Soil Structural Index as a Measure of Bearing Strength of Clayey Lowland Soils

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Introduction

Muda Irrigation Project Area in Peninsular Malaysia covers the Kedah/Perlis coastal plain composed of clayey alluvial deposits. Since the area was installed with the irrigation and drainage system, double cropping of rice became possible. However, one of the impediments in introducing the double cropping is that the soil strength of the paddy fields is low for bearing agricultural machinery. For the development of mechanized agriculture, therefore, it is necessary to conduct a soil survey from this point of view.

Bearing strength of soil depends on soil moisture conditions, and its value at some critical depth in the field as often measured by a cone-penetrometer is directly used for assessing trafficability of machinery. However, it is most desirable to find out some physical and pedogenic factors governing soil strength independently of moisture conditions in order to get a generalization of the soil characteristics concerned. This is especially important for the utilization of soil maps.

Boekel (1958)[1] proposed a stability index of soil structure expressed as plastic limit/pF 2 moisture to evaluate structural stability of clayey soils against mechanical deformation. This index has been proved to be effective in evaluating physical condition of soil improved by application of organic matter (Kubota 1971)[3] and in tracing structural changes of Gley paddy soils due to crop diversification (Nakano 1978).[6] The index is considered to involve factors relating to soil mechanical impedance and seems effective for the above soil survey.

Therefore, the soil strength in terms of stability index of soil structure, and some other physical properties of main soil series of the Muda Area were investigated. The survey was conducted from January to March 1980, under the Research Cooperation between the Muda Agriculture Development Authority, Malaysia, and the Tropical Agriculture Research Center, Japan.

Methods of soil survey

The Kedah/Perlis coastal plain covers 0.1 million ha of land, roughly 70 km long along the coastal line facing Straits of Malacca and 15 km wide from the coast to the edge of hills. The nearer to the hills, the less is the marine influence, so that the deposits are mainly fluvial and colluvial origins. Thus, according to "The Semi-detailed Soil Map of the Plain" published by the Ministry of Agriculture and Fisheries of Malaysia (Soo Swee Weng 1972),[7] the plain consists of three major bands of marine, brackish water, and fresh water alluviums distributing almost in

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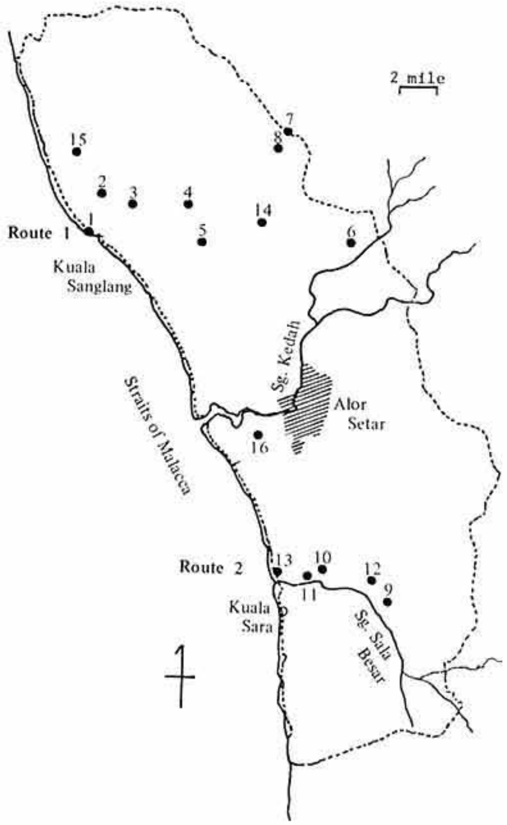

Fig. 1. The Muda Irrigation Project Area, showing the soil-sampling sites (•)

parallel to the coastal line. Therefore, the soil survey was conducted by traversing the plain from the coast to the hills by two routes; route 1 from Kuala Sanglang to Jitra, and route 2 from Kuala Sala to Pendang. Locations of pits for the profile observation and soil sampling in the routes are shown in Fig. 1.

Route 1 Kranji series (Marine Alluvial); site no. 1.
Sedaka series (Marine Alluvial); site nos. 2, 15.
Telok series (Brackish Water Alluvial); site nos. 3, 4, 5, 8, 14.
Tualang series (Fresh Water Alluvial); site no. 6.

