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A Review of Soil Strength Measurement Techniques for Prediction of Terrain Vehicle Performance

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This paper reviews techniques for measurement of soil strength and makes recommendations for suitable methods for off-road vehicle performance prediction. The cone penetrometer and bevameter were found to be the most appropriate largely because they enable measurements to be made in situ. However, even though the penetrometer is the only technique that can assess variation of soil resistance with depth, neither the cone index nor its gradient with respect to depth is uniquely related to soil cohesion or density, but varies with moisture content and structural state. Furthermore, the formation of soil bodies and compaction zones ahead of the cone effectively changes its geometry and the penetration no longer reflects the original properties of the soil. On the other hand, the bevameter technique only characterizes surface soil properties. Nevertheless, the bevameter provides the closest simulation of vehicle-terrain interaction among all the currently available techniques. The main criticism of the bevameter and also of the penetrometer is that the sizes of the penetration and grouser plates and the cones, respectively, are too small.

1. Introduction

The key to off-road vehicle performance prediction lies in the proper evaluation of the strength properties of the terrain and this has long been one of the main objectives of terrain vehicle mobility research. In the early days of vehicle mobility research, several devices were tested at the US Waterways Experiment Station (WES) and it was concluded that a cone penetrometer was a simple instrument that would give the most consistent and reliable results.[1] Results obtained by Mulqueen *et al.*,[2] however, dispute this claim. In 1954, a cone penetrometer with a base area of 3·23 cm^2 was standardized by WES for field application and this is still in use today. Other techniques currently in use for soil strength measurement include the bevameter, direct shear test, triaxial shear test, shear annulus and vane shear test.

The bevameter and cone penetrometer are the two techniques most frequently used in the field. The bevameter consists of a shear annulus which is rotated to measure shear stress and a plate which is pushed vertically into the ground to measure normal pressure. The cone penetrometer consists of a steel cone mounted on a steel rod which is pushed vertically into the ground. It shears and compresses the soil simultaneously and records the resulting force as a single unit of measurement called the cone index, *CI*. Other techniques such as the shear vane and shear annulus measure shear stress only.

Soil deformation due to wheel or track motion on soft terrain is dependent upon the appplied forces as discussed by Chang and Baker.[3] In order to predict these forces accurately, soil strength parameters and soil deformation along the paths of all the points on the wheel or track to soil interface must be measured. Since the wheels and tracks apply both normal and shear stresses to the soil, in the process of sinking and developing traction, it would seem reasonable to evaluate these parameters by applying normal and shear stresses to the soil simultaneously. It is therefore important to select or design

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Notation

A_u	parameter characterizing terrain response to repetitive loading, kN/m^4
CI	cone index, kN/m^2
K	shear deformation modulus, mm
K_r	ratio of residual shear stress to maximum shear stress
K_w	shear displacement where maximum shear stress occurs, mm
T	torque, kNm
a	soil-rubber adhesion, kN/m^2
b, b_1, b_2, b_3	width of a rectangular plate or radius of a circular plate, m
c	soil cohesion, kN/m^2
d	diameter of shear vane, mm
h	height of shear vane, mm
j	shear displacement, m
k_o	parameter characterizing terrain response to repetitive loading, kN/m^3
k_1, k_2	slip coefficients
k_c	Bekker soil sinkage constant related to soil cohesion, kN/m^{n+1}
k_ϕ	Bekker soil sinkage constant related to soil friction, kN/m^{n+2}
k_u	parameter characterizing terrain response to repetitive loading, kNm^{-3}
n	plate sinkage exponent
p, p_i	ground pressure, kN/m^2
r_o, r_i	outer and inner radii of shear head, m
z	plate sinkage, m
z_u	sinkage where the unloading-reloading cycle begins
γ	soil bulk density, kg/m^3
δ	angular displacement of soil shear head, mm
δ_r	soil-rubber friction angle, radians
δ_s	soil-steel friction angle, radians
σ	normal ground pressure distribution, kNm^{-2}
τ	shear stress, kN/m^2
τ_{max}	maximum shear stress, kN/m^2
φ	angle of soil friction

equipment that can both simulate the vehicle action and measure the strength and sinkage soil values (i.e. shear stress, shear strain and normal stress) most accurately at the correct speed.

2. Review of soil strength measurement methods.

Surface soil density and the relevant soil strength parameters are very important in various aspects of agricultural engineering research. One important example is the prediction of forces associated with terrain vehicle performance which generally requires both the soil composition and strength parameters to be known.[4–12] These parameters are dependent on the particular methods of force prediction used[10–19] as reviewed by Plackett.[5] In this section, the different techniques used for evaluating strength/deformation properties of surface soils are reviewed pointing out their advantages and disadvantages.

2.1. *The cone penetrometer*

The penetrometer[20] consists of a right circular 30° stainless steel cone with a base area of 3·23 cm^2 mounted on a circular cross-section stainless steel shaft 15·9 mm in diameter shown in *Fig. 1.* The value of *CI* is defined in terms of the average load exerted by the soil upon the conical head forced down to a depth to which the traction device is expected to sink. It is a compound parameter involving components of shear, compressive and tensile strengths as well as soil-metal friction.[21] Originally, penetrometers were designed to provide a "go/no-go" index for field use by vehicle operators.[22]

Variations of soil properties with depth can be very large. This is illustrated by Wismer and Luth[11] (*Fig. 2*) who give some examples of variations of *CI* with depth. The value of *CI* usually used for prediction of tyre or track traction performance is the average value over a depth that includes or corresponds to the maximum tyre or track sinkage. While the measurement of *CI* with respect to depth is certainly important for purposes of characterizing soil resistance at different depths, it is questionable whether the average value of *CI* is accurate enough for prediction of tractive performance.

Other authors[20,23–25] also studied the relationship between *CI* and compaction, moisture content, clay ratio and soil types characterized by parameters such as cohesion, c, friction angle, ϕ, and bulk density, γ. Freshly tilled soils will compact and increase in strength under heavy tyre loads. *CI* measured after traffic may be several times greater than that measured before traffic. Ayers and Perumpral[24] prepared soil samples by placing them in a mould in layers and then applying a predetermined number of hammer blows per layer. Average dry density was determined by first weighing the mould empty and then with the compacted soil sample. Penetration tests were conducted on the compacted soil in the mould and the average moisture content (dry basis) was determined by taking a small compacted soil sample. They found that for a given soil type and

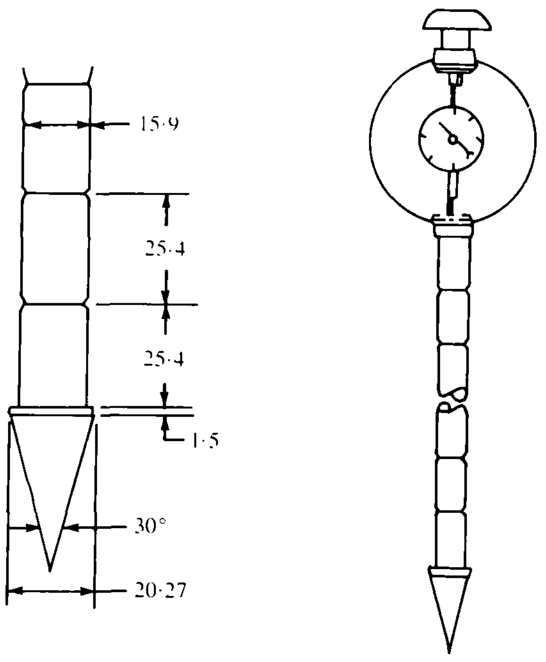

Fig. 1. Soil cone penetrometer (all dimensions in mm) (Reproduced by permission of the American Society of Agricultural Engineers)

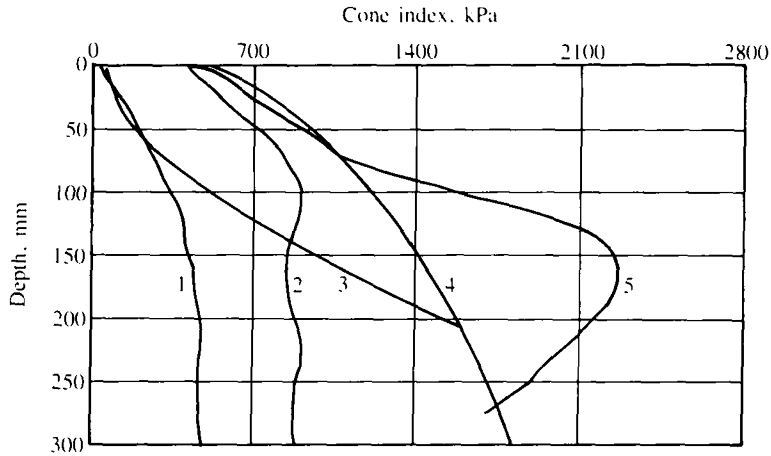

Fig. 2. Typical cone index-depth curves. (1) Silt loam (before corn planting) (2) Silt loam (after corn harvest) (3) Silt (disked wheat stubble) (4) Silty clay loam (after scraper cut) (5) Sandy loam (after maize harvest) (Wismer and Luth,[11] reproduced by permission of Pergamon Press)

different degrees of compaction, *CI* varied widely with water content as shown in *Fig. 3.* Measurement of *CI* in the field could give some indication of compaction. There is, however, no satisfactory technique devised to predict traffic-related measurements of *CI* or indeed other forms of compaction.

