A NEW THEORY OF FROST HEAVING

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SYNOPSIS

The rate of frost penetration into the earth's surface during freezing weather varies to a marked degree, with changes in atmospheric temperature By means of laboratory experiments it has been demonstrated that movements of the frost line, first upward and then downward, result in the formation of ice plates, which through successive fluctuations may become thick enough or numerous enough to cause excessive heaving These results indicate that excessive heaving may occur in soil of almost any grading or texture providing an adequate supply of water is present or available Since capillary water cannot be removed by artificial drainage, those textures which are capable of supplying enough water by capillarity to cause heaving on account of frost line fluctuations, should be removed and replaced with material that will drain Elimination of frost heaving in coarse materials involves only provision for drainage These conclusions are substantiated by the fact that frost action was eliminated last winter at some two hundred locations in Michigan through special treatment

Experiments conducted in the Laboratory of the Michigan State Highway Department, on the freezing and thawing of soils, have been instrumental in the development of a new theory by virtue of which excessive heaving is explained in soil textures hitherto not considered associated with this trouble Stephen Taber (21, 22, 23, 24)[1] and George Bouyoucos (5, 6, 8) concluded in part, from their laboratory investigations of this problem, that heaving is due to the movement of water to the point of freezing resulting in the formation of ice layers and, furthermore, that the old theory which attributed excessive heaving to the change in volume of water present in a soil on freezing was incorrect Their experiments, however, unfortunately, did not include tests upon those soil textures which are known to be productive of the majority of severe frost disturbances in Michigan and other states in the " frost " area and, moreover, freezing of their specimens was conducted at a uniform rate, a condition which is rarely found in nature

It is known that the rate of frost penetration into the earth's surface, during periods of freezing weather, varies to a marked degree and, due to the fact that the outward conduction of heat from the interior of the earth is fairly constant, a change in the atmospheric temperature must obviously result in a shifting of the frost line to or from the surface, the direction of the shift depending upon the direction of the temperature change Substantiating evidence for these

[1] Figures in parenthesis refer to reports listed in the bibliography

statements is contained in Moore's "Descriptive Meteorology" (19) His comments are as follows "There are seasonal temperature oscillations in the thin top crust of the earth, due to heating during summer and cooling during winter, and there are also irregular oscillations due to protracted cloudiness, abundant rainfall and snow covering By day the surface of the earth is heated and at night it is cooled, there is, therefore, a diurnal wave of temperature which is propagated toward the interior Since the surface temperature is a periodic function of the time, the temperature at any depth will vary in a corresponding periodic manner, the amplitude of the wave decreasing as it progresses downward" It is clear from the above, therefore, that a warm spell preceded by freezing weather can induce thawing of the frozen surface from the bottom as well as the top Taber, in a report on "Frost Heaving," has stated that, "If the air temperature remains barely below freezing, for a long enough time, a deeply frozen soil will thaw gradually from the bottom because of the outward conduction of the heat from the interior of the earth"

It is evident from the foregoing, that in an investigation to determine the effects of freezing upon soils in the laboratory, provisions should be made to either vary the rate of cooling with a constant supply of heat to the bottom of the specimens or to maintain a constant rate of cooling above and an intermittent supply of heat below Figure 1 illustrates diagrammatically two methods which can be used to control the frost or isothermal line movements in laboratory freezing experiments It is to be noted that identical results can be attained, namely, a shifting of the frost line upward, by either changing the freezing temperature from — 20°C to 5°C, Case No 1, or changing the soil temperature at the bottom from + 5°C to + 20°C The former represents what happens in nature while the latter is an artificial method productive of the same effect In the development of these graphs, the temperature gradient through the soil was assumed to be constant and, therefore, is represented by straight lines In nature, due to the fact that the lateral absorption and radiation is not always uniform, the gradient plotted graphically would probably be some form of a curve This curve, however, would revolve about its axis in much the same manner as the straight lines indicate and would produce about the same type of frost line movements as are shown by the graphs