Route 2 Kuala Kedah series (Marine Alluvial); site no. 13.
Chengai series (Marine Alluvial with some influence of riverine deposits); site nos. 10, 11, 16.
Tualang series (Fresh Water Alluvial soil); site nos. 9, 12.

The survey was made just after the harvest of rainy season crop, and ground water tables were at the depth of around 1 m in most sites. After observation of soil profile, vertical distribution of soil strength in the profile was measured by the Yamanaka soil strength meter (Matsuo 1964).[4] Undisturbed cylindrical soil samples ($20\ cm^2 \times 5\ cm$) were taken vertically from soil horizons by using metallic tins and the sampler, and their physical properties shown below were measured.

1) Soil strength at pF 2 potential

Water-saturated cylindrical soil samples were brought to equilibrium at pF 2 potential on the porous plate suction system, and mechanical impedance at the bottom face of the samples was measured by the soil strength meter.

2) Soil moisture retained at pF 2 potential

After the measurement of *1)*, the soils were oven-dried at 105°C to determine the moisture retained at pF 2 potential.

3) Hydraulic conductivity of saturated soil

Hydraulic conductivity K_{20} of saturated soil was measured by the ordinary variable water-head method.

4) Plastic limit and liquid limit of soil

Plastic limit and liquid limit of fresh paste soils were measured by the Japanese Industrial Standard method.

5) Slaking properties of dry soil

After oven-drying, the cylindrical samples were put into water to observe breaking-up and dispersion of soil mass on soaking, and slaking properties were graded into five degrees.

Table 1. Characteristics of soil profile of Muda soils

Soil series	Site No.	Elevation (feet)	Soil profile (cm)	Hydraulic conductivity K_{20} (cm/sec)	Slaking properties*
Kranji	1	6	Ag(0-15) ACg(-40) CG(-100)	ACg(10^{-5}) CG(10^{-6})	
Kuala Kedah	13	6	Apg(0-15) ACG(-25) CG_1(-60) CG_2(-100)	ACG(10^{-7}) CG_1(10^{-6})CG_2(10^{-6})	Apg(−) ACG(−) CG_1(+) CG_2(+)
Sedaka	2, 15	6-8	Apg(0-20) $A_{12}g$(-35) C_1g(-65) C_2g(-100)	$A_{12}g$(10^{-7}) Cg($10^{-5}-10^{-7}$)	Apg(−−−) $A_{12}g$(−) Cg(+++)
Chengai	10, 11, 16	6	Apg(0-20) $A_{12}g$(-35) C_1g(-60) C_2g(-100)	$A_{12}g$($10^{-6}-10^{-7}$) Cg($10^{-5}-10^{-7}$)	Apg(−−−) $A_{12}g$(−) C_1g(+) C_2g(+++)
Telok	3	6-8	Apg(0-20) $A_{12}g$(-35) Cg(-100)	$A_{12}g$(10^{-6}) Cg(10^{-6})	
	4	6-8	Apg(0-25) ACg(-60) Cg(-100)	ACg(10^{-6}) Cg(10^{-5})	
	5	6-8	Apg(0-20) ACg(-40) Cg(-100)	ACg(10^{-6}) Cg(10^{-5})	
	14	8-10	Apg(0-18) $A_{12}g$(-25) C_1g(-40) C_2g(-100)	$A_{12}g$(10^{-4}) C_1g($10^{-5}-10^{-7}$) C_2g(10^{-3})	Apg(−−−) $A_{12}g$(−−−) C_1g(±) C_2g(±)
	8	10-12	Apg(0-20) $A_{12}g$(-40) ACg(-55) C_1g(-80) C_2g(-100)	Ag_{12}(10^{-6}) C_1g(10^{-3}) C_2g(10^{-4})	Apg(−−−) $A_{12}g$(−) ACg(−) C_1g(+) C_2g(+)
Tualang	9	6-8	Apg(0-16) ABg(-25) Cg(-100)	ABg(10^{-7}) Cg(10^{-5})	Apg(−−−) ABg(−−−) Cg(±)
	12	6-8	Apg(0-20) ABg(-35) BCg(-65) Cg(-100)	ABg(10^{-4}) BCg(10^{-6}) Cg(10^{-5})	Apg(−−−) ABg(−−−) BCg(±) Cg(±)
	6	12	Apg(0-18) $A_{12}g$(-25) ABg(-45) C_1g(-70) C_2g(-100)	$A_{12}g$(10^{-6}) ABg(10^{-4}) C_1g(10^{-4}) C_2g(10^{-3})	Apg(−−−) $A_{12}g$(−−−) ABg(−) Cg(+)

* −−− stable, − broken up by mild shaking, ± broken up into 4–10 mm aggregates, + slaked into 1–2 mm flakes, and +++ slaked or dispersed into particles less than 1 mm on soaking in water.