For any given soil type, *CI* drops virtually to zero as the moisture content increases. This is shown in *Figs 4* and *5* where the results of the effects of moisture content and soil type on dry density and cone index are presented.[24] The vertical lines marked on the

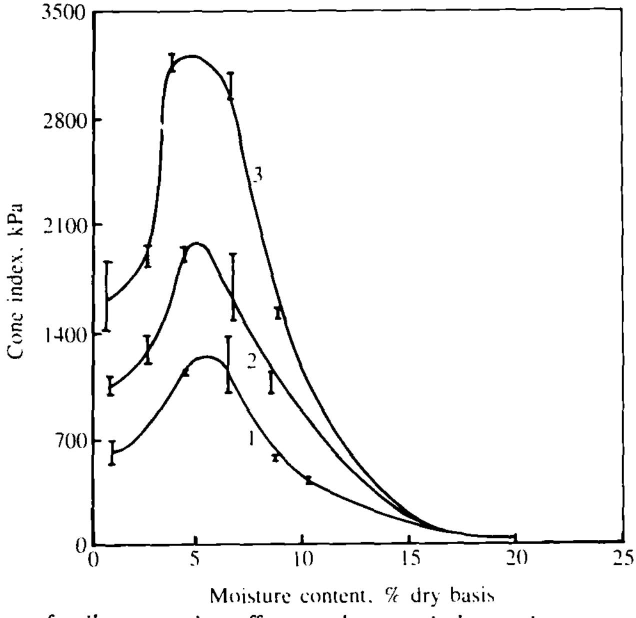

Fig. 3. The influence of soil compaction effort on the cone index-moisture content relationship (50% clay–50% sand). (1) 3 blows/layer (2) 6 blows/layer (3) 12 blows/layer (Ayers and Perumpral,[24] reproduced by permission of the American Society of Agricultural Engineers)

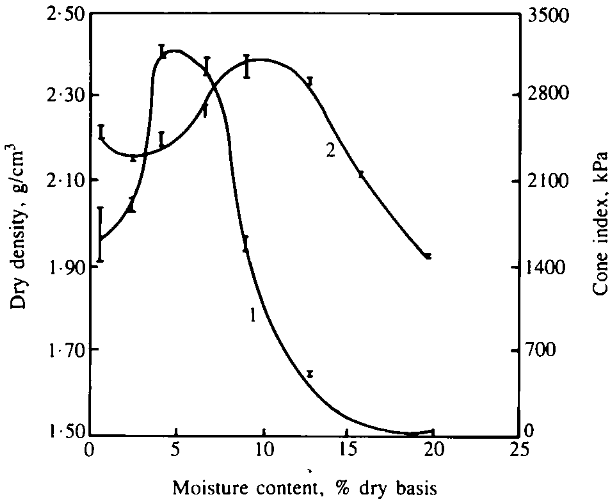

Fig. 4. Effect of moisture content on dry density and cone index for a 50% clay/50% sand soil at 12 blows/layer. (1) Cone index (2) Dry density (Ayers and Perumpral,[24] reproduced by permission of the American Society of Agricultural Engineers)

curves of *Figs 3, 4* and *5* represent the range of observations made at particular moisture contents with fitted curves drawn through them. At 20% moisture content, *CI* for a 50% clay/50% sand soil is zero. It is, however, true to say that because of the bigger surface area presented by a larger cone, the use of the latter would certainly give some value of *CI* for this condition.

Table 1 produced by Dwyer *et al.*[7] shows some field test results obtained by averaging the values of *CI* taken starting with the base of the cone flush with the ground surface and

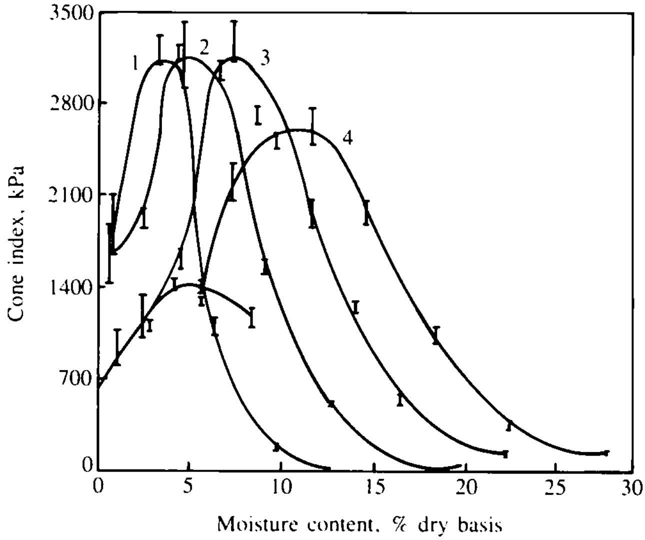

Fig. 5. The influence of soil type on the cone index-moisture content relationship (12 blows/layer). (1) (25% clay/75% sand) (2) (50% clay/50% sand) (3) (75% clay/25% sand) (4) 100% clay. (Ayers and Perumpral,[24] reproduced by permission of the American Society of Agricultural Engineers)

Table 1
Field conditions and soil measurements (Dwyer *et al.*[7])

Field no.	Tyre series tested	Date	Location	Soil	Surface	Moisture content, %	$CI\ \frac{kN}{m^2}$	$c,\ \frac{kN}{m^2}$	$\tan\phi$	K mm	k_c	k_ϕ	n	$\tan\delta_s$	$a,\ \frac{kN}{m^2}$	$\tan\delta_r$
1	I	22.10.71	Wrest	Clay loam	Stubble	39·7	507	32	0·23	—	—	—	—	—	—	—
	II	26.10.71	Park			37·2	514	26	0·38	5·8	−2 130	21 000	1·23	0·34	16	0·45
2	II	28.10.71	Wrest	Sandy loam	Ploughed	13·5	192	0	0·65	12·3	129 000	−150 000	2·76	0·39	7	0·46
	I	1.11.71	Park			14·6	210	0	0·61	18·1	−26 700	235 000	2·57	0·38	9	0·47
3	I	2.11.71	Silsoe	Loam	Stubble	20·7	960	5	0·67	11·3	−1 380	20 000	1·20	0·39	3	0·53
	II	4.11.71				21·5	867	0	0·73	10·0	−4 050	55 200	1·31	0·40	0	0·50
4	II	25.11.71	Wrest	Sandy loam	Grass	23·5	1 057	23	0·57	10·1	−31 000	237 000	1·65	0·42	21	0·44
	I	2.12.71	Park			24·0	955	43	0·38	8·8	−11 800	129 000	1·43	—	20	0·42
5	I	3.12.71	Silsoe	Clay	Ploughed	44·7	278	25	0·24	13·1	—	—	—	—	50	0
	II	7.12.71				43·6	236	25	0·31	17·0	297	1 750	1·27	0·25	26	0·25
6	I	10.12.71	Silsoe	Sandy clay loam/clay loam	Stubble	27·7	433	25	0·32	10·4	−45	2 380	0·80	—	—	—
	II	14.12.71				26·1	486	21	0·42	11·0	199	1 190	0·64	0·41	37	0·32
7	II	15.12.71	Silsoe	Clay	Ploughed	25·6	350	16	0·45	11·0	−2 960	15 800	1·46	0·42	37	0·32
	I	30.12.71				31·0	200	10	0·38	9·1	—	—	—	0·29	45	0·11
8	I	6.1.72	Wrest	Sandy loam	Stubble	22·6	695	24	0·27	4·9	120	7 670	1·07	0·39	13	0·36
	II	10.1.72	Park			23·8	617	24	0·25	6·5	741	−1 120	0·66	—	50	0·18
9	II	12.1.72	Wrest	Sandy loam	After	25·3	690	5	0·43	7·2	−1 500	10 200	0·90	—	20	0·25
		14.1.72	Park		sugar beet	24·5	662	10	0·41	6·8	−107	3 550	0·73	0·28	19	0·25
10	I	17.1.72	Wrest	Sandy loam	Ploughed	23·0	112	23	0·15	9·1	185	1 080	1·08	—	58	0
	II	29.2.72	Park			22·2	250	22	0·28	14·0	148	1 860	1·09	0·31	36	0·23
11	II	2.3.72	Maulden	Sandy clay	After kale	11·7	785	18	0·24	8·8	−9 050	65 500	1·28	0·37	34	0·25
				loam		11·8	754	6	0·38	5·7	−1 550	22 900	1·15	0·35	27	0·28
12	I	15.3.72	Little	Sandy clay	Stubble	20·8	426	39	0·09	6·3	739	−155	0·85	0·48	56	0·23
	II	22.3.72	Barford	loam		17·4	576	34	0·31	8·7	410	33 900	0·96	0·48	10	0·57
13	I	16.3.72	Little	Clay	Stubble	27·0	457	30	0·13	8·3	−2 260	17 300	1·15	—	42	0·15
	II	23.3.72	Barford			24·1	618	34	0·29	7·4	1 260	−2 210	0·84	0·47	31	0·38

Tyre sizes tested: Series I, 12·4/11–36 and 16·9/14–30. Series II, 13·6/12–38, 16·9/14–34 and 18·4/15–30 then at intervals of 7·5 cm down to a depth of 22·50 cm, for different soil types and surfaces. As shown in the table, *CI* varies widely with soil type and condition.

