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A new method of measuring plastic limit of fine materials

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Index properties such as the liquid limit and plastic limit are widely used to evaluate certain geotechnical parameters of fine-grained soils. Measurement of the liquid limit is a mechanical process, and the possibility of errors occurring during measurement is not significant. However, this is not the case for plastic limit testing, despite the fact that the current method of measurement is embraced by many standards around the world. The method in question relies on a fairly crude procedure known widely as the 'thread rolling' test, though it has been the subject of much criticism in recent years. It is essential that a new, more reliable method of measuring the plastic limit is developed using a mechanical process that is both consistent and easily reproducible. The work reported in this paper concerns the development of a new device to measure the plastic limit, based on the existing falling cone apparatus. The force required for the test is equivalent to the application of a 54 N fast-static load acting on the existing cone used in liquid limit measurements. The test is complete when the relevant water content of the soil specimen allows the cone to achieve a penetration of 20 mm. The new technique was used to measure the plastic limit of 16 different clays from around the world. The plastic limit measured using the new method identified reasonably well the water content at which the soil phase changes from the plastic to the semi-solid state. Further evaluation was undertaken by conducting plastic limit tests using the new method on selected samples and comparing the results with values reported by local site investigation laboratories. Again, reasonable agreement was found.

KEYWORDS: clays; laboratory equipment; mineralogy; soil classification

Les propriétés caractéristiques, comme la limite liquide (LL) et la limite plastique (PL) sont très répandues pour l'évaluation de certains paramètres géotechniques de sols à grain fin. La mesure de LL est un processus mécanique, et les risques d'erreur au cours de cette mesure ne sont pas significatifs. Toutefois, il n'en est pas de même des tests PL, en dépit du fait que la méthode de mesure actuelle est adoptée par de nombreuses normes dans le monde entier. La méthode en question repose sur une procédure plutôt rudimentaire, bien connue sous le nom de test « filetage par roulage » (*thread rolling*), qui a toutefois fait l'objet de nombreuses critiques, au cours des dernières années. Il est indispensable que l'on développe une méthode à la fois nouvelle et plus fiable de mesure PL, en faisant usage d'une procédure mécanique à la fois régulière et facilement reproductible. Les travaux reportés dans la présente communication concernent le développement d'un nouveau dispositif de mesure PL, basée sur l'appareil existant à cône tombant. La force requise pour le test équivaut à l'application d'une charge « *fast-statique* » de 54 N sur le cône existant, utilisé dans des mesures LL. Le test est terminé lorsque la teneur en eau du spécimen de sol permet au cône de réaliser une pénétration de 20 mm. On a utilisé la nouvelle technique pour mesurer le PL de 16 argiles diverses provenant du monde entier. Le PL mesuré avec la nouvelle méthode a permis d'identifier raisonnablement bien la teneur en eau a laquelle la phase du sol change de l'état plastique à l'état semi plastique. On a effectué de nouvelles évaluations en appliquant la nouvelle méthode sur des échantillons sélectionnés, et en comparant les résultats avec ceux des PL fournis par les laboratoires de recherche sur site locaux. Ici aussi, on a établi un accord raisonnable.

INTRODUCTION

The physical condition of fine-grained soil can be defined by its consistency limits. The consistency limits are used to define the phase or state of a soil – liquid, plastic, semi-solid, and solid. The limits are defined in terms of the water content of the soil, and are traditionally known as the Atterberg limits. The consistency limits are applicable only to fine-grained soils, as these have the ability to retain water in pore spaces under suction. The most commonly used consistency limits are the liquid limit and the plastic limit. The liquid limit (LL) defines the water content at which the behaviour of the soil changes from the liquid state to the plastic state. The plastic limit (PL) defines the water content at which the behaviour of the soil changes from the plastic to the semi-solid states.

Casagrande (1958) was the first to categorise the properties of soil using index properties, and since then several attempts have been made to establish more rigorous forms of the relationship between the engineering properties of a soil and its index properties (Wroth & Wood, 1978; Nakase *et al.*, 1988; Muir Wood, 1990). The estimation of index properties is an essential component in any ground engineering investigation, regardless of the type or size of the investigation. The index properties provide useful information with regard to the engineering properties of the soil, such as shear strength, shrinkage/swelling and settlement parameters. The limit tests are therefore useful for gaining an insight into the fundamental behaviour of soils. Moreover, they provide an effective way of distinguishing a soil's type: that is, classifying it as either silt or clay fraction dominant. This latter distinction is very important, because of the different responses these soil types produce under load.

