RESEARCH TECHNICAL COMPLETION REPORT

PROJECT A-016 IDA

WATER for IDAHO

HYDROLOGY OF FROZEN GROUND FLOODS

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Hydrology of Frozen Ground Floods

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ABSTRACT

A four year field and laboratory study of permeability of frozen soil is reported. The field studies involved soil temperature and moisture measurements over a two year period during which there were no runoff events when the ground was frozen. A rainfall simulator was constructed and used to a limited extent the second year of the study.

The laboratory study involved measuring the permeability of frozen soil columns at various initial moisture contents. Air was used as a fluid to measure the permeability under isothermal conditions below 32° F. Data were obtained which relate the air permeability to the porosity of the soil and the moisture content or saturation at which freezing occurred. For the three soil types tested, it was possible to obtain impermeable conditions after freezing when the initial moisture content was in the neighborhood of the field capacity. The significant parameter affecting the permeability was $\phi (1 - S)$ where ϕ is the porosity and S is the saturation.

The use of certain critical values of this parameter would enable a person to predict when the possibility of frozen ground floods exist by taking soil samples in the field. The critical values for various soils would have to be determined from field permeability measurements.

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KEYWORDS: Hydrologic properties,* permeability, porous media, soil properties,* frozen soils, percolating water, soil moisture

INTRODUCTION

Frozen ground conditions have been the principal cause of many of Idaho's worst floods. Extremely low infiltration rates associated with frozen soil conditions can result in large flood peaks for relatively moderate storm magnitudes.

There has been little known concerning the mechanics of frozen ground runoff, thus making it difficult if not impossible to conduct hydrologic studies of this type of flood.

This project was begun in 1965 to attempt to learn more about the mechanics of frozen ground runoff. Originally the specific objectives were:

1. To determine relationships between soil moisture, frozen ground temperatures, runoff water temperatures and infiltration rates.
2. To relate frozen ground parameters to runoff rates by hydrograph studies.
3. To examine conditions preceeding and during some recent frozen ground floods to determine whether the developed relationships apply.

In general, the objectives were too broad to be completely accomplished with the time and money allotted to the project. There was some discontinuity in conducting the research since the original project leader resigned from the University in the middle of the project and the succeeding project leader devoted less than one-fourth of his time to the project for the last two years.

Parts of the objectives were accomplished, however, and a great deal was learned about how the remaining objectives could be accomplished in following projects.

FIELD STUDIES

Initially the experimental work was done at a field site on a small (12 acres) agricultural watershed near Moscow which was instrumented and maintained by the Agricultural Research Service. During the winter of 1965-66 soil temperatures were measured at various depths from 3 to 42 inches at two locations on the watershed. Temperatures below 32^{o} F. were measured at the 6 inch depth for about two weeks during December 1965 and for a few days during January 1966.

During the entire winter there were no runoff events when the ground was frozen.

For the 1966-67 winter season a portable raindrop simulator was developed and tested in the laboratory. This device was similar to one designed by Chow and Harbaugh ( ). It was planned that the simulator could be used in the field when the ground was frozen thus eliminating the problem of no storm events occurring. A great deal of trouble was encountered in using the simulator in the field, however, since there is an extremely narrow range of atmospheric temperature in which it can be used. That is, if the air temperature is 32° F. or below the water will freeze in the simulator; if the air temperature is above about 35° F. the ground will begin to thaw at the surface.

In spite of the difficulties of operating the rainfall simulator in the field, one successful run was accomplished during the winter of 1966-67. In this test no runoff occurred with a rainfall rate of over 1" per hour although in the unfrozen state the infiltration rate was only 0.8 inches per hour. During this winter temperatures were unusually mild and the deepest frost penetration was approximately 1/2 inch.

The winter of 1967-68 was also unusually mild but there was one very small frozen ground runoff event. The weir measuring the flow from the entire watershed did not function properly, however, and the data were not reliable. Conditions were not satisfactory anytime during the winter to use the rainfall simulator.

During the 1968-69 winter season there was the lowest recorded temperature in history in Moscow, -42° F., with unofficial temperatures of -50° F. being common. However, there was in excess of two feet of snow on the ground when these temperatures occurred and in many places the ground was never frozen. The snow went off gradually during the spring and there was no flooding of any kind in spite of the heavy snow pack.

