al. (1982) along with sections detailing distribution of instrumentation. By March 1982 the soil had been built up to the level of the pipe. During April and May, instruments were installed on the pipe and in the soil directly beneath it, and the pipe then put in place on the soil. The pipe refrigeration system was also assembled and connected at this time. The final soil layers were added in June and the installation of instrumentation completed.

MODEL AND EXPERIMENTAL CONDITIONS

The experimental conditions and design evolved over many months. Initially the experiment was planned to study the behaviour of a frost-susceptible soil at start-up temperatures marginally above zero. The measurements were to focus on the moisture, heave and thermal regimes. However, the length of the trough at Caen lent itself to the simultaneous study of two separate soils. The chamber was thus divided into two 9m long sections both to be subjected to the same experimental conditions. A frost-susceptible silt (loess from Rouen) and a frost-susceptible clay were envisaged for the soils. The clay, however, presented difficulties (particularly in that it would take many months to saturate) and a slightly clayey fluvial (non-frost-susceptible) sand was selected as the second soil. Frost susceptibilities were determined by the method of Aguirre et al. (1973). Differential heave of a refrigerated pipe traversing two soils of contrasting frost-susceptiblities was considered most likely and interest in the behaviour of the pipe increased. A pipe stress analysis program was added.

As the model developed, modifications were required in the experimental conditions and in the design of some instruments devised for the original experiment. The ambient chamber temperature, at first to be held marginally above 0°C so that the freezing front would only develop outward from the pipe, had to be lowered to temperatures slightly below 0°C during pipe refrigeration. The soil above the pipe in the sand section could thus freeze and ensure anchoring of the pipe in the sand when heave began in the silt.

The final experimental conditions, selected to simulate a buried refrigerated gas pipeline in discontinuous permafrost terrain traversing two contrasting soil units both with initial temperatures marginally above zero, are presented below:

- A 273 mm diameter pipe, 18 m long, is buried at a depth of 30 cm in the centre of a 18 m long x 8 m wide x 2 m deep excavation. The pipe extremities are free. The pipe is not insulated.
- The water table is held at the top of the pipe; the soil below is thus saturated. The system is open and additonal water can be supplied to the base.
- The soils are cooled to temperatures marginally above 0°C before pipe refrigeration begins to reduce ground temperatures and temperature gradients. The ambient air temperature of the chamber is set slightly below 0°C during pipe refrigeration.
- Refrigerated air circulates in the pipe at -2°C, simulating the thermal conditions of a refrigerated gas pipeline.

INSTRUMENTATION

A network of sensors is installed in each soil to measure soil and pipe behaviour and interaction. Figure 2 is a plan view of the pit which shows the location of various instruments and instrumented sections. Since the experiment is symmetric about the pipe axis, most of the sensors are concentrated in one half of the pit. The central area of each soil, furthest from boundary effects, is heavily instrumented to monitor the thermal, moisture and heave regimes. The pipe stress instrumentation is distributed along the length of the pipe with some emphasis near and in the transition zone. Temperatures are also monitored along several cross-sections.

Measurement of Thermal Regime

Air, pipe and soil temperatures are measured with thermocouples and thermistors. The thermistors are incorporated with the TDR instrumentation (discussed below). A total of 160 thermocouples are distributed throughout both soils along two heavily instrumented sections (AA,BB) and four sparsely instrumented ones (CC,DD,EE,FF). In addition a series of frost tubes monitors the position of the 0° isotherm in the transition zone.

Measurement of Moisture Regime

A set of horizontal Time Domain Reflectometry (TDR) probes (Smith and Patterson, 1982) is installed beneath the pipe in each soil to measure the volumetric water content profile and to follow moisture redistribution during soil freezing. Six prototype vertical TDR probes are also installed both beneath and beside the pipe to provide additional information on freezing front propagation and ice lens formation. The longitudinal section in Figure 3 details the horizontal TDR probe array in the silt.

