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STRATEGIC USE OF SOILS IN WAR OPERATIONS II

Trafficability of soils and methods of measurement

(A review)

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Introduction

The first requisite in the strategic planning of war operations is to know the trafficability of the soil in the operational area. Whether the tracked vehicles can move freely without bogging is a thing which must be ascertained by a previous survey. The need for a tank going map is obvious particularly when the soil is damp and swampy. Therefore production of tank going maps over large areas of soil which are likely to be the arena of war operations is of primary importance in the campaign.

In producing such a map it is necessary to understand the factors upon which the ability of a soil to support a tank depends and to develop for measuring the strength of soil, instruments which are light and simple in design, quick in action and capable of giving reproducible values irrespective of the operator. These conditions about the measuring instruments are of great importance particularly in tactical reconnaisance of ground in the field. Therefore an attempt is made in this paper to describe the physical characteristics of soil, its tank bearing property and the practical methods developed for measuring trafficability.

Trafficability of soils

The criterion of trafficability is the sinkage which the vehicle suffers while crossing the soil. The measurement of sinkage is closely related to the ability of vehicles to cross the terrain. If sinkage is small the probability of the vehicle bogging is small. The trafficability of soil depends not only on the soil properties but also on the vehicle.

Before proceeding with the description of the methods of estimating trafficability it is necessary to explain some of the physical properties of dry and wet soils which are responsible for its tank bearing capacity.

Consistency of soils

The physico-chemical properties of soils which affect consistency have been discussed in an earlier paper (9). Soil consistency is usually defined as a term " to designate the manifestations of the physical forces of cohesion and adhesion acting within the soil at various moisture contents. These manifestations include, (1) the behaviour towards gravity, pressure, thrust and fall, (2) the tendency of the soil mass to adhere to foreign bodies or substances and (3) the sensations which are evidenced as feel by the fingers of the observer," (10). The definition implies that the concept of soil consistency includes such properties of the soil as resistance to compression and shear, friability, plasticity, and stickiness. All these properties are manifested differently, as the forces of cohesion and adhesion vary within the soil.

The consistency of a soil varies with texture, organic matter, the amount and nature of colloidal material and especially with the moisture content.

The variation of moisture has a marked influence on soil consistency. At high moisture content, soil is viscous, and at low values soil is stiff, sticky and plastic. With further decrease in moisture content, soil loses its stickiness and plasticity and becomes friable. Finally, in the dry state it is firm and hard. The soil therefore shows different properties at different water contents.

Consistency of dry soil

There are different forms of soil consistency depending upon the dryness or wetness of the soil. A thoroughly dried soil with normal compaction exhibits considerable hardness or coherence. The extent of coherence depends upon the porous structure of the soil. The porosity in turn determines the amount of surface contacts of the soil particles. The coherence of dried soil depends upon the clay content, the shape (3) and size of the clay particles, the extent of surface contact and the magnitude of the surface forces.

In dried soil, the coherence is due to the attraction between the solid particles. Addition of small amount of water to form a thin water layer on the surface, reduces coherence and imparts friability.

Consistency of moist and wet soils

1. Friability.—Friability characterises ease of crumbling of soils. At the friability stage the moisture range is such that the individual soil particles are soft, cohesion is at minimum and the cementation effect least. There is not enough water for the formation of distinct films around particles to produce the cohesion that exists in the plastic range. The particles are probably held together by the orientation of water molecules between the individual particles. The dipole nature of water makes such oriented absorption possible.

2. Plasticity.—With increasing moisture content, friability changes over to plasticity. Mellor (8) defines plasticity as " the property which enables a clay to change its shape without cracking when it is subjected to a deforming stress ". Wilson (15) visualises plasticity as that property of a material which enables it to be deformed without rupture when the material is subjected to a force in excess of the yield value.

In the plastic state the clay particles are completely surrounded by water film. The cohesive forces between the particles in the plastic state varies with the thickness of the water film. Plasticity is a property which expresses the magnitude of the film forces within the soil and the effect of these forces in determining the extent to which the shape of the soil mass can be permanently changed without breaking.

Plastic flow is formulated by Bingham equation $V\text{-}k\mu(F—f)$, where V is volume of flow, μ is the coefficient of mobility, F is the force applied, f is the force necessary to overcome the cohesive forces of the system and just enough to start the flow (yield value), k is a constant. The difference between the viscous and plastic flow is in the existence of a certain pressure which should be applied to plastic bodies before flow is started.

