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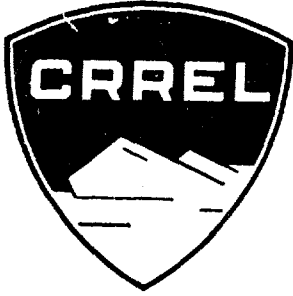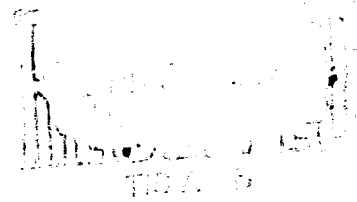
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A Review of Muskeg
and its Associated
Engineering Problems

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A Review of Muskeg and its Associated Engineering Problems

by John A. Pihlainen

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Towards a reassessment of muskeg, an appraisal of the problems
of muskeg showing the complexity of the subject and the implications
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engineer's point of view by considering climatic, biotic, and geologic
factors. Muskeg research in other countries is reviewed with empha-
sis on Canadian research. The Radforth Muskeg Classification System,
its application to problems and modifications are discussed. Empirical
data on the engineering properties of peat are broadly described in four
main categories: (1) index properties, for identification; (2) strength
and deformation properties; (3) thermal properties; and (4) geophysical
properties. Engineering problems, construction equipment, and costs
to be considered in vehicle trafficability, road construction, corrosion
and drainage operations, and frozen muskeg and permafrost construction
when muskeg is involved are fully discussed. Comprehensive conclu-
sions and recommendations on the present state of knowledge of muskeg
and needs for further research are outlined.

A REVIEW OF MUSKEG AND ITS ASSOCIATED
ENGINEERING PROBLEMS

by

John A. Pihlainen

I. INTRODUCTION

Until recently, the chief interest in muskeg has been botanical. The northward advance of industry into the subarctic has aroused a growing awareness of muskeg and its implications for engineering. A reassessment of muskeg is now underway.

Contrary to general belief, a considerable amount of published information is available as the 200 selected references show. As might be expected, much of the botanical material does not contribute to the solution of specific engineering problems. It does, however, form some background for engineering studies.

This study is an appraisal of the problems of muskeg, based on field experience and a study of the literature. The references are representative and have been chosen to give an insight into the complexity of the subject. From a study of these references, which is the body of this report, some conclusions have been drawn and certain recommendations have been developed.

Definition

The term "muskeg" is derived from the Ojibwa Indian term "mashkig", meaning "swamp" or "marsh" (personal communication, A. D. deBlois, National Museum of Canada). The vagueness and flexibility of this original term had been so compounded, having been used to describe a swamp, the shore of a boggy lake, impounded areas covered with vegetation, the thickly carpeted floor of an open spruce woodland, peat, and sometimes open Arctic tundra, that it had questionable value. Today, however, though still attended by lack of agreement in the U. S. and Canada, the term "muskeg" has a more formal definition; the following is generally accepted:

" 'Muskeg' has become the term designating 'organic terrain', the physical condition of which is governed by the structure of the peat it contains and its related mineral sub-layer considered in relation to topographic features and the surface vegetation with which the peat co-exists." (Radforth, 1955a).

Thus, the term "muskeg" is synonymous with "organic terrain" and the "organic material" (non-living) portion of such terrain is synonymous with "peat."

Theory of Origin

The definition of muskeg implies extensive beds of peat saturated with water or heavily charged with ice, covered by a special but varied vegetation, and in some cases underlain by mineral soils with extremely objectionable engineering properties. This whole complex is further characterized by special morphological conditions — ponds, hummocks, etc. A simple and universal theory for the origin of such terrain will be difficult and perhaps impossible to develop. Nonetheless, although the origin of muskeg is a result of diverse and interrelated variables, some ideas on the major factors have been presented. From an engineer's point of view, these ideas are more easily reviewed by considering climatic, biotic, and geologic factors.

Climate

The frequency of the occurrence of muskeg and peat accumulation is controlled principally by precipitation and air temperature. In temperate regions an excess of precipitation over evapotranspiration is conducive to the formation of peat from flourishing vegetative growth if drainage is hindered. Observations on the time needed

for the formation of peat (Hustich, 1957) vary from 1.2 to 33.5 mm/yr and hence the past, as well as the present, climate must be considered.

In the subarctic, although plant growth is restricted, the low evapotranspiration maintains a high water table. This, combined with a low pH, continually preserves the semi-decayed material as peat. There is thus a delicate balance between climate and growth which appears to be achieved only in the higher temperate latitudes and the sub-arctic.

Secondary effects of climate, such as snow cover and wind, also modify the peat environment, less on a regional than on a local basis. Microclimatic effects can have striking local effects on various aspects of muskeg, but these are more closely associated with biotic considerations.

It is also generally acknowledged that there have been climatic fluctuations in the past (Potzger and Courtemanche, 1956). Thus conditions may have been conducive to the formation of peat bogs where at present no such development is taking place. These bogs, remnants of past muskegs, might be called "paleo-bogs". Such peats, although covered by sediments, can also present engineering problems.

Biotic factors (see also Part II. Classification of Peat)

Growing plants vary considerably in their requirements for the basic environmental factors of heat, light, water, and nutrients. Some species can survive under a wide range of growing conditions, while others are more exacting in their demands. The basic climate of the subarctic limits species to those hardy plants that can exist in a cold, wet (and generally nutrient-deficient) environment. However, there can be many variants, and these are reflected by subtle changes in the areal extent of plant species, growth, and associations. Thus plant assemblages in a muskeg zone can impart an areal characteristic which is quickly recognizable both from the ground and from the air.

However, it cannot be assumed that such plant assemblages are static. Plant communities can be replaced by others as a result of subtle changes in the environment, and close observation has disclosed that the plants themselves may be in part responsible for such changes: for example, the accumulation of their dead remains raises the level of the peat and thus changes the drainage pattern; penetration of roots aerates the soil and brings mineral elements into the surface material; and the plant mass development also changes the evapotranspiration factors. The distribution is further complicated by the dependence of plants upon insects for pollination and upon animals, wind, and water for seed dispersal. Each community in a muskeg zone is thus a result of a delicate adjustment to a continuously changing bio-environment.

Geologic factors

The geologic setting for the existence of muskeg is also not to be simply described. In general, terrain features that impede the natural flow of surface or subsurface water are of primary importance. Lowlands, rock depressions, and plains (even slightly sloping plains in areas of impervious subsoils or permafrost) are potentially favorable for muskeg occurrence.

The regional geomorphological environment for muskeg is also made up of many local variables that can affect plant life in varying degrees. Among these, the parent rock and soils, topography or relief, and drainage are thought to be the most important. Parent rock material, soils, and drainage make available the nutrients. The topography or relief influences microclimate, thus varying the conditions of insolation, radiation, and convective or turbulent heat losses — which determine the evapotranspiration factor, and many of the conditions of the bio-environment.

Extent

A considerable amount of literature is available on specific occurrences of peat in North America (For example, Dachnowski-Stokes, 1941; Hamelin, 1957; Hustich, 1957; Potzger and Courtemanche, 1954, 1956; Rigg, 1951; Rigg and Gessel, 1956; Sjors, 1959; Terasmae, 1960; and Terasmae and Hughes, 1960). Much of this

information has been summarized in <u>Bogs and Peats of North America</u>, by N. Ia Kats (1959). Although difference of opinion on the value of this study are inevitable, some extracts (which follow) are useful to point out the extent and diversity, and to make a comparison with Europe.

In North America predominant occurrence of muskeg is in Canada and Alaska. Peat bogs of considerable extent do exist in the United States. Some of these, however, might be considered to be of paleobotanical origin.

Legget (National Research Council, Canada, 1961b) has estimated the areal extent of muskeg in Canada at almost 500,000 square miles. North American workers have described individual but extensive areas. Beyond these local statements, there appears to be no overall discussion of the total extent of muskeg in North America. Radforth (1960), attempting to fill this void, has produced a somewhat oversimplified map for the Defence Research Board.

Sjors (1959) has described the largest single areal expanse of muskeg in Canada, the Hudson Bay lowland, in some detail. Ritchie (1957) has examined and described the bogs of northern Manitoba, and Allington (1959) has treated, though more exclusively, some bogs of Ungava. There are also some descriptions of the muskeg in Alberta and the Northwest Territories by Keeling (1961). Potzger and Courtemanche (1956) have recorded observations on the bogs of the St. Lawrence Valley to James Bay. There is thus a reasonable amount of material which could be compiled.

The only general description of the areal distribution of peat bogs for all North America appears to be in the Soviet literature (Kats, 1959, 1960). Kats (1959) has reviewed some, though certainly not all, of the North American papers and mentions that "... the author's acquaintance with bogs in many parts of the U.S.S.R. and the great similarity in the general distribution of bogs in the U.S.A. and Eurasia have made it possible to unify the often sketchy descriptions for North America." From these descriptions, Kats (1959) has published a map for North America. This map shows little detail for Canada, far less than Radforth's. However, Kats' description of the distribution of bogs of the continent is pertinent. Certain relevant extracts are therefore included.

> "In the northern continent surface swamps are widespread in the permafrost region, and an organogenic layer, generally not exceeding 30 cm thick, covers large areas. Peats are scarce here. In southeast Canada and the adjacent part of the U.S.A., the climate is conducive to peat formations. There are large accumulations of peat in the plains area — in the St. Lawrence lowland and in the region of former lakes of the late glacial period (Algonquin, Agassiz), of which the Great Lakes are relics. In the central U.S.A., in the prairie and arid areas, the droughty climate hinders peat formation. For this reason and also because of the mountain ranges, the peat formation belt in America is not continuous, as it is in Europe and Western Siberia but is interrupted in the center of the Continent. In Eastern Canada, owing to the cooling influence of the Polar Sea which dips deep into the Continent, this belt — and the tundra with it — sweeps further south than anywhere else in the world. On the west coast, on the other hand, melt water of peats stretches north beyond the polar circle.

> "On the coastal plains of the Atlantic and Mexican Gulf large bogs and peats descend into the subtropical latitudes. This is explained by the relief of the plains and the high level of soil waters in this arid zone and also by the abundant precipitations wind-borne from the Mexican Gulf. Large peats also stretch far to the south along the alluvia of the Mississippi. Their formation was due to river flooding. In general, the large expanses of tundra, steppe, desert and mountain ranges considerably reduce a percentage of the peat areas in North America as compared with Europe and Western Siberia. A rough estimate would put the peat areas in the U.S.A. (excluding Alaska) at 0.4% to 0.5% of the whole territory; in Canada (not including unexplored provinces) at 1.0% to 1.2% and in North America as a whole at 0.7% to 0.8%. Europe's peat areas are about 5.5%."

Flora of Bogs

Radforth (1954) has shown that plant material is a fundamental factor in the classification of organic terrain. He identifies and lists the flora to be found, mainly from the Churchill area.

Sjors (1959) in his paper on the "Bogs and Fens of the Hudson Bay Lowlands" also describes in some detail the flora of this much larger area. Other papers by Potzger (1953a, b), Porsild (1958), Osvald (1949), Ritchie (1957), and Sjors (1950) have described bog and fen flora in various areas of North America, Ireland, Great Britain, and Fenno-Scandia. However, Kats (1959) has again summarized the bog flora of North America succinctly and makes comparisons with Eurasia:

"The dendroflora of North America does not have species in common with Europe. There are, however, a number of species among the shrubs, and particularly among the stunted woody plants (shrubs), growing in the bogs of North America, which are encountered in Europe. The flora of the bog mosses, especially sphagnums, is also similar to that found in Europe. It is only in the southeast of the Continent that the number of sphagnum types not found in Europe increases. The northern bogs, particularly the oligotrophic sphagnums, most closely resemble the raised bogs of Europe insofar as their species are concerned — except for trees. As for the sphagnums, their species are the same as in Europe. Further south forest bogs with broad-leafed trees and with swamp cypresses have not only species, but many genera and even certain families which are foreign to Europe. Some components of these bogs have related species and genera which have completely died out in Europe, but which are encountered here in Tertiary deposits. The ancient character of the flora of such bogs is a heritage of the distant past. In Europe and Siberia these features were obliterated as a result of the invasion of the boreal flora with the cooling of the climate at the end of the Tertiary."

It is of interest to note that Sjors (1959) in comparing the paludification of the Hudson Bay region with Europe mentions the part played by beaver dams. He notes that beavers, once common and now nearly extinct in Europe, must have played a role in the development of riparian basins and the associated flora there as they are now doing in North America.

Muskeg Research

Today there is no scarcity of interest in muskeg from both the scientific or engineering point of view, although much of the research is carried out in highly specialized fields. In Canada and Ireland, coordination of the many diverse interests and research programs has been achieved. In the U.S.S.R. the study and development of peat resources is a well developed science, for basic economic reasons.

A brief review of muskeg research in individual countries follows. Trends and developments of research in Canada will receive the greater attention since these are applicable for the most part to North America.

Canada

Muskeg research in Canada prior to 1946 was confined largely to botanical studies on peat or its implications for agriculture or forestry. In 1945 the National Research Council, as a result of an urgent wartime problem involving soil and snow, formed the Associate Committee on Soil and Snow Mechanics (ACSSM), to develop, encourage, and coordinate research in Canada in the fields of earth materials. Such coordination is carried out by four subcommittees, Soils, Snow and Ice, Permafrost, and Muskeg. The latter subcommittee (under the chairmanship of Dr. N. W. Radforth of McMaster University) has sponsored muskeg research during the past ten years.

The Muskeg Subcommittee is concerned with the study of fundamental physical, chemical, and mechanical properties of muskeg with reference to practical engineering problems. The subcommittee gathers necessary information on the state of knowledge

in the field, particularly on research work in progress in Canada, and advises the
Council, through the parent committee, on the collection and dissemination of research
information. The subcommittee also attempts to stimulate research work in its as-
signed field and serves as a liaison between the National Research Council and govern-
ment, educational, and other organisations or agencies engaged in or concerned with
research on muskeg.

A major function of the subcommittee has been to organise research meetings. To
date seven conferences have been held (see Appendix A) and the proceedings (National
Research Council, Canada, 1955, 1956, 1957, 1958, 1959, 1961a, 1961b) are a major
source of information for the development of muskeg research in Canada. Representa-
tives of many agencies and companies have attended and participated in these conferences.

A descriptive muskeg system (Radforth, 1952), for terrain identification for access
and other diversified needs, formed the basis for much of the work which was to follow.
The very serious economic implications of muskeg for military installations, mobility,
and petroleum exploration fostered the utilisation of the Radforth muskeg classification
far more rapidly than could have been expected. Unfortunately, engineering properties
have not been sufficiently related to the Radforth classification.

The National Research Council for Scientific and Industrial Research fosters both
intramural research through divisions and associated laboratories and extramural re-
search by grants to universities. The Division of Building Research, as its name would
imply, conducts research into all aspects of construction. This necessarily includes
all soils.

The objective of the muskeg research project at the Division of Building Research
is simply "To determine the physical and mechanical properties of muskeg" (NRC,
Canada, 1958). Active work began in 1954 and shortly after "A Preliminary Annotated
Bibliography on Muskeg" was prepared (MacFarlane, 1955). Exploratory, laboratory,
and field studies on the engineering properties of muskeg have been continued (MacFar-
lane, 1955, 1959a, 1959b, 1961a, 1961b, 1961c). For administrative and technical
continuity, the Secretary of the Subcommittee on Muskeg is appointed from the muskeg
research personnel of the Division of Building Research.

Research on organic terrain at McMaster University, begun in 1947, has been
carried out by or under the direct supervision of Dr. N. W. Radforth, a paleobotanist.
Research has included visits to European areas in addition to field work in Canada.
Notable results of the work have been a classification system of muskeg (Radforth,
1952) and two manuals on the interpretation of organic terrain from the air (Radforth,
1955b, 1958a). Muskeg research is still continuing at McMaster University, primarily
in fields associated with terrain access although work in fundamental muskeg properties
is also actively under way (Radforth and Ashdown, 1961; Eyot, Stewart and Radforth,
1961).

Oil companies. The petroleum industry's interest in muskeg is recent (about 1957)
and concerned with access to muskeg areas. Imperial Oil Limited and Shell Oil Company
of Canada Limited, have been engaged on terrain interpretation and the mechanical
properties of muskeg for both route selection and vehicle design. Both companies have
developed muskeg vehicles which are radical in concept (Stoneman, 1959, 1961b; Nuttall
and Thomson, 1960).

Highways. All ten provinces in Canada (with the exception of Prince Edward Island)
are concerned with muskeg and its implications for road construction. In British
Columbia, Alberta, Saskatchewan, and Ontario, research projects on specific muskeg
problems have been sponsored (e.g. Brawner, 1958, 1959, 1961; Hardy and Thomson,
1956; Mickleborough, 1961; Rutka, 1960; Savage, 1961; Walsh, 1961). These projects
have helped to form the broad policies for road construction in the specific regions.

U.S.S.R.

Peat in the U.S.S.R. is an economic asset and is mainly exploited in the Belorussian
Republic. The Ministry of Power of the Soviet Union currently uses, for electric power
stations, approximately 50% of all the peat produced for fuel, and about 6% of Soviet

electric power is produced from this material. There is therefore a sound economic base for a peat research program.

To elucidate all the administrative aspects of research in any industry or discipline in the U.S.S.R. is always difficult and this is not less so in the case of peat research, but there appear to be four main organizations involved in research. These are:

1. The Ministry of Power Stations
2. The Ministry of Agriculture
3. The Ministry of Higher Education
4. Moscow University

The Ministry of Power Stations operates the following major research establishments:

(a) The T.O.S. Experimental Station near Kalinin. This organization's chief interest is in the extraction of peat.

(b) The Dehydration Plant at Boksitogorsk.

(c) The Soviet Central Research Organisation for peat at the Leningrad Institute in Leningrad.

The Ministry of Agriculture operates a "Peat and Bog Research" Laboratory near Moscow. This laboratory's main interest is in the geology of peat and its use for agricultural purposes. There are probably other smaller affiliated stations similar to this in the U.S.S.R.