DETERMINATION OF CONSISTENCY LIMITS

Set procedures for measuring LL and PL are incorporated in various standards. BS 1377 Part 1 (BSI, 1990) clearly stipulates the procedure that has to be adopted to measure the LL and PL of fine-grained materials. The preparation of material for index testing involves sieving it by passing the

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selected sample through a 425 μm-sized sieve. The test currently used to determine LL is a mechanical process that is widely known as the cone penetrometer or fall-cone test. The device itself was first produced by the Laboratoire Central des Ponts et Chaussées in 1966. The liquid limit is evaluated by determining the water content of the soil at the point that allows a cone, weighing 80 g and with a tip angle of 30°, to penetrate the specimen by 20 mm. Usually the test is repeated for various water contents, and the relationship between penetration and water content is established. It is common for this relationship to be linear, with LL being recorded as the water content at 20 mm penetration.

Although there are a number of methods proposed for the measurement of plastic limit, the laboratory standard used throughout the world (BS 1377 Part 1; BSI, 1990) still adopts the method suggested by Casagrande (1958). This procedure is not a mechanical process, and PL is evaluated by determining the water content of the soil when a thread, made by hand-rolling the soil specimen on a glass plate, breaks up at a nominal diameter of approximately 3 mm. The reliability of the PL result relies heavily upon the expertise of the operator performing the test. This method has been described by Belviso *et al.* (1985) as 'a rather crude procedure', and has long been criticised by others, such as Houlsby (1982), Whyte (1982) and Brown & Downing (2001). The drawbacks of the test are well documented, and include its highly subjective nature, its over-reliance on operator judgement, and variations in the amount of pressure applied during rolling, the speed of the rolling technique used, and the geometry of the thread. The vagueness of the guidelines on the test procedure, friction between hand, soil and glass, and the risk of contaminating the soil sample all contribute to devaluing the standard thread-rolling method. Sherwood (1970) carried out a detailed study of the reproducibility of PL of three soil types under different conditions, which included tests performed by a single operator, eight operators from the Road Research Laboratory, and further operators from different laboratories. The results clearly demonstrate wide differences in PL values – as much as 12% in terms of water content – which would normally have a significant influence on the basic soil classification of the material being tested, including the undrained shear strength. Accordingly, there is a need for a more consistent and accurate laboratory procedure to determine PL.

Researchers have identified the main issues or primary problems relating to the standard evaluation of PL and, in an attempt to improve accuracy, have developed several revised methods, many of them based on the falling cone approach used for liquid limit tests. Four significant alternatives have been proposed: by Medhat & Whyte (1986), Harrison (1988), Stone & Phan (1995) and Feng (2000). Medhat & Whyte (1986) examined two different approaches to the determination of PL: the displacement control and load control methods. Using the displacement control method, Medhat & Whyte (1986) concluded that the value of PL is sensitive to the undrained shear strength in the range between 110 and 170 kPa. The load control test – essentially a fall cone test under elevated mass – produced values of PL for different clays similar to those obtained with displacement control methods, although the exact mass applied to the fall cone is not given. Harrison's (1988) approach relies on the relationship between the liquidity index and the logarithm of cone penetration in a range of 5–14 mm under a cone mass of 80 g. PL is obtained by extrapolating the relationship over the range and finding the water content at a penetration of 2 mm. Feng (2000) adopted a similar approach by plotting both water content and penetration on logarithmic scales, and then determining PL by extrapolating the water content at a penetration of 2 mm.

In a remarkable work, Stone & Phan (1995) established a method where an instrumented cone is allowed to penetrate the soil at a constant rate of 1 mm/s. The specimen is prepared in the standard cup used for LL measurement over a range of different water contents. This approach is based on the theory described below.