ADHESION AND COHESION

Water film and cohesion

Adhesion refers to the attraction of the liquid phase on the surface of the solid phase. Cohesion in wet soils takes place between the molecules of liquid phase that exist as bridges or films between adjacent particles. Haines (7) has developed a theoretical concept of cohesion in an ideal soil on the basis of surface tension forces which arise from the water films between the particles. The ideal soil is looked upon as an aggregate of spherical particles arranged either in open or close packed state. At low moisture content, most of the film water exists as annular rings around the points of contact of soil particles. According to Haines the maximumcohesion is obtained at the moisture content at which a moisture film is established at all points of contact. Beyond this limit as the film thickness increases the cohesion decreases. The number of films is dependent upon the colloidal contents. Clay soils, therefore, exhibit higher cohesive forces than sands. Plate shaped particles produce greater cohesive effects than spherical ones.

Variation of cohesion with moisture

Starting with a pasty soil the cohesion increases with decreasing moisture content. At a certain stage an inflection in the moisture content-cohesion curve is noticeable. At this point the dark colour changes over to light brown indicating the limit of shrinkage of the soil and the entrance of air into the pores. Cohesion at moisture contents above this point is due to film forces and below this point to molecular attraction between the clay particles.

Factors affecting plasticity

Soil plasticity varies with the particle size and shape as it is a surface phenomenon associated with water films. Coarse particles exhibit no plasticity whereas fine particles favour plastic behaviour. Plate shaped particles are more plastic than spherical ones. Therefore plasticity is a function of the amount of surface and number of contacts per available surface.

The plastic behaviour of soils and its variation with water and clay contents have been adequately explained by the film theory of soil plasticity (3).

ATTERBERG CONSTANTS

Atterberg has defined the range of water content over which plasticity is manifested. The liquid limit is the moisture content at which the soil will just flow under an applied force and the plastic limit is the moisture content at which the soil begins to crumble when rolled into thin threads. The range of water content between the two limits is called the plastic range or the plasticity index when the limits are expressed in percentage (6).

Significance of Atterberg constants

The plastic limit represents the moisture content of the change from friable to the plastic consistency. Orientation and sliding over of particles take place at this point as there is sufficient water to provide film round each particle. Cohesion is at the maximum at the plastic limit. The liquid limit signifies the moisture content at which the water film becomes so thick that cohesion is decreased and the soil mass flows under an applied force.

A low plasticity index indicates a soil of silty or sandy nature *i.e.* only a small addition of water is required to transform it from a solid material to something closely resembling a liquid. A high plasticity index indicates a high proportion of clay and organic matter in the soil. The liquid limit in particular is very sensitive to the amount of colloidal matter and with certain soils it increases almost linearly with the percentage of clay in the soil.

Factors affecting the Atterberg constants

1. *Clay.*—Increase in the clay content increases both the plastic and liquid limits and also the plasticity index. According to Russell (11), plasticity index is a linear function of the clay content, soil containing less than 15% clay is not plastic.

2. *Nature of soil.*—Minerals that have plate or sheet like structure exhibit plasticity.

3. *Chemical composition of colloid.*—The plastic range on the moisture scale is lowered by a small silica-sesquioxide ratio when two soils with the same clay content but different chemical composition are compared.

4. *Nature of exchangeable cations.*—The three Atterberg constants vary according to the nature of the ion. The following ions of Na, K, Ca and Mg behave differently. The plasticity increases with the hydration capacity of the ions.

5. Organic matter.—Removal of organic matter by oxidation lowers the plastic and liquid limits. The plasticity index however is not materially changed.

LABORATORY METHODS OF DETERMINING SOIL PLASTICITY

In determining the ability of the soil to carry traffic, the fundamental property of the soil which is of importance is the resistance which it offers to shearing forces. Therefore measurement of shearing resistance is indispensable. Determining shearing resistance is a skilled laboratory work requiring experienced workers and complicated apparatus. Portable instruments such as unconfined compression machines, the vane and varieties of penetrometers have been developed.

1. *The flow of clay paste through capillary tubes.*—The method is most widely used. When a clay paste is forced through a capillary tube there are four stages in the volume of flow-pressure curve. The yield value of Bingham is obtained and this represents the shearing strength of the material. It is

also called " static rigidity " by Keen and Blair. This represents the energy that is required to produce flow and is considered a measure of the cohesive properties of the system (4, 5).