The Ministry of Higher Education, through the Moscow Peat Institute, undertakes the training of individuals for the extraction of peat and carries out research in this direction, including graduate research work. The Moscow Peat Institute has over 7000 day students and graduates over 250 students per year.

The Faculty of Chemistry at Moscow University is currently undertaking (1960) a research program on the chemistry of peat and its application for industrial uses, such as the addition of peat to plaster of paris, the colloidal properties of peat, and interestingly enough the extraction of bitumins, waxes, resins, and sugars.

Europe

Finland. Some ten million acres of peat in Finland are now being exploited for both agriculture and fuel purposes. Peat research is carried out by the Department of Agricultural Chemistry at the University of Helsinki and at the State Peat and Oil Institute, also in Helsinki. The Institute is working on the development of peat coke for metallurgical purposes and the production of waxes and resins.

Sweden. In Sweden research is also directed towards the use of peat as a fuel, and under the Swedish Peat Association there is a well developed peat research laboratory at Lund, near Upsala.

Norway. The Norwegian Bog Association maintains some research activity in the problems of bog utilization for agricultural purposes.

Ireland. The Republic of Ireland, like the Belorussian Republic of the U.S.S.R., has large expanses of peat and a lack of other types of fuels. For this reason it maintains a thriving extraction industry and a large amount of peat is used for the operation of thermal power stations and for domestic uses. The lack of hydrocarbon fuels (other than peat) has led to a planned development of peat resources over the years by the "Peat Development Board." The Board was set up in 1946 by an act of the Irish Parliament and is now better known as "Bord na Mona."

The board undertakes the production of peat fuel for certain thermal power stations and conducts research into the thermal properties of peat and the origin and nature of Irish bogs. The board employs over 7000 workers and maintains a research station with an extensive library.

The Research Station, at Droichead Nua, County Kildare, maintains close contact with other peat-producing countries.

Great Britain. In Great Britain, as in Ireland, much of the research in peat is directed towards the problems of developing peat as a fuel. However, both the Ministry of Agriculture and the Ministry of Scientific and Industrial Research have focused a certain amount of attention on the problems of land utilization and road building. The Road Research Laboratories at Harmsworth, near London, are undertaking an intensive program for the construction of roads over peat.

In Scotland, where peat is very much more widespread, the Secretary of State for Scotland formed in 1949 the "Scottish Peat Committee." The aims of this committee were:

1. To conduct a survey of Scottish peat deposits,

2. To conduct research into the use of closed-and open-cycle gas turbines,

3. To investigate the economic methods of extracting peat.

The committee is still in being and research is being conducted at a number of centers.

The utilization of bogs for land use is also receiving much research attention; here, the McCauley Institute for Soils Research at Aberdeen is foremost.

The universities in Glasgow and Cambridge also undertake peat research, mainly in the botanical and palynological fields.

Other North European countries. Research is also carried out in Holland, West Germany, and France. The following organizations are involved:

1. Holland — Algemeene Norit Maatschappij, Amsterdam. This commercial company produces activated carbons for water purification and sugar clarification. It undertakes certain related research in these fields.

2. West Germany — Heseper Torfwerk G. Mb. h. This company in West Germany at Meppin on Ems in Westphalia produces peat for fuel and agricultural purposes. There appears to be little or no research undertaken.

3. France — Société des Produits Chemiquis et D'énergies d'Auby. This company is conducting research into the production of ammonia from peats and certain types of sugars.

The above review indicates that in most North European countries research is mainly aimed at peat as a fuel resource. In the European U. S. S. R. , where the largest peat research program is taking place, natural gas will probably displace peat as a fuel during the next few years. Research emphasis in this field therefore may well shift to the study of agricultural, chemical, and engineering uses of peat.

Japan

The northern islands of Japan, Hokkaido in particular, are climatically much like Scotland, and peat or muskeg constitutes a most difficult terrain for road building. The Civil Engineering Research Institute of the Hokkaido Development Bureau has undertaken considerable research into the construction of roads over peat.

Agricultural research is also being undertaken by the Hokkaido Agricultural Laboratory. Among others, the Japanese Society of Soil Mechanics and Foundation Engineering also sponsors small research programs.

United States of America

Minnesota has the largest known peat deposits in the United States. These contain some 10 billion tons of peat. This state, through the Iron Range Resources and Rehabilitation Committee and with the assistance of the University of Minnesota, conducts an intensive research program into the possibility of utilizing these resources.

Elsewhere in the United States diverse research programs directed mainly to engineering problems are being carried out by the U. S. Army Cold Regions Research and

Engineering Laboratory and Engineer Research and Development Laboratory, the Highway Research Board, the New York State Department of Highways, the Michigan State Department of Highways and the U. S. Geological Survey.

II. CLASSIFICATION OF PEAT

There are many classifications of peat and peat bogs. Dachnowski (1920) has reviewed the philosophy of various systems of classification of peat based on

1. Surface vegetation,
2. Topographic features,
3. Chemical analysis, and
4. Stratigraphic systems.

Early workers, translating from German, summarized the general changes in peat profile insofar as they are reflected in the present vegetation of deeper bogs as "low moor," "transition moor," and "high moor" (present day terminology is eutrophic, mesotrophic, and oligotrophic, respectively).

More recently, Fraser (1954) has proposed a classification system that differentiates (a) the climatic or zonal distribution of peat and (b) azonal, or interzonal peat developed under the influence of local features and not climate. Four groups of climatic or zonal bogs are recognized:

1. Bogs of cool temperate regions formed under maritime rainfall at lower elevations,
2. Peat bogs of hill and montane masses developed under high rainfall and low temperature,
3. Subarctic climatic bogs of tundra regions,
4. Arctic alpine bogs — climatic bogs of some alpine plateaus.

Two major subdivisions of interzonal bogs are recognized:

1. Peat developing in or on free water (lakes or pools of some depth),
2. Peat developing on water-logged or intermittently flooded mineral soil and vegetation.

From a material or stratigraphic point of view, Dachnowski-Stokes (1941) is concerned with the sequence of materials to show how plant organisms in toto contributed to the bulk in peat constitution. Thus the peat type — pulpy, fibrous, or woody — is further subdivided as to the contributing plant source and the texture of the peat.

Farnham (1957) proposes a similar but more simplified classification system for peat soils in Minnesota. Highly decomposed peats with unidentifiable plant remains are subdivided into

1. Aggregated peat (muck) — fine particles of well decomposed peat with granular structure, and
2. Amorphous peat — highly decomposed, sticky, organic material lacking structure, often mixed with mineral silts and clays.

Partly decomposed peats with readily identified plant remains are also subdivided into

1. Moss peat — remains from mosses,
2. Herbaceous peat — remains from sedges, reeds, grasses, and other perennial herb plants,
3. Aquatic peat — remains from water plants, and
4. Woody peat — remains from trees and shrubs.

In many engineering studies, peat is not classified or even described in detail. Colley (1950) differentiates between peat and muck on the basis of organic material content. Hanrahan (1952, 1954a, 1954b) only refers to peat as "fibrous" or "humified"; and Smith (1950) classified British (muskeg) areas according to "fen" peat, raised bog, and blanket bog.

Radforth Muskeg Classification System

A first approach to the classification of muskeg for engineering purposes was made by Dr. N. W. Radforth of McMaster University under the sponsorship of the National Research Council and the Defence Research Board of the Department of National Defence (Radforth, 1952). The Radforth classification system is recognised now in Canada as the basis for field description of muskeg (MacFarlane, 1958).

In the Radforth system the term "organic terrain" is used to describe what is commonly called "muskeg." The surface of this terrain is composed of a living organic mat of mosses, sedges, and/or grasses, with or without shrubs and tree growth. Under-neath the surface there is a mixture of partially decomposed and disintegrated organic material, commonly known as "peat" or "muck." Accordingly, the descriptive system of muskeg attempts to record surface vegetation, topographic features, and subsurface characteristics.

Surface vegetation

The many possible natural combinations of plant species and associations appear at first glance to defy organisation. Nonetheless, classes of vegetation and their limits can be defined. In the Radforth classification system the description of the surface vege-tation is based on qualities of vegetation such as stature, degree of woodiness, external texture, and certain easily recognised growth habits. Nine pure vegetation classes are recognized (Table I). A particular location may be described by the use of two or three letters designating pure classes. If one coverage class is not present to the extent of 25% of the terrain, it is not included in the composite cover description. The most prominent class type is placed first and others follow in order of prominence. Although a multitude of letter combinations are possible, only 18 combinations are common in Canada.

Topographic features

Terrain relief is also important in the appraisal of organic terrain. Changes in topography are sometimes caused by irregularities in the mineral substrata, but much of the unevenness of the surface is due to structural changes within the organic material itself. Table II gives the descriptive information for identifying topographic features of organic terrain. Several of these features are not necessarily peculiar to muskeg areas, but do occur and therefore are normally described.

Subsurface characteristics

After examining samples from various sites, Radforth established 16 categories of peat (Table III) based on the extent to which wood and fibers are present. Organic ma-terial is roughly grouped into 3 basic types:

    1. Material composed chiefly of soils of an amorphous-granular base.
    2. Material chiefly made up of fine fibers. These fibers may be woody or non-woody.
    3. Material predominantly of wood particles and coarse fibers. The coarse fibers are always woody.

Table I. Summary of properties designating nine pure coverage classes.
(Radforth classification).

Coverage type (class)	Woodiness vs non-woodiness	Stature (approx. height)	Texture (where req'd)	Growth habit	Example
A	Woody	15 ft or over	-	Tree form	Spruce Larch
B	Woody	5 to 15 ft	-	Young or dwarfed tree or bush	Spruce Larch Willow Birch
C	Non-woody	2 to 5 ft	-	Tall, grass-like	Grasses
D	Woody	2 to 5 ft	-	Tall shrub or very dwarfed tree	Willow Birch Labrador tea
E	Woody	up to 2 ft	-	Low shrub	Blueberry Laurel
F	Non-woody	up to 2 ft	-	Mats, clumps or patches, sometimes touching	Sedges Grasses
G	Non-woody	up to 2 ft	-	Singly or in loose association	Orchid Pitcher plant
H	Non-woody	up to 4 in.	Leathery to crisp	Mostly continuous mats	Lichens
I	Non-woody	up to 4 in.	Soft or velvety	Often continuous mats, sometimes in hummocks	Mosses

Table II. Topographic features. (Radforth classification).

Contour type	Feature	Description
a	Hummock	Includes "tussock" and "nigger-head." Has tufted top, usually vertical sides. Occurs in patches, several to numerous.
b	Mound	Rounded top. Often elliptic or crescent-shaped in plan view.
c	Ridge	Similar to Mound but extended. Often irregular and numerous. Vegetation often coarser on one side.
d	Rock gravel plain	Extensive exposed areas.
e	Gravel bar	Eskers and old beaches (elevated).
f	Rock enclosure	Grouped boulders overgrown with organic deposit.
g	Exposed boulder	Visible boulder interrupting organic deposit.
h	Hidden boulder	Single boulder overgrown with organic deposit.
i	Peat plateau (even)	Usually extensive and involving sudden elevation.
j	Peat plateau (irregular)	Often wooded, localized and much contorted.
k	Closed pond	Filled with organic debris, often with living coverage.
l	Open pond	Water rises above organic debris.
m	Pond or lake margin	(Abrupt).
n	Pond or lake margin	(Sloped).
o	Free polygon	Forms a rimmed depression.
p	Joined polygon	Formed by a system of banked clefts in the organic deposit.

Applications

The application of the Radforth muskeg classification system, particularly in solving the problems of route access for the petroleum industry in northern Alberta, has led to some modification or simplification. Hughes (1960) suggests a broad or first approximation of organic terrain by areal mapping units such as

O   - organic terrain
Os - shallow - less than 5 ft deep
Od - deep - over 5 ft deep

and suggests other observations on the species of trees.

Hemstock (1959) suggests a simplification of topographic features into

1. Muskeg hummocks, mounds, and ridges;
2. Rocky features;
3. Peat plateaus and permafrost polygons, and
4. Lakes and ponds.

Stoneman (1961a) has also greatly simplified muskeg description for his purpose (a vehicle testing program) as follows:

Type 1 muskeg is recognized as a black spruce or tamarack swamp. The live timber varies from 5 to 15 ft high, is small in diameter, and occurs in dense stands. The brush undergrowth is light and often nonexistent. The surface mat of the muskeg is composed of a thick layer of moss interwoven with the boughs of fallen timber. Quite often the surface mat of the muskeg is uneven. In general, type 1 muskeg is relatively shallow.

Type 2 muskeg is recognized as a willow bog. The live woody growth consists of a dense willow bush up to 10 ft high. The surface mat is usually a tight interwoven thick grass cover. This type of muskeg is usually accompanied by considerable standing dead timber and deadfall loosely imbedded in the surface mat. Willow bog usually borders intermittent streams and in many cases covers large areas along the axis of the stream and is often several hundred yards wide. Type 2 generally is of medium depth, ranging from 3 to 6 ft.

Type 3 muskeg is recognized as brown moss and is the most common muskeg type. The live timber consists of a scattered and stunted spruce growth as well as a low shrub cover. The surface mat is a thick tough moss layer occurring in mounds and hummocks. The uncleared moss is a purple-gray color when wet, but when cleared and dry it takes on a readily recognized brown tone. Type 3 is also characterized by small-diameter standing dead timber up to 15 ft high as well as by considerable small-diameter deadfall. Type 3 often occurs adjacent to type 2 with overlapping of classifications at the boundary. Type 3 muskeg is found in large areas with no recognizable pattern of occurrence. The depth of brown moss is also inconsistent, varying from a few inches to many feet.

Type 4 muskeg is recognized as a floating bog. This type is the most severe muskeg class for a vehicle and approaches a swamp condition. There is generally no timber or woody vegetation present. The surface cover consists of tall sedge-grasses and moss occurring in clumps or mounds, with the water table at or near the surface. Type 4 muskeg is usually found within type 3 muskeg areas, where it occurs as a pocket a few hundred feet in diameter and several feet deep.

III.   TERRAIN ANALYSES

The assessment of organic terrain involves a correlation of observed terrain features and an inference of terrain behavior under specified requirements. Most terrain analyses for engineering purposes in Canada are based on the Radforth muskeg classification system and utilize aerial photographs. Organic terrain analyses have been used largely for access or exploration, trafficability studies, and site selection, but their use for road route selection has been recorded.

For field or airphoto studies of organic terrain, Mollard (1961) suggests three important factors for interpretation:

1. Surface vegetative cover,
2. Topographic position and its relation to internal and surface drainage, and
3. Surficial deposits — specifically the geomorphological units or landforms — their origin, inferred history, and probable composition.

For the interpretation of surface vegetative cover, the Radforth muskeg classification system has been utilized directly for ground-level or low-altitude observations (e.g. Mollard, 1961; Radforth, 1955b).

For higher altitude observations (1000 to 5000 ft) either direct or from air photographs, many of the Radforth muskeg classification indicators are not visible but must be inferred. To aid in description and inferences, Radforth (1958a) has proposed six broad "air forms" or patterns:

1. Planoid, an expanse lacking textural features; plane
2. Apiculoid, fine-textured expanse; bearing projections
3. Vermiculoid, striated mostly coarse-textured expanse; featured markings tortuous
4. Cumuloid, coarse-textured expanse with lobed or finger-like islands prominent; components like cumulus clouds
5. Polygoid, coarse-textured expanse cut by intersecting lines; bearing polygons
6. Intrusoid, coarse-textured expanse caused by frequent interruptions of unrelated, widely separated mostly angular islands; interrupted.

For high altitude observations (30,000 ft), Radforth (1961b) recently suggested air form descriptions that are more closely allied with physiographic conditions. To avoid misunderstanding by misuse of geomorphological nomenclature, Radforth proposes that the observations relate to shape, size, and distribution of the physiographic entities but not to their academic definition or genesis. Thus the significant mineral terrain features are in the first analysis either "axial" or "areal." In an axial mineral terrain (soil or rock) conformation, the foundation to the organic terrain may be a single diagnostic feature such as a straight, curved, sinuous angular, sinuous smooth, reflexed, or discontinuous unit. For a compound axial unit, the feature may be barred complex, concentric curves, or paired sinuous. In an areal mineral terrain conformation, Radforth suggests that the diagnostic unit may be featureless, pitted, with clefts, with shallow depressions, with folds, or contorted.

In contrast to Radforth's "geometric" landform units, Mollard (1961) suggests that muskeg interpretation is a facet of established airphoto interpretation principles. Thus the airphoto interpreter should be able to competently identify, classify, and delineate not only muskeg patterns but also landforms. If landforms, possessing varying construction qualities, cannot be reliably recognized and delineated, Mollard's opinion is that the role of airphoto interpretation is only a fraction of what it should be.

Any inferences on the potential significance of various types of organic terrain will depend largely on the experience of the interpreter (Mollard, 1961). Radforth (1955b, 1958a, 1960) has correlated organic terrain types with various access properties such as:

1. Ground ice conditions
2. Subsurface organic material
3. Trafficability and vehicle design.

Radforth has suggested an "access rating." Thus for access in a muskeg region, as elsewhere, it is important to know how far a route must deviate from a straight line to reach a location. Tree-covered organic terrain impedes access, as do hummocking, knolling, hidden boulders, highly irregular subsurface ice contours, imponding, and peats of low shear strength and high saturation. Therefore, it is suggested that the interpretation should include relative information on what may be called a "deviation" or

"access rating." It is expressed numerically, 10 being the maximum for conditions where penetration, for a variety of reasons, is practically impossible and zero (0) being the minimum, designating conditions where a straight line route for the entire distance is feasible.

It is also often important to know the extent to which single terrain features will impede vehicle progress. Thus, estimates of tree density are frequently valuable. Here a vegetation hindrance rating is given, with 10 as the maximum, indicating impenetrability. Similarly subsurface ice can be estimated, with a 10 rating representing the highest amplitude of ice contour. Other factors that can be expressed relatively on a numerical basis are terrain roughness, peat depth, and terrain bearing strength.