In summary, the field work on this project was not productive of data principally because the weather conditions to be investigated occurred only once in four years of operation, and that was a rather limited occurrence. It is felt, however, that considerable was learned about the occurrence of this type of flood from observation and from the literature.

1. If soil is frozen it is possible to have a greater permeability than in the unfrozen state. This has previously been reported

in the literature.

2. If there is considerable snow cover the ground is not likely to freeze unless there are long periods of cold weather. This has also been previously reported.
3. Since there must be a particular set of weather occurrences in a particular order a conditional probability analysis should be made. This will be discussed more extensively later in the report.

LABORATORY STUDIES

When soil freezes in its natural state in areas without permafrost, it is a one dimensional heat flow problem with quite complex boundary conditions. At a depth of 20 to 30 feet the temperature is relatively constant throughout the year. When atmospheric temperature is lower than this constant temperature, heat flow will be upward as the soil cools--first at the surface and progressively downward. There are essentially three sources of the heat which flows upward: 1) the heat stored in the soil particles, 2) the heat stored in the water or ice and 3) the heat of fusion which water releases when it becomes ice.

There have been many analyses of various aspects of this problem in the literature, some of which are: Smith (1943), Gurr and others (1952), Woodside and Kuzmak (1958), Cary (1963), Dirksen (1965), Hoekstra (1966), and Gardner (1959). A complete review of these articles appears in the thesis by Wang (1969).

Several of the above articles consider the moisture movement in the vapor phase due to temperature gradients and the resulting vapor pressure gradients. Movement of moisture both in the liquid and vapor phases is the cause of formation of ice lenses which are of such importance in the failure of highway pavement. Considering the reduction of infiltration rate due to frozen soil, however, it is felt that ice lenses are of less importance. This is because lenses are usually of limited horizontal extent and do not tend to form at the ground surface. The reduction of the infiltration rate due to freezing, it is felt, is largely a phenomena occurring in the top three to six inches of soil.

In the initial laboratory work plastic boxes approximately 1 ft. by 1 ft. by 1 ft. were packed with soil. After wetting to a uniform moisture content, the soil was frozen from the top by insulating the sides and bottom and placing in a cold room. After freezing, rainfall was simulated and the runoff was measured and the data were used to calculate the infiltration rate. These experiments were largely inconclusive in that it was difficult to obtain and measure uniform moisture content. Thus it was not possible to obtain a relationship between moisture content and infiltration rate.

The next experimental work involved packing soil into plastic cylinders approximately 2 1/2 inches in diameter and freezing. These cylinders were also insulated on the bottom and sides in order to allow freezing from the top only. It was hoped that by using cylinders it would be easier to obtain a uniform moisture content. With cylinders it would also be possible to measure the moisture distribution by means of a gamma ray attenuation device. With the soil in cylinders it was not practical to simulate rain, so an ordinary permeability test was conducted. In order to do this under isothermal conditions it was necessary to use a fluid other than water so the experiments could be run at a temperature below freezing.

The most obvious fluid to use was air. An unsteady flow apparatus was used since it is more difficult to measure the amount of air in a steady flow situation. It was realized, of course, that the actual value of permeability to air would not be the same as for water due to slip flow and the so-called Klinkenberg effect which occurs for flow of gases through porous media, however, it was felt that it would be possible to obtain a relative value of permeability as a function of the moisture content or saturation.

It was decided that every effort should be made to eliminate ice lenses and non-uniform freezing conditions. There are several reasons for this:

1. Ice lenses are probably not of great importance in reduction of infiltration rate as previously stated.

2. It is impossible in the laboratory to duplicate all the combinations of depth to water table, non-uniform moisture conditions, diurnal temperature fluctuations, temperature extremes, and soil types which may occur under field situations. All of these factors affect the formation of ice lenses.

3. It is difficult to obtain true one dimensional heat flow in a cylinder so that ice lenses would form as they do in the field.