Results and discussions

1) Characteristics of soil profile of Muda main soil series

Soil profile characteristics, hydraulic conductivity, and slaking properties of every horizontal soil are shown in Table 1.

Muda main soil series distribute at elevations ranging from 1.8 to 3.6 m above sea level. The elevations are in the order of Kranji ≒ Kuala Kedah < Chengai ≦ Sedaka ≦ Telok < Tualang series. These soils were all heavy clay in soil texture, but some soils located near hills such as some of Telok and most of Tualang series were slightly coarser with higher contents of silt and fine sand fractions. Most soils belonged to highly plastic inorganic clay on the Casagrande Plasticity Relationship.

Kranji and Kuala Kedah series on the fresh marine alluvium had A-CG horizon. Gley subsoils with massive structure had low hydraulic conductivity as 10^{-6}cm/sec, and the dry soil slaked into 1–2 mm flakes very quickly on soaking in water, indicating a very poor consistence of soil under saturated field conditions.

Sedaka series on the marine alluvium had A-C horizon. The A horizon with a depth to about 35 cm was rich in humus, and the dry soil mass was stable on soaking. Grayish yellow-colored C horizon soils were structureless, and the dry soils dispersed into water very easily. Hydraulic conductivity of this

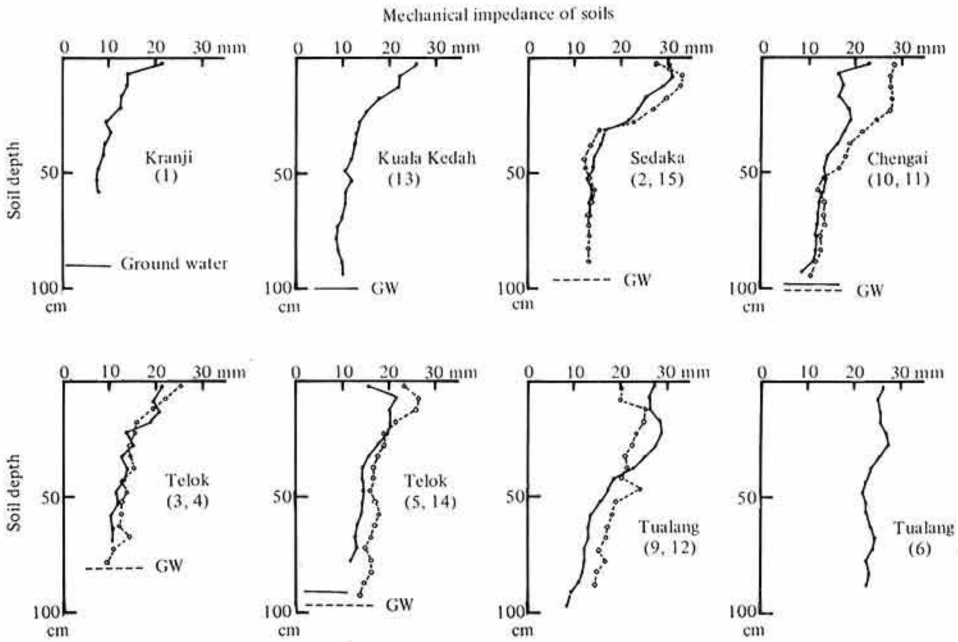

Fig. 2. Mechanical impedance of soils in the field measured by the Yamanaka soil strength meter in terms of mm
The value of X(mm) is convertible to the pressure, P(kg/cm^2), by the equation:

$$P = \frac{100X}{0.795 \times (40-X)^2}$$

horizon was extremely low. Chengai series on marine deposits with some riverine influence had the similar profile characteristics as Sedaka, except that nearly structureless C horizon contained plenty of reddish brown mosaics of iron compounds.