Certain remaining factors can be expressed in other ways, often in absolute rather than relative terms. The type of mineral sublayer is sometimes definable. Presence or absence of aggregate and its nature are also assessable. For those interested in drainage, advice can be offered on whether ditching will (a) improve or worsen drainage, (b) control thaw, and (c) weaken organic mat structure.

IV.. ENGINEERING PROPERTIES OF PEAT

The investigation of the engineering characteristics of peat has scarcely begun (MacFarlane, 1959b). Most of the research so far has been concerned with botanical or chemical characteristics of organic material. In most cases correlation of results is almost impossible, for the authors have used their own descriptive systems for the terrain and the material under test.

Even though many gaps and confusing and contradictory views exist in the published information on the engineering properties of peat, literature on the subject is available (e.g., MacFarlane, 1959b). The empirical data can be broadly subdivided into:

1. Index properties, which serve principally to identify various types of peat,
2. Strength and deformation properties,
3. Thermal properties, and
4. Geophysical properties.

Index Properties

In botanical or related studies, quantitative values of physical and chemical properties such as ash content, acidity reaction, and some measure of water content are frequently given. In engineering studies the vegetative cover is usually described by the Radforth muskeg classification system, and measured properties of peat are generally confined to water content and unit weights.

Organic content is the percentage of the total dry weight of a peat sample lost through ignition. In many investigations the proportion of organic material is expressed as percent ash or the percentage of the total weight of ash or mineral residue remaining after a dry peat sample has been ignited.

The proportion of organic material in peat varies with locality and with the types of samples tested. Peat mainly free of mineral matter has up to 95% organic content and every gradation down to a pure mineral soil can be found. Some published ash contents are shown in Table IV.

The measure of soil acidity is pH, defined as the negative logarithm of the hydrogen ion concentration in an aqueous suspension of the soil.

Usually peat has an acid reaction owing to the presence of carbon dioxide and humic acid arising from its decay. Humic acid is probably a mixture of acids of high molecular weight and relatively low solubility in water (Lea, 1936, 1956). Some of the simpler organic acids (such as acetic acids) may also be produced in small quantities. A saturated solution of humic acid in water has a pH of from 3.6 to 4.1, between that of carbonic and acetic acids. Because of its low solubility, about 0.9 g/liter, the quantity of free acid which can be carried in the water is small.

Table IV. Summary of observed ash contents.

Source	Ash content (%)	Remarks
Adams (1961)	12.2 to 22.5	
Anderson and Hemstock (1959)	10 to 25	
Colley (1950)	17	
Farnham (1957)	4.5 to 66.6	Moss peat Amorphous peat
Feustal and Byers (1930)	8.81	Anhydrous peat
Lin and White (1958)	10	
Passer (1958)	11.25	
Risi, et al. (1950-55)	2.5 to 11.34	
Shea (1955)	less than 10	
Smith (1950)	2	Cotton gross peat
	20.1	Grass moor peat (contaminated with mineral soil)
Smith (1958)	0.5 to 3.0	

Peaty waters, which are practically free from salts, show pH values between 4 and 7 (Lea, 1956). Occasional lower values of pH are due to the presence of small amounts of free mineral acids, mainly sulphuric. According to Lea (1936, 1956), acidity of peat waters fluctuates with the seasons and weather conditions and is usually highest after a heavy rain following a warm dry period.

Farnham (1957) reports pH values of 3.8 for moss peat to 7.5 for aquatic peat. Feustal and Byers (1930) observed pH values from 3.1 for heath peat to 7.1 for saw grass peat. Risi, et al. (1950-55) gives values ranging from 4.8 to 5.6 and notes a general decrease in acidity with depth. MacFarlane (1961c) reports pH values ranging from 5.0 to 7.2 for peats underlying muskegs in northern Manitoba and Quebec.

Radforth (MacFarlane, 1961a) states that in many large areas of the Canadian north, for example in the vicinity of Churchill, Manitoba, the peaty member of muskeg is alkaline rather than acidic in reaction. Because of flooding conditions (spring freshet), which occur in some of the muskegs at least once a year, dissolved materials are brought up into the organic material from the mineral soil below, thereby charging the peat with agents which are frequently alkaline in reaction. Where plateaus of peat occur, the top portion is often acidic (pH 5 to 7) while the bottom is alkaline (pH 8 to 8.5). Where the terrain is flat and poorly drained, all the peaty material is frequently alkaline (pH 8). Where the terrain is uneven and drainage is better, the reaction may be predominantly acidic (pH 4 to 7).

In published literature unit weight, mass specific gravity, volume weight, bulk density, and wet density are all terms used to describe the weight of a material (including soil particles and any contained water) per unit volume, including voids. Dry unit weight or dry density is the weight of dry material (dried to a constant weight at 105C) in a unit volume of the original material.

The unit weight of peat depends upon the moisture conditions of the sample and can range from 0.4 to 2.2 g/cm³. The dry unit weight or dry density of peat is therefore only a fraction of the wet density or unit weight; observations suggest that it is in the range of 0.04 to 0.34 g/cm³ (See Table V).

The specific gravity (absolute specific gravity, oven dried; specific gravity of soil solids) is the ratio of the density of the soil solids to that of water. The eight references in Table VI show a range in specific gravity from 1.1 to 2.45. Values over 2.0 indicate a considerable degree of mineral contamination.

Table V.   Summary of peat unit weights.

Source	Natural (g/cm³)	Dried (g/cm³)	Remarks
	Unit weight		
Colley (1950)	0.95		Wet peat
	0.20		Dry peat
Farnham (1957)	0.4		Moss peat
	0.6		Woody peat
	0.7		Herbaceous peat
	0.9		Aquatic peat
	1.1		Aggregate peat
	2.2		Amorphous peat
Feustal and Byers (1930)	0.41-1.16		
Hanrahan (1954a)	0.94-1.02		Wet peat
	0.06-0.13		Dry peat
Lewis (1956)	1.1		
MacFarlane (1961a)	1.0	0.08-0.25	Peat in Japan
Mickleborough (1961)	0.96-1.28	0.04-0.34	
Shea (1955)		0.08-0.16	
Smith (1950)		0.08-0.31	Higher values with mineral soil
Thompson and Palmer (1952)	0.95-1.13		Wet peat
	0.23-0.33		Dry peat

Table VI.   Summary of some peat specific gravity observations.

Source	Specific gravity	Remarks
Adams (1961)	1.62-1.70	
Cook (1956)	1.85-2.45	Higher values with mineral material
Feustal and Byers (1930)	1.105-2.161	Range of values
	1.510	Sphagnum peat
	1.405	Heath peat
	1.637	Everglades peat
	1.505	Sedge peat
Hanrahan (1954a)	1.1-1.8	
Hardy and Thomson (1956)	1.4	
Mickleborough (1961)	1.6-1.8	
Thompson and Palmer (1952)	1.795-2.036	
Ward (1948)	1.2-1.5	

Table VII. Summary of some peat water contents.

Source	Moisture content (%)	Remarks
Adams (1961)	375-430	
Anderson and Hemstock (1959)	650-1350	
Brawner (1958)	200-300	Edge of deposit
	800-1400	Remainder of deposit
Feustal and Byers (1930)	3235	Highest value
Hardy and Thomson (1956)	470-760	
Hanrahan (1954a)	700-1400	
Lake (1961)	1850	
MacFarlane (1961a)	700-1200	
Mickleborough (1961)	480	Maximum
Ripley and Leonoff (1961)	1000	Average
	100-2100	Range

The water or moisture content is the loss in weight when the material is dried to a constant weight at 105C and is expressed as a percentage of the dry material. Peat has a great ability to soak up water which is one of the most important characteristics of this material. The quantity of water held in peat varies considerably, being less in the more decomposed types than with more fibrous peats. The water content also varies with season and the corresponding position of the ground water table.

Table VII records some peat water contents. The most common water contents range from 600% to 1400%, but extremes of 100% (Ripley and Leonoff, 1961) and 3235% (Feustal and Byers, 1930) have been noted.

The void ratio is the ratio of the volume of the voids to the volume of the soil solids. For a fully saturated soil, void ratio is equal to the product of the water content and the specific gravity of soil solids, divided by 100.

Fibrous peats have very high void ratios and amorphous peats low void ratios. Void ratios noted range from 3 to 25, although a range from approximately 5 to 15 is most common (Table VIII).

Shrinkage: As peat dries out, it will shrink and become harder and more firm. Under drought conditions or because of drainage, the surface area of a muskeg may develop wide shrinkage cracks.

Colley (1950) reports shrinkage of samples from 10% to 50% of the original volume. Hanrahan (1952) attempted the correlation of shrinkage with various properties of peat (such as degree of humification, compressibility, and dry density) but found it difficult.

Permeability may be defined as the property of a substance which permits the passage of fluids through the pores of the material.

Colley (1950) measured the permeability of undisturbed peat samples using both the variable and the constant head permeameter. He found the average value of permeability in the vertical direction to be 1.06×10^{-3} to 4.6×10^{-3} cm/sec.

MacFarlane (1961a), reporting on organic terrain research in Japan, states:

"Permeability varies widely depending upon the amount of mineral matter in the soil, the degree of consolidation, and other factors. In the Kushiro District, the permeability co-efficients of peat are 2 to 13×10^{-3} cm/sec. in the horizontal direction and 2 to 7×10^{-3} cm/sec. in the vertical direction, and an anisotropy ratio of approximately 2. In the Ishikari

District, the permeability co-efficient of peat is 6 to 50 x 10^{-5} cm/sec.
in the horizontal direction and 2 to 7 x 10^{-5} cm/sec. in the vertical
direction with an anisotropy ratio of 3 to 6. The comparative imperme-
ability of a peat layer consisting of more than 80% water by volume is
a paradox, but possibly can be attributed to the effect of the colloidal
properties of the decomposed organic material."

Hanrahan (1954a) carried out a falling head permeability test in a consolidation
cell. He noted that permeability is affected considerably by the magnitude and duration
of loading. One sample of partly humified peat with a natural void ratio of 12 had a
permeability of 4 x 10^{-4} cm/sec. After 2 days under a load of 0.56 kg/cm^2, the void
ratio was reduced to 6.75 and the permeability to 2 x 10^{-6} cm/sec. After 7 months
under the 0.56 kg/cm^2 load, the void ratio was reduced to 4.50 and the permeability to
8 x 10^{-9} cm/sec — or 1/50,000th of the initial permeability. In a similar series of
observations, Adams (1961) noted a reduction in permeability from 5.1 x 10^{-2} to
0.51 x 10^{-6} cm/sec under load in increments up to 2.89 kg/cm^2.

Strength and Deformation Properties

Many engineering problems in muskeg are solved by avoiding this troublesome
type of terrain. In some instances this is not possible, however; access or construc-
tion in muskeg requires some assessment of the strength and deformation character-
istics of the peat. In most engineering evaluations, the principal requirements can be
subdivided into

1. Shear strength of peat,
2. Bearing capacity, and
3. Settlement characteristics.

Published observations are scanty and at times contradictory, but modified soil me-
chanics methods can be utilized. The scarcity of published observations and the lack
of a consistent system for correlating various results severely restrict this summary
to a record of individual experiences.

Table VIII.   Summary of peat void ratios.

Source	Void ratio	Remarks
Adams (1961)	3.4	Remolded sample
Colley (1950)	4.6-10.3	
Cook (1956)	2.84-13.08	
Hanrahan (1954a)	9-25	
Mickleborough (1961)	3.21-9.86	
Thompson and Palmer (1952)	5.1-7.09	
Ward (1948)	6-17	

Shear strength

Shear strength is one of the most important characteristics of soil. Three methods
of assessing the shear strength of peat have been recorded. These are:

1. In situ measurements such as vane tests,
2. Stability analyses where a shear failure has occurred, and
3. Laboratory shear tests.

In situ tests: A common in situ measurement of shear strength is made with the
vane tester. Smith (1950) measured the shear strengths of near-surface layers of mus-
keg in Great Britain. He found that the shear strength of moss peats decreases linearly
from 176 g/cm^2 at a 10-cm depth to approximately 35 g/cm^2 at a 56-cm depth. Smith
concluded that all peats which have not dried out and which retain elements of their origi-
nal vegetation have strength profiles of a similar form. He also points out that

1. Mineral material, if present in amounts greater than 20%, can increase the strength of peat,

2. The effect of mineral contamination and drying-out can increase the strength of surface layers from 50% to 150%,

3. The moisture content of the peat can give no guide to its strength unless the degree of humification and the degree of mineral contamination are known.

Hardy and Thomson (1956) investigated the possibilities of adapting the vane tester for muskeg and carried out field tests at mile 253 of the Alaska Highway. The muskeg varied from 4 to 6 m in thickness and was underlain by a soft blue clay. Test results showed that the strength increased with depth but that maximum shear strength was developed only after an extraordinarily high degree of deformation. A typical set of shear strengths for one location showed a range from 52 g/cm^2 at a depth of 0.5 m to 705 g/cm^2 at a depth of 3.7 m.

Anderson and Hemstock (1959) utilized the vane shear tests to determine the maximum safe height of fill approximately 70 miles southwest of Edmonton. The depth of muskeg generally ranged from 3 to 4 m. Measured shear strength increased with depth in a FI surface-cover type (see Table I), but type BEI showed a loss in strength down to a depth of 1.5 to 2.5 m, then an increase with depth. They also noted that the BEI muskeg had consistently higher shear strengths than the FI type down to a depth of about 2.5 m. At this depth there was an insignificant difference in measured shear strengths. It would appear from a review of the data that this higher strength under the BEI type is due to the lower moisture content brought about by evapotranspiration from the surface, rather than to a reinforcing effect of any root structure.

A plot of moisture content versus undisturbed shear strength showed a direct variation from about 122 g/cm^2 at 700% moisture content down to 49 g/cm^2 at 1400%. A band of plus or minus 25 g/cm^2 from a straight line joining these two points encompassed nearly 90% of the test results. A similar plot of the remolded shear strength showed only very slight variation with moisture content with all values being below 49 g/cm^2.

MacFarlane (1961c), in an evaluation of road performance over muskeg in Northern Ontario, investigated the effect of vane size on the shear strength of peat. Three vanes were used; all had conical ends, the edges were sharpened, and they were of the recommended H/D ratio of 2. MacFarlane reports an excellent reproducibility of results for each vane in a series of tests at any particular location. However, when the average shear strength of peat for the three different vanes was plotted against depth, there was a marked variation in the results. He notes that, even though the vane test results cannot yet be completely evaluated, it appears quite clear that, because of the unusual nature of peat, the size of the vane does have some effect on shear strength measurements. Although the optimum size is not known, MacFarlane considers it advisable to use vanes somewhat larger than those used in clays.

Mickleborough (1961) utilized the vane tester for a study of embankment construction at Prince Albert, Saskatchewan. The vane used was either 9.2 cm OD by 15.2 cm long or 6.3 cm OD by 11.3 cm long. The larger vane was used unless the shear strength exceeded the limit of the torque wrench. Shear strength values observed ranged from 98.5 g/cm^2 to 633 g/cm^2.

Ripley and Leonoff (1961) utilized vane tests to investigate an embankment site in the lower Fraser Valley a few miles east of Vancouver. The peat deposit, beneath a marginal strip of land between the river and the rising ground at the side of the valley, has a uniform thickness of approximately 9 m. The shear strength of the peat prior to placing the fill ranged from 100 to 210 g/cm^2 for the undisturbed condition, and from 53 to 70 g/cm^2 for the remolded condition. The vane, 12.7 cm long and 6.4 cm wide, was rotated at a rate of 0.4 deg/sec. Vane tests were made adjacent to the initial test holes after different stages of fill construction. Ripley and Leonoff conclude from experience at this site that the undisturbed shear strength measured by in situ vane tests may not be reliable for stability computations of fills above deep peat deposits. Large

shear deformations occurred in the deep peat deposit at this site even though the average shearing stresses induced by the fill were about one-half the undisturbed shear strength of the peat measured by the vane test. The average shearing stresses at the time of initial shear deformations corresponded closely with the remolded shear strength determined by a vane test. Analysis of shear failures at two other embankments above deep peat deposits in the Vancouver area revealed similar relationships.

MacFarlane (1961a), reporting on muskeg research in Japan, notes that a good correlation had been found between the penetration index $\underline{P}$ of a cone penetrometer and the shear strength $\underline{S}$ determined by the vane tester. This relationship is:

P = 10 S.

Peat is noticeably anisotropic. The shear resistance (measured by the vane) in the vertical plane was approximately twice that in the horizontal plane. The measured shear strength of peat in Japan is within the range of 50 to 250 g/cm^2 and in most cases is around 100 g/cm^2.

Stability analyses: A second very satisfactory method of assessing the shear strength of a natural soil is a stability analysis in an area where a sliding failure has occurred. A simple survey of the overall dimensions of an area where the slide has occurred, along with knowledge of the original topography, will permit a computation of the average shear strength of the soil involved. Actually this method can give an average value for shear strength that is usually more accurate than any ever achieved by laboratory tests on small representative samples from the area. The method has obvious limitations, however, since suitable slide areas may not be available for analysis in a chosen area, and it is impractical to wait until an embankment failure occurs to assess the shear strength of the material.

Hardy (1955) reports one such case in which the average shear strength within the zone of failure was computed to be approximately 40 g/cm^2 — a value so low that the material cannot be successfully sampled and subjected to laboratory strength tests with the conventional methods of sampling and testing.

Hardy and Thomson (1956), comparing measured shear strengths with the rather scant results available based on slide analyses, found that the vane tests show higher strengths at depth than would be expected from the stability analyses. The shear strengths from the vane tests at shallow depths are in fairly close agreement with the available data from stability analyses. Ripley (discussion, Brawner, 1961) reports the analyses of two cases of shear failures during construction of embankments over muskeg. These analyses indicated that the computed average shearing stresses at failure were remarkably close to the remolded vane shear strength, which was about one-half to one-third the undisturbed vane shear strength. In each case, average shearing stresses were computed for the most critical circular arc passing through the observable toe and heel of the ruptured surface. The vane used for determination of shear strength had a diameter of 6.4 cm and a length of 12.7 cm. It was rotated at a rate of 0.4 deg/sec. Thicknesses of peat were 10 m in case A and 5.8 m in case B. The embankment in case A failed when the total fill thickness was 1.8 m only, of which 1.2 m was placed in the first lift, followed by 0.6 m placed 5 weeks after the first lift. The embankment in case B failed when a total thickness of fill equal to 2 m had been placed in one lift.