Preliminary experiments in the cold room (Figure 2) involved the freezing, at a uniform rate of cooling, of fairly large soil specimens cored out of known silt frost heaves These specimens were laterally insulated and supplied with water from below, maintained at a constant temperature Under these conditions no heaving occurred The fact was, however, disclosed by these tests that a non-uniform rate of freezing may cause an upward movement of the frost line and it was therefore decided to investigate the effect of a variable rate of freezing upon smaller specimens, any number of which could be prepared and frozen in a comparatively short length of time A special freezing cabinet was constructed, in which specimens in containers

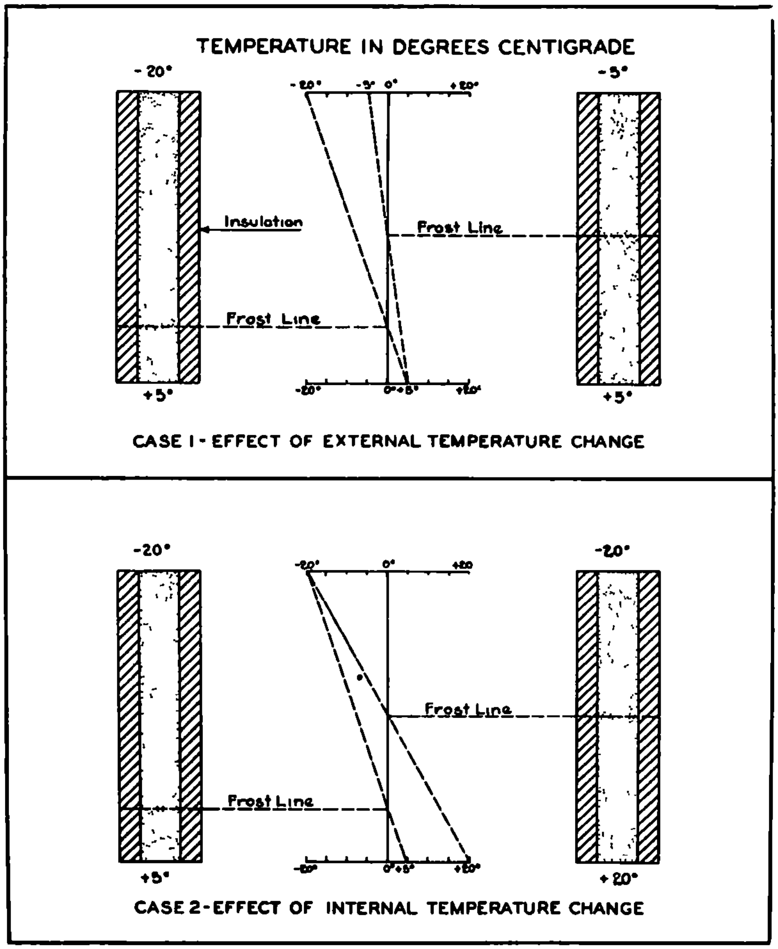

Figure 1. Theoretical Analysis of Temperature Movements in Soil Specimens

of various types and sizes, either having or not having access to water from below, could be frozen at either a rapid or slow rate of uniform or non-uniform cooling The temperature within the cabinet could either be held constant or varied periodically by a set of electrical heaters controlled by means of a relay and a thermostat. All the conditions necessary to control movements of the isothermal line in soil specimens prepared for freezing in this apparatus are satisfied and a positive control of temperatures assured.

In order to observe actual developments and movements of the frost line, specially prepared specimens in glass tubes were first frozen in the cabinet One end of the open tube (Figure 3) is closed with a cork so that expansion developed during freezing causes a pushing out of the cork rather than rupturing of the tube Generally about three inches of sand is placed in the bottom of the tube, the remainder being filled with the soil to be tested By using a porous cork, the samples may absorb water from the bottom until moist on top With this method of preparation each specimen has its own water supply