To assess the effect of soil type and condition on the relative contributions to penetration resistance of shear, compressive and tensile strengths, the forces required to push blunt and sharp probes into different soil types were investigated by Mulqueen *et al.*[2] They found that the maximum penetration force in homogeneous soils is not uniquely related to dry bulk density or cohesion but varies with soil moisture content. They also found that the formation of soil bodies and compaction zones ahead of the cone effectively changes the geometry of the cone and the penetration forces never reflect the original soil properties. These results seriously question the value of the penetrometer in assessing the relative strength of soil. The paper also discusses many other factors related to soil behaviour which limit the accuracy of this instrument. Despite its limitations, however, the penetrometer remains the most commonly used device, as confirmed by Olsen.[26] This is not simply because it is convenient and easy to use, but also because with proper consideration of its limitations, it still provides valuable information about the soil's mechanical state.[26] The value of such information can best be assessed by comparing *CI* with the information obtained from other devices such as the bevameter (Section 2.2).

The shearing response of soil depends on the confining pressure and the rate of loading and also varies with its cohesive and frictional properties. For purely cohesive soils, the shear strength is affected by strain rate but is independent of confining pressure.[10] The converse is true for pure frictional sandy soils. The shear strength of mixed soils depends on both confining pressure and rate of shear. This behaviour was also observed by Stafford.[27] He found that, for clay with 38% moisture content, cohesion increased significantly with strain rate but the angle of soil friction remained constant. Since *CI* is a function of compressive and shear stress, this phenomenon will affect its measurement for a given cone size and operating speed.

The ASAE Standard: ASAE S313.2 gives the basis for the design and use of the cone penetrometer[28] so that measurements can be interpreted and compared. It specifies maximum index capacity of different penetrometer types, penetration speed and depth increments for readings.

Various workers[29–31] have designed and constructed specialized penetrometers to facilitate retrieval of large quantities of data from the field and to ease operation. These are generally divided into two groups: the relatively lightweight manual types (*Fig. 1*) and the larger and relatively more powerful ones normally mounted on a tractor (*Fig. 6*). Both groups carry the standard cone outlined above. The former is easily carried and operated by one person pushing it into the ground while the latter relies on hydraulic power for deeper penetration into harder soils.

Other researchers[2,32,33] have carried out pressure sinkage investigations using standard penetrometer cones, spheres and relatively small plates of various shapes in yielding soils. Unfortunately, most results obtained from these experiments and many similar ones contradict each other. This prompted Holm *et al.*[34] to carry out a penetration investigation with different body shapes and sizes in different soils. They used round plates (3·23 to 900 cm^2 in area), rectangular plates (300 to 900 cm^2 in area) and cones of base areas ranging from 3·23 to 450 cm^2 with soil pressures and sinkages close to those encountered in the field. These experiments were conducted in five different soils (two loams, two sands and a clay) all having different moisture contents and densities. They found that small plates and penetrometers were very sensitive to small changes in soil consistency but those with areas larger than 300 cm^2 gave less variation. To illustrate the point more clearly, some of the variations due to size differences are shown in *Figs 7a* and *b* for sandy soil and loam soil, respectively.

Fig. 6. Tractor mounted bevameter and penetrometer designed and built at AFRC Engineering, Silsoe, UK

These results suggest that the size of the body is more important than whether a plate or a cone is used. It can also be inferred from this that mobility prediction can never be obtained from cone index, *CI*, alone.

2.2. *The bevameter*

The bevameter technique developed by Bekker is well known for identifying soil cohesion, c, and friction angle, ϕ, in relation to vehicle mobility. Since traction devices apply both normal and shear stresses to soil in the process of sinkage and developing traction, it seems reasonable to apply both stresses to the soil simultaneously in order to simulate the real phenomenon. A bevameter attempts to represent this situation better than other techniques currently available. It consists of two separate tests: (a) a plate penetration test for determining pressure-sinkage relationship, and (b) a shear test to determine the shear strength of the soil. These are illustrated pictorially and schematically in *Figs 6* and *8* respectively.

2.2.1. *Plate sinkage tests*

In order to characterize the pressure-sinkage relation of homogeneous terrain, the following equation was proposed:[22]

$$p = \left(\frac{k_c}{b} + k_\phi\right) z^n \tag{1}$$

where p the ground pressure
b the width of a rectangular plate or radius of a circular plate
z sinkage
n the exponent of deformation
k_c and k_ϕ empirically determined terrain constants

p and z are measured but the latter three constants are derived by fitting experimental data to the above equation. To obtain these constants, a minimum of two tests with two

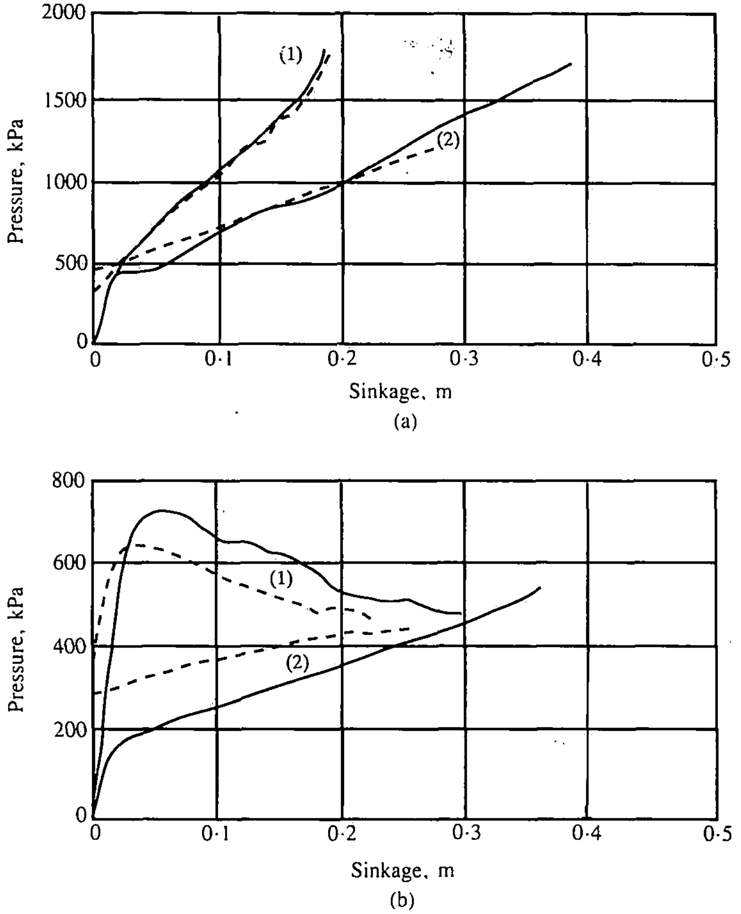

Fig. 7. Comparison of cone and round plate sinkage in soil (a) Sand and (b) Loam. (1) Base area 3·23 cm²: ----, cone; ———, plate. (2) Base area 450 cm²: ----, cone; ———, plate

plates having different widths (or radii), b_1 and b_2 are required. The two tests produce two curves:

$$p_1 = \left(\frac{k_c}{b_1} + k_\phi\right) z^n \tag{2}$$

$$p_2 = \left(\frac{k_c}{b_2} + k_\phi\right) z^n \tag{3}$$

When plotted on a logarithmic scale, these two represent two parallel straight lines where n is the slope of the parallel lines. The values of k_c and k_ϕ are then obtained from the pressures for the two plates at $z = 1$. This procedure has many practical problems. Very often, data obtained from the field do not exactly fit Eqn (1). Thus, a straight line to approximate the experimental data on a log–log scale cannot be fitted accurately. This also means that the two straight lines representing data from the two plates may not be parallel. Thus, adjustment is necessary for them to conform to Eqn (1) indicating that n

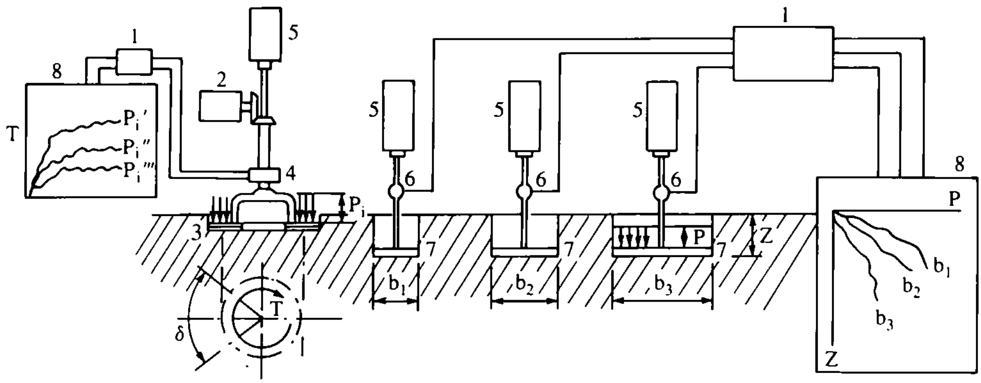

Fig. 8. Schematic of a bevameter (Bekker[22]). (1) Amplifier (2) Torque motor (3) Shear ring (4) Torque and angular motion sensor (5) Loading cylinders (6) Pressure gauge (7) Penetration plates (8) Record tape (Courtesy of John Wiley and Sons Inc)

corresponds uniquely to a particular terrain. Details of this procedure are discussed by Wong.[35]