Laboratory tests: The shear testing of peats presents many problems. Obtaining undisturbed samples is difficult, sometimes impossible (Hardy, 1955), and the fibrous nature of the material, the presence of woody erratics, and the high compressibility all contribute to the problem.

Adams (1961) carried out some laboratory tests on peat obtained from the James Bay area in northern Ontario. He concludes that the compression tests on peat show an exceptionally high drained strength on axial loading ($\phi' = 50°$). Consolidated undrained tests, corrected for pore pressure, are in general agreement with the drained tests. Adams found the peat to have a low K_0 value which indicates that high shearing stresses

are developed under anistropic consolidation. The total strength of the peat can vary therefore from very low values to relatively high values depending on the pore pressures set up during consolidation. Adams is of the opinion that a consideration of pore pressure is very important in analysing the strength of peat.

In some early and pioneer laboratory shear strength tests, Hanrahan (1954a) carried out unconfined compression and triaxial tests on peat samples. For peat not previously loaded, the shear strength from unconfined compression tests was found to range between 0 for undrained peat to about 281.2 g/cm^2 for drained peat of about 0.11 g/cm^3 dry density. Average values of drained peat were 141 to 281 g/cm^2, the strength being related to a deformation of up to 20% of the initial length of the sample. Hanrahan notes that unconfined compressive strengths of up to 703 g/cm^2 are not uncommon for specimens consolidated under pavements. A typical stress-strain modulus of such a material is 7 kg/cm^2. After a description of triaxial (as well as pore pressure) apparatus and tests used, he concludes that the strength of peat is of a wholly cohesive nature and depends primarily on the water content.

Jankowski (1955) states that the angle of "internal friction" in peats decreases with an increase in the degree of decomposition, making water content unimportant at a degree of decomposition not exceeding 50%. Not until the degree of decomposition exceeds 50% does the angle of internal friction decrease sharply.

Shea (1955) carried out direct shear and triaxial tests on peat samples. He states that direct shear tests give completely erroneous results. The predetermined failure plane cuts across the fibers and the apparent angle of internal friction is usually between 20 and 25 deg. When the same material was tested in a confined compression apparatus, where failure can occur on any plane, a very low shear strength was obtained. From triaxial tests the angle of internal friction was usually found to be less than 5 deg. The only shear strength considered in design by Shea was cohesion of about 98 g/cm^2.

Ward (1948) ran a series of unconfined compression tests on peat to determine quickly the shear strength for the analysis of a slip of a flood defense bank constructed on muskeg. The mean unconfined compressive strength (excluding the upper crust) in the vicinity of the slip was 123 g/cm^2 (range of 39 to 184 g/cm^2); from other parts of the bog, the mean strength was 121 g/cm^2 (range of 35 to 195 g/cm^2). Appreciable quantities of water were squeezed out during the tests but were included in the water content determinations. Ward observed that an appreciable change in the water content of this peat had little effect on its strength, the variation in strength being largely due to the different plant fiber structures and to the degree of humification.

Ward, Penman, and Gibson (1955) performed a series of drained triaxial tests and equilibrium shear box tests on some peat samples. Each specimen was consolidated for about a week. The results indicate that $C' = 49$ g/cm^2 and $\phi' = 18°$ for the range of principal stresses involved on the slip under investigation. The shear resistance of the peat under the overburden at the start of construction was about 132 g/cm^2, although the great variability of the peat caused uncertainty as to how typical these test results were.

Bearing capacity

A qualitative evaluation of bearing capacity for vehicles for seven common types of muskeg (AE, AEH, BEI, DFI, EH, EI, and FI) is described by Radforth (1957). The "displacement" possibility for a vehicle arises infrequently in AEH but is progressively greater for other types (in particular EI, DFI, and FI). For towed vehicles, no displacement should be encountered in summer conditions for AE and AEH types; type BEI has a moderate possibility; and in types DFI to FI full buoyancy of the hull should be provided for.

Smith (1950) developed a simple formula for translating the measured values of shear resistance into effective bearing capacity at the surface of the muskeg by considering that the peat behaves as a purely elastic medium until plastic flow begins. The bearing capacity is proportional to shear resistance when the plastic condition is first reached. The ultimate bearing capacity is arbitrarily assumed to be twice this value. He estimated

that the peats examined average an ultimate surface bearing capacity of about
700 g/cm². The average ground pressure should be considerably less than this figure
owing to the high peak stresses set up under a wheel or track. From limited records,
Smith suggests that pressure should be about 210 g/cm² or 3 psi if a vehicle is to cross
the terrain with ease.

Consolidation

The most obvious characteristic of peat is an exceptionally high compressibility
under load. Results of a number of conventional and nonconventional tests have been
published and there is divided opinion as to what type of consolidation actually occurs.

Adams (1961) concluded that the consolidation of the peats he tested was due to the
expulsion of water under excess hydrostatic pressure, and that a large portion of the
settlement took place very rapidly when the material was still relatively pervious. With
time, the permeability was reduced with a corresponding reduction in the rate of settle-
ment. He argues that the consolidation occurring under excess pore pressure is extended
to relatively long-term consolidation by the large reduction in permeability.

Anderson and Hemstock (1959) observed settlements under a load of approximately
200 g/cm² on light fill sections which indicated that the initial or primary consolidation
takes place within a matter of days. This was further indicated by the observed excess
pressures being dissipated at an 8-ft depth in 3 to 4 days. Additional settlement appeared
to continue at a rate proportional to the log of time. This settlement can be thought of as
secondary consolidation, which is observed to be independent of drainage but is influenced
primarily by the soil type in this state of stress. For this particular condition of loading
on the FI muskeg, the amount of settlement over the first several weeks was 1.1% per
day of the given layer thickness. With the depth being 2.9 m, the observed settlement of
the fill after 60 days was 1.5 m or 45% of the total depth.

Anderson and Hemstock also reported that field observations of settlement gages
installed at a tank farm in the Pembina oil field in 1956 also indicated the settlement
versus log time ratio although in this case the rate was much lower. The original depth
of ABI muskeg was 1.8 m. Initial settlement under a load of 145 g/cm² was 0.36 m,
with total settlement being 0.41 m or 21% of the total depth. This gave a rate of second-
ary consolidation of 1.7% of depth per unit of time.

Colley (1950) carried out consolidation tests with the conventional consolidometer
and with the triaxial apparatus. With the latter, a scale-size sand drain was installed
in the center of the sample to observe its effect on the rate of consolidation. He reports
that, in a typical sample consolidated in this manner, the rate of consolidation increased
approximately 12 times.

Cook (1956) shows by a graph the relationship between coefficient of compressibility
and water content of unconsolidated peat (i.e., no preloading). The coefficient of com-
pressibility decreased in a straight line relationship with a decrease in the water content.
Lea (1958) attempted to duplicate this plot but was not successful. Lea's data suggests
that the relationship is more nearly logarithmic, which would follow from the Terzaghi
theory.

Hanrahan (1954a) investigated the compressibility and rate of consolidation of peat.
He found that compressibility of peat decreases with increasing load and that, for a given
load, the greater the dry density the less the settlement. He notes that the curve of
settlement plotted against time for peat is quite different from the curve setting out the
solution of the basic differential equation of consolidation. He ascribes the discrepancy
to a variety of phenomena including the abnormally large decrease in permeability which
accompanies the application of load, the decreasing coefficient of compressibility, and
thixotropy. The surface activity and absorption properties of peat are also high so that
considerable secondary consolidation may be expected. Hanrahan concludes that, for
peat layers of varying thickness, the magnitude and time of settlement depend upon the
ratios of the thickness and the square of the ratio of the thickness, respectively, for a
considerable period after the completion of the primary consolidation phase.

Keene (1960) found that settlement estimates based on conventional consolidation tests with good, large-diameter, undisturbed samples gave quite good agreement with field observations. The preconsolidation load obtained by using the Casagrande method on the void ratio-log pressure curve was in close agreement with the calculated over-burden load for normally consolidated peat. In the matter of rates of settlement, Keene found that data are less reliable. From his observations, the slope of the secondary line gives a settlement, in one cycle of time, equal to about 10 to 20% of the primary settlement. For example, if primary consolidation was 1.2 m and was completed in one year after application of load, secondary consolidation would cause a settlement of about 0.16 to 0.32 m between 1 and 10 yr and an additional 0.08 to 0.32 m between 10 and 100 yr. Keene noted that it is often difficult to determine from the data at which point the primary settlement is about completed and the secondary settlement has begun.

Lake (1961) showed that reducing the length of drainage path, either using thin samples in the laboratory or installing vertical sand drains in the field, did not significantly affect the rate of settlement of the peat under load but did appear to increase the rate of dissipation of excess pore-water pressure. The experimental conditions appear to have been reasonably satisfactory and it seems probable that the behavior of peat under load is affected by properties of the peat itself which are not fully understood as yet.

Lewis (1956) presents the results of an investigation into the approach embankments to a new bridge. Since the underlying soil contained a 1-m layer of very compressible peat, an appreciable settlement of the embankment was anticipated. Three settlement gages were installed at the site before the embankment was constructed. Long-term laboratory consolidation tests were carried out on peat samples prior to construction. When compression was plotted against square root of time for the first 24-hr period, the curve was linear over only about the first 2 min. In theory this corresponds to about 60% of the primary consolidation, and Lewis suggests that almost 100% primary consolidation had been completed within the first 10 min. Because much of the consolidation of the laboratory test samples was of a secondary nature, it was not possible to calculate the settlement-time curves for the embankment on the basis of the classical consolidation theory. However, the results of the long-term consolidation tests together with data obtained at a second site were used to estimate the ultimate settlement likely to occur at three other sites where settlement observations were made.

MacFarlane (1961a), reporting on the consolidation testing of peats and their clay substratum in Japan, notes that, in addition to the complex phenomena found in the clays, there is an additional factor of colloidal action in the highly compressible organic frame-work containing large quantities of water. Consequently, the time-settlement phenomenon is somewhat different from the Terzaghi theory and settlement continued over a long period of time. While the one-dimensional consolidation test on peat has some limitations, such tests were carried out on Ishikari peats. A straight-line relationship was shown to exist between the compression index (C_c) and both the moisture content and the void ratio.

Mickleborough (1961) reports on embankment construction in peat at Prince Albert that primary settlement has generally been somewhat less than estimated from consolidation tests. The trend on the field time-settlement curves indicates that, in the deep peat, the most extensive maintenance work will be required in the first 3 or 4 yr after the temporary pavement is placed. This was expected when the decision was made to use the normal consolidation method for construction. In deeper peat areas, settlements have reached the secondary consolidation stage. The observed settlement was about two-thirds of the estimated settlement.

Ringeling (1936) investigated the settlement characteristics of a peat layer 2 to 3 m thick beneath a projected road. It was necessary to determine how fast the compressible peat layer would settle and when the consolidation would be complete. Consolidation tests were run on several samples and an experimental road section was constructed to check the actual settlements against those computed from the laboratory tests. The observed settlement did not altogether agree with the calculated settlements, being less for lower loads and greater for higher loads. Ringeling also constructed a device for

measuring the pore-water pressure of peat in the field. He observed a fast increase in pore-water pressure with increased load and a subsequent slow decrease in pressure. Curves show that, immediately after loading of the peat, about 75% of the load is taken by the pore water.

Ripley and Leonoff (1961), from an embankment settlement study, concluded that analysis of field settlement measurements of fills about deep peat bogs on the basis of consolidation and secondary compression considerations only may not be valid. They noted large shear deformations at the site without evidence of a definite rupture surface, their occurrence being noted only as increased settlement. The data also indicated that long-term settlements during the period normally attributed to secondary compression may amount to 50% of the total settlement. The measurements revealed a high rate of continuing long-term settlements. During the past 3½ yr, settlements of raft sections of the embankment where no fill has been placed have continued on a straight line relationship at a relatively steep slope.

Shea (1955), in a study of the construction of levees on peat in the Florida Everglades, estimated on the basis of consolidation tests, that settlement would be equal to 50% of the peat thickness and that half of the settlement would occur during construction. Subsequent observations showed a total settlement very close to the original estimate of 50% of the peat thickness. Apparently almost 100% of the settlement occurred during construction, as there was very little change in the elevation of settlement plates after the first reading. Thus, consolidation tests predicted the amount of settlement with reasonable accuracy, but the predicted length of time required for settlement was not even approximately correct. The consolidation tests indicated 15 to 20 yr for 90% settlement whereas the actual settlement took place in a few days or weeks. Shea did not investigate this discrepancy further.

Thompson and Palmer (1952) carried out consolidation tests on several samples of peat in order to determine the magnitude and rate of settlement of two earth-filled concrete barricades built on a tidal marsh underlain by nearly 50 ft of peat. They found that the thickness versus log time curves were similar for all samples; curved for the first minute, a straight line from 1 min to approximately 1 day, and then changing to another and steeper straight line for 1 day until the end of the tests. They observed no similarity between these curves and those obtained for clay. There was no line of demarcation between primary and secondary consolidation. The primary consolidation was apparently completed in less than 1 min. Actual observations of the settlements over a period of about 4 yr confirmed a prediction that the plot of the settlement of the barricades versus log time would be a straight line, in keeping with the results of the long-term consolidation tests.

Ward (1948) notes that the peat he investigated appeared to be the weakest and most compressible material of its type ever encountered in soil mechanics studies in Great Britain. The upper 1.5 m was subject to drying and exhibited considerable tensile strength, but owing to the compressibility of the underlying peat the load of the banks produced an appreciable surface curvature. Several tension cracks were observed on one side or the other of the banks. One bank settled 1.2 m in 2 yr. It was necessary to build the banks (constructed of peat) 75% higher than specified to allow for subsidence caused by settlement of underlying peat and drying shrinkage of the bank peat. As the banks dried out, the contraction produced cracks 2 to 5 cm wide which required maintenance.

Thermal Properties

Investigations on the thermal characteristics of muskeg, in common with many other peat properties, have but just begun. Much of this recent interest is related to the growing awareness of the interrelation between muskeg and permafrost.

An organic mantle at the ground surface forms a natural insulator for permafrost from the thawing effects of the summer. This concept has been recognised qualitatively for many years. Some of the early attempts at a quantitative appraisal of the insulation of peat recognised the abnormally high water-retention capacity of peat and the varying conductivity of peat in the thawed and frozen states.

Müller (1945) points out that

> ".... Peat can absorb water up to 300% of its volume. It is there-
> fore permissible to assume that the heat conductivity of saturated peat
> will be close to that of water, which, in the range of temperature from
> 0 to 20C will be about 0.5, but in the frozen state it will be about 2.0.
> Dry peat, which is commonly used as an insulating material, has the
> heat conductivity coefficient of 0.06. It will be thus seen that the heat
> conductivity of peat will vary between wide limits depending upon the
> amount of moisture, compacting, and whether or not the material is
> frozen. It can be thus concluded that during summer a greater amount
> of heat is transferred through the water-saturated peat into the under-
> lying layers of soil than through dry peat. In winter when water-satur-
> ated peat is frozen the heat is transferred in the opposite direction,
> from the soil into the air, and the amount of heat passed into the air will
> thus be four times as great as in the summer. When dried this negative
> factor of loss of heat may be considerably decreased. From the above
> it can be easily seen that such an exchange of heat through peat will
> have a marked effect on the accumulation of cold in the ground and on
> the formation of permafrost. "

The early estimates of depth of freezing and thawing based on air temperatures also recognized the importance of surface cover (Carlson, 1952). A correction factor was used which in effect converted the basis of calculations from normal air temper-atures to surface temperatures. The surface temperature was then assumed to be dependent upon the solar radiation received and emitted, heat lost to the air by conduc-tion and convection, heat lost or gained due to evaporation or condensation of surface moisture, thermal diffusivity of the soil below the surface, and heat transferred from the interior of the earth.

These first inquiries into the existence and occurrence of permafrost were based principally on the effect, such as ground temperatures, rather than on the cause, or energy transfer. More recently, investigations have been initiated that are based on a measure of energy levels and the basic factors that affect these energy changes.

Legget et al, (1961) point out the many components of the exchange of surface energy. One of the many terrain influences on the thermal regime of the ground is vegetation. Although the entire vegetative complex exerts an influence, the effect of plant cover such as mosses and lichens appears to be paramount. The influence of a vegetative cover is not clearly understood but the suggestion that it provides resistance to heat flow by con-duction only is almost certainly too simple a view. Vegetation contributes to evapotrans-piration, and thus a very considerable part of the solar radiation received can be re-jected without the soil beneath being affected. Mosses are strongly hygroscopic and are capable of losing moisture rapidly and in large quantities. Lichens, moreover, have been found to have extremely dry surfaces at times, even when lower layers near the soil are very wet. It may be that they are able to protect the soil against heat gain more by an insulating or albedo effect rather than by an evaporative cooling effect. Some in-vestigators have suggested that low soil temperatures (and a high permafrost table) are maintained by rapid evaporation at the wet basal layers.

The thermal properties of the ground itself have a marked influence on the net heat exchange. In the simplest cases, involving only transient heat flow by conduction, the thermal diffusivity of the soil becomes important in determining the rates at which heat is transferred from the surface into the soil itself. This affects the surface temperatures, which influence, in turn, the surface heat exchange rate. Thus the thermal conductivity, density, specific heat, and moisture content of soil all have an influence on its thermal regime.

Unfortunately, the transfer of energy through actual soils, especially peat, is often greatly complicated by their variability and by the presence of moisture. When perma-frost is present, there are further complications because of the different properties of

frozen and unfrozen soils and the latent heat of fusion released when water is frozen. This is not readily taken into account by the heat conduction theory.