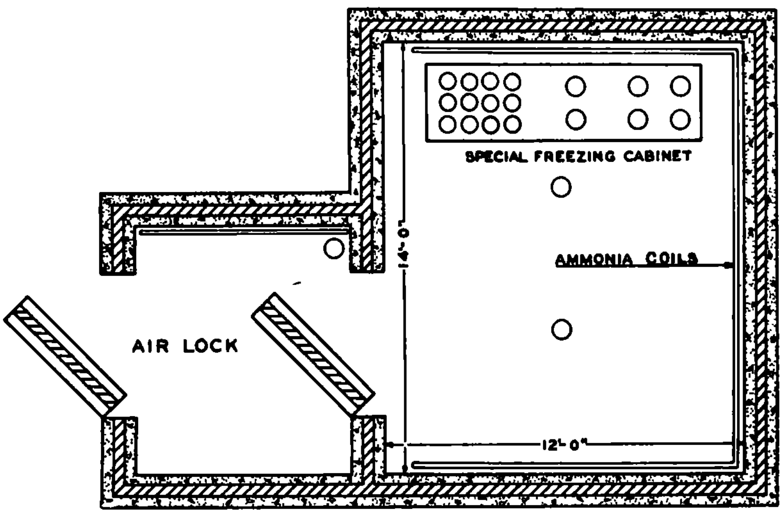

Figure 2 Plan View of Cold Room

and may be removed from the freezing cabinet at any time without danger of disturbing conditions existing in the freezing specimen

The first series of specimens prepared in this manner were frozen at a uniform rate of cooling, a temperature of approximately —2°C being maintained in the cold room proper and of about 2°C within the insulated cabinet Periodic visual examinations of these specimens, during the course of freezing, revealed the development of only a slight amount of expansion due to the change in volume of the interstitial water being converted into ice. A second series of specimens, prepared in the same manner, were then frozen maintaining a constant temperature in the cold room as before The temperature within the freezing cabinet was, however, periodically increased and decreased by means of the automatic control mechanism. Vertical isothermal line movements were thus introduced and, during the experiment, the following phenomena were observed On the downward movement of the isothermal line a slight expansion of the specimen occurred. On the upward movement a break or void in the soil column became visible which followed the contact of the frozen and unfrozen soil upward. As the movement continued the frozen soil particles could be observed to detach themselves as the ice films surrounding them melted and settle through water present in the void coming to rest in a more compact state on the unfrozen soil beneath. Before the

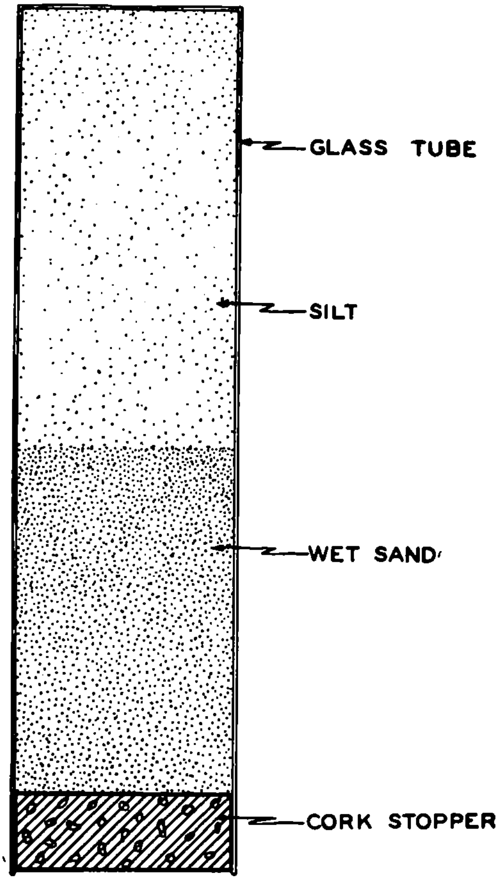

Figure 3. Specimen of Silt Prepared for Freezing Test

water void reached the top of the specimen a reduction of the temperature within the cabinet caused the isothermal line to again move downward. The water in the void space was then converted into ice and, as the frost line progressed below this level, a second increment of vertical expansion occurred due to another freezing of interstitial water. A second thaw or upward movement of the isothermal line resulted in the formation of another cumulative water void which was subsequently converted into an ice plate in the same manner as before. The total thickness of the ice plates introduced and the vertical expansion of the soil column were measured and found to be approximately equal in magnitude. In Figure 4, A represents unfrozen soil; B frozen soil slightly expanded due to freezing of interstitial water; C represents the cumulative water void after the frozen column has been partially thawed; D shows the water void after conversion into ice with an added increment of vertical expansion due to a second freezing of the soil beneath; E and F show the presence of a second ice plate developed in the same manner as the first.