Wroth & Wood (1978) proposed the following relationship between undrained shear strength c_u and the depth of penetration d under dynamic loading conditions.

$$\frac{c_u d^2}{w} = k(\alpha, \chi) \tag{1}$$

where w is the weight of the cone; α is the cone factor, which is dependent on the cone angle; and χ is a measure of the frictional effects between the soil and the cone. If χ does not vary, equation (1) reduces to

$$\frac{c_u d^2}{w} = k_\alpha \tag{2}$$

where k_α is the cone factor. This relationship is based on the cone falling under its own weight. Houlsby (1982) proposed a similar form of relationship between penetration h and undrained shear strength c_u when the cone is allowed to fall slowly into the clay (i.e. under quasi-static conditions):

$$c_u h^2 = \frac{P''}{F} \tag{3}$$

In this case F is a non-dimensional factor, and P'' is the vertical component of soil resistance to penetration. Using a quasi-static analysis, Houlsby (1982) showed that the depth of the penetration h under quasi-static conditions is approximately $d/\sqrt{3}$, assuming $P'' = w$. Based on this, 80 g of cone will penetrate 11·55 mm (i.e. $20/\sqrt{3}$) into the soil prepared at the LL under quasi-static loading conditions. Stone & Phan (1995) extended this analogy to soils prepared at water contents close to the PL.

Stone & Phan (1995) assumed that the ratio of the undrained shear strength of the soil at PL compared with that at LL is 100 (Skempton & Northey, 1953; Hansbo, 1957; Wroth & Wood, 1978). In other words, the force on the cone required to achieve the same penetration at PL as that at LL is believed to be 100 times the weight of the standard cone. Accordingly, they introduced an additional index property known as PL_{100}. This value is not exactly similar to the actual PL of the soil tested. They established a relationship between water content and penetration for a cone load of 80 N, with PL_{100} being defined as the water content at a penetration of 11·55 mm.

The research reported in this article builds upon the progress made by Stone & Phan (1995). The proposed method uses 'fast' or immediate application of a force on the existing cone used for measuring LL: consequently this loading condition is referred to in the rest of the paper as the 'fast-static loading' test, although the PL is measured on a targeted penetration of 20 mm.

Based on the work of many researchers, the cone mass required to carry out an accurate evaluation of PL is about 8 kg, on the assumption that the ratio between the undrained shear strengths at PL and LL, $c_{u(PL)}/c_{u(LL)}$, is approximately 100. However, researchers have postulated a wide range of $c_{u(PL)}/c_{u(LL)}$ ratios, up to as high as 170. Understandably, the application of 8 kg under dynamic conditions is not only problematic and cumbersome, but might even raise concerns over safety.

PROPOSED METHOD

For the purposes of this investigation, the main considerations were to design a device that is user-friendly, inexpensive and requires minimum skill to operate. The study based its design on the idea that by applying a certain force to the standard 80 g, 30° cone, the PL could be found at a penetration depth of 20 mm.

The application of an 'increased' or elevated load could be achieved by simply incorporating a heavier cone in the apparatus; however, this was deemed impractical, owing to the inherent difficulties in handling such a heavy cone. As an alternative, it was proposed to apply a small pressure to a cylinder and piston arrangement attached to the existing fall-cone apparatus. This, in turn, would then apply a predetermined force to the standard 80 g cone. Fig. 1 shows a detailed drawing of the system. The drawing shows the piston, with the loading ram extending each side of the cylinder chamber, supported by a rolling diaphragm. It has been designed so that the friction between the cylinder and the piston is almost negligible, with the piston free to fall under its own weight. The maximum travel distance of the piston is 30 mm.

Application of a regulated air pressure system generates the required force on the loading ram. The loading ram is attached to the plunger of a standard cone apparatus used for evaluating LL, as illustrated in Fig. 2. A Norton-type regulator is used to control the air pressure. A specified pressure can be preset on the supply line (Fig. 2), and the pressure is delivered within a fraction of a second to the cylinder by opening the valve V_1 located on the pressure line between the regulator and the cylinder. To prevent the build-up of pressure below the piston in the cylinder during