Geophysical Properties

Geophysical methods of exploration involve the measurement of changes in certain physical characteristics of the earth at or near its surface (Hvorslev, 1949). They are classified as gravitational, magnetic, electrical, electromagnetic, and seismic methods. These methods have been developed primarily for oil and mineral prospecting, but some electrical and seismic methods are used in subsurface explorations for civil engineering purposes.

No utilization of geophysical methods specifically for peat and muskeg exploration, appears to be recorded in published literature. Limited references to the organic mantle, peat, or muck are made in some recorded observations as an aid to the better interpretation of mineral soils or bedrock. These few comments are generally associated with seismic and resistivity exploration methods. However, a preliminary appraisal of exploring peat density and water content by radioactive methods has been made (Radforth and Ashdown, 1961).

Seismic methods are based on the fact that the velocity of propagation of a wave or impulse in an elastic body is a function of the modulus of elasticity, Poisson's ratio, and the density of the material. Accordingly, wave velocity differences exist in solid rock and in loose, sedimentary deposits. Table IX records the velocities of some earth materials and Table X some longitudinal wave velocities in permafrost areas.

Although earth materials are characterized by certain group velocities, the velocity spectra tend to overlap and to show considerable variation even within materials of the same type. High and varying water contents contribute to these variations of velocity in peat. Thawed organic material has a relatively low velocity, and the general effect of a surface organic mantle is high attenuation of seismic energy. The higher velocities in frozen organic material overlap with some soils and even bedrock. In addition to the large range in ice or moisture contents, velocity variation in frozen peat can also be affected by the nature and form of ice segregation.

Electrical methods. Most electrical methods of exploration are based on differences in electrical conductivity or resistivity of the subsurface materials (Hvorslev, 1949). Evaluation is based more on the relative than on the actual values of resistivity.

Moore (1951) reports on the success of resistivity tests to determine depths of "muck" in a marsh in Virginia. Investigations were carried out on 800,000 m² of swamp land, normally covered by 0.5 m of water at high tide, to determine possible useful deposits of sand and gravel. The observations indicated that approximately 7.5 m of muck were above the granular formation. Moore (1950) also notes similar exploration work in Georgia, New Jersey, and the Michigan peat bogs.

It has also been noted that a marked resistivity contrast can exist between frozen and unfrozen soils (including peat) and thus between permafrost and the seasonally thawed layer. Varying ice form, content, and distribution add considerably to a large dependence on knowledge of local conditions as well as on the skill and experience of the operator.

Sampling

Sampling of peat deposits may be required to define the areal limits of the organic deposit or to obtain actual samples to assist in identification or for laboratory testing. Thurber (1961) reported on penetration tests with a probe consisting of a 1.6-cm (⅝-in.) diam steel rod joined by thin couplings and having a bullet-shaped nose. Two men forced the rod downward; the depths reached by an estimated 45.4-kg (100-lb) and 171.6-kg (400-lb) pressure were recorded. A few holes were advanced to correlate the soils encountered with the penetration results.

Table IX.   Velocities of some earth materials.

Material	Longitudinal wave velocity (m/sec)
Weathered surface layer	150 - 450
Sands and gravel	335 - 975
Alluvium	500 - 2000
Clay	975 - 2800
Shale	2300 - 4700
Sandstone	1400 - 4300
Limestone	4125 - 6100
Granite and igneous rocks	4000 - 6250
Water	1500
Ice	3850

Table X.   Longitudinal wave velocities in permafrost areas.
(after Joesting, 1954)

Material	Longitudinal wave velocity (m/sec)
Light muck	300 - 500
Thawed muck	550 - 1200
Frozen muck	1300 - 3050
Thawed gravel	600 - 3050
Frozen gravel	4000 - 4650
Bedrock (schist)	2300 - 6100

Hughes (1960) describes a boring tool used to determine muskeg depth.   It consisted of a 3.2-cm ($1\frac{1}{4}$-in.) "coal" auger with a shank to fit a 1.9-cm ($\frac{3}{4}$-in.) carpenter's electric drill.   A 2500 w light plant carried on a scout car supplied the necessary power.   Extension pipe to drill 4.6-m deep holes was carried, although 10- to 12-m deep holes would have been feasible.   This boring tool was subsequently found to work very well in frozen ground when using sharpened tips.

Samples for laboratory testing have been obtained in a variety of ways.   Specialized peat samplers or their modifications, such as described by Bastin and Davis (1909) and Stockstad (1939), are in limited use (MacFarlane, 1961c).   Brawner (1961) and Lea (1958) report good, undisturbed samples using a steel foil sampler (for description see Hvorslev, 1949, or Lea, 1952), but most other investigators rely on standard equipment such as thin-wall sample tubes (MacFarlane, 1961c; Adams, 1961) or split spoons (Mickleborough, 1961).

Most investigators acknowledge some disturbance before the peat samples reach the laboratory.   Hillis and Brawner (1961) ascribe disturbance to factors such as:

   1.   The inability of the sample to retain its original volume on stress relief due to the presence of gas
   2.   The loss of moisture on extrusion and preparation
   3.   The usual disturbance caused to a soft soil sample as it is forced into a retainer.

Sample preparation has also been found to be difficult. Brawner (1961) reports some success by quick-freezing the peat sample, trimming it while in the frozen state, then placing it in the consolidometer and allowing it to thaw for 24 hr before testing.

A novel method of sampling is to introduce a thin steel tube into the muskeg and then fill it with liquid nitrogen. Peat then freezes to the tube and is relatively undisturbed. The sample is then removed, trimmed, and preserved by quick-freezing for transfer to the laboratory (personal communication, T. A. Harwood, Defence Research Board, Department of National Defence, Canada, February 1962).

V. ENGINEERING PROBLEMS

For solutions to engineering problems in muskeg an assessment of organic material (including its properties and environment) is necessary. As with all engineering studies, the "common denominator," or the yardstick by which success is measured, is one of cost without failure of the structure. Fundamentally there can be only three basic approaches to "construction in muskeg." These are:

1. To avoid muskeg,
2. To eliminate muskeg, or
3. To design for and utilise muskeg.

In primary road construction it is often difficult to avoid or to utilise muskeg as a subgrade; this dictates muskeg removal with resultant abnormal costs. In contrast, the economics of petroleum exploration suggest that a solution to the access problem must be based on the design of a vehicle rather than on a stabilised access route for wheeled vehicles.

At the present time, an incomplete knowledge of muskeg properties and qualitative methods of correlating these properties to the performance of structures makes design extremely difficult. However, some guide to the problems and present-day solutions can be obtained by a review of two engineering fields where muskeg is recognised as a distinct terrain problem — vehicle trafficability and road construction. A number of other special muskeg considerations have also been reported. Two of these, drainage of muskeg and frozen muskeg (including perennially frozen muskeg), have such potential implications in the future that individual mention, even if brief, is warranted.

Vehicle Trafficability

A quick reference to the Radforth muskeg map of Canada (Radforth, 1960) shows that a broad belt of muskeg extends in a northwesterly direction across the country. Here, Radforth states, the probability of engineering problems, one of which is trafficability, is high. This belt is on the northern fringe of the present-day access routes and of roads and railroads into the area. Mineral and oil exploration and the Mid-Canada Radar Line have made off-road access into this belt a necessity. In the oil exploration areas in the west, an AEI or BEI (Radforth classification) muskeg predominates. This particular muskeg includes trees up to 15 cm in diameter and non-woody materials such as mosses and lichens. The whole of course overlies various types of peat which may be as deep as 120 m in the sedimentary basin of northwestern Alberta.

To gain access to these areas designers of vehicles were faced with a dilemma, for the vehicle had to be rugged enough to handle the treed muskeg but with track flotation low enough to handle the water-filled moss and lichen muskegs. Inevitably such an approach had to lead to a heavy vehicle with wide tracks; in the case of the better vehicles which were later developed this is, in effect, what occurred.

Thomson (1958) pointed out another dilemma for the designer, that "tests could not be run on vehicles which did not exist, and vehicles could not be built because desirable design data was not available"; i.e., no soil or muskeg strength parameters were available.

While the Radforth Classification System has been "suggested" as a classification of muskeg for the engineer, its virtue has so far been in its simplicity rather than as

any real classification of engineering properties. Up to 1959 what little research had been done in this particular problem area had for the most part been undertaken by the Imperial Oil Company at Calgary, Alberta, Canada. There, Thomson (1958), in a series of tests on some commercially obtainable vehicles, found that in muskeg:

1. The drawbar performance of a vehicle decreased as the shear strength of muskeg was reduced by operating the vehicle on it (destruction of the mat).
2. Shear vane tests produced a shear vane profile which was found to be compatible with vehicle test results (for a unique area).
3. Muskeg of a specific classification did not have an exclusive shear strength. Moisture content and thickness of the formation appeared to influence these strengths.
4. The towed motion resistance of a vehicle was found to be about one-fifth of the powered external motion resistance.
5. An increase of a track pitch of certain vehicles (Nodwell RN10) resulted in a 10% increase in drawbar performance.
6. As long as sufficient bearing capacity is available to prevent ultimate (bellying) sinkage of the vehicle, the net traction of the vehicle can probably be predicted from the shear strength of the muskeg mat.
7. The shear stress values of peat are in all probability strain-rate dependent.

Nuttall and Thomson (1960) described the development of a very large (22,600 kg, 50,000 lb curb weight) muskeg vehicle employing some of the results of the above tests and a novel vehicle concept. They state that the vehicle design concept "had been extensively researched over a period of ten years all with Canadian and U. S. Army funds, and that one of the major concepts dated from the turn of the century ("Engineer," Volume CXXIV, 1917)." This concept was, of course, the articulated vehicle.

The vehicle conceived by Nuttall and Thomson had to be, in effect, bellyless with a ground pressure of not more than 210 g/cm² and with broken-back steering. The final product, the "Musk-Ox," has had a successful operational career for the past 3 yr in the muskegs of northwestern Alberta.

The Shell Oil Company of Canada in conjunction with the Nodwell Company of Calgary (Stoneman, 1961b) designed and built a somewhat different vehicle, the Nodwell Transporter (9100 kg, 10,000 lb curb weight). This vehicle was based on the design of the highway tractor trailer combination, though with both the tractor and the trailer portions being powered. The trailer platform is connected to the tractor by the fifth wheel method. The steering is also "broken-back." This vehicle is now in quantity production and can therefore also be considered successful for its purpose.

However, it was generally found that the Nodwell 20T Transporter would only traverse a floating bog (FI) once or twice; therefore, the usual practice has been to circumvent such areas. Much the same considerations have to be applied to the use of the "Musk-Ox." Thus, even with adequately powered and low flotation articulated vehicles, carefully chosen access routes are still of great importance.

The problems of the correct determination of such access routes have been described by Radforth and Evel (1959), Thomson (1960), Russ (1956), Gillespie (1961), and Keeling (1961). Russ mentioned the use of aerial photographs for reconnaissance but on the whole recommended winter access over the muskeg. Radforth pointed out that the micro-terrain features can be very diverse, and, what is more, these terrain features change from winter (late spring in the subarctic) to summer.

Thomson (1960) reports that in the exploration of an oil field in central Alberta (Pembina) approximately $400 million was expended, and $30 million of that could be directly attributed to muskeg. Thomson estimated that if all costs are computed for winter trail to a drill site, using truck transportation, the unit cost will amount to about $1.20 per ton mile. If the drill rig has to be moved in the summer by tracked vehicles, the costs rise to approximately $10.00 per ton mile. Thomson thus concluded that there is room both for sophisticated vehicle design and for the use of access route selection studies.

Stoneman (1961a) considers that, with proper access studies,charges can be as low as $1.40 to $2.30 per ton mile under certain conditions.

There are other smaller articulated vehicles; these are:

1. The Polecat (Wilson, Nuttall & Raimond) and
2. The Rat (Canadair and the Canadian Army).

The U. S. Army is also at the moment (1962) developing a 1-ton articulated trans-porter in Canada which will basically follow the principles utilised by Nuttall and Thomson (1960).

While the emphasis has been on articulated vehicles, properly designed single hull vehicles with low ground pressure may also be used over muskeg. The main drawback to the single hull vehicle, however, is that, without broken-back steering, the tracks on a turn destroy the muskeg mat in the first pass. For this reason, where cost is not a consideration, they appear to offer only a marginal solution to the problem of vehicle trafficability over muskeg.

Roads

The term "road" is used here in the sense of any improved or stabilised "track" utilised for travel. Roads may be subdivided, by degree of improvement, involving road standards and costs, into (1) Tote roads, (2) Secondary roads, and (3) Primary roads. In practice there is a considerable amount of overlap in cost, construction methods, and performance tolerances between each subdivision. Instead of assigning specific con-struction methods for the road types, general road construction methods on muskeg will be described and mention will be made where any one method is applicable to a specific road type.

There are two general types of failures with roads built over organic terrain:

1. Failure by lateral flow (or shear), and
2. Failure by compression (excessive settlement).

Lateral flow failure is the more common type in very wet muskeg. The gravitational force of the fill placed on the surface "squeezes" the subsurface organic material later-ally out from beneath the fill. The fill then subsides and heaving of the muskeg surface to the sides of the embankment frequently results.

In drier muskeg areas, failure of the road may be simply by excessive (often differ-ential) settlements caused by the weight of the fill and the compressible nature of the peat, rather than by actual structural failure of the peat itself.

Construction methods

Where muskeg abounds, it is essential that all construction should be preceded by a terrain study. Low cost roads (tote roads) may be designed for only winter operations (winter or "snow roads") or, with only minimum location improvement, for tracked vehicles in the summer. Secondary roads are usually "floated" on muskeg. Such roads have a greater summer and winter capability than the tote road. With primary roads the most common construction methods are removal of muskeg, the techniques of con-solidation, and in some rare instances the utilisation of pile foundations for the roadway.

Terrain study (route location). Although terrain studies in muskeg areas have em-phasised location of temporary access routes, the techniques have been utilised for more permanent route locations   (Evel, 1959). Established procedures of airphoto interpreta-tion (Bridcut, 1961; Hughes, 1960; Mollard, 1961) have been found most useful in a first appraisal of road location. With the degree of success depending largely on the skill of the airphoto interpreter, it is possible to determine the extent and general characteristics of peat deposits, and to assess the problems that might arise.

For "winter" roads some types of muskeg (with little or no tree clearing) may be favored. In secondary or primary roads, airphoto interpretation techniques allow the

length of muskeg crossings to be kept to a minimum. In all cases, airphoto techniques allow a preliminary appraisal without the many difficulties of a field survey.

In some relatively unmapped areas of northern Canada, air photographs have been utilized for ground locations of routes (Roads and Engineering Construction, 1959). A tentative route is plotted from a study of the aerial photographs, then checked by air-plane, adjusted, rechecked by a low-flying helicopter, and adjusted further. All features that may cause construction difficulties, such as muskeg, rivers, hills, etc., are deter-mined.

The ground survey crew is then moved into the area, the road is plotted on foot to the first contact point, and any slight adjustments are made in accordance with actual ground conditions. Exact compass bearings and distances from curve to curve are deter-mined from aerial photographs. A bulldozer, lined up by compass bearing, travels the specified distance and opens up a center line. At this point the machine is deviated for the next tangent and continues to clear a path to the next point. The center line is then staked on this route.

Winter roads. Winter roads are considered here to be a form of tote road, utilized seasonally and relying on the increased bearing strength induced by freezing of the sub-grade, muskeg, and/or an aboveground layer of compacted snow or ice. Although main-tenance after construction depends on the continuance of cold weather, construction and surfacing with snow are simple and inexpensive. The load-carrying capacity is extremely high, and except for snow plowing (which can be kept to a minimum by judicious location) maintenance costs are usually low.

Ager (1960, 1961) has reviewed snow-road preparation in Scandinavia and summarized the research and development work in Sweden. The following summary of winter road construction for forestry practice in northern Ontario by Davis (1961) illustrates well the cperational problems that are involved.

> "Winter roads take advantage of the frost. In muskeg areas the mer-chantable timber is first removed. When the cold weather comes, the right-of-way (generally cut 66 feet wide) is tramped with small tractors or the large type snowmobile. When there has been sufficient frost penetration into the peat, large bulldozers (generally in the 16 or 26 ton class) equipped with shearing blades, bulldoze a swath about 50 feet wide down the middle of the right-of-way. Shearing is merely the action of cutting or shearing off the stumps, unmerchantable trees and debris at ground level. This leaves an excellent root mat for future use. The secret of shearing is adequate 'tramping down' of the snow to ensure sufficient frost penetration into the peat. The stumps and trees, if not frozen firmly into the peat, tend to tear or lift out rather than shear.

> "Shearing is usually done the winter before the road is required. When it becomes very cold the following winter, the snow covering the sheared muskeg is packed down with snowmobiles and later with tractors of the 10 ton class. When the snow has been sufficiently packed and the frost has penetrated the peat, a large 'V' plow (usually made of timber balks, author's note) pulled by three or four 10 ton tractors is drawn over the road. The packed snow, the slightly frozen peat, and the supporting action of the root mat permit relatively trouble-free passing of the plow and tractors. After exposure to sub-zero temperatures for two or three nights, the road is 'tanked.' Successive layers of water (hauled by tandem trucks equipped with piggy-back tanks) are poured on until a smooth, strong road surface is obtained. On the average, the ice thick-ness is about 2 to 3 inches. Such a road easily handles 50 to 75 ton loads.

> "On some of the main winter roads, in an effort to prolong their seasonal use and to eliminate the yearly preparation costs, additional construction is carried out after shearing. Wherever and whenever

practical, a shallow lift of fill (usually clay) is laid down over the sheared muskeg road. This fill is about one foot in depth and laid down 30 to 40 feet wide. If the sheared section of the road is less than 400 feet long and has good borrow pit possibilities on each end, then the cushion is made by a straight tractor push. Sections over 400-feet long with clay fill available are done with tractor drawn scrapers. On these longer sections if good clay fill is not readily available it has been found necessary to truck in fill. This is usually of granular nature. Where it is necessary to protect these shallow cushions from spring wash-out, cross drainage in the form of corrugated steel culverts is provided."