Telok series on the brackish water alluvium had A-C horizon. Angular blocky structures developed moderately or prominently were observed in both horizons. The C horizon contained plenty of iron mottles and concretions, and tubular iron oxides deposited along the holes left by roots were characteristic. Due to this and the structural development, hydraulic conductivity of the subsoils was rather high, showing the range of $10^{-3} \sim 10^{-6}$ cm/sec. The dry soils of both A and C horizons showed considerable resistance against slaking. It suggests favorable bearing capability of the soils, especially in the subsurface layers, under wet field conditions.

Tualang series on the thick riverine deposits with underlaid marine alluvium had A-B-C horizon. There was iron-accumulated B-horizon beneath the cultivated soil layer. A and B horizons had rather high hydraulic conductivity and low slaking properties probably due to more or less coarse texture and moderate structural development in these soils.

2) Mechanical impedance of soil

Vertical distribution of mechanical impedance of soil in the field is shown in Fig. 2.

Mechanical impedance of soil in the field decreased with depth on the whole due to soil desiccation occurring from the upper part of the profile. However, in Tualang series, A_{12} or AB horizon exerted high mechanical impedance irrespective of the moisture conditions. The mechanical impedance of deep part of soil profile showing the similar moisture condition was compared among different series. It was obvious that mechanical impedance was in the order of Kuala Kedah < Sedaka ≒ Chengai < Tualang series. That of Telok series varied according to microtopography, but was considered to fall between Chengai and Tualang series.

In order to compare pedogenic soil strength among soil series, soil strength under the pF 2 moisture condition was measured.

Soil strength at pF 2 potential of Muda soils varied from 0.9 to 11 kg/cm^2. That of Gley horizon of Kranji and Kuala Kedah or C horizon of Sedaka series was very low, being less than 2 kg/cm^2. In case of Chengai, C horizon had the similarly low soil strength, while A_{12} horizon had higher soil strength (4–6 kg/cm^2). That of Telok series was higher than the Marine Alluvial soils as a whole, and soil strength as high as 5–6 kg/cm^2 was shown at the depth down to about 50 cm. Tualang series had the highest soil strength, and especially at A_{12} or AB horizon it was as high as 10 kg/cm^2. These differences in soil strength among soil series or soil horizons were considered to be closely related with pedogenic nature of soil such as parent materials, soil structure, soil texture, the amount and type of iron oxides and the content of organic matter.

3) Index of soil structural stability against mechanical deformation

Actual structure of soil in the field as measured by the pore size or the aggregate diameter is never constant under the influence of outer forces. Boekel (1958)[1] considered that evaluation of stability of soil structure against destructive forces is necessary. As for clay soils the combination of both plastic limit and field moisture condition may give information on the structural stability, because deterioration of the structure of clay soils is mainly caused by plastic deformation, sensitively near the moisture content of plastic limit. On the basis of this idea, Boekel (1963)[2] demonstrated how plastic limit/pF 2 moisture varies according to textures and contents of organic matter of clay soils.

The present author considers that this index

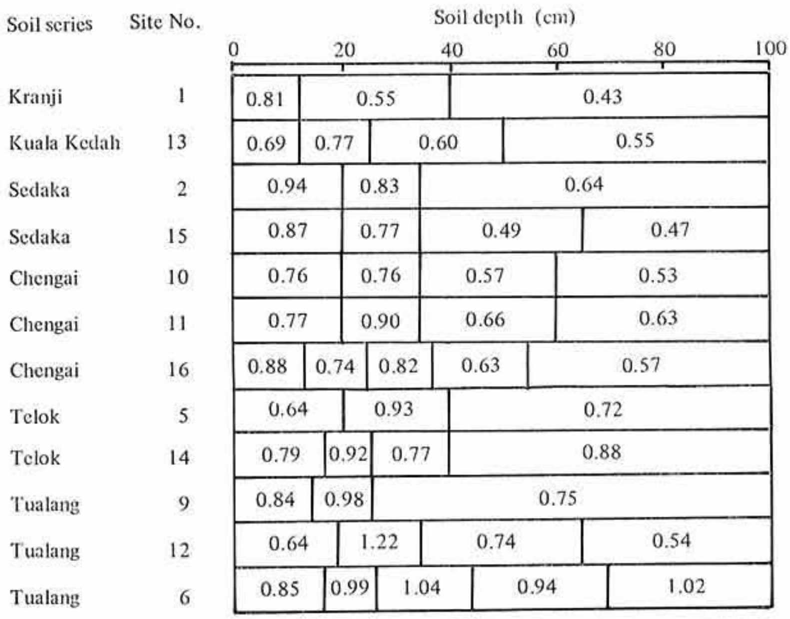

Fig. 3. Index of soil structural stability against mechanical deformation, plastic limit/pF 2 moisture, of Muda soils