An additional series of experiments involved the freezing of fairly coarse sands in glass tubes. It was found that the behavior of such material, when containing an excess of water, was essentially the same

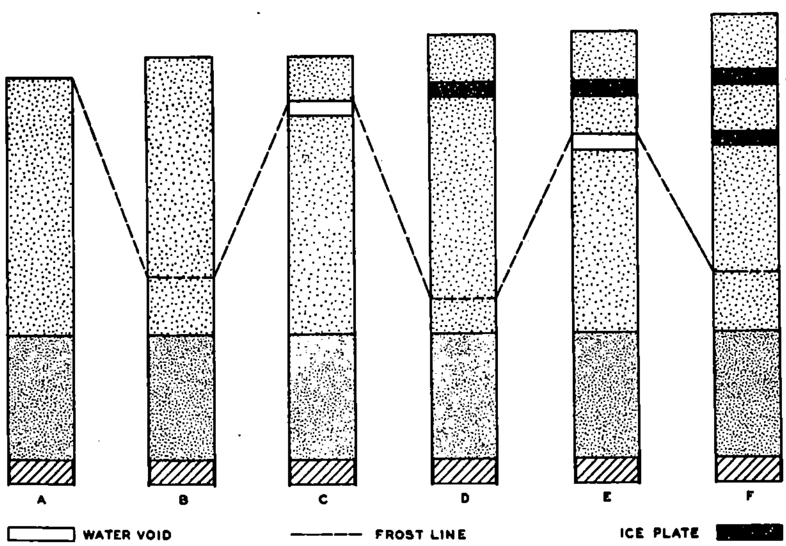

Figure 4. Ice Plates Formed by Controlled Isothermal Line Movements

as that previously described in the case of silts. A slight vertical expansion accompanied the initial uniform freezing. Water voids formed, when the frost line shifted upward, which were converted into ice layers on a subsequent downward movement of the freezing temperature.

Ice formations which developed in various of the specimens frozen are shown in the photographs, Figure 5. Photographs 1, 2, and 3 are of a silt specimen showing the absence of segregation due to simple freezing and the presence of one and two ice plates from isothermal line movements. Photograph 4 shows a very fine sand specimen containing one plate and a water filled void. A soil containing nearly 80 per cent clay is shown in Photograph 5. Three thin ice plates are visible due to movements of the frost line. The fine irregular ice lenses visible between the more well defined plates are probably due to water being drawn from the smaller to larger capillaries in a manner similar to that which Taber has described in his experiments for clay. On the other hand, it is possible that minute fluctuations of