Ten porous cup tensiometers are distributed along a broad section in each soil to measure the unfrozen pore water pressures. Fifteen Gloetzl earth pressure cells monitor changes in total soil pressure. The water table level is monitored by 12 piezometers and 6 observation wells. The water balance is also monitored by measuring the water added to maintain the water table level and the water recovered from defrosting the refrigeration system. A vapour diffusion box is placed on the surface of each soil to gauge vapour diffusion through the frozen soil surface layer.

Soil Heave Measurements

Two sets of telescoping aluminium heave tubes (based on Mackay et al. 1979) are placed in each soil. Each set consists of 10 tubes, spaced every 10 cm below the pipe to measure differential heave (Fig. 4). One set is installed directly below the pipe, the other directly alongside. Displacements are measured at the surface.

A dual gamma ray technique, 'doubles sondes' (Valeux, 1982) is used to profile soil density. Movement of buried PVC discs can thus be discerned and related to soil heave. Discs are buried at 4 sites in each soil (Figs. 2 and 3).

Finally the soil surface is levelled by surveying metal pins distributed on a grid throughout the pit.

Pipe Deformation Measurements

Several systems measure pipe deformation. Strain gauges are installed at 22 locations along the pipe and are more closely spaced in the transition zone. At each location 2 gauges are positioned in a half-bridge configuration, one on the top of the pipe, the other on the bottom. Temperature compensation is thus unnecessary and the distribution of bending stress along the pipe is thus measured.

Twenty six pointed rods, spaced at 50 cm intervals, are welded to the top of the pipe and yield information on the deformation and position of the pipe. The measurement of the relative displacement of three consecutive rods allows an estimate of the curvature of the pipe and thus of the bending moment (Bowes, 1982).

Levelling of the rod tips and tilt measurements of plates fixed to the rods also give information on the deformation of the pipe and on its position relative to a fixed datum.

DATA ACQUISITION

Acquisition of data and its dissemination to all participants for interpretation and modelling is coordinated by the CNRS's Centre de Géomorphologie. A data acquisition system (Orion by Solartron/Schulumberger) automatically records and stores thermal parameters. All other measurements are manually recorded. All data are stored on files through a Goupil mini-computer dedicated to the project.

SOIL PROPERTIES

Laboratory tests of physical, thermal and hydraulic properties of the two soils are being conducted at the Geotechnical Science Laboratories of Carleton University. These tests include grain size analysis, particle density, mineral identification, salinity, freezing characteric curves and thermal properties. The Ecole Polytechnique de Montréal is performing tests on the creep properties of the frozen soils.

PRE START-UP PROGRESS

By June 1982 all instrumentation had been installed, and the pipe and soil were in place. Soil wetting, through the irrigation tubes at the base of the soil layer, began in late June. Two months were required to saturate the soil to the level of the pipe due to the low permeability of the silt. Average saturation volumetric water contents were 27.7% for the sand and 37.8% for the silt. Initial saturated soil temperatures were high, 14°C. Cooling of the soil, by refrigerating the chamber to + 1° to + 2°C, began in late August so as to reduce soil temperature gradients. In late September the chamber temperature was lowered to -0.75°C and pipe refrigeration began at -2°C.

Results of the experiment are to be reported in various papers by members of the research team.

Note: This paper was prepared for presentation at the Fourth International Conference on Permafrost, Fairbanks, Alaska, July 1983.