To improve the efficienty of the above technique, Wong *et al.*[36] developed a more rigorous, automated data processing approach. *Fig. 9* is a pressure-sinkage relation for a sandy terrain obtained by a 10 cm diameter circular plate using this technique. It is a repetitive load-unload sinkage process, following the path OA, AB, BA, AC, CD and DC. Subsequent loading/unloading characteristics such as AB and CD are quite similar. Response of the terrain is idealized so that OAC conforms to Eqn (1) but the unloading/reloading relation such as AB and BA (*Fig. 9*) is described by:

$$p = \left(\frac{k_c}{b} + k_\phi\right) z_u^n - k_u(z_u - z) \tag{4}$$

where z_u is the sinkage when unloading begins and k_u is the average slope of the unloading-reloading line, AB. k_u is obtained from the relation

$$k_u = k_o + A_u z_u \tag{5}$$

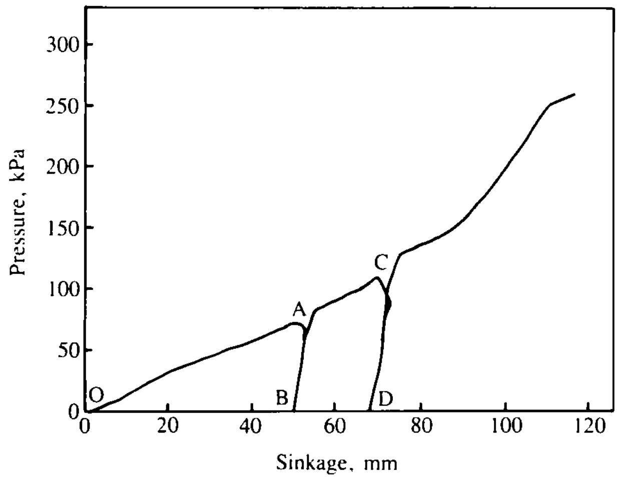

Fig. 9. Repetitive plate loading characteristics of a sand (footing radius, 50 mm) (Wong et al,[36] reproduced by permission of the Council of the Institution of Mechanical Engineers)

Table 2
Values of the pressure-sinkage and repetitive loading parameters for a sandy terrain (LETE sand) (Wong *et al.*[36])

k_c, kN/m^{n+1}	k_ϕ, kN/m^{n+2}	n	k_o, kN/m^3	A_u, kN/m^2
102	5 301	0·793	0	50 300

where k_o and A_u are parameters derived from the experimental data. These parameters are shown in Table 2. When there is no repetitive load such as that of a front wheel tractor tyre, the load-sinkage relation simply follows curve AC i.e. Eqn (1).

Although the technique improves the efficiency of evaluating k_c, k_ϕ and n, there are still inherent problems such as differences in behaviour of a metallic plate compared to that of a tyre or track, the effect of strain rate and speed of penetration and the fact that the plate can only characterize surface soil parameters.

Other authors[32,33,37–39] also reviewed and investigated other plate sinkage relations. Youssef and Ali[37] found that the accuracy of plate sinkage analysis is affected by the size and shape of the plate used as well as the soil strength parameters. They concluded that to achieve a more realistic result, the plate penetration rates must always be uniform and of such a speed as to simulate the situation under a track or wheel.

McKyes and Fan[33] used five small circular plates of different sizes (ranging from 4·5 to 6·5 cm in diameter in steps of 0·5 cm) on dry sand to investigate the variability of plate sinkage measurements. A least squares best fit was plotted for groups of two, three and four plates in order to evaluate k_c, k_ϕ and n. When two plate sizes were used the variability was found to be 82% but three and four plates lowered the variation to 27% and 16% respectively as shown in Table 3 and *Fig. 10.* Although these tests were conducted only down to a sinkage of 20 mm in sand, the predicted pressure—sinkage behaviour of a larger plate (15 cm diameter), using the mean constants obtained from four test series (Table 3, conducted with different number of smaller plates) and Eqn (1),

Table 3
Values of constants k_c and k_ϕ and their coefficients of variation using different numbers of plate sizes (Mckyes and Fan[33])

Test series	*Number of plates used*	k_c, kPa/m^{n-1}	k_ϕ, kPa/m^n	n	*Coefficient of variation, %* k_c,	k_ϕ,	n
1	2	−3·62	566	0·624	−53·4	18·3	3·1
	3	−3·67	565	0·624	−21·6	9·6	2·1
	4	−3·83	571	0·623	−11·2	5·9	1·3
2	2	−4·50	626	0·651	−126·1	34·6	1·5
	3	−4·45	615	0·651	−32·9	8·5	0·9
	4	−4·40	607	0·651	−13·2	4·8	0·5
3	2	−0·70	655	0·644	−52·9	34·6	0·6
	3	−0·54	606	0·644	−16·0	3·4	0·6
	4	−0·60	637	0·644	−8·4	1·9	0·4
4	2	−0·25	494	0·634	−94·0	17·8	0·9
	3	−0·27	496	0·634	−37·3	7·2	0·6
	4	−0·27	499	0·634	−29·7	5·7	0·4

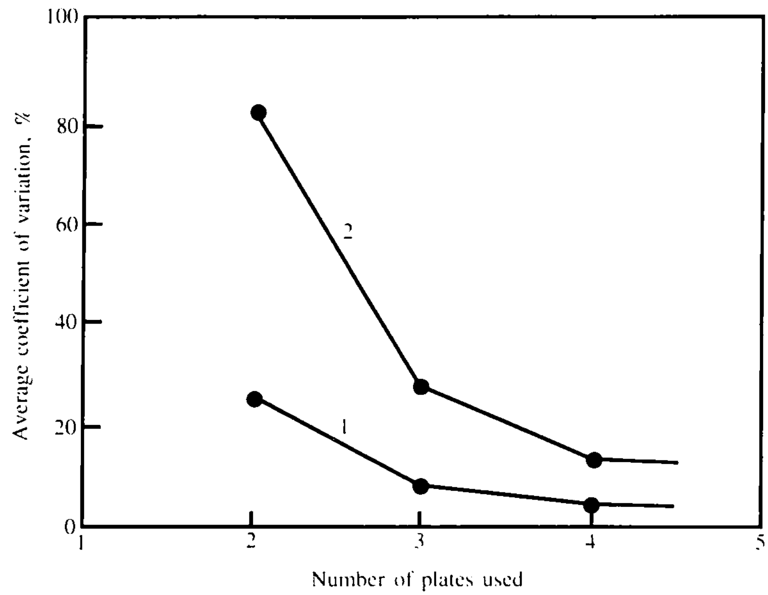

Fig. 10. Average coefficients of variability in k_c *and* k_ϕ *as a function of the number of plates (1)* k_ϕ*, (2)* $-k_c$ *(McKyes and Fann,*[33] *reproduced by permission of Pergamon Press)*

were found to match the experimental sinkage behaviour of the larger plate to within 3·1% variability, as shown in *Fig. 11.* The major significance of this work is that, in order to reduce soil sinkage variability, regardless of soil type, no less than four or five plates of fairly similar sizes should be used to determine the mean plate sinkage constants. Secondly, the results of this work indicate that variability in plate sinkage behaviour is a function of plate size as found by Holm *et al.*[34] and hence the reason for recommending the use of more than two plates of similar sizes to determine the mean soil sinkage parameters.

2.2.2. *Soil shear strength measurement*

Drawbar pull, an important performance parameter in off-road vehicle motion, is dependent on the rolling resistance and the horizontal tractive force produced by vehicle action on the soil. The latter is called soil thrust. This thrust, exerted by the vehicle, is caused by the shearing of soil under the wheels or tracks. To predict the thrust, soil shear strength must be measured by determining soil cohesion, c, and friction angle, ϕ, by an appropriate means. Ideally, the size, form, load and shear stress distribution of the test device should reproduce those of the vehicle ground contact area. Unfortunately this is not possible and so a compromise must be reached.