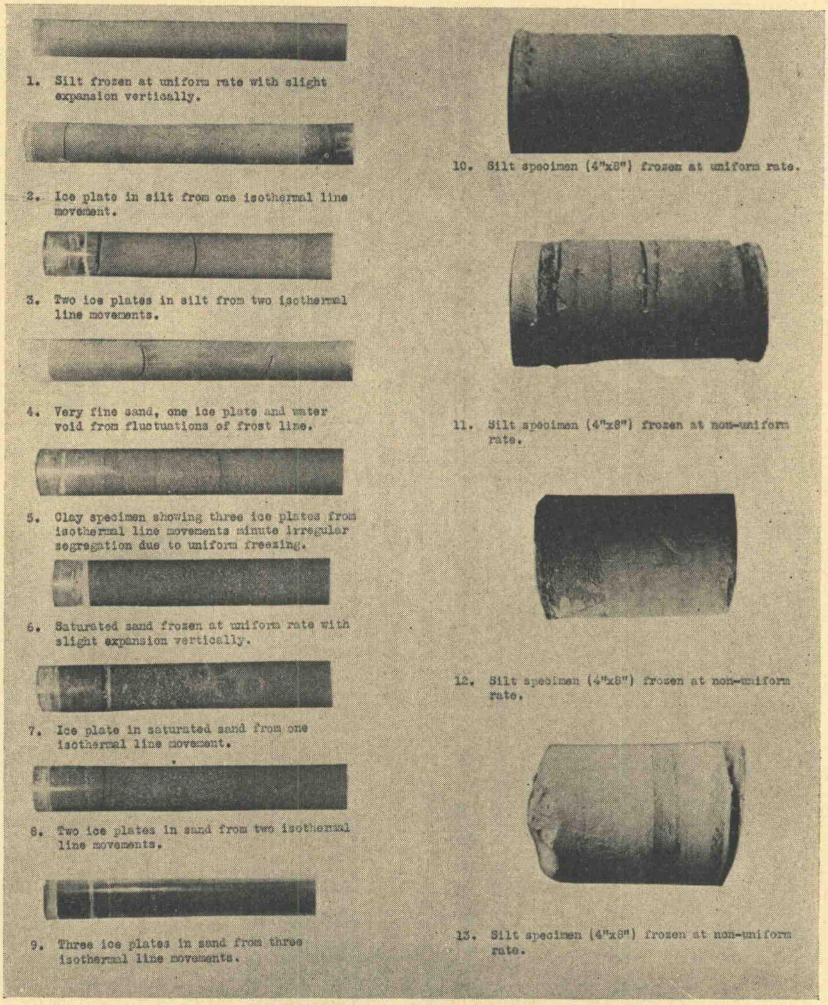

Figure 5. Photographs of Soil Specimens Frozen in the Laboratory Experiments

temperature within the specimen may affect soil particles of the clay size and not soils of coarser textures. Further investigation of this particular phase of the problem is needed. Photographs 6, 7, 8 and 9 show ice formations which developed in coarse saturated sand from fluctuations of the freezing line. Photographs 10, 11, 12 and 13 show 4 by 8 inch specimens of silt, one of which was frozen at a uniform rate and the other three at a variable rate In these tests the freezing temperature was periodically fluctuated, the bottom of the specimens being held at approximately 2° C , whereas in the case of the silt specimens frozen in glass tubes, the freezing temperature was held practically constant and the temperature at the bottom fluctuated It can be seen that no visible segregation developed in the specimen frozen at a uniform rate, Photograph 10, while pronounced segregation is visible in the other three specimens, particularly the two shown in Photographs 11 and 13

The results obtained from the investigation, to date, would thus seem to indicate that excessive heaving may occur in soils of almost

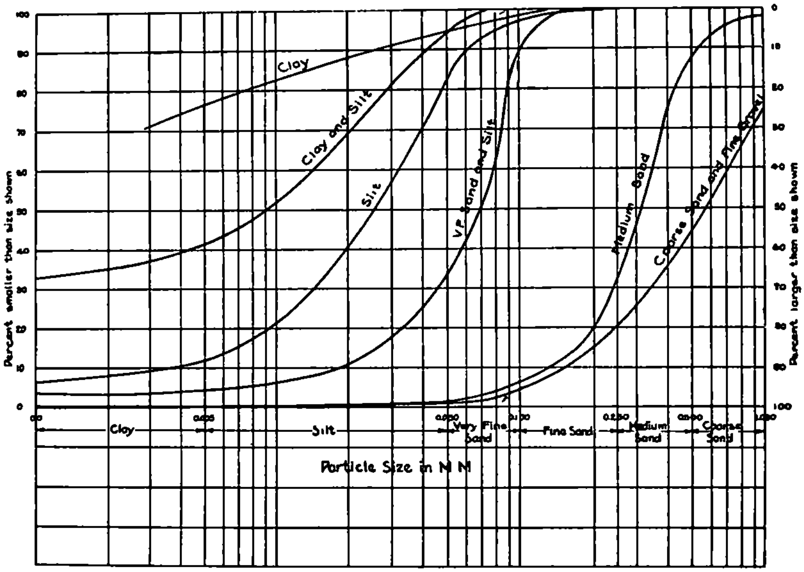

Figure 6 Mechanical Analysis of Soils in Which Ice Plates Formed From Isothermal Line Movements

any grading or texture providing an adequate supply of water is present or available Supporting evidence for this statement is had from the mechanical analysis curves, shown in Figure 6, for a number of the soils in which ice plates developed during the freezing and thawing tests in the Laboratory