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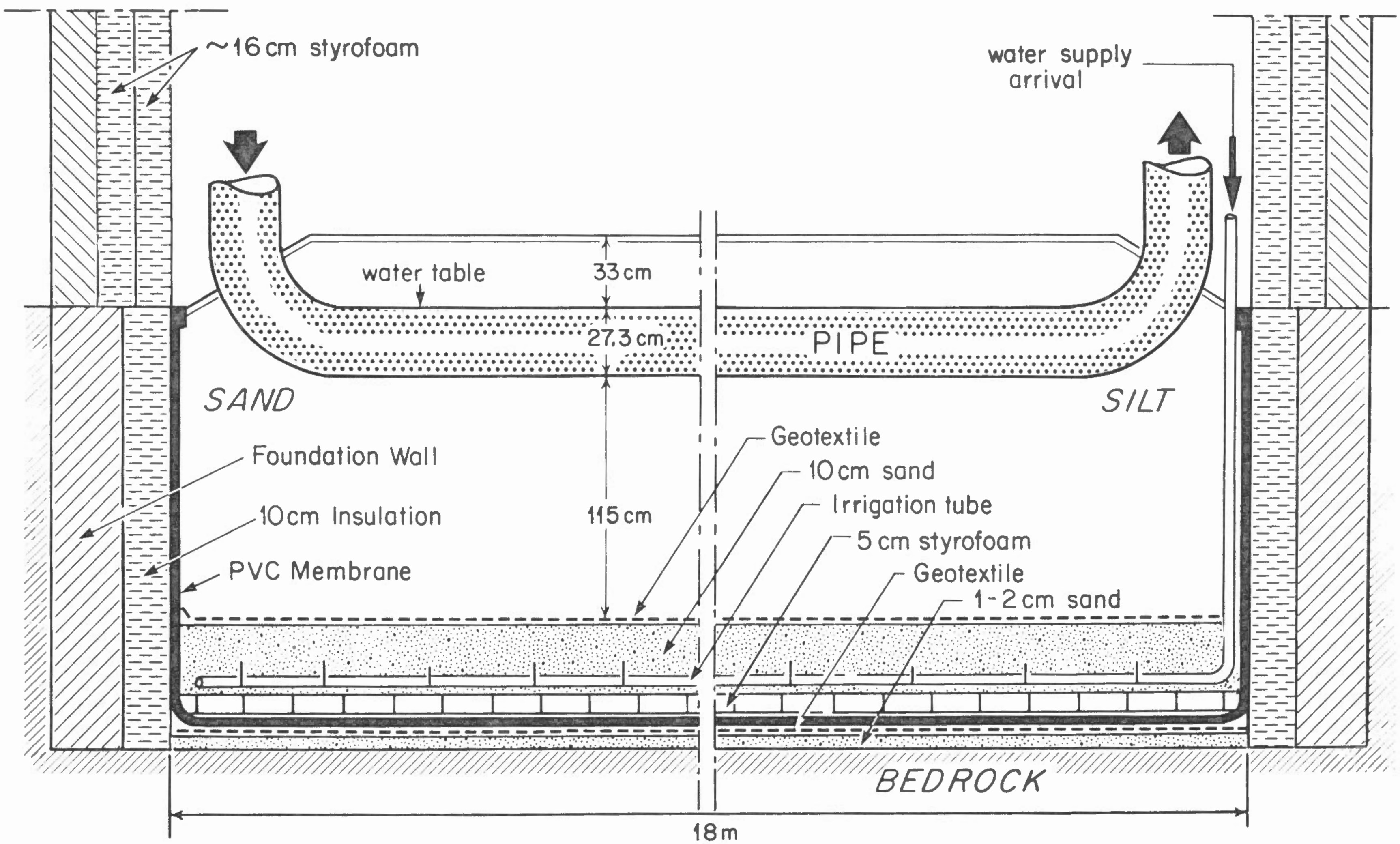

Figure 1a Longitudinal section through test chamber outlining basal layers involved in pit preparation and general experimental set-up.