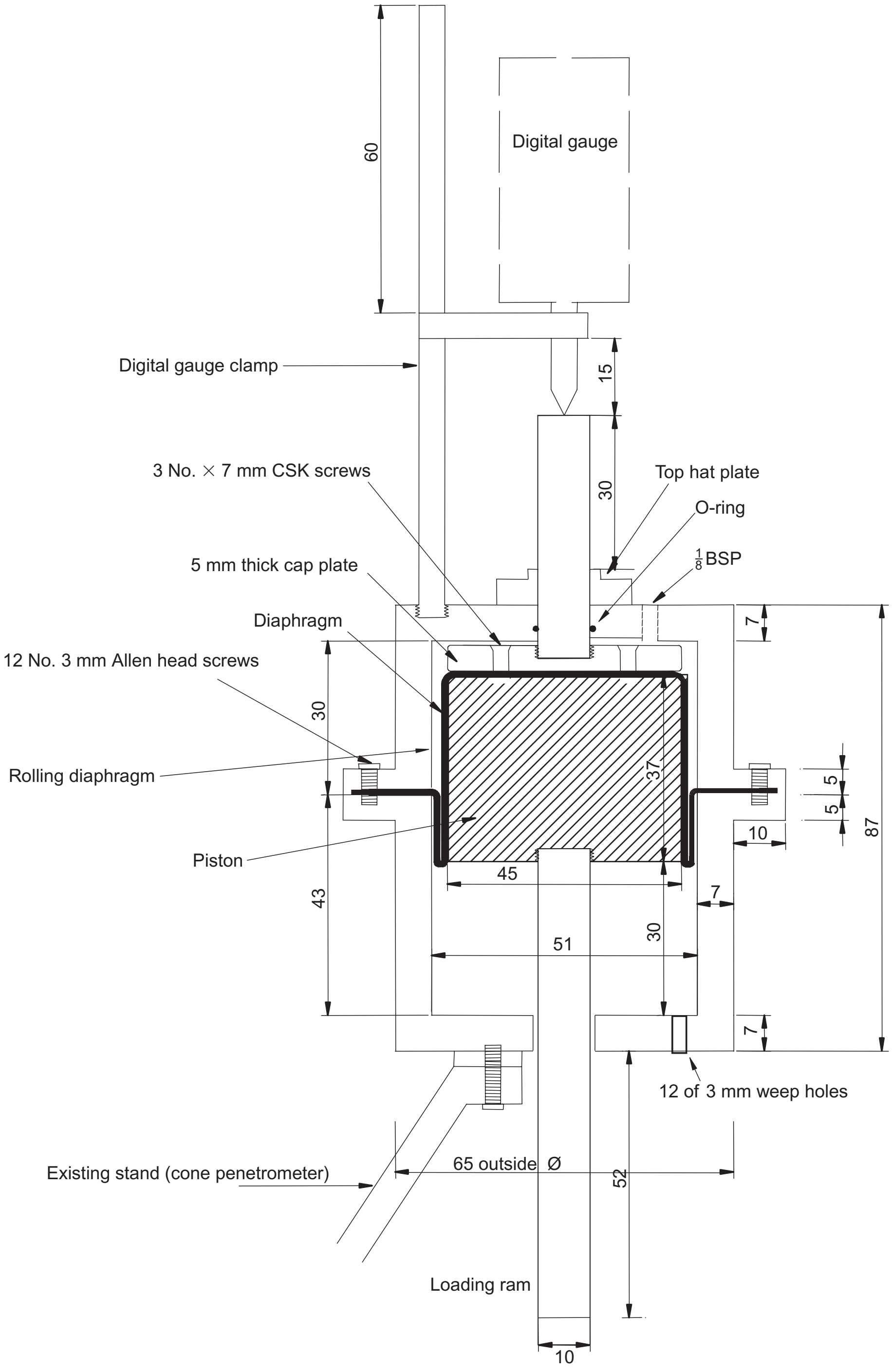

Fig. 1. Design of the new plastic limit device (all dimensions in mm)