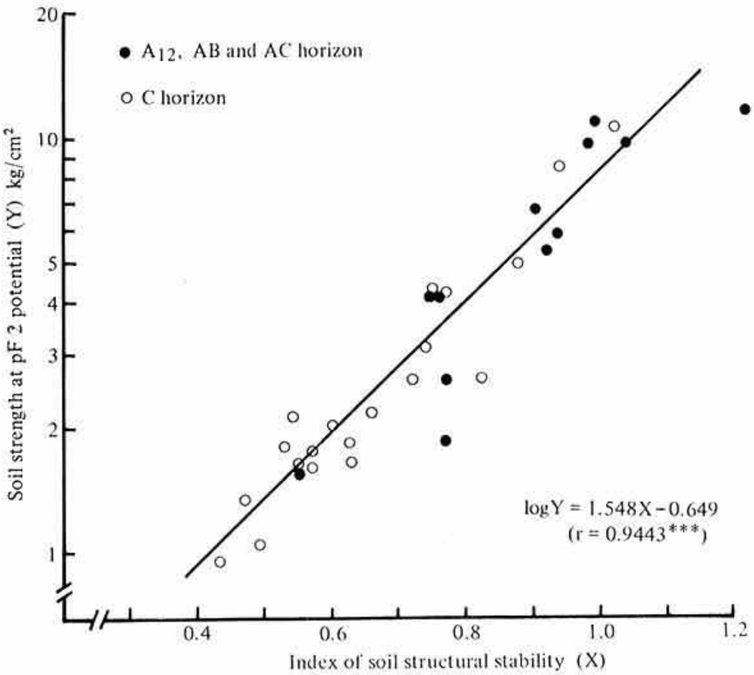

Fig. 4. Relationship between index of soil structural stability and soil strength of Muda soils (Ap soils were excluded)

implies the insensitivity of plastic deformation of clay soil to the possible moisture changes in the field. It may also imply whether water film thickness of soil paste is enough or not to exert plasticity when the retained water in the structural mass is brought to even distribution on the unit particles of soil. Thus the index may express the structural resistance of soils to mechanical force independent of the moisture condition.

The index of Muda soils varied between 0.4 and 1.2 as shown in Fig. 3. As shown in Fig. 4, it was found out that there was a linear relationship between the index and the logarithm of soil strength at pF 2 potential for Muda soils.

4) Bearing strength classification of Muda soils

The stability indices of soils were plotted on the plastic limit-pF 2 moisture relationship as shown in Fig. 5. It was obvious that Muda soil series can be classified into three groups based on the index; Marine Alluvial soil group (Kranji, Kuala Kedah, Sedaka and Chengai series), Brackish Water Alluvial soil group (Telok series) and Fresh Water Alluvial soil group (Tualang series). In Marine Alluvial soils the indices of C horizon soils were less than 0.7 and those of A horizons were between 0.7 and 1.0. This suggests that C horizons have a very poor bearing capability, while some degrees of bearing strength can be expected only in A horizon in this group. In Brackish Water Alluvial soils the indices of both A and C horizon soils ranged between 0.7 and 1.0, and considerable degrees of bearing strength may be exerted in both horizons. In Fresh Water Alluvial soils those of most soils ranged between 0.7 and 1.2, indicating that a favorable bearing strength might be expected in this group, especially in B horizon soils.