In the final procedure, to obtain a completely uniform moisture distribution the soil was mixed with water before packing in the plastic cylinder. The samples were then frozen with no insulation being used such that freezing occurred from all sides. Air permeability tests were then run on each sample with the equipment shown in Figure 1. First the tank was pumped to a pressure several psi greater than atmospheric and the frozen sample was fastened to the inlet device. The value was then opened and the time was measured until the pressure had dropped a specified amount as measured by the manometer. Knowing the initial pressure, the final pressure and the time increment it was possible to calculate the permeability coefficient by means of the equation below. This equation was originally developed by Kirkham and states that

$$K = \frac{23L\ V\mu}{A\ \ Pa} \left(\frac{\log_{10} Y_1 - \log_{10} Y_2}{t_2 - t_1} \right)$$

where K is permeability in units of length squared; L is the length of sample; A is the cross-sectional area of sample; V is the volume of the tank; μ is the absolute viscosity of air; Pa is atmospheric pressure; Y_1, Y_2 are the corresponding times.

After the permeability was determined the sample was weighed, oven dried, and again weighed to obtain the porosity and saturation of the sample. The value of permeability was then plotted versus ϕ (1 - S) where ϕ is porosity and S is the water saturation or the percentage volume of voids originally filled with water. This particular parameter is felt to be the most significant parameter affecting the permeability since it should indicate the relative volume of pores which are not filled with either soil particles or ice and are, therefore, available for fluid flow. Figures 2 and 3 are plots on semi-logarithmic paper of permeability versus ϕ (1 - S) for a coarse sand and a fine sand respectively. A straight line was fitted to these data by the method of least squares. The coefficients of determination were .75 and .90 respectively, that is, 75 and 90 percent of the variation in permeability is accounted for by this parameter using a straight line relationship on semi-logarithmic paper.

Figure 3 shows the same data for a silt soil. There is considerable scatter in the data that is due to problems in the experimental procedure. The procedure of wetting the soil and mixing it to obtain a uniform moisture content worked well with granular materials such as sand but did not work well with silt since there was considerable aggregation and formation of small soil balls. Since there was considerable scatter a line was not fitted to the data.