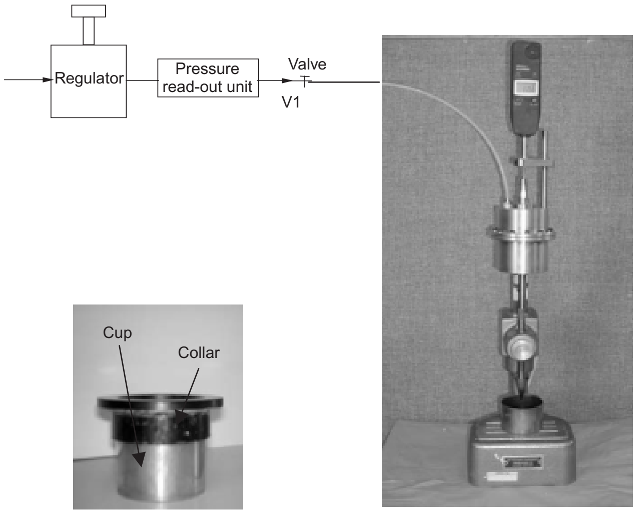

Fig. 2. Digital image of the plastic limit measuring device

the loading stage (when the force is transmitted to the loading ram), the bottom plate of the cylinder is perforated with 'weep' holes. Load activation is almost instantaneous. Since the volume of the cylinder is only about 63 cm^3, the time taken to establish the requisite pressure in the supply line is a mere fraction of a second. During the trials no noticeable pressure variations were observed in the pressure transducer – located close to the regulator – once valve V_1 was opened. Accordingly, the process of applying the force using this device is 'fast', albeit that it is not the same system as that of an elevated mass falling under its own weight. The actual depth of the penetration is recorded by readings taken from a digital gauge.

EXPERIMENT, RESULTS AND DISCUSSION

Calibration of the device

The device is calibrated in such a way that the force required on the existing cone of 80 g is assessed using a material whose PL is widely known. Speswhite kaolin is frequently used in soil mechanics research, and so this soil was adopted as a suitable 'benchmark' or calibration material to use in this instance. The LL and PL of this clay are 69% and 34% respectively (Navaneethan & Sivakumar 2002).

As part of the study, the force required to be exerted on the cone to achieve 20 mm penetration was investigated. Initially, 200 g of kaolin powder was mixed with de-aired water at preselected water contents of 32·0, 34·0, 35·5 and 37·0%. The mixed material was allowed to hydrate for 24 h. The following day the material was carefully placed in layers inside the standard cup used for LL (as per Fig. 2) using the 'kneading' technique. A collar was attached to the cup to facilitate the kneading process. Each layer was tamped using a 0·25 kg brass rod with a diameter of 25 mm. When kneading was complete, the collar was removed and the soil in the cup was levelled off using a wire saw. There were some concerns about the repeatability of this procedure, particularly with regard to generating samples with similar bulk densities at a given water content. Accordingly, many trials were conducted to assess the repeatability and to perfect the reproduction of similar samples. One important aim here was to rule out the influence of any additional energy being exerted by the tamping rod. If the soil is saturated, then additional energy delivered by the tamping process will not influence the bulk density of the soil in the cup. This was independently verified by statically compacting the soil in the cup using various predetermined vertical pressures (500, 1000 and 1500 kPa). It transpired that the variation in the initial bulk density at given water contents was only about $\pm 0{\cdot}5\%$. Note that this observation is valid only if the material is prepared at water contents close to or above PL.

The cup was then placed on the cone penetrometer base plate and, making sure that the cone tip was resting on the rim of the cup, the digital gauge was set to zero. Note here that the surface of the smooth cone is not smeared with oil, although some researchers have done so in measurements of LL. The cone tip was positioned at the centre of the sample and in contact with the soil surface. The cone was then released and the pressure was applied instantaneously to the chamber by opening valve V_1 (Fig. 2). With the aid of a stopwatch, penetration depths were recorded at elapsed times of 15, 30, 60 and 120 s respectively. The pressure in the chamber was then released and the sample was removed from the cup. As further penetration of the cone after 15 s (Fig. 3) was insignificant, this value of penetration was adopted for the subsequent analysis.

Various trials were then carried out to determine the required pressure in the cylinder (Fig. 2) to yield a penetration of 20 mm at a water content of 34%. This pressure was subsequently found to be about 30 kPa, which translates to a force of 54 N being exerted on the existing 0·8 N cone. All remaining tests were performed at this piston load. Fig. 4 shows a plot of penetration against water content for kaolin, in which two such trials were performed to evaluate the reproducibility of test results. It shows that the apparatus performed well in terms of repeatability of the results