2.3. *Shear annulus*

To predict the shear stress distribution under a track, the shear stress-displacement relationship of the terrain must be known. This can be obtained by using a shear annulus (*Figs 6* and *8*). Normal and shear stresses are assumed to be evenly distributed over the annular area of the shear head and the shear stresses are then given by Janosi and

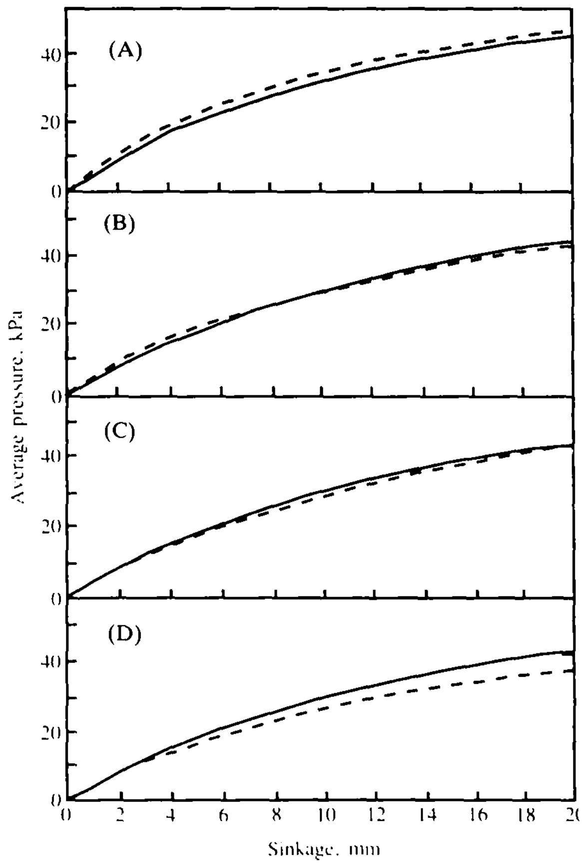

Fig. 11. Prediction of pressure vs sinkage behaviour of a 15 cm diameter plate from the results of five plates having diameters of 4·5 to 6·5 cm. ————, measured; ------, predicted. (A) Series 1 (B) Series 2 (C) Series 3 (D) Series 4 (McKyes and Fan[33] reproduced by permission of Pergamon Press)

Karafiath,[40] as reported in Bekker:[22]

$$\tau = \frac{3T}{2\pi(r_o^3 - r_i^3)} \tag{6}$$

where τ is the shear stress, T is the torque and r_o, r_i are the outer and inner radii of the shear head, respectively. During the test, the torque and angular displacement of the shear ring are measured and the shear stress-displacement relationship can be determined.[15,22,35]

Based on the results of a large number of shear tests on a variety of natural terrains such as snow, peat, muskeg and sand, Wong *et al.*[36] found that there are three basic types of shear stress displacement relations. Two of the relations display a hump and were observed[36] in the internal shearing of certain particular types of terrain (*Figs 12* and *13*). Although Wong *et al.*[36] produced distinct expressions for these curves, they can both be generalized to fit the relation formulated by Bekker[22] in accordance with the Coulomb-

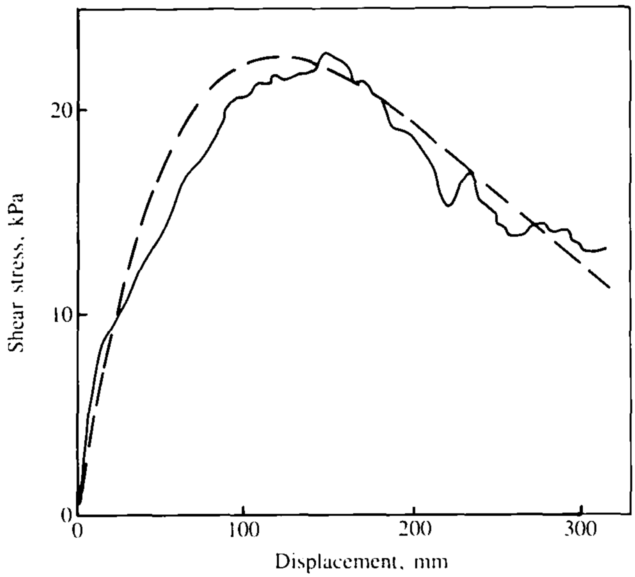

Fig. 12. Shear stress-displacement relationship of a muskeg mat. Normal pressure, 11·2 kPa ------, fitted; ———, measured (Wong et al.[36] reproduced by permission of the Council of the Institution of Mechanical Engineers)

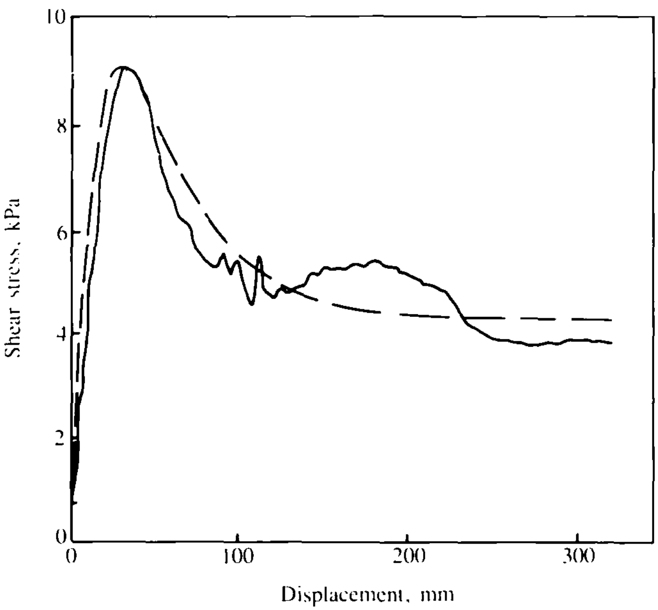

Fig. 13. Shear stress-displacement relationship of a snow covered surface. Normal pressure, 11·1 kPa. ------, fitted; ———, measured (Wong et al.[36] reproduced by permission of the Council of the Institution of Mechanical Engineers)

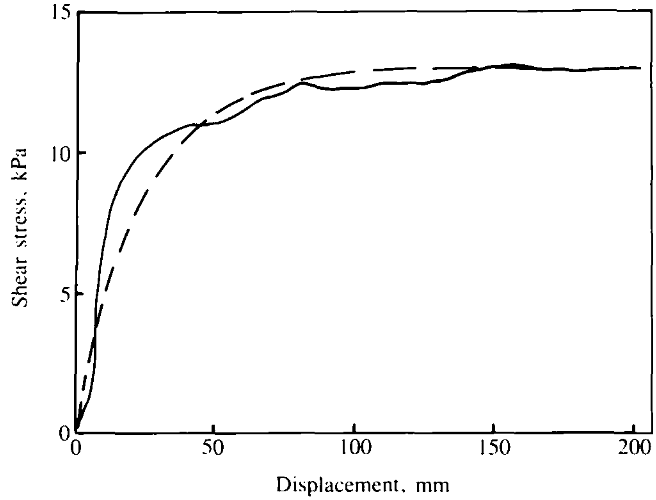

Fig. 14. Shear stress-displacement relationship of a sand (Wong et al.[36] *reproduced by permission of the Council of the Institution of Mechanical Engineers) Normal pressure, 17·8 kPa ------, fitted; ————, measured*

Micklethwaite equation[41] to give:

$$\tau = (c + \sigma \tan \phi)\,(e^{(-k_2+\sqrt{(k_2^2-1)})k_1 j} - e^{-k_2-\sqrt{(k_2^2-1)})k_1 j}) \tag{7}$$

where k_1 and k_2 are slip coefficients and j is the shear displacement that produces τ.

The third relation does not display a hump but the shear stress increases with shear displacement and approaches a constant. This characteristic is exhibited by plastic soils and was observed[36] in the internal shearing of a dry sand and a peat, and in friction between rubber and sand, peat, snow and muskeg respectively (*Fig. 14*). This relation simplifies to

$$\tau = \tau_{max}(1 - e^{-j/k})$$

$$(\tau_{max} = c + \sigma \tan \phi) \tag{8}$$

where K is the shear deformation modulus and j, the shear displacement. To obtain k_1, k_2, K and other parameters from measured shear curves, various methods[22,35] were proposed. Due to practical difficulties and inaccuracies associated with them, an automated methodology was developed.[36] Wong found from field trials (*Figs 12–14* and Table 4) that the bevameter offers a suitable method of identifying mechanical properties of soil in relation to vehicle mobility.

Part of Eqn (8) describes the relation between maximum shear stress τ_{max} and normal pressure, σ, cohesion, c and soil friction angle, ϕ, for most terrains. The values of soil strength parameters for sand, snow and muskeg are given in Table 4.

It is important to note that for most terrains, the shear strength is affected by the shear rate. For this reason Wong *et al.*[36] predict the shear stresses at the tyre or track-terrain interface by considering a shear rate equivalent to the slip velocity of the tyre or track. This phenomenon affects the type of technique used to obtain the soil shear parameters experimentally.

Table 4
Shear strength parameters of various types of terrain (Wong *et al.*[36])

Terrain type	*Type of shearing*	*Cohesion (adhesion), kPa*	*Angle of shearing resistance (degrees)*	*K, cm*	K_r	K_w, cm
LETE sand	Internal	1·3	31·1	1·2	—	—
	Rubber-sand	0·7	27·5	1·0	—	—
Petawawa snow A and B	Internal	0·4	24·0	—	0·655	2·2
	Rubber-snow	0·12	16·4	0·4	—	—
Petawawa muskeg A	Peat (internal)	2·8	39·4	3·1	—	—
Petawawa muskeg B	Peat (internal)	2·6	39·2	3·1	—	—

Others[3,10,40,42] also did useful work aimed at solving problems associated with the bevameter. Baladi[10] argued that the bevameter results are misleading because the torque required to rotate the shear head to a large angular displacement does not level off after an initial angular displacement. The reason for this is that contrary to the fundamental assumption that the soil failure plane coincides with the horizontal plane running across the bottom of the shear head, the failure plane is oblique. Janosi and Karafiath[40] solved this problem by incorporating a surcharge plate with suitable loads. Chang and Baker[3] built another device called the Penetro-shear apparatus which they used to solve the same problem. Golob[42] also constructed a bevameter for use at constant ground pressure, with pressure plates designed for soft and normal forest soils all with different plate dimensions, but was not very successful.