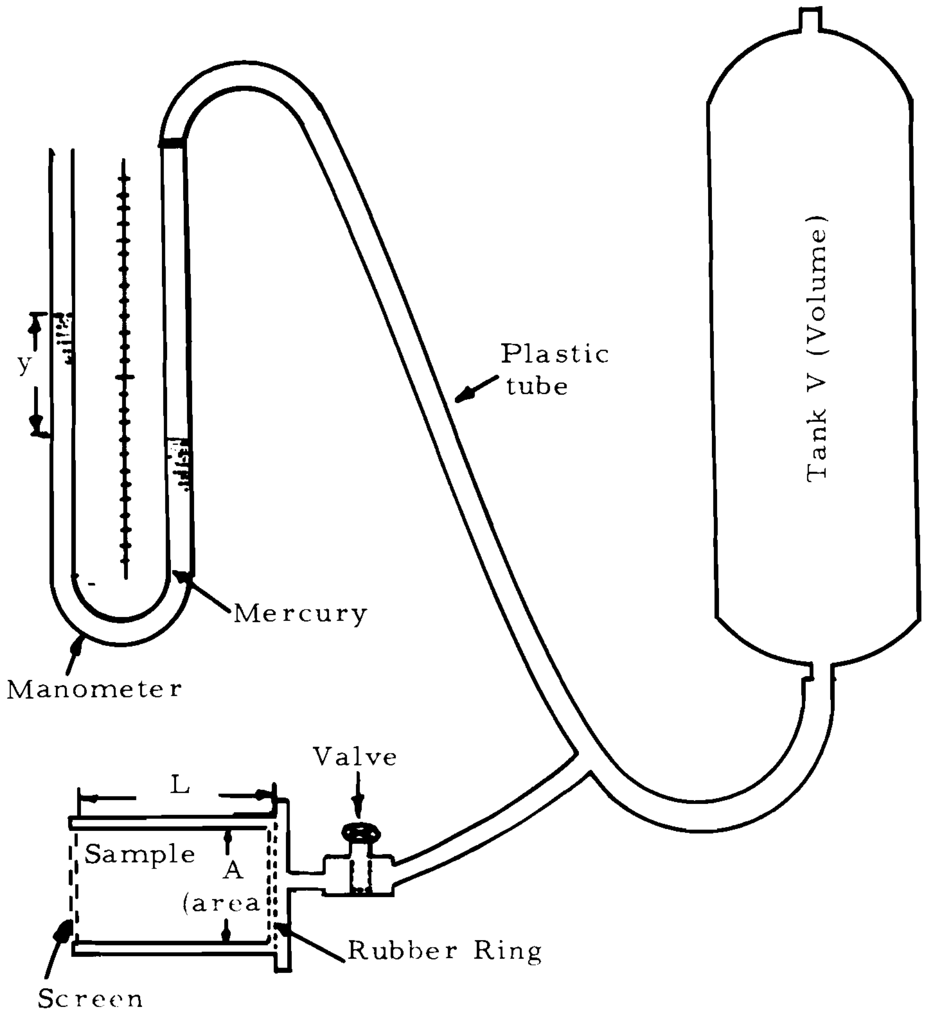


Fig. 1 - Schematic diagram of the equipment.