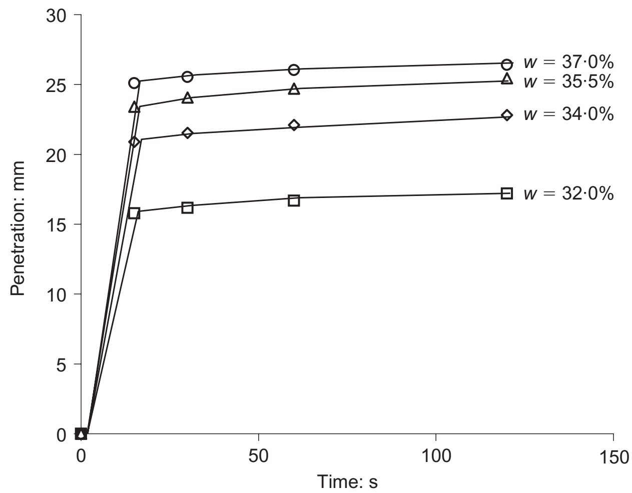

Fig. 3. Measurement of plastic limit: penetration against time

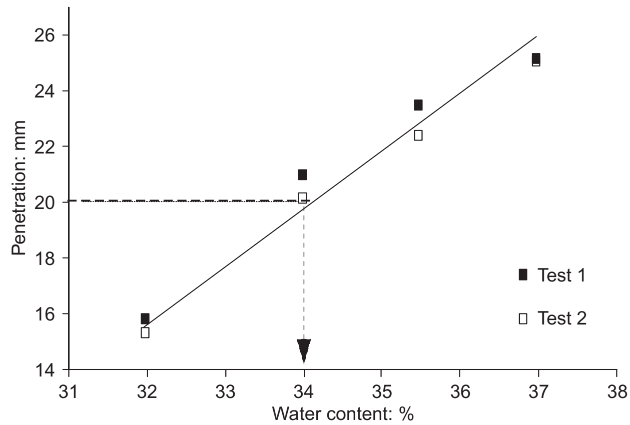

Fig. 4. Calibration of plastic limit device using kaolin clay (at t = 15 s)

obtained. Furthermore, the relationship between water content and penetration was found to be generally linear within the range of water contents examined, although such a linear relationship should be treated as a simplification.

Assessment of the loading conditions

A set of additional tests was performed to establish the effects of loading type on penetration depths. Again, a piston load of 54 N was applied instantaneously (i.e. following the above procedure) on kaolin and Belfast clay (BC) samples prepared at waters content close to the PL. The tests were repeated on the materials with the same water contents, but in this case the load (on the piston) was applied by gradually increasing the pressure in the cylinder from zero to 30 kPa. Table 1 lists the penetrations observed in each case. Repeat tests were also performed, and the results clearly show that, in the plastic state, the magnitude of penetration is not particularly affected by the type of loading employed. This in effect confirms the insignificance of inertia effects associated with the cone and piston mass on the depth of penetration. In contrast, when the tests were performed on kaolin and BC prepared at the LL, the penetrations achieved during fast-static loading (i.e. where only the 80 g cone is gently allowed to fall into the clay under its own weight) are significantly lower than those obtained when the cone is allowed to free-fall (i.e. dynamic loading conditions). The relevant observations are listed in Table 1, and the findings support the theory, proposed by Houlsby (1982), that the penetration h during quasi-static loading is approximately equivalent to $d/\sqrt{3}$, where d is the penetration during dynamic loading. This clearly suggests that the load of 54 N applied on the piston is instantaneous (i.e. fast-static loading), and the energy associated with this action is not directly comparable or analogous to the energy exerted by a free-falling cone weighing 5·5 kg (i.e. under dynamic loading conditions).

As part of a limited study, a further set of tests was carried out on Ampthill clay in which the cone was allowed to fall under the influence of a dead weight of 5·5 kg. For this purpose, provision was made to support the 5·5 kg mass on the existing falling cone apparatus. The results show that a penetration of 23·5 mm was observed at a water content of 35·5%, whereas, at the same water content, 19·5 mm penetration was observed under the fast-static application of 54 N using the new method. The increased penetration of cone under dynamic loading (i.e. free fall of 5·5 kg mass) over fast-static loading of 54 N does support the theory reported by Houlsby (1982), although this penetration is less than 33·8 mm (i.e. that predicted by $h\sqrt{3}$, where h is the penetration under quasi-static loading or fast-static loading). It is speculated that the reduced penetration under dynamic loading could be due to a different failure mechanism prevailing when the soil is close to the PL compared with that at the LL.