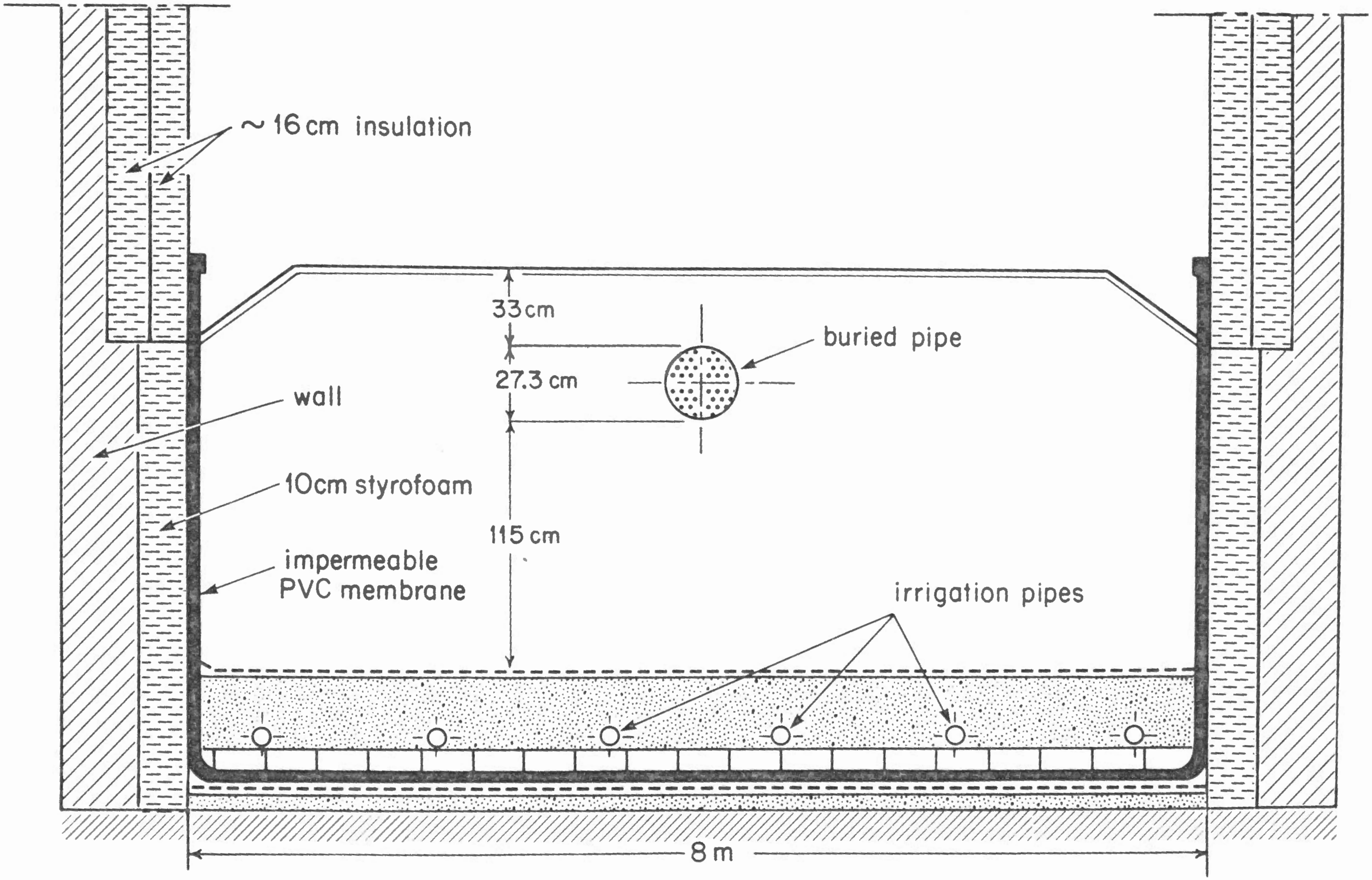

Figure 1b   Cross section.