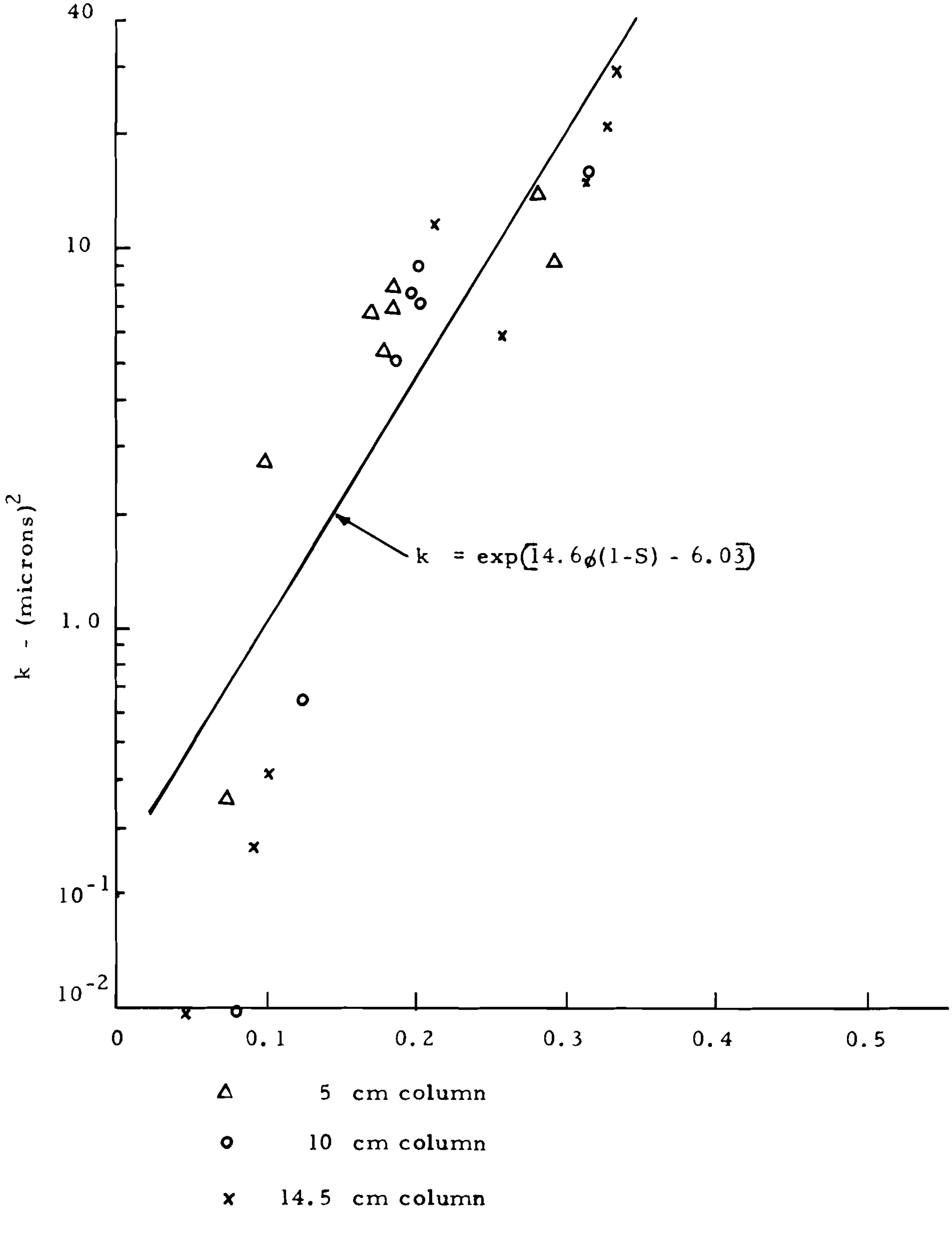


Fig. 2 Relationship between k and $\phi(1-S)$ for course sand.