All these constructive methods and those by other researchers do not, however, specify standard design features (i.e. plate size, size and form of head) of the bevameter for use in various soils. This is a problem that faces researchers using devices such as the penetrometer and the bevameter. However, the work done by Holm *et al.*[34] (Section 2.1) may provide a clue to this problem.

2.4. *Vane shear test*

The vane, shown in *Fig. 15*, is rotated at a constant angular velocity and the volume of soil contained within the blades is sheared off. Assuming that the shear stress, τ, over the whole surface of the cylinder is uniform, then the total torque required to turn the vane and shear the soil is divided into two parts as follows:

(a) Response of shear outside the cylinder:

$$\text{torque, } T_1 = \pi \,.\, d \,.\, h \,.\, \tau \,.\, d/2 \tag{9}$$

(b) Response of shear at the top and bottom of vane (assuming soil covers the top):

$$\text{torque, } T_2 = 2(\pi/4)d^2 \,.\, \tau \,.\, d/3 \tag{10}$$

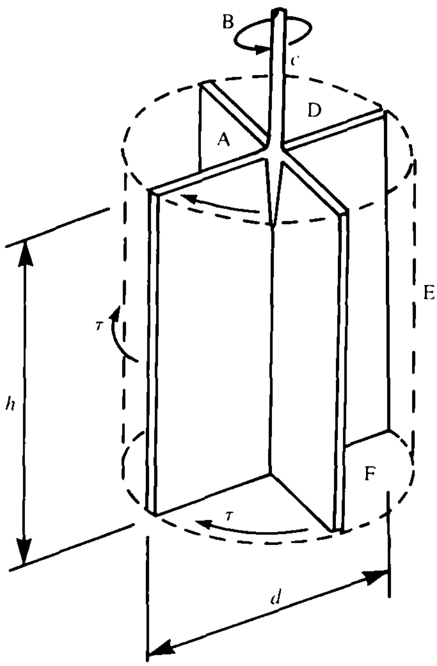

Fig. 15. The shear vane action in soils. (A) Vane blade (B) Torque, T (C) Vane rod (D) Horizontal sheared surface (top) (E) Vertical sheared surface (F) Horizontal sheared surface (bottom) τ Shear stress. (Kogure et al.[43] reproduced by permission of Pergamon Press)

Thus, total torque

$$T = T_1 + T_2 = \pi \, . \, \tau \, . \left(d^2 \frac{h}{2} + \frac{d^3}{6}\right)$$

i.e.

$$\tau = \frac{T}{\pi d^2 \left(\frac{h}{2} + \frac{d}{6}\right)}$$

The torque due to vane rotation is normally measured by means of a torque ring. When measuring soil strength from laboratory samples, the stress reduction in the soil element caused by cutting the sample is an important problem. In general, a negative pore water pressure is produced within the soil sample due to stress reduction. The persistent presence of negative pore pressure in the soil sample influences the undrained strength of the soil during shearing.[44]

2.5. *Triaxial shear test*

The triaxial shear apparatus was initially used to measure soil properties for analysing various civil engineering stability problems as discussed by Bishop and Henkel.[44] When pore-pressure is independent of the stresses acting in the soil, it is used to study long-term stability of slopes, earth fills and earth retaining structures by measuring c and φ. When pore-pressure is a function of stress in soil then it is used to study initial stability of foundations and open cut in saturated clay.[44]

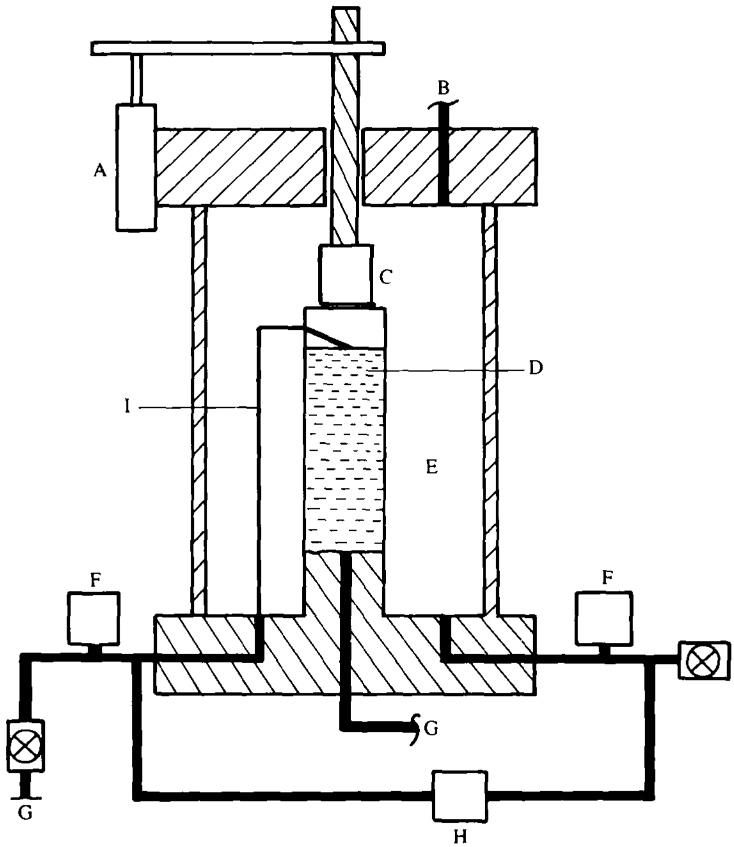

Fig. 16. A sketch of the WES low pressure triaxial device. (A) Film pot (B) Chamber pressure (C) Load cell (D) Test specimen (E) Chamber fluid (F) Pressure transducer (G) Back pressure (H) Differential pressure transducer (I) Top drainage line. (Baladi[10] reproduced by permission of Pergamon Press)

The most commonly used type of triaxial test method both for research and routine testing is the cylindrical compression test. Its principle of operation is fully described by Bishop and Henkel[44] and Lambe.[45] The device consists of three principal components. These are the base that forms the pedestal on which the soil sample rests and which incorporates the various pressure connections, a removable cylinder sealed in a water tight rubber membrane and enclosing the sample to which fluid pressure can be applied and a ram, acting on the top cap, which is used to apply the deviator stress, as shown in *Fig. 16.* Apart from the stress–strain measurement of the response of soils, the device can also be used to study column-change and pre-pressure phenomena.[10,44,45] Due to the inaccuracies involved in measuring soil properties in general, this device is usually used to check soil parameters obtained by other methods[35,36,40] for the evaluation of soil-vehicle interaction. Examples of test data obtained from this device are presented in Baladi.[10]

A number of advantages and limitations of this method have been discussed.[44] The major disadvantage is that it cannot be used in situ. It relies on bringing soil samples back to the laboratory and this can lead to unrepresentative results; since the state of stress in the sample inevitably changes during removal and transportation. As noted by Kogure *et* al.[43] persistent presence of negative pore pressure in the soil sample influences the undrained strength of the soil during shearing. Secondly, it is difficult to obtain an adequate representation of a whole field because of the time required to take sufficient samples.

2.6. *Direct shear test*

This is a device for field use which consists of an open rectangular box separated into two equal halves, a shear yoke, a load cell, a winch and a guide rail to prevent twisting of the shear yoke[10] as shown in *Fig. 17.* During operation, the hollow box is inserted into the ground with one half resting on top of the other and a vertical load is then applied to the top half. Keeping the lower half stationary, the top half is moved horizontally along rails by means of a winch and the soil sample is sheared.

The three basic parameters cohesion, c, shear deformation modulus, K, and soil friction, ϕ, can be obtained directly from the test.[10] For each test, a graph of shear load versus deflection is plotted. The initial slope of the plot then gives K, the peak stress is the maximum shear stress and deflection rate is defined by the deflection at peak stress/Δt where Δt is the time taken to achieve peak stress. Again, an example of characterizing soil parameters obtained from field tests is given in Baladi.[10]

Dexter[46] describes the design of an unusual shear box which was used to investigate the effects of stress acting in a direction tangential to a shear plane and perpendicular to the direction of shear. He found that the applied tangential stress greatly affects soil dilation, resulting in a much larger value of ϕ in the case of sand. He also found that the shear strength is not greatly affected by the tangential stresss at values up to twice the normal stress. He did not verify the upper limit at which this phenomenon stops.

2.7. *A comparative analysis of the shear strength measurement methods*

The methods briefly outlined in Sections 2.3 to 2.6 and others such as the shear plate technique[22] have been developed and used widely. Nonetheless, these devices do not reproduce the true situation (shear stress distribution) associated with the traction to ground surface contact area. This is because it is not possible to build an instrument having the same form, size and loading as the vehicle.