2. *Determination of the Atterberg constants.*—The liquid limit was determined by Atterberg (1,2) by placing a small amount of soil in a round bottomed dish working it into a stiff paste, pressing it lightly against bottom, cutting a V shaped grove in the plastic mass and jarring the dish to make the two segments flow together. If flow was not produced additional water was added and the process was repeated. If too much flow was obtained dry soil was mixed with the plastic mass. This process was repeated until the correct flow was obtained. The moisture content of the plastic soil was then determined.

The plastic limit is determined now in the same manner. Dry soil is mixed with water in a round-bottomed dish until it begins to lose its crumbly feel and shows a tendency to become plastic. The mass is then kneaded in the hands. A small portion is rolled between the fingers and a glass plate or piece of glazed paper until a wire is formed. The process of adding water or soil is repeated until that moisture content is reached at which the plastic mass will just barely roll out into a wire that breaks into pieces about 1/4 to 3/8 inches long.

FIELD METHOD OF ASSESSING TRAFFICABILITY

1. *Moisture content as a measure of soil sinkage.*—In the study of the trafficability of soil, attempt has been made to measure the soil sinkage produced by the movement of a vehicle and relate the sinkage with the moisture content of the soils. The sinkages were measured by taking the depth of the ruts left by the tracks by a simple and easy device. The moisture content was determined by taking out a vertical plug of soil from just below the surface. A plot of the vehicle sinkage against moisture content indicates a simple linear relation between the two quantities.

Knowing such a relation with respect to a particular vehicle and soil, measurement of moisture content of the soil by a simple and a quick method will be helpful in assessing a value for soil sinkage or the trafficability of soil.

2. *Penetrometer.*—The instrument consists of a coiled spring and a plunger in a tubular case. On releasing the compressed spring the plunger is driven into the soil. The depth of penetration of the plunger indicated on a scale is a measure of the strength of the soil, all the variable conditions kept constant. If the instrument is calibrated with respect to soil sinkage for a particular soil and vehicle it affords a very simple and convenient method of assessing soil strength.

In a trial for each penetrometer reading the vehicle sinkage and moisture content of the soil are also measured. The results show that the penetrometer can be used to give an indication of the likelihood of bogging.

3. *The Fissure test.*—In view of the non-availability of skilled labour required for certain methods of measuring plasticity constants and the limited time within which the tank going maps are to be prepared, it is desirable to have some simple non-instrumental field tests which could be made by unskilled workers and yet would enable inferences of quantitative nature to be drawn about the strength of the soil. One such simple test called " The fissure test ' has been developed by Evans (6).

With gradual decrease of water, a pat of wet soil exhibits changes in consistency. The fluid mass becomes sticky, then plastic and nonsticky and then moist but crumbly. There is a certain stage between the plastic and crumbly consistency which can be defined with precision. A small ball of soil exhibits at this stage a net work of fine cracks on the surface. On squeezing the ball the cracks develop into large fissures around the periphery of the flattened pat. The moisture content at this stage is termed the " fissure limit " of the soil. The condition is reproducible with accuracy. It represents a visible and quite a rapid change in the physical condition of the soil. This affords a method of developing a simple and ready test called the " fissure test".

The strength at the " fissure limit " is measured for a large number of soils. Cohesion at the " fissure limit " is plotted against plasticity index. There is a decided trend for cohesion to increase with plasticity index i.e. in general with the clay content of soil. The shearing resistance of soils at the " fissure limit " varies from 4 lbs./sq. inch for medium clay loams to about 2 lbs./sq. inch for sandy loams and silty and organic loams.

The bearing capacity for a smooth continuous footing is about 5 times the shearing resistance of the soil on which it rests (13). The measurements above indicate a bearing capacity of 20 lbs./sq. inch to 10 lbs./sq. inch.

Most heavy tanks are built to about the same nominal ground pressure of about 12 lbs./sq. inch. Knowing the exact nominal ground pressure of the vehicle and the bearing capacity of the particular soil at the " fissure limit " it is possible to decide about the trafficability of the soil at the " fissure limit ". Based on the conventional standard of the nominal ground pressure, the " fissure limit " can be said to be the approximate limit on one side of which the trafficability is safe and on the other uncertain. With vehicles of different nominal ground pressure, it is possible to have a comparative idea of their performance at the " fissure limit " of any soil.

If the soil is drier than " fissure limit " tank going is safe but if wetter difficult or impossible for tanks designed to the conventional standard of nominal ground pressure. The " fissure limit " is simple and easily adaptable for field work. It can be used for both strategic and tactical purposes.