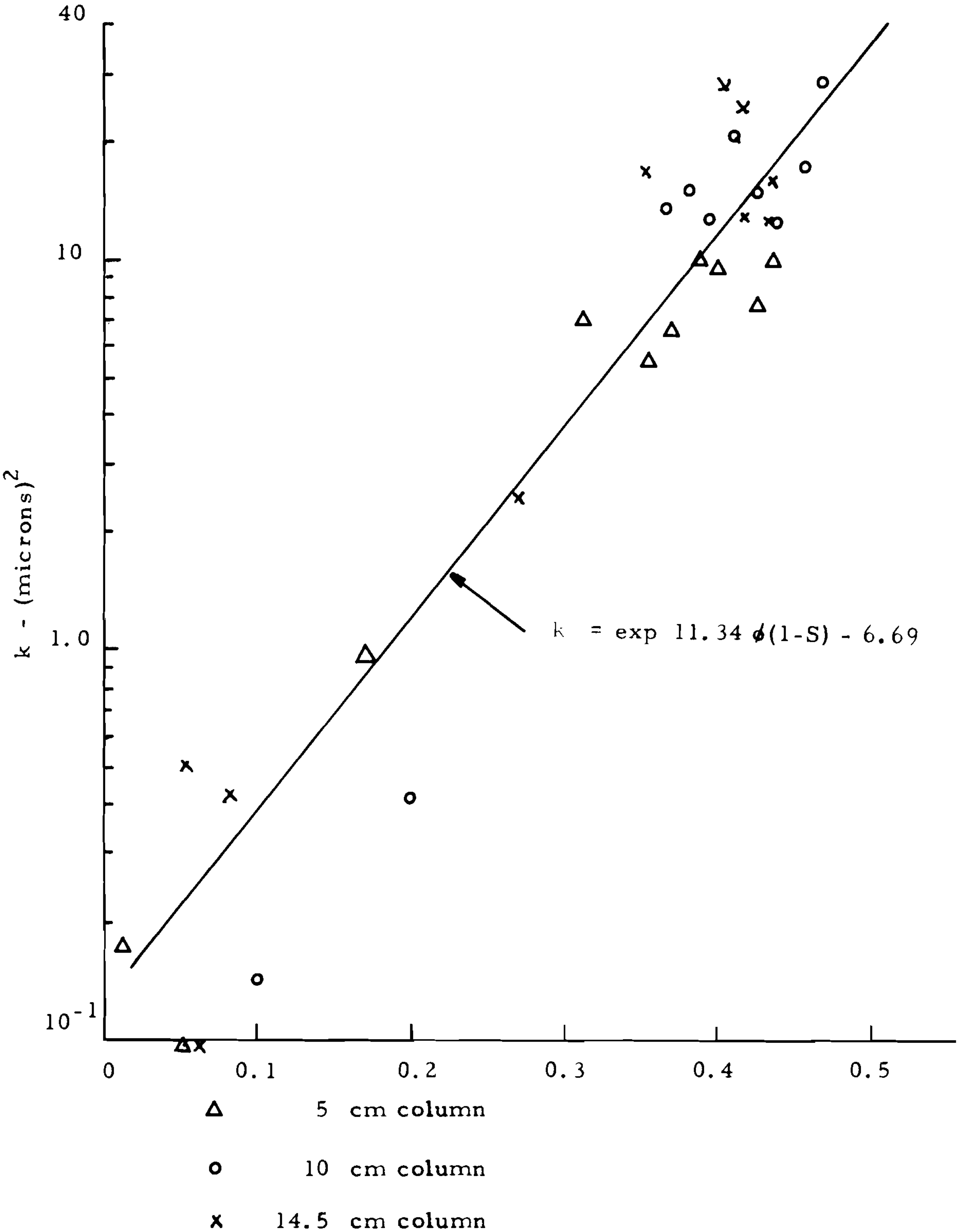
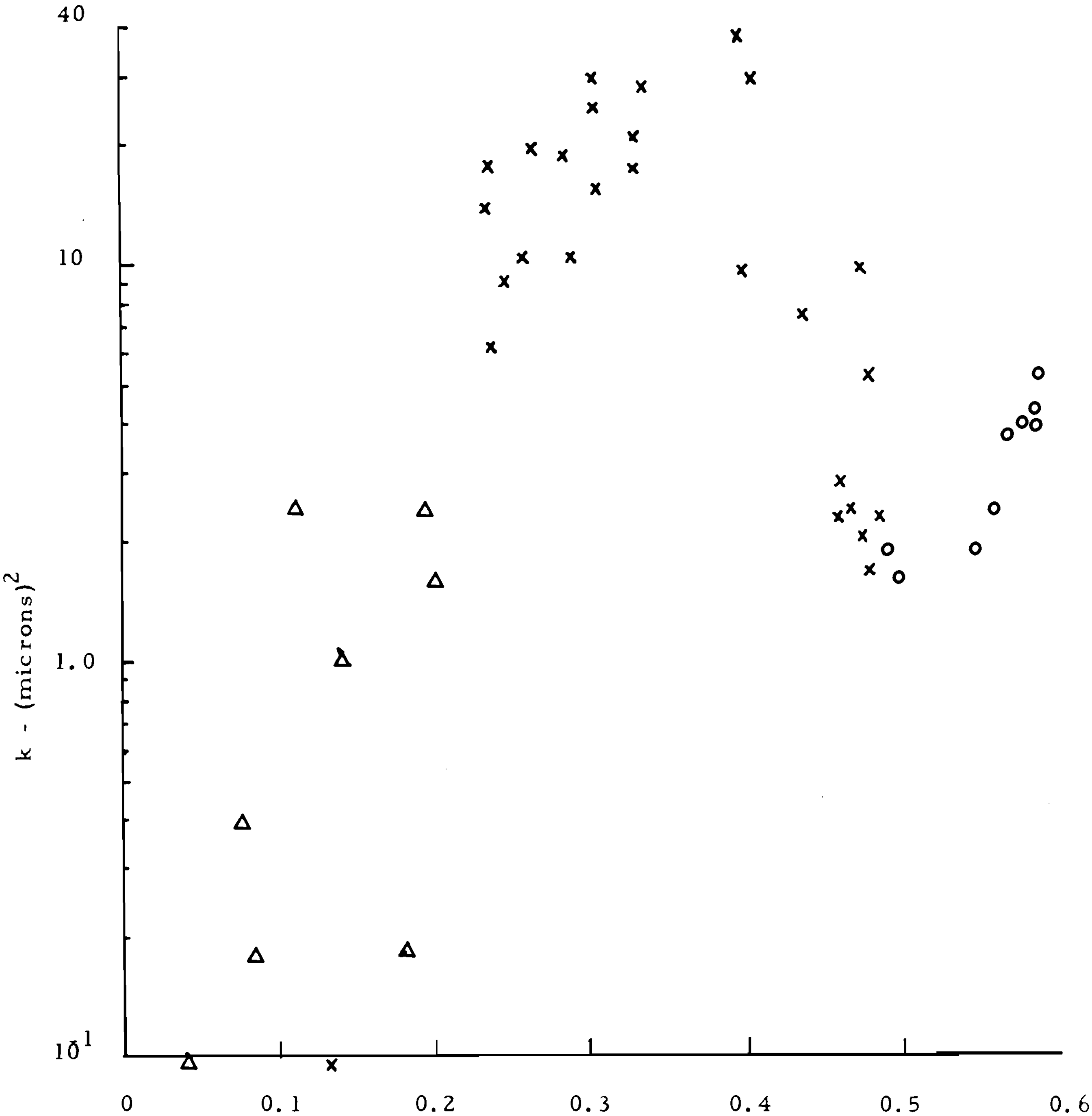


Fig. 3 Relationship between k and $\phi(1\text{-}S)$ for fine sand.



o Group 1 - undisturbed soil

x Group 2 - soil mixed with water

Δ Group 3 - soil placed in column then wetted

Fig. 4 Relationship between k and ϕ(1-S) for silt.