THEORY APPLIED TO FIELD CONDITIONS

If the phenomena of the formation of ice plates by frost line movements are applied to field conditions, a satisfactory explanation may be had for excessive frost heaving in any saturated soil It is a known fact, from field observations, that soils in which frost heaves occur are saturated either by capillarity or seepage It has also been shown that variations in the air temperature when occurring below zero will cause thawing to occur from the bottom of the frozen soil with a resulting shift of the frost line Since the freezing fluctuations and the water supply are all the above mentioned phenomena require for excessive heaving by segregation of water into ice plates, a theory to explain heaving in saturated soils has been developed which may be stated as follows

When the air temperature drops below freezing, the frost line will move downward into the soil The rate of penetration depends upon the rate of radiation and absorption of the soil As the frost line penetrates the saturated soil it converts the interstitial water into ice causing a very slight expansion and separation of the soil particles

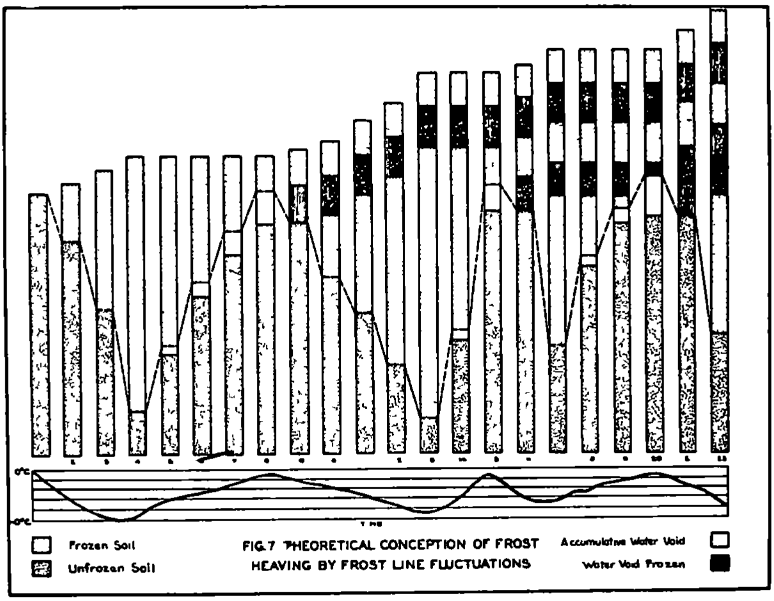

Figure 7

due to the volume change of the water films around the particles into ice films If the freezing isothermal line moves rapidly through the soil the ice crystals will probably grow perpendicular to the surface of the soil particles, since due to their lower specific heat, they will cool faster than the capillary water in the soil When, however, the freezing line moves slowly through the soil the ice crystals will orient themselves more in the direction of cooling and give a slightly greater separation of the soil particles in this direction In either case there will be a slight expansion and a separation of the soil particles due to the freezing of the interstitial water. If the frost line has penetrated an appreciable distance, a very slight heaving will result, the magnitude of which will depend upon the vertical volume change of the interstitial water into ice (Figure 7, parts 2, 3 and 4, show this effect of freezing of the interstitial water This sketch is, of course, made to a greatly exaggerated scale) As the freezing temperature becomes warmer, the frost line will move toward the surface due to a decrease in the radiation rate of the unfrozen soil As the frost line moves upward, a cumulative water void will follow the contact of the frozen and unfrozen soil The magnitude of this water void will depend upon the accumulative volume change of the ice films converted back into water films Due to the interfacial tension between water and ice, aided in some sense by hydrostatic head, atmospheric pressure and other possible pressures that may exist below the frozen soil, this void will be entirely filled with water furnished from the saturated soil below The maximum size of this cumulative water-filled void will depend upon the magnitude of the frost line movement towards the surface and the pressure exerted by the surface load In the region near the surface, the thickness of the void may be reduced due to the inability of the overlying frozen soil to support the superimposed load However, if the frozen soil is able to support the surface load by bridge action, the size of this cumulative water void will depend upon the magnitude of the frost line movement (Figure 7, parts 5, 6, 7 and 8, show this cumulative water void at various intervals during the upward movement of the frost line caused by a surface temperature change) As the surface temperature becomes lower, the frost line will again start to move downward trapping this water void as an ice plate or layer (Figure 7, part 9) and on further penetration, a second increment of expansion will occur due to another separation of the soil particles by the freezing of the water in the interstitial spaces (Figure 7, parts 10, 11, 12 and 13) Another surface change will cause a second cumulative water void to develop and follow the frost line If this frost line starts to drop before it reaches the previously formed ice plate, a new ice plate will form (Figure 7, part 16) If, in another fluctuation, the cumulative water void has been brought in contact with a previously formed ice plate, it will be added to the previously formed ice plate on the downward movement of the frost line (Figure 7, parts 20 and 21) When the freezing isothermal line fluctuates in one region for a considerable period of time, thick ice plates will develop even if the magnitude of the fluctuations is very small These small fluctuations will only bring a proportionally small cumulative water void to the bottom of a previously formed ice plate These numerous additive amounts attached successively to the bottom of an ice plate may easily account, however, for the development of ice plates of considerable thickness In nature this is probably the case except in some instances where a large fluctuation may be responsible for the formation of a thick ice plate in one cycle of an isothermal line movement Excessive frost heaving thus may be caused by the accumulative expansions of interstitial water stored up in the form of ice plates by repeated frost line fluctuations