ASSESSMENT OF TRAFFICABILITY AND TANK PERFORMANCE

Methods of assessing trafficability of soils and tank performance have been developed. " One method of assessing the trafficability of a soil is to state the sinkages of a given tank at given moisture contents. Similarly the performance of a tank over a given soil can be specified as a sinkage at a given moisture content. However neither of these methods is helpful in indicating the chances of bogging.

APPLICATION OF ATTERBERG CONSTANTS AS A MEASURE OF SOIL STRENGTH

The possibility of applying Atterberg constants as a measure of soil strength has been studied. The results are far from being satisfactory. " Though Atterberg limits are correlated with many properties of soil, they do not help in cataloguing in a simple way the strength of soil in the field. The range of strength between the two limits is enormous. London clay has a cohesion (i.e. shearing resistance per unit area) in the region of 30 lbs./sq. inch at the plastic limit (19·8% of dry weight of soil) and of the order of 0·1 lb./sq. inch at the liquid limit (69% of dry weight). It is not enough to say of a soft soil that its water content lies between the liquid and plastic limits. This might be said of practically all soils which give trouble to vehicles but the condition applies over a range of strength of more than a hundred fold. At a moisture content below the plastic limit the soil is usually firm and unlikely to give trouble. Above the liquid limit the soil is incapable of support " (6).

TANK GOING IN RELATION TO PLASTICITY INDEX

Smith (12) has studied the trafficability of different sois in relation to their plasticity indices. The results of his analysis have been indicated in Table I.

TABLE 1

Serial No.	Tank going conditions	Type of soil	Plasticity index
1	Good going under all conditions ..	Medium to heavy clays..	15-70.
2	Going liable to deteriorate, Soil friable and can be incorporated with water. Treacherous after cultivation.	Light soils—sands and silts colloidally inactive clays.	Less than 15.
3	Bad going under all conditions. Low strength below surface crust. Strength reduced when soil is churned by tank track.	Oganic soils—peats and loams, colloidally active clays.	Greater than 70.

Atterberg limits provide a fairly reliable method of measuring trafficability.

COMPARISON OF TANK PERFORMANCES

For comparing performances of different tanks it is necessary to construct curves relating moisture content and sinkage with references to a standard soil. From these curves the relative performances of various tanks can be studied.

TYPES OF SOILS AND LIQUID LIMIT-PLASTICITY INDEX RATIO

A system of classifying soils has been developed by A. Casagrande (6) in which the liquid limit is plotted against plasticity index for different varieties of soils Fig. 1. If the type of soil is known it is possible to obtain from the above figure, the plastic limit of the soil. Knowing the shearing resistance of the soil at the plastic limit, it is possible to form an idea of its tank bearing capacity