For all three types of material there were several samples that had zero permeability. These data points were not used in the regression analysis since zero cannot be plotted on a logarithmic scale. In all cases ϕ (1 - S) was less than 0.13 when the permeability was zero. Theoretically, ϕ (1 - S) would be zero when the permeability was zero; practically, however, there are likely to be some empty pores left which are not interconnected and, therefore, have zero permeability. It seems likely that in any type of soil there is some value of ϕ (1 - S) below which the permeability approaches zero.

Assuming that natural soils of the type worked with here have typical porosities of approximately 0.4 and assuming the maximum value of ϕ (1 - S) at which a negligible permeability occurs is 0.15 then saturation would have to be at least 0.625 to have negligible permeability when the soil is frozen. This is quite wet--greater than the field capacity for most soils.

In summary the laboratory work in this project produced knowledge of the mechanics of flow in a frozen soil by developing a parameter which is a good index to the permeability. More work will have to be done in the field on soils in situ to determine critical values of ϕ (1 - S) for various soil types, that is, the values of ϕ (1 - S) at which the permeability is nearly zero. This field work should be done using an air permeameter under frozen soil conditions. If the critical values of ϕ (1 - S) were determined for all the soil types in an area then it would only be necessary to determine the porosity and saturation from field samples to determine whether there is the possibility of a frozen ground flood.

PREDICTION OF FLOODS

After observing weather conditions closely for the four years of this study it is felt that frozen ground floods are due to a particular series of weather phenomena. These are:

1. There must be considerable rain before the ground freezes because the soil moisture must be quite high - greater than field capacity in many soils.
2. The soil must freeze to a depth of at least several inches.
3. There must then be a significant storm period. This is usually snow followed by rain although high intensity rain on frozen ground could also produce significant floods.

The prediction of frozen ground floods could be approached by two different procedures.

1. A strictly probabilistic approach in which the probability distribution of each of the above phenomena is determined from weather records. These distributions would have to be combined using a conditional probability analysis to determine the probability of the final event--the frozen ground flood. This procedure has a number of difficulties to be solved. Among them are: 1) Before weather records can be used limitations have to be attached to each weather phenomena, that is, a certain amount of rain must occur in a given time, temperature must reach a certain value for a specified time and then a specified storm must occur; 2) For most conditional probability analyses the variables must be independent. In this case they would be highly dependent. At best this analysis could only give the probability that a frozen ground flood would occur any given year.

2. An approach that the U.S. Army Corps of Engineers has expressed interest in would be to determine when conditions are such that a frozen ground flood is possible, i.e., when the ground is frozen such as to be impermeable. The work done in this project is a start towards developing the data and procedures for such a program. The prediction procedure would involve extensive soil moisture measurements during the fall and early winter. If the soil moisture was high enough warnings could be issued about the possibility of floods if the weather became cold. When the ground actually froze, warnings could be issued as to the possibility of floods is a storm of sufficient intensity occurred. Under a system such as this there is the possibility of using photographic techniques such as infra-red photography to survey large areas which might have conditions suitable for a flood

RECOMMENDATIONS FOR FURTHER WORK

1. Field studies should be done with an air permeameter in various soils under frozen soil conditions, in order to determine critical moisture contents for various types of soil.

2. Investigation should be carried out to determine whether there are any photographic techniques which could be used for frozen soil detection. If so, this would then be correlated with the information under 1 to give warnings of flood dangers.

3. A basic laboratory study should be done on the mass transfer of water from the solid (ice) to liquid phase during non-isothermal movement of water through frozen soil. This would lead to information on the rate at which the infiltration rate may increase when rain begins.

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