Digital images were taken in order to assess the displacement rates (rate of cone penetration) when the cone was allowed to fall into clay under its own weight, and when acted on by an external force. Fig. 5 shows the penetration

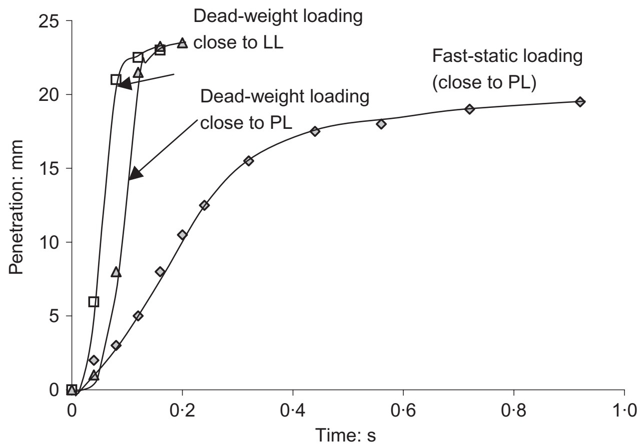

Fig. 5. Cone penetration against time

of the cone plotted against time for Ampthill clay when: (a) the cone falls freely under its own weight into clay prepared at water content close to LL; (b) the cone falls freely under the application of a dead weight of 5·5 kg into clay prepared at water content close to the PL and; (c) the cone penetrates into the clay prepared at water content close to the PL under the fast-static 54 N force. The observations suggest that the average rate of penetration is close or nearly identical when the cone falls under the influence of dead weight. However, the rate is significantly reduced – by as much as fivefold – and indeed not particularly constant when the penetration is generated by the fast-static force of 54 N. This suggests that possible strain rate-effects associated with the depth of penetration under fast-static loading are not comparable to the cone falling under the influence of dead weight.

Measurement of PL of various materials

As part of the assessment for measuring PL using the new method 16 different clays, collected from around the world, were examined. The various clays tested include: London clay (LC) from two different sites (Fricton and Jarwick) and two different depths; Belfast clay (BC) from two different locations; estuarine alluvium or 'sleech' (SL) from Belfast; mudstone (MU); glacial till (GT) from two different locations in Northern Ireland; Vancouver clay (VC); Norway clay (NR); Winnipeg clay (WP); Saskatchewan clay (ST); and red clay (CH).

The clays tested had a wide range of reported index properties. Table 2 lists the range of particle sizes of the various deposits, and the relevant mineralogical compositions. The predominant minerals in all the materials are quartz and feldspar, and the variation in the mineralogy for a particular geological deposit is not significant (e.g. LC and BC). The samples were prepared by initially oven-drying at 105°C (BS 1377 Part 1; BSI, 1990), then grinding and subsequently sieving through a 425 μm sieve. With the exception of the glacial till, most of the original materials tested were generally fine-grained. The particle size analyses

Table 1. Effects of dynamic and fast-static loading on the cone penetration

Soil type	Dynamic cone penetration: mm		Quasi-static cone penetration: mm	
	Close to LL state (0·8 N cone load)	Close to PL state (54 N cone load)	Close to LL state (0·8 N cone load)	Close to PL state (54 N cone load)
Kaolin	20·5	21·0	13·0	20·5
Belfast clay	20·3	20·8	14·7	20·8

Table 2. Clay mineralogy and percentage of clay-, silt- and sand-size particles

Soil type	Clay minerals	Clay % (<2 μm)	Silt % (2–63 μm)	Sand %			
				63–250 μm	250–500 μm	500 μm–1 mm	1–2 mm
Kaolin (KC)	Q, CH, K	54	46	0	0	0	0
Belfast clay (BC1)	Q, F, C, D, CH, M, S	46	49	2	1	1	
Belfast clay (BC2)	Q, F, CH, M, S	25	59	8	2	3	1
Mudstone (MU)	Q, F, D, CH, M, V, PA, T	7	62	4	7	13	5
Sleech (SL)	Q, F, P, CH, M,	10	85	4	0	0	0
Glacial till (GT1)	Q, F, CH, M, S	11	38	33	15	2	0
London clay (LC1 F)	Q, F, M, S, K	53	44	0	0	2	0
London clay (LC2 F)	Q, F, M, K, V	47	45	1	2	3	0
London clay (LC1 J)	Q, F, M, S, K	16	60	10	10	4	0
London clay (LC2 J)	Q, F, M, S, K	21	71	4	1	2	0
China red clay (CH)	Q, F, CH, M, S	12	55	5	17	10	0
Winnipeg clay (WP)	Q, F, C, D, M, K, V, T	72	25	2	2	0	0
Saskatchewan clay (SK)	Q, F, D, M, S, K	67	30	1	2	0	0
Vancouver clay (VC)	Q, F, A, CH, M	61	39	0	0	0	0
Norway clay (NR)	Q, F, A, CH, M	19	80	1	0	0	0