Stafford and Tanner[47] cite many researchers who noted discrepancies between the shear values measured by the different techniques. While some workers have reported identical shear parameters, others have found that different devices yield different cohesion, c, and frictional, ϕ, values for the same soil conditions. Studies to rationalize these discrepancies often contradict each other.

Stafford and Tanner[47] conducted a comparative test of six shear devices (torsional shear box, torsional shear annulus, shear vane, direct shear box, triaxial fast undrained and triaxial slow drained, the latter two at different ram loading speeds) in six different soil types under different soil conditions. Shear tests and soil sampling were performed on four field soils in as small an area as possible to minimize differences in soil strength. Sand and remoulded clay were prepared in a laboratory soil tank and metal bin respectively. Up to five sets of tests were conducted with each method in each soil. The results are presented in Tables 5 and 6.

It was found that in many methods, especially the shear box and the annulus, regression analysis did not yield a significant linear fit. This was apparently due to experimental scatter rather than to curvature of the shear stress-normal stress relation. They found a few cases of agreement between two methods but generally different methods produced different strength values for both undisturbed and remoulded soils.

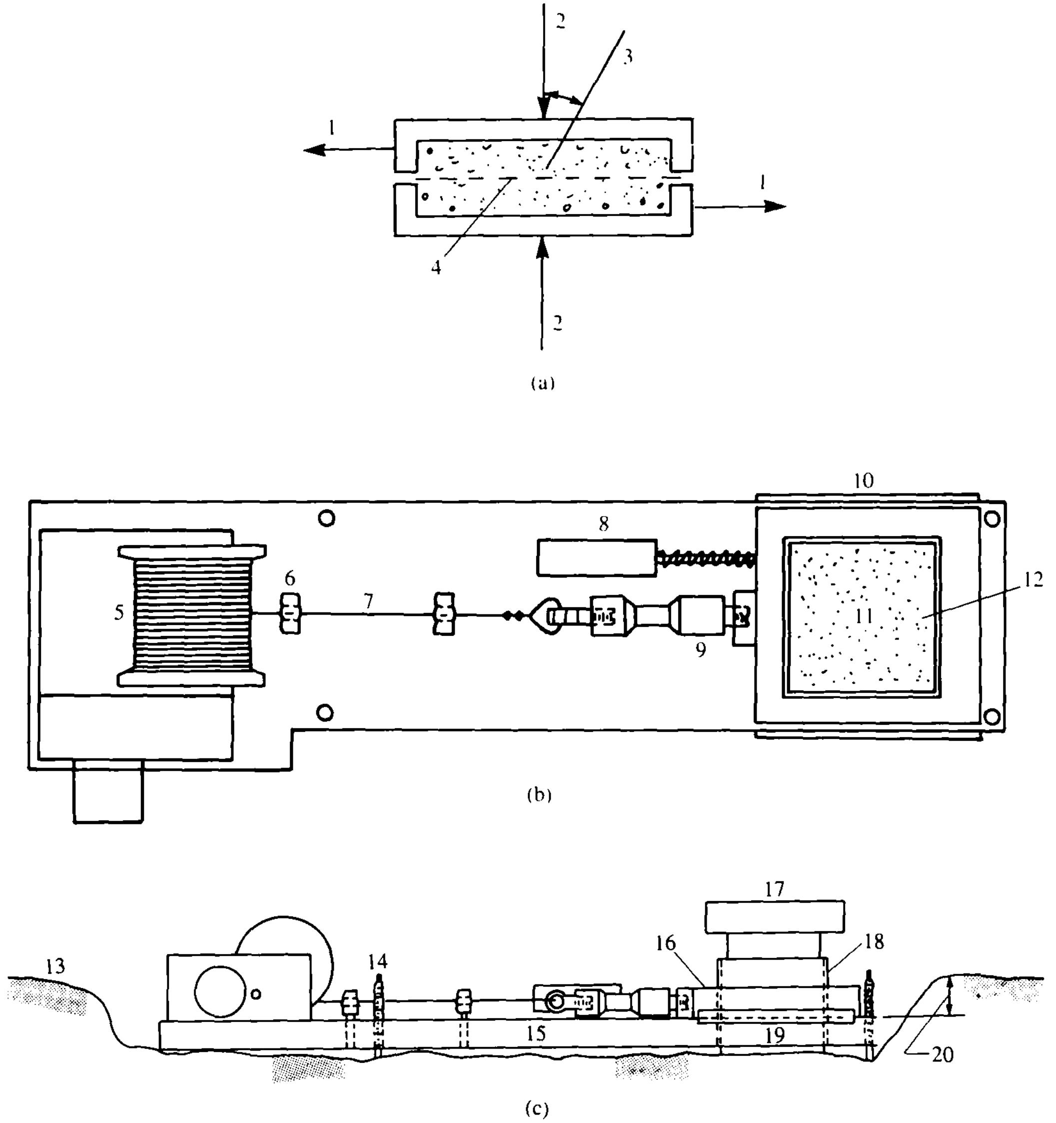

Fig. 17. Direct shear device (a) Sketch of a direct shear box with soil sample (1) Shear force (2) Normal force (3) Resultant force (4) Surface A. (b) Plan view of direct shear device, (5) Winch (6) Centering guides (7) Cable (8) Film potentiometer (9) Load cell (10) Guide rail to prevent twisting of shear yoke (11) Soil specimen (normal loads removed) (12) Specimen container, (c) Elevation view of the direct shear device in place (13) Original ground surface (14) Level adjustment (15) Base (16) Shear yoke (17) Normal loads (18) Top specimen container (19) Lower specimen container (20) Depth of shear plane (Baladi,[10] reproduced by permission of Pergamon Press)

Table 5
Values of cohesion, kPa (Stafford and Tanner[47])

Soil	Torsional shear box	Torsional shear annulus	Direct-shear box	Triaxial test undrained	Triaxial test drained	Shear vane
1	28·5	39·3	14·8	6·5	17·4	43·3
2	36·3	41·9	54·3	11·1	14·4	54·1
3	81·9	88·6	50·1	33·5	41·9	92·8
4	33·0	36·1	19·9	11·3	15·5	50·3
5	40·4	62·3	28·2	10·3	21·1	38·5
6	(1·6	4·2)	6·2	4·9	3·1	5·5

1, Sandy clay; 2, Loam; 3, Clay with stones; 4, Sandy loam and remoulded soils; 5, Clay; 6, Sand

The major conclusions drawn were that:

(a) although use of the shear vane is generally restricted to saturated clays, the results showed that the apparent cohesion values from the vane were in reasonable agreement with values from the annulus for undisturbed mineral soils;
(b) the results also showed that to obtain c and ϕ, an annulus is preferred to a box;
(c) in situ methods (shear box, annulus or vane shear) are to be preferred to direct and triaxial shear methods as minimum disturbance is caused to the soil under test.

Stafford and Tanner[47] designed a shear meter incorporating an annulus which is easily operated by one man and produces quicker field test results. A shear stress/strain curve is recorded automatically as the test proceeds. It was found to produce similar results to other shear annulus equipment.

A fundamental conclusion reached from this study is that the choice of a test method must be determined by the particular application for which shear strength is required. Also, the variation of results produced by shear annulus and direct shear tests are in general far less than the variation of *CI* values recorded by the penetrometer (Table 1).

Kogure *et al.*[43] also compared the shear properties of soil obtained by means of vane shear tests with those produced by a direct shear test and a triaxial compression test. The soil samples used were prepared from preconsolidated clay. Various clay samples prepared specifically for the corresponding tests (vane, triaxial and direct shear) underwent various treatments before being laid vertically, horizontally and at 45° to the vertical in a preconsolidation cell. Preconsolidation pressures of 100, 200 and 300 kPa were then applied (one at a time) to the samples simultaneously before testing.

They found that the maximum shear torques by vane were practically constant for the

Table 6
Values of friction angle, deg. (Stafford and Tanner[47])

Soil	Torsional shear box	Torsional shear annulus	Direct-shear box	Triaxial test undrained	Triaxial test drained	Shear vane
1	28·2	33·2	33·2	25·4	29·7	—
2	20·2	13·7	21·4	17·3	26·4	—
3	38·1	22·9	24·0	11·3	11·3	—
4	29·0	30·8	34·4	16·9	21·9	—
5	20·5	21·3	8·3	6·0	2·8	—
6	14·8	8·8	31·6	31·8	33·3	—

1, Sandy clay; 2, Loam; 3, Clay with stones; 4, Sandy loam and remoulded soils; 5, Clay; 6, Sand elapsed time between sample cutting and testing of approximately 100 to 10,000 min. This means that the negative pore-pressures due to stress reduction, caused by taking the sample, disperse after 100 min. The maximum shear torque by vane was found to occur between angular speeds of 10^{-3} and 5×10^{-3} rad/s and the shear strength was independent of the sample orientation.

For the unconfined triaxial compression test, the peak values of shear stress and strains at failure were larger and the peak values appeared very distinctly for samples laid vertically. For direct shear, characteristics of samples in the vertical and horizontal directions were similar but for the 45° samples, both the shear stress peak values and deformation characteristics differed. The vane method was found to give the highest values of shear strength and direct shear the lowest values among the methods used in the study.