In J. G. Thomson's opinion (1957) winter roads will usually safely carry axle loads of 6000 kg (13,000 lb) single or dual wheels at inflation pressures of 6 kg/cm^2 (85 psi). He notes that, for good traction, the vehicle should be loaded so that about 60% of the gross vehicle weight is borne by the powered wheels, if all-wheel drive is not provided. Thomson does not recommend the use of snow or other cross-country tires on heavy equipment over winter roads. Many, if not all, of these tires induce very high stress under the tire contact and result in road surface spalling with high maintenance costs.

Thomson also notes that it is possible to induce 2 ft of frozen muskeg below a well-packed winter road. He has seen payloads of 11,000 kg carried on 35 cm of frozen muskeg. Harwood (personal communication, T. A. Harwood, Defence Research Board, Department of National Defence, Canada, February 1962) arranged for a landing of a 26,000 kg aircraft on an airstrip with 18 cm of frozen snow underlain by 18 cm of frozen muskeg.

Flotation. The principal of the "flotation" ("corduroy") method of road construction in muskeg is to rely on the natural organic surface mat (or to provide one) to support a certain height of fill (by lateral tension of the fibrous mat). Thus the road fill is "floated" on muskeg.

The flotation method of road construction was one of the earliest attempts at utilizing peat as a bearing material. "Corduroy" or fascine construction, consisting of logs, planks, or brush to provide for a certain amount of buoyancy, to spread the weight of the road evenly over muskeg, and to prevent the fill material from penetrating the surface of the mat of the muskeg, has been used extensively. For fascine construction, wire mesh has been used in the U.S.A., dry bundles of peat in Scandinavia and Holland, and bundles of straw in Great Britain.

When roads that must sustain heavy traffic loads are floated on muskeg, it may be necessary to provide lateral support. This can be accomplished by building counter-weight fills or "berms" on either side of the roadway to stabilize the unstable organic material beneath the main embankment. An alternative method, used in Scotland, is to dig a trench on either side of the roadway embankment and fill it with rock.

Past experience indicates that the flotation method is undesirable for primary road construction. Brawner (1958) has cited two examples of secondary road failures on muskeg. In one case on Lulu Island, south of Vancouver, an extensive peat deposit was crossed, but since the surface mat was quite strong no lateral support or artificial mattress was used. A mattress was placed where the surface was weak but it did not spread the load sufficiently. In a second instance, around 1930, a portion of the Trans-Canada highway between Salmon Arm and Canoe was constructed over a muskeg deposit which was about 1500 ft long and 4 to 15 ft in depth. Two layers of corduroy followed by 2 to 3 ft of gravel were placed. Both procedures were adequate for the vehicles in use at that time. As the amount and weight of traffic increased, excessive differential settlement and quasi-deflection (alternate deflection and rebound of the grade under a vehicular load) occurred, and frequent and extensive maintenance was required. Finally, it was only after 15 to 20 yr that some degree of stability was achieved. This was probably due to the continued addition of surfacing material, which increased the weight of the fill eventually displacing most of the underlying peat, as well as to consolidation.

The flotation method of road construction is exploited chiefly in haul roads and some secondary roads (Brawner, 1958; Davis, 1961; Harrison, 1955). Brawner (1958) has cited an empirical rule to determine the maximum height of fill that may be placed without shear failure; where peat is less than 12 ft in depth, a 12-ft fill may be placed; where the peat is greater than 12 ft in depth the fill must not exceed 8 ft. These heights include the depth of fill that sinks below the original ground level.

Harrison (1955), on the basis of experience on the Alaska Highway, concludes that the most feasible method of road construction over organic terrain in that part of Northern Canada is to place a fill as conveniently as possible and to accept the heavy maintenance requirement imposed for the next 3 to 5 yr. He notes a slight advantage to flotation in that the cost is spread out over several years. His reasons for the choice of the flotation construction method are that excavation and displacement are difficult due to the nature of muskeg, the time element, and the possible presence of frost. If permafrost is encountered, a distinct advantage of the flotation method is that the fill may be placed when the active layer is frozen down to the permafrost and is thus passable for heavy wheeled vehicles.

Excavation. An obvious approach to the problem of road construction over muskeg is to excavate the unstable material and backfill with mineral soil. It is the only procedure that will guarantee stability and is considered by many engineers to be the only method of dealing with muskeg (Brawner, 1958; MacFarlane, 1956). However, it is usually only economically feasible for shallow depths and opinion differs on the maximum feasible depth: approximately 3.5 m in Canada, Holland, and the United States, and 5.5 m in Germany.

In addition to excavation by mechanical means (dragline or crawler tractor for shallow depths), displacement of peat by gravity, jetting, or bog blasting have also been reported. (Displacement methods will be treated separately.)

As would be expected, excavation in muskeg can be difficult. The Department of Highways of Ontario has noted that excavation rates can vary from 28 to 117 m^3/hr and show no apparent correlation with total yardage excavated, type of muskeg, size of machine, or the number of hours worked (Rutka, 1960). As a result, the Operations Branch of the Department of Highways of Ontario has encountered substantial claims for heavy overrun in excavation and backfill. The present departmental policy toward muskeg excavation (or displacement) may be summarized as follows (Rutka, 1960):

1. For muskeg up to 3.5 m in depth, 100% excavation is assumed.
2. For muskeg greater than 3.5 m deep, the amount of muck, marl, or soft clay below this depth which is displaced into the open excavation and subsequently excavated by the contractor is estimated by the Highways Department and is indicated on the soil design profile as a percentage of the total volume. For example if the underlying material is extremely soft, 100% displacement into the open excavation is assumed. In other cases where a firmer material is encountered, the displacement quantities may range from 25 to 75%. It is acknowledged by the department that the displacement quantities will not in all cases be accurate but will be estimated on the best knowledge of the material that is available. The percentage of displacement is normally considered in conjunction with knowledge of muskeg types, type of underlying material, height of fill, and the influence of other features such as old road beds.

3. Where the embankment is of sufficient height to displace the muck and soft clay without excavation, no excavation quantities are included. In such cases the displacement is estimated by the Highways Department and the backfill quantities are estimated on this basis.

4. Contractors often claim additional excavation quantities because of sloughing of the trench walls. The width of excavation is established by standards or by supplemental soils information, and the contractors are not normally paid beyond these limits. The sloughing is usually caused by the surcharge of muck piled up adjacent to the open excavation. The contractor can usually eliminate this problem by controlling the proper disposal of the muck.

5. Where it is obvious that more material will be excavated than can be accommodated on the slope, the road design office usually adjusts the grade upward in such a manner that the final section has a pleasing appearance.

6. The width of excavation will be governed by the depth of the swamp; the deeper the swamp the wider the excavation.

Gravity displacement. When a fill is placed on the surface of muskeg or peat it will settle until either equilibrium is reached or the fill reaches the solid substratum. This may take years and so the period of natural settlement due to gravity is accelerated in a number of different ways. All these methods involve displacing the unstable organic material from beneath the embankment after it has been placed.

A surcharge of 4.5 to 6.0 m in excess of the fill may be used to accelerate displacement. The excess is removed when the fill has settled adequately.

Hardy (1955) notes that this procedure is somewhat wasteful of fill material and does not produce a particularly stable embankment. Considerable settlement and distortion usually follow but it is less than that which would occur by floating the fill on the muskeg. The economical use of the method is usually confined to conditions where the embankment required is of such a height that the subsoil would fail in shear in any case.

If the peaty material is too stiff to be easily displaced by the weight of the embankment and a surcharge alone, it can be softened by water jetting. In this case, after an embankment has been built across a muskeg area, water jets are directed through the fill into the organic material below. These jets are sunk rapidly to the bottom of the organic deposit, then slowly withdrawn. The increase in water content considerably reduces the stability of the organic matter and the fill settles to the bottom.

The Michigan State Highway Department has used a water jet method extensively but the principle is somewhat different to that outlined above. The embankment is constructed across the muskeg and about 3 m of surcharge is added. This fill is then saturated to a near "quick" condition by proper arrangements of the water jets. The increased weight of the embankment due to the water displaces the peat and causes the fill to settle. The surcharge is then removed and the fill brought to grade.

Bog blasting. There are three general methods of utilizing explosives to displace organic material from beneath the embankment: "trenching," "toe shooting," and "underfill." (Canadian Industries (1954) Limited, 1955).

Canadian Industries (1954) Limited (1955) suggests the "trenching" method for narrow fills, 9.0 to 12.0 m wide, in depths of peat up to 2.5 to 3.0 m. The method consists of blasting as large a ditch as practical along a center line and immediately dumping fill material into the trench. Best results are obtained if blasting is confined to comparatively short sections of ditch at a time, so that the fill can be placed soon after shooting and before the peat has time to "set up" again. It is of course necessary to use fill material of a higher density than the organic material, and it is preferable to carry the fill forward in a "V" point to assist in pushing the organic material out to the sides. The post hole method of ditch blasting is usually employed. Panter (1960) is of the opinion that this method is too extravagant since it requires approximately 2.4 kg of explosive per cubic meter of organic material moved. In his experience, no matter how the cross section shot is loaded, the organic material will pile up in a heap on the center of the roadway and, unless it is very liquid and the fill high, the organic material will have to be dug out. It would be more economical to dig out the organic material in the first place.

Canadian Industries Limited suggests the "toe shooting" method where the depth of peat is between 3.0 and 6.0 m. Fill material is dumped on the unstable ground until a substantial surcharge is built up above grade. Charges of explosives are then loaded around the toe of the fill. The firing of these charges displaces the unstable peat or muskeg or liquifies it sufficiently so that the fill settles to a firm foundation. The fill is then built up again and the operation is repeated.

Panter (1960) notes that rock fill is not satisfactory for "toe shooting" since much of the explosive force (gases) is dissipated through the voids in the rock. Clay soils are also unsatisfactory because they mix with the water and settle for years or bridge over voids and subside later. Gravel or sand appear to be the best fill material, for either is easily handled and readily enters the voids left by the blasts. He also notes that it is important to keep the fill built in such a way as to plow the muck to both sides; otherwise the organic material can develop into a large muck wave ahead of the fill where too much explosive is required to move it. In regular work this wave usually increases the amount of muck to move with each blast from 50% to 100%. In his experience 0.59 kg of explosive per cubic meter of original muskeg is required for "toe shooting". Panter again is of the opinion that in most cases it is cheaper to dig the muskeg than to "toe shoot" it.

Brawner (1958) reports on "toe shooting" in a muskeg deposit on the Caribou Highway which was 365 m long and had a maximum depth of 4.3 m of peat. The surface mat was broken mechanically and 3.0 to 4.0 m of fill was placed in a "V" advance. Pipes (3.8 cm in diameter) were forced through the peat 1.2 m from the fill at an angle of 30° to the vertical and to two-thirds the depth of the peat; 2.2 kg of 50% ditching powder per meter of peat was then placed through the pipes which were spaced 2.5 m apart. One charge was detonated and the others fired sympathetically. The fill sank approximately 2 m. The operation was repeated for more complete displacement. The operation has been described as successful, and levels taken 6 and 18 months after construction revealed no appreciable settlement.

Canadian Industries Limited suggests the "underfill" method where the depth of organic material is more than 6.0 m. As the name implies, the unstable material is blasted out from under the fill, the charges being placed in the muck directly beneath the fill. It is essential to build up a proper surcharge of fill above grade level. Thus the force of the explosion will be confined by the weight of the overlying fill and by the hard bottom below, the major part of the thrust being directed laterally, pushing out the unstable material to the sides and allowing the fill to settle to a firm foundation.

Under average conditions approximately 0.2 kg of explosive per cubic meter of combined organic material and fill above the charges should be loaded. For average depths of muck and widths of road it is customary to load from 4.5 to 7.5 kg per meter of depth of unstable material in a single row of holes spaced 3 to 4.5 m apart along the center line of the roadway.

Panter (1960) notes that the best fill materials to use for "underfill" blasts are rock, gravel, or sand. Clays and silts are not desirable since they may result in some bridging or may become mixed with water during the blast.

Preconsolidation. Preconsolidation, a method often used to stabilize soft mineral soils, has been studied and used principally by the British Columbia Department of Highways (Brawner, 1958, 1959, 1961; Hillis and Brawner, 1961). A load in excess of that which will be finally carried by the soft ground is placed and allowed to settle until the ultimate settlement that would occur under the final load has been reached. The excess load is then removed and road construction is completed.

Brawner (1959) suggests that the major problems of low shear strength, high differential settlement, excessive quasi-deflection, and poor drainage characteristics can be overcome by preconsolidation. Low shear strengths can be increased by a slow rate of fill placement and shear failures can be prevented by the installation of field instruments that will indicate impending instability. Differential settlement can be maintained within tolerable limits by consolidating the peat during the construction period by an amount equal to or greater than that which would occur in 25 years if no surcharge were utilised. Quasi-deflection can be controlled by employing a depth of pavement (where "pavement" refers to the combined thickness of the asphaltic concrete and base gravel) not less than 1 m thick on the preconsolidated peat. The drainage problem is simplified, since drainage of the peat mass itself is not recommended. Where cross-drainage is necessary, temporary culverts can be utilised until settlement is largely complete and permanent structures installed.

Hillis and Brawner (1961) point out that observations have not been taken for a long enough period to prove that preconsolidation is completely successful as a highway construction technique in peaty soils. They note that effective preconsolidation will require that a reasonable ratio of surcharge load to final embankment weight can be obtained and that negligible continuing shear movements will occur under the final load. For high design loads it may be impossible to fill to the required surcharge heights. For these reasons they conclude that it is unlikely that the technique will be successful under high fills without recourse to lightweight materials.

Hillis and Brawner (1961) also outline some details and techniques of preconsolidation. These include:

    1. Three methods (two of which involve laboratory testing) of calculating long-term settlements,
        2. Two methods of calculating the surcharge required, and
        3. A method of adjusting the surcharge from field observations.

Brawner (1958), reporting on field tests, notes that vertical sand drains did not increase the rate of consolidation to any extent. Theoretically the rate should have increased 14 times or more. He concludes that the rate of consolidation in peat at this location was independent of the length of the drainage path. This interpretation of peat behavior has been presented previously by various investigators, based principally on field measurements (e.g., Lake, 1960). Brawner's field observations did reveal that the sand-drained area was more stable than the floating fill. Much less differential settlement occurred and no vibration or quasi-deflection under heavy traffic loads was noted where sand drains were placed. On the other hand Brawner reports that a floating area was subject to considerable vibrations. The sand drains therefore appear to act as piles carrying the load to a firm strata and the resultant greater stability is attributed to this factor.

Ripley and Leonoff (1961), in the study of embankment settlement on deep peat, conclude that the preloading method of inducing settlements of a completed fill may not be practical for floated fills placed above deep peat bogs because of the extremely slow rate of fill placement necessary to avoid rupture of the peat. On the other hand, if large shear deformations or rupture can be permitted, the fill may be placed more quickly and the preload method may be applicable. In such a case, however, the operation is considered to be a displacement fill rather than a truly floated fill. Ripley and Leonoff also found that large shear deformations occurred without evidence of a definite rupture surface. They were noted only as increased settlement. Their data also indicate that long-term settlements during the period normally attributed to secondary compression may amount to 50% of the total settlement. The settlement measurements reveal a high rate of continuing long-term settlements.

Pile foundations. Pile foundations transmit the weight of a road directly to some firm stratum underlying the muskeg. By this method all settlement is eliminated and there is a minimum of disturbance of the peat during construction. The use of pile foundations is very expensive and thus has been limited chiefly to roads in built-up areas where other methods of construction are inconvenient. The method has, on the whole, been restricted to Europe, particularly Holland, although it has been used and reported in the United States. Both wood and metal piles have been used to support highway slabs over poor ground, forming pavement bridges (Chellis, 1951). Creosoted wood-pile bents under concrete roads through peaty swamps have been used by the Illinois Division of Highways. Chellis also notes that monotube piles 6 to 20 m long were used to support a roadway slab over a muck pocket 180 m long on U. S. Highway 31 near Kokomo, Indiana. (For additional examples of pile foundations for roads on peat, see Engineering and Contracting, 1931; Engineering News-Record, 1960; Swart, 1954.)

Construction equipment

Thomson (1957) notes that the loads imposed by construction equipment on muskeg are usually greater than the traffic loads that are later transferred to the muskeg through a granular or clay fill. The cost of such roads has been substantially reduced in some Alberta operations by the use of light construction equipment, thereby reducing the depth of fill pushed down into the muskeg during construction.

Walsh (1957), in a description of secondary road construction for oil fields, notes that in normal soil conditions it is usual to supply crawler-drawn scrapers for hauls up to 175 m; for longer hauls, a switch to self-propelled rubber-tired scrapers is advisable. However, the use of self-propelled rubber-tired scrapers for grade construction of secondary roads requires the fill to be deeper than otherwise necessary; the larger the unit used the greater will be this increase in depth of fill. In addition he notes that a road of from 5 to 7 m in width is sufficient for the traffic requirements of secondary roads. The large self-propelled scrapers require turning radii in excess of 12 m. They must have good footing at all times and this requirement is more pronounced as the capacity is increased. Therefore, though a 6-m top grade may be all that is required, the factor of operating radius will increase width and consequently yardage. A crawler-drawn scraper can efficiently work on grades and even close to the toe of the fill as long as the power unit has some footing.

Walsh notes that one of the main arguments for self-propelled rubber-tired scrapers is their speed. However, in muskeg these machines begin to bounce at speeds of from 10 to 16 km/hr (6-10 mph). The grade that will carry such equipment at 13 km/hr may be completely flattened out and punched full of ruts when the speed is increased to 24 or 32 km/hr (15-20 mph). The use of the self-propelled scraper is not ruled out for construction of secondary roads over muskeg. However, Walsh makes the following points for their evaluation:

1. The shorter the turning radius, the more practical the unit,
2. Capacity is not as significant as in the construction of highways,
3. Speed of the unit does not pay off as it would on grades outside of muskeg,
4. A high horsepower yardage ratio is advantageous,
5. Low-pressure tires are important, and
6. As much clearance as possible is preferred under the power wheels.