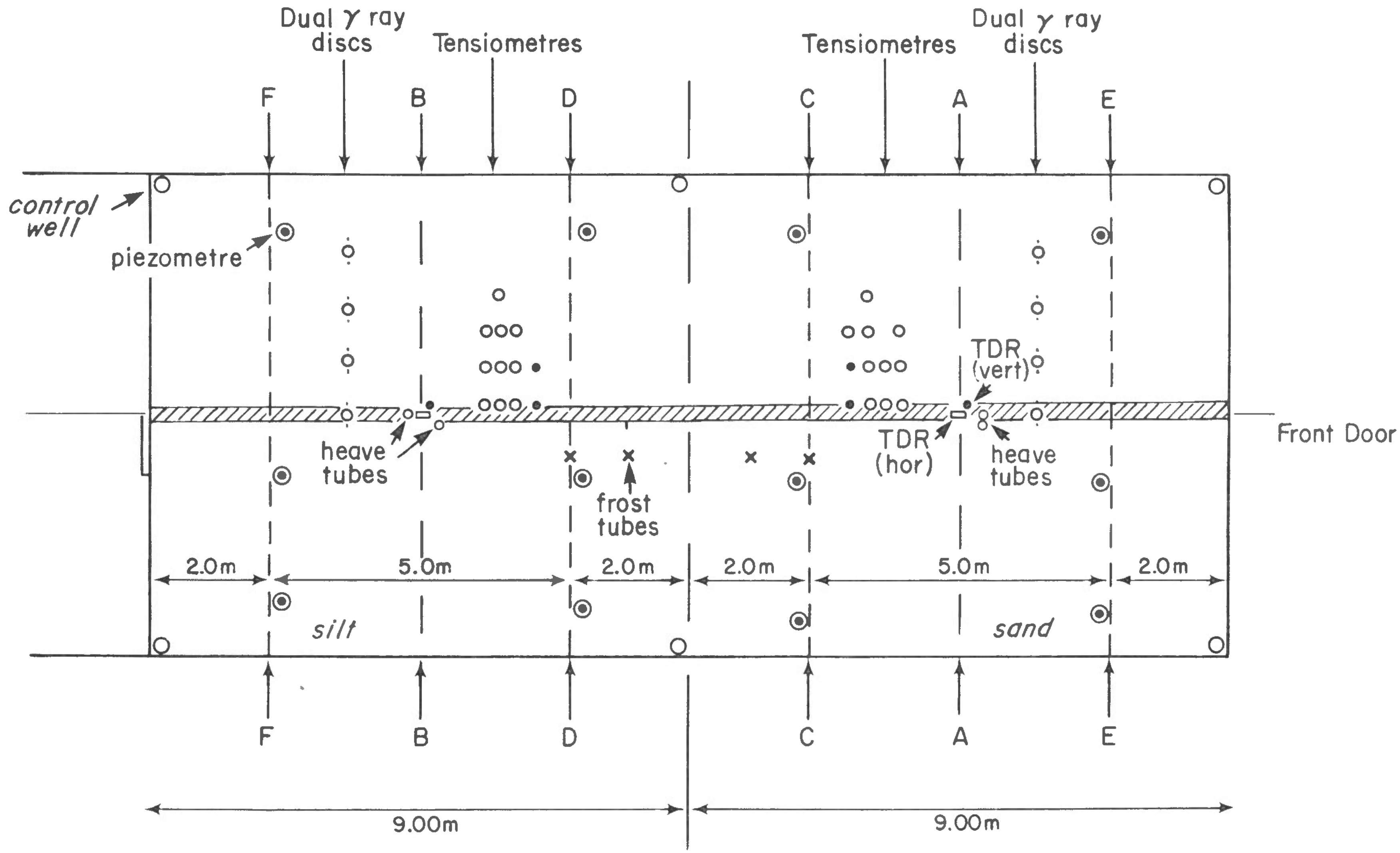

Figure 2 Plan view of chamber showing location of various instruments and instrumented sections (AA,BB, etc.).