The authors concluded, very uncommittedly, that it may be suspected that the shearing mechanism of the direct shear test is most closely allied to that of soil under a vehicle among the three considered methods. This shows how difficult it is to define the shear curve or soil parameters in practice.

Although shear annular rings are more commonly used, rectangular plates are favoured if in situ test performance of heavy vehicles is to be measured in hard soils.[22]

3. Experimental substantiation

Gee-Clough *et al.*[48] used a dimensional analysis technique to predict the tractive performance of a tractor and plough draught forces using cone penetrometer resistance as a measure of soil strength. They compared measured and predicted values of work rate in 14 different field conditions. The results showed that 86% of the predicted values were within ±20% of the measured values.

Dwyer[49] used a similar techinque to compare the measured and predicted performance of front-wheel assist, two-wheel and four-wheel drive tractors in different field conditions. It was found that although the maximum drawbar power of the two-wheel drive tractor, which was generally traction limited, was accurately predicted, those of the front-wheel assist and four-wheel drive tractors, which were generally limited by engine power, were over-predicted, unless account was taken of fluctuations in drawbar pull.

Wong *et al.*[36] produced a detailed theoretical prediction and experimental verification of uneven ground pressure distribution and tractive performance of tracked vehicles in soft soil conditions. Using repetitive plate sinkage tests to characterize the soil sinkage parameters (*Fig. 9*), they found that the predicted results agreed very closely with the experimental pressure distribution between and under the different track rollers in various soil types. Using grouser plates to determine soil cohesion, c, friction angle, φ, and shear modulus, K (*Figs 12, 13, 14*), they also predicted and verified the drawbar pull-slip characteristics of a tracked vehicle over different types of terrain very accurately. For purposes of comparison, they also predicted the drawbar pull curve using nominal ground pressure which produced less accurate correlation with the experimental results.

The major conclusion to be drawn from these different approaches relating the various soil tests to actual vehicle mobility in the field is that accuracy of prediction not only depends on the type of approach used but also on the accuracy of the measured soil parameters and hence the techniques used for the measurement of such parameters.

4. Discussion

As revealed by the literature search reported in this paper, there seems to be no standard, proven and above all, reliable technique currently available that can be universally applied to measure soil strength parameters appropriate to prediction of vehicle performance. All the devices described in Section 2 will measure some sort of strength of the supporting soil. The conversion of such a measurement to correlate with the real situation presents the greatest difficulty. It can be argued that the technique required in assessing soil strength parameters for purposes of predicting terrain vehicle performance is a simple and fundamental one that characterizes the way soil behaves and not necessarily a device that reproduces the shape and size of a tyre or track. The answer to this is that it has not been easy to come up with such a technique without, in some way, relating its features to the size and action of the lugs under tyres or tracks. In addition, the behaviour of a tyre or rubber track in soft soil is quite unique. The question to be answered therefore is whether or not the penetration resistance measurements obtained by the various instruments e.g. cones and plates are directly related to vehicle mobility performance.

First, because of their geometric differences, the penetration resistance measured, for example, by the cone and plate for the same soil are very unlikely to be the same. Secondly, their shapes, sizes and deformation characteristics are obviously not comparable to those of a tyre or track. It therefore seems that such a proposition may be unrealistic and in fact the first argument has been clearly demonstrated by Stafford and Tanner[47] and to some extend by Kogure *et al.*[43] However, as stated above, there is no universally acceptable and reliable soil strength measurement technique that directly relates to the real situation. And yet, to achieve an accurate terrain vehicle performance prediction, it is essential that reasonably accurate soil strength measurements must be obtained. From this viewpoint, it would appear that the only sensible alternative is to use or select the best soil characterization techniques among those currently available (Section 2).

The next question, therefore, is which methods should be considered? Quite obviously, taking soil samples and testing them in the laboratory is not only laborious and difficult to perform but it may be unrepresentative of the soil state in the field, especially if the soil is loose. In situ methods are, therefore, preferable as minimum disturbance is caused to the soil. Of these, the cone penetrometer is the most widely used (perhaps because of its simplicity and cheapness) as confirmed by other researchers.[4,26,40] However, the cone index, *CI*, cannot be a substitute for soil strength characterized by soil cohesion, c, and friction angle, ϕ, in the linear Coulomb form and perhaps even more so if non-linear strength envelopes are used. The development and validation of a simplified cone penetration model[20] that correlates *CI* with cone geometry (length and diameter) and soil parameters (cohesion, friction angle, density and shear modulus) is a simple and suitable method of verifying the measured cone index. Despite its limitations, it is recommended that the cone penetrometer should be used perhaps with some increase of the cone size to provide some comparison against other methods.

It is, however, essential that the cone index readings obtained by means of larger cones should be interpreted correctly with respect to the standard 30° angle cones. The formulation produced by Rohani and Baladi[20] in conjunction with the results obtained by Holm *et al.*[34] appear to be the most reasonably practicable and useful techniques to follow.

Since one cannot rely on the above techniques alone, it is essential that an additional method is used for purposes of comparison. The bevameter method seems to be the most suitable technique for evaluating soil strength. This is mainly because it does not require interpretation of soil parameters via a model such as suggested for the cone and, perhaps more importantly, it is the one that most closely simulates the real situation. It characterizes c, ϕ, k_c and k_ϕ directly which cuts out errors resulting from such interpretation. As Golob[50] discussed, the bevameter is the only device which can provide a value for the maximum soil shear in the topmost layer in contact with the vehicle.

In addition, the bevameter gives more information on soil properties which can be used in more analytically based prediction systems. Maclaurin[4] states that the cone penetrometer and bevameter have remained the most popular instruments for soil characterization.

Some problems still exist in accurately predicting soil parameters using the bevameter. One of these is continual sinkage of the shear head which has been solved by use of a surcharge plate[40] but perhaps the most important problem that involves both methods is the size of the cone or plate used. As outlined at the end of Section 2.1, this problem also seems to have been solved[34] but it has not yet been proved. The other problem is that there are no known data processing methods which are absolutely reliable for evaluating k_c and k_ϕ. Thus, the use of more than three plates as discussed by Mckyes and Fan[33] is recommended. Above all, c, ϕ, k_c and k_ϕ can only be evaluated for the top soil. There is no known practical method that can measure the variation of these parameters with depth and this is the advantage of the cone penetrometer which gives an average value of *CI* over a given depth. Other field test methods such as the vane-cone device and especially the vane shear method are inaccurate and unrepresentative and can therefore be dismissed. They have very little scope for modification and there appears to be nothing to be gained by incorporating a vane onto a cone to produce a vane-cone device.

Since the penetration tests are made in order to predict the mobility of vehicles, it is quite obvious that the size of the bodies must be comparable to the lugs or track elements. In view of the work done by Holt *et al.*[34] and the above discussion, it is recommended that the two techniques should be modified by increasing the plate and cone sizes to over 350 cm^2 in area and a surcharge plate incorporated in the case of a bevameter. Due to the increase in size, the devices would need to be tractor mounted because they would require more power for penetration than can be provided manually.

The identified soil strength measurement techniques must then be used in conjunction with the appropriate force prediction methods. Since the numerical prediction approach is, in general, difficult to implement, especially from the viewpoint of constitutive formulation, it appears more desirable to use the semi-empirical as well as the analytical approach in conjunction with the cone and bevameter techniques.

5. Conclusions

(1) In situ methods of soil strength measurement are to be preferred to laboratory techniques because they cause minimum disturbance to the soil and are therefore more realistic.

(2) Strain rates affect c and ϕ values. Since the plate sinkage parameters k_c and k_ϕ are related to soil cohesion and friction respectively, it is important to operate the bevameter at the correct speed; and to use at least four or five plates of similar sizes to determine the mean values of k_c, k_ϕ and the soil index n. This applies to the cone penetrometer too because *CI* is a function of c and ϕ.

(3) Small cones and plates are sensitive to changes in soil consistency. It is, therefore, recommended that the cone penetrometer and bevameter be modified by increasing the cone and plate size to about 350 cm^2 base area.

(4) Although the bevameter only measures surface c and ϕ values, this review reveals that this is the technique which most closely simulates the vehicle motion. However, there is substantial variation of soil properties with depth. Although the penetrometer is the only way of assessing soil resistance at large depths, the cone index, *CI*, or its gradient is not uniquely related to either soil cohesion or density, but varies with its moisture content and structural state. In addition, the formation of soil bodies and compaction zones ahead of the cone effectively changes the geometry of the cone and the penetration force no

longer reflects the original properties of the soil. Thus, CI cannot be a substitute for strength characterized by c and ϕ which means that the mobility prediction cannot be obtained from CI alone but must always be checked against other techniques.
(5) The translational shear technique is easy to perform in the field and usually produces some reasonable results. Tests should, therefore, be conducted using this technique to provide additional data for comparison with the bevameter method.
(6) The disparity between the measured and predicted values of the performance characteristics of agricultural tractors is attributed to the inaccuracy of the measured soil parameters, assumptions or errors made in formulating the equations and the evaluation of parameters other than the soil properties which form the equations.

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