From personal experience, Walsh suggests that a practical size of crawler-drawn scraper is a 7-m^3 scraper with a 101 hp (metric) tractor.

A dragline is generally used for the excavation of peat. For increased bearing, oversized tracks, up to 1 m wide, are sometimes provided. More commonly pads, made up of logs cabled and bolted together, are placed under the tracks of the dragline (Harrison, 1955).

Davis (1961) notes that, although draglines on mats have been used to do a limited amount of peat excavation during the summer months, success has been obtained in the late winter months by using a large bulldozer of the 26,000 kg class (57,000 lb). The peat at this time of year is quite dry and peat depths of from 1 to 2 m have been excavated by this method. The bulldozer works at right angles to the road axis and humps the peat up on the edges of the right-of-way where it is later levelled. The method is employed mainly on haul roads where there is a strong possibility of heavy summer pulpwood hauling. Davis reports that placement of fill in muskeg areas has been done by all three methods of straight tractor pushing, tractor-drawn scrapers, and by trucked-in fill. In the bush mat or floating method, draglines have also been used to cover the mat. The method used depends on existing physiographic and economic conditions.

Davis also reports a "communication" problem in organic terrain. Although an effort is made to carry a finished road as close as possible to the advance construction unit, there are times when certain pieces of machinery become isolated in the spring and summer. To fuel and serve these, rubber tracked vehicles with bearing pressures of 105 to 210 g/cm^2 (1.5-3.0 psi) have been used. Nevertheless, isolated machines can develop into quite a problem. It has been found that bulldozers of the 16,000 and 26,000 kg class with experienced operators can cross muskegs in single passes for fuel and servicing. Walking the bulldozers over muskegs, of course, does not apply to muskegs of the FI and EI cover classes.

Costs

Information on the costs of access in muskeg areas is scarce. The lack of information and the difficulties of correlating individual reports make costs estimates extremely

difficult. For convenience, individual published estimates of access costs have been subdivided into two categories.

Access costs (off-road vehicles). The technical and operational successes of special muskeg vehicles, while they demonstrate the feasibility of satisfactory transport in even the worst muskeg areas, do not mean that they are a cure-all for transportation in muskeg. Nuttall and Thomson (1960) estimate that the initial cost of special muskeg vehicles capable of carrying the unit loads required for a drill program is of the order of $4000 to $6000 per ton of capacity. This cost is high and there appears to be little that can be done to reduce it. First-class components and first-class workmanship are essential. A machine the size and complexity of the Musk-Ox can fail in so many different ways that only by extreme care in maintenance can a reasonable life expectancy be obtained.

The economics of tracked vehicle operation in muskeg have not yet been well established. Development of these vehicles has been carried on while the bulk of the machines are in field service. Thus it is difficult to separate operating and development costs. However, Thomson (1960) has estimated that tracked transportation machines can be operated for $1.00 to $2.00 per ton mile. The high cost can be justified only when road construction costs can be avoided or when access to a remote location at a particular time is worth a premium. For comparison, rail freight rates average 5 cents per ton mile and truck rates vary from 5 cents to 20 cents per ton mile on highways, and from 20 cents to 50 cents per ton mile exclusive of road costs on winter roads. A summer road over muskeg to a wildcat well will cost from $2000 to $12,000 per mile and will be abandoned after 1200 tons have been moved over it. The road charge is then $1.60 to $10.00 per ton mile and the total freight cost $1.80 to $10.50 per ton mile.

Despite claims to the contrary, some trail preparation is necessary, particularly for the larger, specially designed muskeg vehicles. Stoneman (1961b) reports on the use of two International Harvester TD-142 crawler tractors, fitted with 1-m wide tracks, to prepare trail for the Robin-Nodwell 10-Ton Transporter. On firm ground the surface cover was stripped and dozed to the side to make a 6-m wide trail. In the muskeg the timber and brush were "high-bladed" and then tramped into the muskeg's surface mat. Only trees larger than 20 cm in diameter were removed from the trail. To avoid driving into the tops of the fallen timber, .two one-way trails had to be prepared (one in each direction) so that the vehicles could travel with the lay of the timber. Trail construction costs averaged $300 per mile. Costs of winter trail preparation in the same area averaged $700 per mile. Stoneman further notes that summer road costs to carry conventional tracked units are estimated to be a minimum of $2000 per mile.

Road costs. The cost of winter timber-haul roads in muskeg areas varies from $150 to $600 per mile (Davis, 1961; Harrison, 1955). Davis (1961) reports the following figures for timber-haul roads constructed in the Kapuskasing area of Ontario, by both flotation and excavation methods.

     1. Brush mat or corduroy (18 in. thick) — 20 to 30 cents per lineal foot (18 to 36 ft wide)
     2. Excavation (bulldozer) — 22 cents per cubic yard
     3. Backfill — 20 to 30 cents per cubic yard
     4. Backfill, truck, winter operation — 86 cents per cubic yard
     5. Costs for haul roads have varied from a low figure of $3700. per mile (12 ft wide) to as high as $20,000 per mile.

Walsh (1957) reports the cost of oilfield access roads in Alberta to be 1.45 times the cost outside muskeg areas or approximately $10,000 per mile.

Capt. S. Thomson (1957) reports that the flotation method of road construction on the Alaska Highway System approximated $15,000 per mile for a 5-yr period. His figures for straight grading operations on the Alaska Highway indicated that highway sections with a high proportion of the road over organic terrain cost about 60% more to grade than sections over inorganic soil. He estimated about $100 to $150 per mile per year more than on roads over good soil. This is an average figure only and varies from section to section. Thomson also reports that the cost of bringing the road up to grade after placing

a fill on a muskeg will run about \$1500 to \$2000 per mile per year but it may be more depending on the gravel haul and the amount of material necessary. During the 3- to 5-yr period of settling of the road the surface required grading about three times as frequently as sections on mineral soils. Thus he estimated that the grading costs are three times above normal or approximately \$900 per mile instead of the usual \$300 per mile per year. Thomson also notes that for a stable road crossing organic terrain the life of the surface is shorter. Generally this is made up by patch surfacing which costs from \$800 to \$1000 per mile. If a grade rise of 3 ft is contemplated, then about \$8000 per mile is necessary if gravel is nearby.

Special Problems

Muskeg can also present many problems to other fields of engineering, such as building foundation design, and construction of railroads and airfields. The corrosive effect of muskeg and the importance of drainage also present problems.

In the case of small buildings, the peaty areas, where possible, are usually avoided or excavated. If, however, the peat deposit must be considered in the design, then it is usually treated in a manner similar to soft or unstable mineral soil.

For structures which cover larger areas, such as airfields or certain very large defense installations, avoiding or excavating muskeg still appears to be the economical approach. Airport building on New England bogs (Engineering News-Record, 1942) called for excavation of the peat and backfilling with stable material. Paralleling road construction experience, bulldozers were used on shallow peat excavations and for deeper excavation clam shell buckets were used with haul to spoil banks.

In northern railway construction on muskeg, Charles (1961) has suggested that the principal factor to be considered is location. Railways, to transport heavy loads, should be located with low ruling grades and minimum rise and fall. In this respect, railway location requires very much more care than highway location and, in seeking favorable grade, it may be more of a problem for railways to avoid unfavorable terrain. Railways, however, are not rigid structures; their design is fundamentally a problem of the flexible distribution of the heavy loads through the wheels to the rails, which are then bridged on ties and passed through the ballast and subgrade to the natural formation.

Charles has noted that the problem of construction across long continuous sections of muskeg can be overcome by laying skeleton track on the grubbed natural surface when frozen during winter and then lifting by train fill methods as soon as climatic conditions permit. Settlement must be expected and embankments should be constructed of additional width and height to provide for this. Track can be lifted and reballasted between the passage of trains without undue detriment to traffic.

Charles (1961) suggests rail of not less than 100 lb/yd as there is less deflection than with lighter rail. Adequate anchors per panel are essential to prevent rail creep. Longer track ties than normal assist in distributing loads and also reduce rail creep, which is aggravated by a comparatively soft road bed.

The dimensions of culverts should be sufficient so that they are never expected to carry more than one-half of their capacity. This is a precaution against continued settlement into the muskeg and possible distortion. Where there is a possibility of "icings" or the progressive accumulation of ice during winter, supplementary culverts should be installed at elevations above the highest ice level in order to insure a free drainage-way during the initial spring freshet.

Corrosion

The corrosive ability of muskeg and, in particular, the corrosion of concrete structures in muskeg have been of increasing concern during the past few years. In an excellent review and summary of this subject, MacFarlane (1961c) comes to the following conclusions:

1. Muskeg waters are usually, but not always, acidic and are therefore potentially aggressive to concrete and to metals.

2.   The hydrogen-ion concentration (pH) alone is not necessarily the only criterion for aggressiveness of muskeg waters. Of equal importance is the amount of dissolved salts in the water. Soft waters can be highly aggressive to concrete (see 4 below). Nonetheless, a low pH value appears to be an indication of potential aggressive action against concrete and appropriate precautions under such conditions are advisable.

3.   The color of muskeg water is not necessarily an indication of the degree of its aggressive effect.

4.   Running water is generally more dangerous than stagnant water since harmful substances are constantly renewed (i.e., pH is maintained at a constant level).

5.   Attack at a changing water-structure interface is usually stronger than attack on parts of the structure continually under water.

6.   Fresh concrete is more susceptible to attack than is old and age-hardened concrete. Consequently, precast concrete is more resistant to corrosion than cast-in-place concrete.

7.   Even if the concrete structure has ample strength to fulfill the purpose for which it was designed, it does not automatically follow that those parts subject to corrosion will resist attack and possible disintegration. Mechanical strength is therefore not necessarily related to resistance to corrosion.

8.   For any given cement, the less permeable the concrete produced, the greater will be the resistance to corrosion. It cannot be too strongly emphasized that concrete subjected to an aggressive environment should be dense and of high quality. The best cure for aggressive action is prevention.

9.   High alumina cements, as well as air-entraining agents introduced into the concrete, have produced concretes which are more resistant to attack than ordinary portland cement concrete.

10.   Most surface treatments applied to the concrete have a life considerably less than the design life of the structure and generally have not been too successful over a long period of time.

11.   Thin-walled concrete structures, such as drain tile, are much more susceptible to aggressive action than are mass concrete structures.

12.   In general, muskeg waters can be used for the mixing of concrete.

13.   Finally, with the use of high quality materials currently available and utilizing good workmanship to produce a reasonably impermeable concrete, together with any extra precautions which circumstances may dictate, there is no reason to expect that a concrete structure will not be highly resistant to any corrosive action of muskeg waters.

Drainage

The importance of drainage in muskeg areas is heavily stressed in almost every investigation of peat. Cuthbertson (1959) points out that... "Drainage is an essential feature of any land improvement in muskeg, whether the land improvement is directed towards agriculture, increased yield in forestry production, the exploitation of mineral wealth, or simply to enable transport to be undertaken over the muskeg areas." He notes the complexity of the problem in that... "There are many types of muskeg and each one requires a special technique in tackling the problem of drainage."

Although the importance and complexity of drainage in muskeg is universally acknowledged, only a limited number of investigations have been carried out on the subject, except perhaps in the U.S.S.R. (Kutais, 1955). The investigations of Conway (1960) on the hydrology of some peat-covered catchments point out the complexities of water storage capacities of some different vegetative surface covers. Ostwald (no date) divides peat water into five types:

1.   Water of occlusion, held in pores 1 mm or more in diameter,
2.   Capillary water,
3.   Colloidally bound or absorbed water,
4.   Osmotically bound water, and
5.   Chemically combined water.

Even though the fundamental principles of muskeg and peat drainage are not even partly understood, a considerable amount of empirical knowledge on the reclamation of peat through drainage is available (for example, Cuthbertson, 1959; Healy, 1961). For agricultural purposes, large areas of peat are drained by "underground," "tile," or "covered" drainage systems. There are many methods and techniques of accomplishing "underground" drainage and most utilize "tiles," timber box sections, mole drains, or perforated plastic pipe.

A common form of drainage used for agricultural reclamation and highway construction is the open drainage channel which carries off the surplus water from the land. Machines now in general use can cut a lateral or minor drain 1 m deep at a rate of 1.6 to 4.8 km/hr (1-3 mph)(Cuthbertson, 1959). For the mechanical preparation of main ditches, in both agricultural and highway applications, the most effective machinery is the dragline. In Cuthbertson's opinion, the dragline, although slow in operation and costly to operate, can at the present still handle a greater variety of conditions than any other type of machinery.

Brawner (1959) points out one of the few instances in which the provision of drainage is not a problem. In the preconsolidation method of highway construction over muskeg, he does not recommend drainage but notes that, if cross-drainage is necessary, temporary culverts can be utilized until settlement is largely complete and then the permanent drainage structure can be installed.

Frozen Muskeg and Permafrost

Muskeg and peat are most important factors in maintaining the natural stability of permafrost. The exact mechanism by which muskeg provides natural insulation to underlying frozen material is not known but is an active field of research today. Enough is certainly known of the interaction of muskeg and permafrost to point to the necessity of disturbing muskeg to the minimum extent possible. It has been noted that the thermal properties of muskeg are extremely complex. In the following some specific details on the relationship of the thermal properties of muskeg to permafrost (which have been observed by the author) are described (Legget and Pihlainen, 1961).

Field description. As would be expected, permafrost alters the surface and sub-surface of organic terrain in such a way that the classification used for a muskeg over unfrozen ground becomes, in certain instances, of doubtful validity. Thus some extension of the present field description of organic terrain appears to be necessary when permafrost is present.

The vegetative cover is presently described by qualities such as height, degree of woodiness, growth habit, and texture (Radforth, 1952). It has been suggested that some attempt should be made at the identification of species. In many cases, particular species or plant associations are invaluable for the inference of terrain properties in a permafrost area, particularly in exploratory engineering surveys.

At a first glance the identification of species may appear formidable. Fortunately, the most apparent indicators are trees and the number of northern species is limited to around seven, depending on the area. Shrubs are not generally regarded as important indicators, but in any case the number of northern species is also limited. Small, non-woody plants are numerous but, with some exceptions, their indicator value is in the plant associations or communities that they form.

Experience has shown that the 16 topographic features in the existing field classification of organic terrain (Table II) might be enlarged in permafrost areas. In such areas the organic cover is more extensive and not confined by relief to small areas. There it has been found useful to describe and identify the large-scale land form, and following this, the small-scale or micro-relief features. These micro-relief features are usually described with particular emphasis on slope, exposure to solar radiation and micro-drainage details.

As a first extension of the present method of describing the subsurface organic material, the amount and form of the enclosed ice must be taken into consideration. In a

description of ice in frozen soils (including peat), it has been found useful to subdivide the ice form into three groups in which the ice is: (a) not visible by eye; (b) visible by eye with individual ice layers less than 1 in. thick, and (c) visible by eye with individual ice layers greater than 1 in. thick.

A subsurface observation of great value in muskeg where permafrost is present is a record of the seasonal depth of thaw. Surface conditions such as vegetation, relief, and drainage drastically influence depth of thaw. Thus there can be considerable variation in the depth of thaw within an area as small as a 5-ft square. For this reason it has been found useful and even essential to make many random observations in areas of differing species or of diverse plant communities. It should be noted that the seasonal depth of thaw is the thawed zone at some particular time during the thawing season. Only at the time of its maximum depth (autumn) can it correspond to what is known as the "active layer". Since the maximum depth of thaw may occur when surface freezing is well advanced, it is necessary to record and describe the depth of thaw for the construction season and the maximum depth of thaw.

Special construction problems

The principal guide for construction design in muskeg areas underlain by permafrost is to minimize the disturbance of the natural organic cover. Unfortunately it is impossible not to disturb the cover to some extent and therefore some disturbance of permafrost is inevitable. For temporary construction, such as camp buildings, additional moss and peat may be used as insulation to keep the depth of thaw to a minimum. For permanent construction the design must be more elaborate and may incorporate several methods for minimizing thawing, protecting the permafrost, or dealing with results arising from thawing. Experience has shown, however, that the greatest success can be achieved by proper site selection.

Permafrost should be considered in trafficability over muskeg, although it is difficult to visualize terrain conditions in permafrost areas which are more severe for vehicles than those which have been experienced and solved farther south. The presence of perennially frozen soil at a shallow depth may actually be welcome, for it can provide a firm bearing for tracked vehicles. However, when the organic mantle is disturbed by repeated traffic, the permafrost table recedes very quickly, leaving a saturated mass of mascerated peat in a sloppy "guck." Since the underlying still frozen soil is impervious, this saturated condition of the peat is widespread and, except in the case of favorable natural drainage conditions, is not easily remedied.

As with most construction in permafrost areas, the design of roads across muskeg must be based on the preservation of the permafrost. Present practice is to place an additional insulating layer of organic material on the undisturbed road location.

Drainage in a muskeg area with permafrost is a special problem for two reasons:

1. The permafrost table may rise or seasonal frost may persist under the road fill, impeding or actually impounding natural drainage. These impounded waters, on the higher side of the road, can induce degradation of permafrost.
2. Ponding in ditches beside the road can cause permafrost degradation.

Both conditions can cause severe settlement of the road bed. For these reasons longitudinal subgrade drainage is best supplied by utilizing natural drainage with a minimum of ditching at some distance from the shoulder; low areas may be drained by lateral ditches which direct potential ponding areas to some distance from the road, and side hill road location should be avoided.

CONCLUSIONS

The implications of muskeg (organic terrain) and peat, with associated engineering problems, are still not fully appreciated. There are at least 900 papers related to peat, its uses and chemical, botanical, and engineering properties (personal communication, I. C. MacFarlane, Division of Building Research, National Research Council, Ottawa, February 1962). Yet many gaps exist and the lack of detail in specific facets is obvious.

The following conclusions and associated recommendations offer some suggestions whereby the many isolated studies could be integrated into a more comprehensive understanding of the engineering aspects of organic terrain.

1. The definition of muskeg proposed by Radforth is adequate.

2. The theory of origin of muskeg is extremely complex in relation to climatic, biotic, and geologic factors. A comprehensive theory is still wanted.