Current practices of agricultural machinery were surveyed by hearing from farmers and combine operators. The results indicate that in Kuala Kedah series farmers use only two-wheeled cultivators. In Sedaka series four-

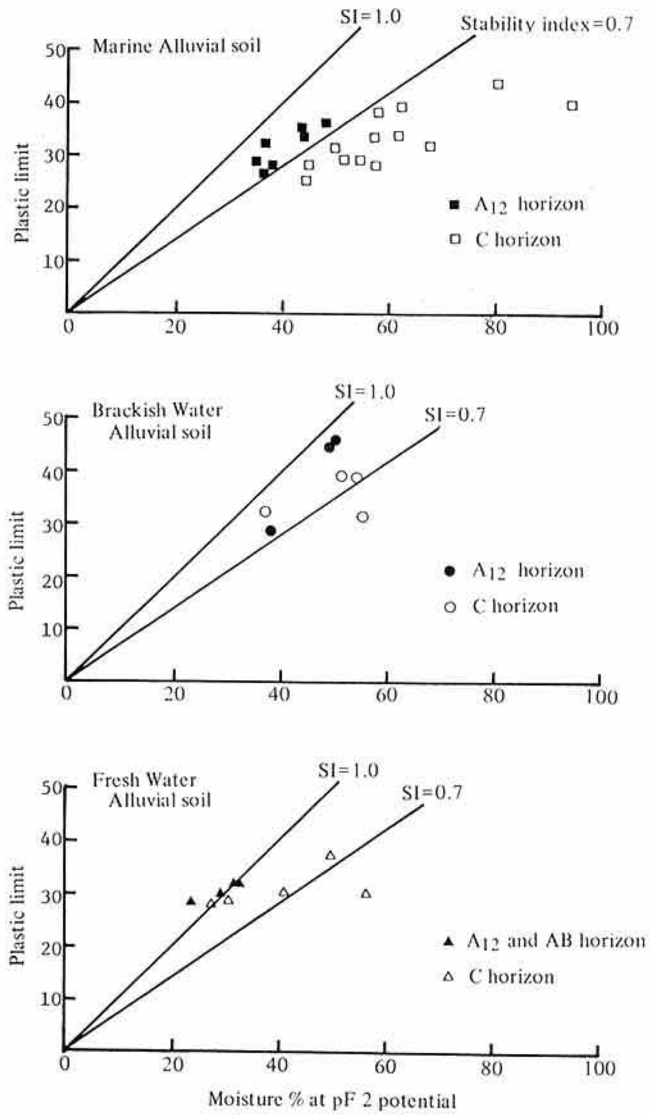

Fig. 5. Plastic limit-pF 2 moisture relationship of Muda soils

wheel tractors are workable only in the dry season. In Telok series except for swampy spots or places near the coast, four-wheel tractors and combines are trafficable in some seasons. In Tualang series all these machinery are trafficable all year round. These farmer's practices well coincide with the above classification with some sub-grouping of Marine Alluvial soils.

Criteria of soil strength needed for operation of tractors which are recommended by the Ministry of Agriculture, Forestry and Fisheries, Japan (1969)[5] (A), and the relevant values obtained by Yashima (1979)[8] for Muda soils (B) are as follows.

		Possible		Desirable		
(A)	Four-wheel tractor tired (FE 35, MF 25) Mechanical impedance at the depth 0-15 cm (kg/cm²)	(Rotary) 2.5-5	(Plow) 4-6.5	(Rotary) 5.0	(Plow) 6.0	
(B)	Four-wheel tractor (60-70 HP)	1.5-3 kg/cm²		3 kg/cm²		(at the depth of 20 cm)
	Semi-crawler combine (7 tone)	3-5		5		(at the depth of 20 cm)

As for the bearing capability of the field, soil strength at the subsurface layer is the most important. The index and soil thickness of this layer soil in Chengai and Sedaka series were somewhat larger than those in Kranji and Kuala Kedah series. Therefore it is better to classify these Marine Alluvial soils into two subgroups, Chengai-Sedaka and Kuala Kedah-Kranji. This may better fit the current practices of agricultural machinery in the Muda Area. Because there have been troubles of sinking of heavy machinery in Chengai-Sedaka series, development of rational use of agricultural machinery in these soil series would be the most necessary.

Conclusion

The stability index of soil structure expressed by plastic limit/pF 2 moisture was proved to be useful for the evaluation of bearing strength of clayey soils in the Muda Irrigation Project Area. With this index abstraction and numeration of pedogenic and structural properties of soils regarding mechanical deformation or mechanical impedance were made possible. By taking into account the index and soil strength in the field or at a constant moisture potential, Muda soils were tentatively classified into four groups based on bearing capability of soil; Kuala Kedah-Kranji (very poor), Chengai-Sedaka (poor), Telok (moderate) and Tualang (good). Detailed survey and associated research on the use of agricultural machinery in the Muda Area are most desired.

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