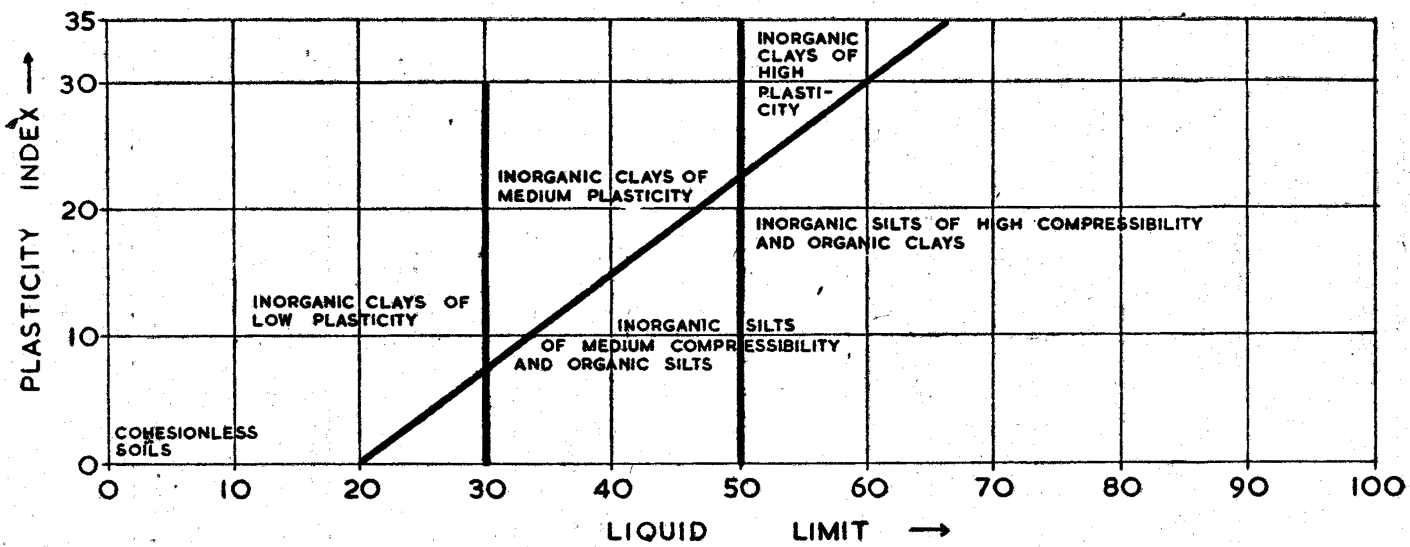

FIG I LIQUID LIMIT PLASTICITY INDEX CHART BY A CASAGRANDE

TRAFFICABILITY OF ALLUVIAL SOILS

A survey has been made of alluvial soils in regard to their properties, strength characteristics and trafficability (12).

Prediction of the bearing capacity of alluvial soils is particularly difficult in view of the fact that it is a deposit carried from a distant and uncertain source such that the solid geology of the area over which it is deposited gives no clue to the nature of the soil.

Shearing strength of soil was determined with a vane. Information regarding vegetation, land utilization, drainage and water level in the ditches at each site were obtained. Auger soil samples were used for determining moisture content, Atterberg limits and mechanical analysis.

A common feature of all alluvial soils is that they are water logged at a few feet below if not at the surface.

Strength profile of alluvial soils

The soil strength profiles as determined by the vane are of three different types.

1. The profile of a normally consolidated soil.

The profile indicates a uniform cohesion of about 7 lbs./sq. inch upto a depth of 15″ and later the strength steadily decreases to 5 lbs./sq. inch at 22″ depth and 1-2 lbs./sq. inch at 5-10 feet depth.

The profile in summer conditions indicates slightly higher values of strength upto a depth of 12″ owing to drying of the surface. Beyond 12″ the profile is the same and this indicates the absence of drying below 12″.

2. The profile of a soil consolidated by being raised above water level at some time since deposition.

The profile shows steady increase in strength from a cohesion of 8 lbs./sq. inch at 4″ to about 12 lb./sq. inch at 15″. The softening near the surface is probably due to the development of a top soil in the agricultural sense associated with an increase in root development and general organic content.

3. The profile characteristic of soils which support marsh vegetation.

The profile exhibits a rapid decrease in strength with depth. The cohesion at the surface is about 7 lbs/sq. inch and about 4 lbs./sq. inch at a depth of 12″ with a further fall to 2 lbs./sq. inch at 24″. Such a characteristic profile is not connected with any seasonal desiccation of the soil but is connected with marsh vegetation likely to be troublesome to vehicles.

The possible distribution of these three different types of soils has also been discussed by the author (12).

TRAFFICABILITY OF PEATY SOILS

An extensive survey of some of the peaty soils of Great Britain has been made by Smith (13) with the object of measuring their shearing resistance for producing trafficability maps. Peat formation has been indicated. Different types of peaty soils are classified. The factors affecting the peat strength are discussed. The factors which determine the strength are (1) the degree of humification (2) the mineral content and (3) the moisture content.

Strength profile of peaty soils

The strength profiles of different peaty soils have been determined. All peats which have not dried out, and which retain elements of their original vegetation have strength profiles of similar form. For moss peats the strength profile exhibits a linear decrease in strength with depth from a shearing resistance of $2\frac{1}{2}$ lb./sq. inch at 4 inches, to about $\frac{1}{2}$ lb/sq. in. at 22 inches. For fen peats these values should be increased by 1 lb./sq. inch a tall depths.

VEGETATION AND TANK SINKAGE

There is often a large scatter in the tank sinkage-soil moisture graph and this is due to error caused by dense vegetation in the measurement of sinkage. Vegetation on the surface of the soil can offer resistance to the force of the wheel of the moving vehicle. The vegetation provides an excellent mat on which the tank track could grip and probably reduce sinkage to some extent.

NONHOMOGENEITY OF SOIL AND TANK GOING

In addition to the effect caused by surface vegetation, the nonhomogeneity of the soil beneath the surface is another factor which vitiates the measurement of tank sinkage by the various methods. The decision on the trafficability of the soil based upon these measurements will consequently become unreliable.

CONCLUSION

The existing literature on soil strategy is meagre. The problem of trafficability of soils for strategic and tactical use is of great importance and needs extensive investigation. Practical methods of measuring trafficability of soils which are useful for field work are few. New methods and instruments which are simple and light in design, quick in action and of a fairly high degree of accuracy and reproducibility must be developed.

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