3. The extent of muskeg in North America and its relation to engineering problems has not been completely outlined.

4. Muskeg research in Canada is well integrated and, while the problems arising from muskeg are not so pressing in the United States, possibilities for some coordination might be explored.

5. A significant shortcoming in the knowledge of muskeg concerns "description and classification." The Radforth muskeg classification system has contributed much to the description of organic terrain. It is admirably suited for "areal" descriptions of muskeg and has been utilized successfully for a variety of "terrain access" or trafficability problems. However, the description of peat (or the "subsurface constitution" of muskeg) in the Radforth classification system has not been utilized extensively. This is due to the fact that the classification is mainly <u>qualitative</u> and visual, although certain aspects of "vehicle response" have been taken into consideration. Thus until a more <u>quantitative</u> description of peat itself is available, which can describe, among other things, composition, moisture content, permeability, colloidal properties, and possible structure, correlation of properties with engineering experience cannot be made.

In addition, the Radforth system implies, certainly for "vehicle response" (Radforth, 1956b), that the surface vegetation is an expression of underlying peats. The implication is that similar assemblages of coverage classes indicate peat of similar engineering properties. The question immediately arises as to whether this is correct. It would appear that research on a statistical basis is required to settle the problem.

There should be as wide an assessment of the Radforth classification as possible both in North America and Eurasia to determine the validity of the system as an indicator of the engineering properties of the subsurface peats.

6. Terrain assessment methods utilizing existing techniques of airphoto interpretation and the Radforth muskeg classification system are now so developed that no major shortcomings are apparent. However, a need is recognized for a constant review of new techniques and the accumulation of local or specific applications.

7. Quite apart from the lack of a general quantitative descriptive system of peat, which hampers the correlation of peat properties, there is still a lack of knowledge of specific engineering characteristics. For example, relatively little can be stated about the thermal and other physical properties which may have geophysical application.

Among the many index properties that have served in the past to describe peat, water content, unit weight, void ratio, and permeability are judged to be most effective for engineering purposes.

The shear strength of peat warrants a considerable amount of additional study. The further development of vane tests and the documentation of actual shear failures are considered to be a first approach to this end.

In general the consolidation of peat in laboratory tests shows agreement with field observations. At present there is not sufficient information for definite conclusions on many aspects of consolidation. Many questions on primary and secondary consolidation, rate of settlement, and plastic flow are still not fully answered.

Investigation of the bearing capacity (and shear strength) of peat and the complicated surface mat of living and dead plants with which it is associated has hardly been touched. The utilization of the Radforth muskeg classification system for a first correlation of bearing capacity and types of organic terrain is suggested. This is particularly important for vehicle development.

8. The design of vehicles for access over muskeg has progressed to a point where rational and sophisticated design appears possible. The variability of organic

terrain, vehicle requirements, and climate suggest, however, that no one type of vehicle can successfully meet all possible situations. However, when vehicle design is based on specific terrain conditions and loading, vehicle access over muskeg appears to be economically feasible for certain projects. The cost and maintenance of special muskeg vehicles will probably always be high and thus their effectiveness can be justifiably increased by additional planning employing preliminary terrain analyses.

9. A considerable amount of experience is available on the construction of roads over muskeg. For primary road construction, the techniques of preconsolidation offer a potential solution for some types of muskeg but, in many cases, excavation of objectionable material is highly desirable. The investigation of muskeg excavation techniques based on a more complete knowledge of the properties of muskeg is suggested.

10. Although secondary and tote road (including winter road) construction techniques are well established, considerable economies will be achieved by terrain studies for route location and construction material.

11. One of the most obvious gaps in the present knowledge of muskeg concerns drainage. Although the importance of drainage is stressed in almost every engineering paper on muskeg, very few specific investigations have been undertaken. Any future study of muskeg hydrology should be encouraged.

12. There is an interrelation between muskeg and permafrost. The role of vegetation and its influence on the energy exchange at the ground surface as well as the thermal properties of peat warrant considerable study.

RECOMMENDATIONS

1. A research program should be undertaken with the aim of classifying peat by its physical properties rather than by qualitative and visual methods.

2. A definitive study is needed to determine the extent and the objectionable characteristics of muskeg.

3. As military installations, for a variety of reasons, cannot be sited to take advantage of optimum terrain conditions, research on foundation design might also receive some attention. Certain aspects of this research could be carried out concurrently with recommendation no. 1.

4. In conjunction with other programs studying the problems of energy exchange in permafrost areas, particular attention should be given to the role of organic terrain and the thermal properties of peat. It is especially applicable where military installations or operations may cause aggradation or degradation of permafrost.

5. In view of the fact that little or no research has been carried out in the hydrology of muskeg terrain, some research should be undertaken in this direction.

6. Concurrently with recommendation no. 1, a program for developing vehicle design parameters in muskeg might be initiated, particularly if recommendation no. 2 indicates such a need.

7. While not an engineering or military problem, the theory of origin of muskeg still requires further study.

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APPENDIX A.

ATTENDANCE AND PARTICIPATION AT ACSSM MUSKEG CONFERENCES
(1955-1961)

(A denotes Attendance — P denotes Paper)

AGENCY	MUSKEG CONFERENCE*						
	1	2	3	4	5	6	7
FEDERAL DEPARTMENTS							
Agriculture, Soil Survey	-	A	-	A	-	-	A
Canadian National Railroads	A	A	A	A	A	A	A
Defence Construction Limited	-	A	-	A	A	A	-
Mines & Technical Surveys	-	-	-	-	-	-	-
Mines	-	A	-	-	-	-	-
Geological Survey	-	-	A	-	-	P	P
Public Works, Trans Canada Hwy.	-	A	-	-	A	P	P
National Defence, Army	A	A	P	-	A	A	A
RCAF	-	A	-	A	A	A	A
DRB	-	-	-	-	A	P	A
National Research Council	A	P	P	P	P	P	P
Northern Affairs & Nat. Resources	-	A	-	-	A	A	A
Transport	A	A	A	-	-	-	-
PROVINCIAL DEPARTMENTS							
Alberta, Highways	A	-	-	-	-	A	-
British Columbia, Highways	-	A	A	P	P	P	P
Manitoba, Health & Public							
Welfare	-	-	-	-	A	-	-
Public Works	-	-	-	-	A	-	-
Forest Service	-	-	-	-	A	-	-
Highways	-	-	-	-	A	-	-
Newfoundland, Bogland Development	-	-	-	P	A	-	P
Ontario, Highways	-	-	-	A	A	A	A
Lands & Forests	-	P	-	-	-	-	A
Hydro Electric Power							
Commission	-	A	-	-	-	P	P
Quebec, Highways	P	A	-	-	-	-	-
Public Works	-	A	-	-	-	-	-
Mines	-	A	-	-	-	-	-
Saskatchewan, Highways	-	-	-	-	A	A	P
Agriculture	-	-	-	-	-	A	-
Natural Resources	-	-	-	-	-	A	-

*LOCATION OF CONFERENCE (Total attendance in parenthesis)

1. Edmonton, Alberta, March 1955 (55)
2. Quebec City, Quebec, February 1956 (70)
3. Vancouver, British Columbia, February 1957 (58)
4. Ottawa, Ontario, March 1958 (59)
5. Winnipeg, Manitoba, March 1959 (112)
6. Calgary, Alberta, April 1960 (160)
7. Hamilton, Ontario, April 1961 (121)

APPENDIX A.

ATTENDANCE AND PARTICIPATION AT ACSSM MUSKEG CONFERENCES (Cont'd.)

AGENCY	1	2	3	4	5	6	7
UNIVERSITIES							
Alberta, Engineering	P	P	A	A	P	A	A
British Columbia, Civil Eng.	-	-	A	-	-	-	-
Geology	-	-	A	-	-	-	-
Laval	-	P	-	-	-	-	-
Manitoba, Arch. & Eng.	-	A	-	A	A	-	-
McGill, Geography	-	-	-	A	-	-	-
McMaster, Biology	P	P	P	P	P	P	P
Ont. Agri. College	-	-	-	-	A	-	A
Queens	-	A	-	A	-	-	-
Saskatchewan, Geology	-	-	-	-	-	A	-
Civil Engineering	-	-	-	-	-	-	A
Waterloo	-	-	-	-	-	-	A
Western Ontario	-	-	-	-	-	-	A
OIL COMPANIES							
Amereda Petroleum	-	-	A	-	-	A	-
Atlantic Refining	-	-	-	-	-	A	-
British American	-	-	-	-	-	A	-
California Standard	A	-	-	-	-	A	-
Canadian Fina Oil	-	-	A	-	-	-	-
Canadian Gulf Oil	A	-	-	-	-	-	-
Canadian Petroleum Assn.	A	-	P	-	-	-	-
Home Oil	-	-	-	-	A	P	-
Honolulu Oil	-	-	-	-	A	-	-
Hudson's Bay Oil & Gas	-	-	A	-	A	A	-
Imperial Oil	A	P	P	P	P	P	P
Mobil Oil	-	P	P	-	-	-	-
Ohio Oil	-	-	-	-	-	A	-
Oilwell Operators Ltd.	A	-	-	-	-	-	-
Pan American Petroleum	-	-	-	-	A	A	-
Richfield Oil	-	-	A	-	A	-	-
Shell Oil	A	A	-	A	P	P	-
Sohio Petroleum	-	-	-	-	-	A	-
Stanolind Oil & Gas	A	-	-	-	-	-	-
Texaco Exploration	A	-	A	-	-	A	-
Triad Oil	-	-	-	-	A	A	-
Union Oil of California	-	-	-	-	A	-	A
Western Minerals	-	-	-	-	-	P	-
CONSULTING ENGINEERS							
H. G. Acres	-	-	-	-	-	-	A
Blanchet, Trorey & Associates	A	-	-	-	-	-	-
Canadian-British Engineering Consultants	-	-	-	-	A	-	-
J. L. Charles	-	-	-	-	-	A	P
Geocon Ltd.	-	A	-	P	-	A	A
Haddin, Davis & Brown	-	-	-	-	A	-	-
R. M. Hardy & Associates	A	A	A	A	A	A	A
C. A. Meadows	-	A	-	A	-	A	-

ATTENDANCE AND PARTICIPATION AT ACSSM MUSKEG CONFERENCES (Cont'd.)

AGENCY	MUSKEG CONFERENCE						
	1	2	3	4	5	6	7
CONSULTING ENGINEERS (Cont'd.)							
J. D. Mollard & Associates	-	-	-	-	A	P	-
Montreal Engineering	-	-	-	-	-	A	-
Morton Engineering	-	A	A	-	-	-	-
C. C. Parker & Associates	-	-	-	-	-	-	A
Brian R. Perry	A	A	-	-	-	-	-
John A. Pihlainen	-	-	-	-	A	P	A
Racey, MacCallum & Associates	-	A	A	-	-	-	-
Ripley & Associates	-	-	A	-	-	A	P
Shawinigan Engineering	-	A	-	-	-	-	-
Stanley, Grimble & Roblin	-	-	A	-	-	A	-
Stock, Keith & Associates	-	-	-	-	-	A	-
R. C. Thurber & Associates	-	-	-	-	-	P	-
Wm. A. Trow & Associates	-	-	-	-	-	-	A
Underwood, McLellan & Associates	-	-	-	-	A	A	-
W. L. Wardrop & Associates	-	-	-	-	A	-	-
FOREIGN							
Caterpillar Tractor Co., Illinois	-	-	-	-	-	A	-
Connecticut State Hwy. Dept.	-	-	-	-	-	-	A
Cornell University, Civil	-	-	-	-	-	-	A
W. I. A. Cuthbertson, Scotland	-	A	-	-	P	-	-
Food Machinery & Chem. Corp., California	-	-	-	-	-	A	-
Michigan State Highways Dept.	-	-	-	A	-	A	-
Shell Oil Co., Houston, Texas	-	-	-	A	-	-	-
Shell Oil Co., Los Angeles	-	-	-	-	A	A	A
Tippetts, Abbott, McCarthy, Stratton, N. Y.	-	-	-	-	-	-	A
University of Maine	-	-	-	-	-	A	A
University of Minnesota	-	-	-	-	A	A	-
U. S. Geological Survey, Wash.	-	-	-	A	-	-	-
U. S. Corps of Engineers, SIPRE	-	-	-	A	-	-	-
U. S. Army, CRREL	-	-	-	-	-	-	A
U. S. Army, OCRD	-	-	-	-	-	-	A
U. S. Army, Quartermaster Command	-	-	-	-	-	A	A
U. S. Army, TREOG, Virginia	-	-	-	-	-	A	-
U. S. Army, Waterways Expt. Sta.	-	-	-	-	-	A	-
Wilson, Nuttall, Raimond, Mary.	-	-	-	-	-	A	A
MISCELLANEOUS							
Abitibi Power & Paper Co. Ltd.	-	A	-	A	A	-	-
Accurate Explorations	-	-	-	-	-	A	-
Bell Telephone Co. of Canada	A	P	P	A	-	-	-
Bombardier Snowmobile Ltd.	-	-	-	-	-	A	A
Brooks Equipment Co. Ltd.	-	-	-	-	A	-	-
Canada Creosoting Co. Ltd.	-	-	-	-	A	-	A
Canadian Aero Service	-	-	-	-	-	-	A
Canadian Brentel Ltd.	-	-	-	-	-	-	A
Canadian Car Co. Ltd.	-	-	-	-	A	-	-

ATTENDANCE AND PARTICIPATION AT ACSSM MUSKEG CONFERENCES (Cont'd.)

AGENCY	MUSKEG CONFERENCE						
	1	2	3	4	5	6	7
MISCELLANEOUS (Cont'd.)							
Canadian Industries Ltd.	-	-	-	-	-	-	A
Canadian Pacific Railways	A	-	-	-	-	-	-
Caterpillar Tractor Co.	-	-	-	-	-	A	-
Cyanamid of Canada	-	-	-	-	A	-	A
Dominion Rubber Co.	-	-	-	-	-	-	A
Geophoto Services	-	-	-	-	-	A	-
Geophysical Associates	A	-	-	-	-	-	-
Hunting Survey Corp.	-	-	-	-	-	A	A
Industrial Engineering Co.	A	-	-	-	-	-	-
Kimberly-Clark Pulp & Paper Co.	-	-	-	-	P	-	-
Manitoba Paper Co. Ltd.	P	A	-	-	A	-	-
Mannix Co. Ltd.	-	-	-	-	-	P	-
Marine Pipeline & Dredging Ltd.	-	-	-	-	-	A	-
Midwest Diamond Drilling	-	-	-	-	A	-	-
Northwest Telephone Co.	-	-	-	-	-	A	-
Ontario Paper Co.	-	-	-	-	-	-	A
Parker Drilling Co.	A	-	-	-	-	-	-
Patrick Farmer Ltd.	-	-	-	-	-	-	A
Peter Bawden Drilling Co.	-	-	-	-	-	A	-
Peter Kiewit Sons Co. of Canada	-	-	-	-	-	A	-
Phoenix Assurance Co.	-	-	-	-	A	A	-
Piggot Construction Co.	-	-	-	-	-	A	-
Powell Equipment Co.	-	-	-	-	A	-	-
Price Brothers & Co. Ltd.	-	A	-	-	-	-	-
Pulp & Paper Research Institute	-	A	-	A	-	-	-
Quebec Forest Industries Assn.	-	A	-	-	-	-	-
Robin-Nodwell Manufacturing	-	-	-	-	-	A	-
A. V. Roe Canada	-	-	-	-	-	-	A
Rupertsland Trading Co.	-	-	-	-	-	A	-
St. Anne Power Co. Quebec	-	A	-	-	-	-	-
Seismic Service Supply	A	-	-	-	-	-	-
Spartan Air Services	-	-	A	A	-	P	A
Spruce Falls Paper & Power	-	-	-	-	-	-	P
Standard Aero Engine Ltd.	-	-	-	-	A	-	-
Standard Gravel & Surfacing of Canada	-	-	-	-	-	A	-
Tract Equipment Limited	-	-	-	-	-	A	-
Trans Canada Pipe Lines	-	-	-	-	-	-	A
Toronto Industrial Leaseholds	-	-	-	-	-	-	A
United Geophysical Co.	-	-	-	-	-	A	-
United Trailer Ltd.	-	-	A	-	-	-	-
Velocity Surveys Ltd.	-	-	-	-	-	A	-
Arthur A. Voice Construction	A	-	-	-	-	-	-
Western Geophysical Co.	-	-	-	-	-	A	-

UNCLASSIFIED
1. Construction--Peat regions
2. Peat--Classification
3. Peat--Geophysical properties
4. Peat--Physical properties
5. Peat--Thermal properties
6. Peat (Construction material)
I. Pihlainen, John A.
II. U. S. Army Cold Regions Research and Engineering Laboratory
III. Contract DA-27-021-ENG-2

Accession No.

AD
U. S. Army Cold Regions Research and Engineering Laboratory, Army Materiel Command, Hanover, N.H. A REVIEW OF MUSKEG AND ITS ASSOCIATED ENGINEERING PROBLEMS -- John A. Pihlainen

Technical Report 97, Dec 1963, 56p - tables - app. DA Task 8S66-02-001-01; Contract DA-27-021-ENG-2 Unclassified

Towards a reassessment of muskeg, an appraisal of the problems of muskeg showing the complexity of the subject and the implications for engineering is presented based on field experience and a study of the literature. A theory of the origin of muskeg is given from the engineer's point of view by considering climatic, biotic, and geologic factors. Muskeg research in other countries is reviewed with emphasis on Canadian research. The Radforth Muskeg Classification System, its application to problems and modifications are discussed. Empirical data on the engineering properties of peat are broadly described in four main categories: (1) index properties, for identification; (2) strength and deformation properties; (3) thermal properties; and (4) geophysical properties. Engineering problems, construction equipment, and costs to ing problems, construction equipment, and costs to be considered in vehicle trafficability, road construction, corrosion and drainage operations, and   (over)

frozen muskeg and permafrost construction when muskeg is involved are fully discussed. Comprehensive conclusions and recommendations on the present state of knowledge of muskeg and needs for further research are outlined.

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