THEORY SUBSTANTIATED BY FIELD OBSERVATIONS

The above theory offers a direct explanation of the formation of ice plates of any size or number All that is required is a soil saturated with water and a fluctuating frost line In Michigan, during the past summer, examinations of the subgrade soil at about two hundred locations in the northern section of the state revealed ample evidence that heaves in excess of a few inches may occur in coarse sands or even in gravelly materials providing an excess of water is present It was found that approximately 70 per cent of the heaves occurred in sandy materials of decidedly low capillarity in which, however, a large excess of free water was present, either from seepage over impervious strata or from a naturally high water table It must be understood that in more "open" materials a supply of free water must always be available to fill void spaces created by upward thawing because, if an opportunity for drainage prevails, these soils will not ordinarily contain sufficient moisture by capillarity to satisfy the requirements for heaving according to the stated theory In silts and very fine sands, however, even though drainage is provided, the amount of moisture either present by capillarity or drawn to the zone of freezing will be sufficient to fill voids created during a cycle of isothermal line fluctuations and cause excessive heaving

SIGNIFICANCE OF THEORY AS RELATED TO THE DESIGN OF SUBGRADES

As mentioned before, field observations have definitely established the fact that excessive frost heaving is not restricted to soils of any particular grading or characteristics Heaving has been observed to occur in clays, silts, very fine sands and in textures approaching the grading of gravels

It is an accepted fact that capillary water cannot be removed by artificial drainage and, therefore, those textures which are capable of supplying water in sufficient amount by capillarity for heaving to occur by virtue of frost line fluctuations, must be removed from the grade and replaced with materials having favorable drainage characteristics. On the other hand, elimination of frost heaving in coarser materials involves only the installation of properly designed tile drainage systems in order to remove gravitational water which may enter the soil by seepage over impervious strata or which may exist from a naturally high ground water elevation

This knowledge, together with that acquired from many years of study of pavement behavior, has been instrumental in the adoption of definite methods of subgrade design now being used as a matter of routine in Michigan It has been found, from the behavior studies, that the more common type of cracking in concrete pavements may be largely eliminated by the use of light weight fabric or mat reinforcement except where either vertical or lateral movements, or both, of the soil composing the subgrade occurs The use of reinforcement has therefore been adopted as standard pavement design practice and, in addition, every effort is being made to eliminate differential movements in the subgrade, namely, those due to plastic flow of the soil and those due to frost action Preconstruction soil surveys are made and features involved in general grade design, method of drainage, etc, are considered in their relation to this preliminary soil information when the plans are drawn up Subsequently, during or after grading, detailed examinations of the grade, particularly in cuts, are made by the soil surveyor for the purpose of locating frost heaving textures or areas which require drainage to prevent this action In the majority of cases sketches are prepared showing the exact locations of undesirable texture or the location of impervious strata with respect to the finished grade An opportunity is therefore had to thoroughly review and study the soils data before deciding upon any particular method of treatment

The fact that frost action, throughout the past winter, was entirely prevented at some two hundred locations, accorded special treatment in 1930, was largely responsible for increased activity along this line during the construction season just past Approximately five hundred locations were treated during this period and plans are now being formulated for a continuation and expansion of this activity again next year

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