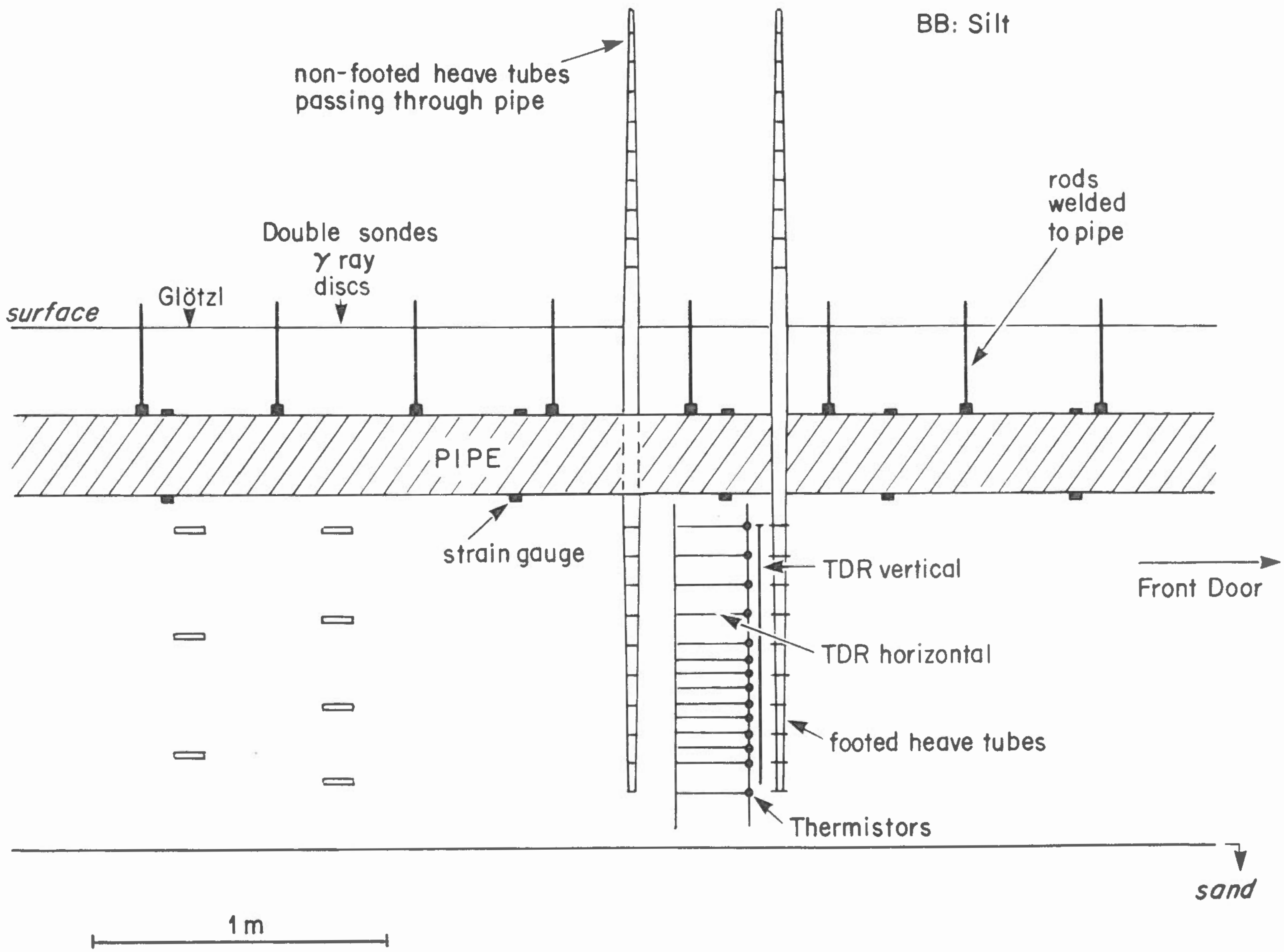

Figure 3 Longitudinal section detailing pipe deformation instrumentation, TDR probes and telescoping heave tubes.