F, Fricton-on-Sea, J, Jarwick.
Q, quartz; F, feldspar; C, calcite; D, dolomite; P, pyrite; A, amphibole; Ch, chlorite; M, muscovite/illite; S, smectite; K, kaolinite; V, vermiculite; PA, palygoriskite; T, titanite.

reported in Table 2 refer to particles passing a 2 mm sieve, though the parent material may have contained a small amount of gravel, particularly in the case of the glacial till.

Two hundred grams of each clay sample (passing 425 μm) was mixed with water and stored in a constant-temperature environment for 24 h before testing. The specimens were then subjected to cone penetration tests at a minimum of three water contents for each material using fast-static loading on the cone of 54 N. Selection of the water contents was a random process, although the operator(s) were able to judge the range of water contents finally chosen by using their experience, and basing it on the feel of the material during preparation. The final water content was measured in the usual manner, and the relationship between penetration and water content was established.

About 20 g of material from each soil type was prepared for plastic limit tests using the standard procedure. Four trained operators were asked to perform the PL tests. Table 3 lists the plastic limit of the soil using the existing method. The variation in the range of values reported by the four operators is significant, although comparable to the wide variations reported by Sherwood (1970). In general, Operator 1 underestimates PL values, whereas Operator 3 overestimates PL.

Figures 6(a)–6(d) show the magnitude of penetration plotted against water content for the various soils tested in the present study. In all cases the relationship is reasonably linear within the range of water contents used. The PL of the soil is estimated by determining the water content for 20 mm penetration, and the relevant values are listed in Table 3. Also listed in the table are the average PL values obtained by the four operators. Closer inspection reveals that there is generally reasonable agreement between the average values of PL and those measured using the revised procedure. Fig. 7 shows the standard deviation of the PL measurements obtained by the four operators plotted against the plasticity index (PI), where the PL is based on the new method. It appears that the amount of deviation increases with the plasticity index. Given the individual variation in PL values obtained by the four operators, the standard

Table 3. PL values obtained by four different operators using standard and new method

Soil type	PL obtained by four operators (standard method): %					PL by new method: %	LL: %
	1	2	3	4	Average		
Kaolin (KC)	31·0	37·4	29·9	35·4	33·4	34·1	68·0
Belfast clay (BC1)	26·8	25·9	–	–	26·3	27·1	57·0
Belfast clay (BC2)	17·5	22·1	30·8	26·1	24·1	31·9	60·2
Mudstone (MU)	33·1	42·5	29·3	36·7	35·4	35·4	59·0
Sleech (SL)	47·0	53·7	60·1	54·4	53·8	41·6	111·0
Glacial till (GT1)	16·8	15·7	–	–	16·3	19·9	32·0
Glacial till (GT2)	15·2	13·9	19·3	16·2	16·2	18·5	35·5
London clay (LC1 F)	22·2	27·8	47·1	33·4	32·6	39·6	90·8
London clay (LC2 F)	22·5	31·0	41·4	32·8	31·8	41·0	86·2
London clay (LC1 J)	17·5	16·1	21·2	18·9	18·4	22·8	43·4
London clay (LC2 J)	22·0	30·2	35·8	32·7	30·2	39·6	83·3
China red clay (CH)	–	–	–	–	–	22·0	–
Winnipeg clay (WP)	26·5	33·2	29·3	34·4	30·8	37·5	67·4
Saskatchewan clay (SK)	21·1	31·9	42·5	37·6	33·3	42·2	89·9
Vancouver clay (VC)	–	–	–	–	–	34·5	–
Norway clay (NR)	14·4	16·4	18·7	18·9	17·9	18·4	34·5

F, Fricton-on-Sea; J, Jarwick.

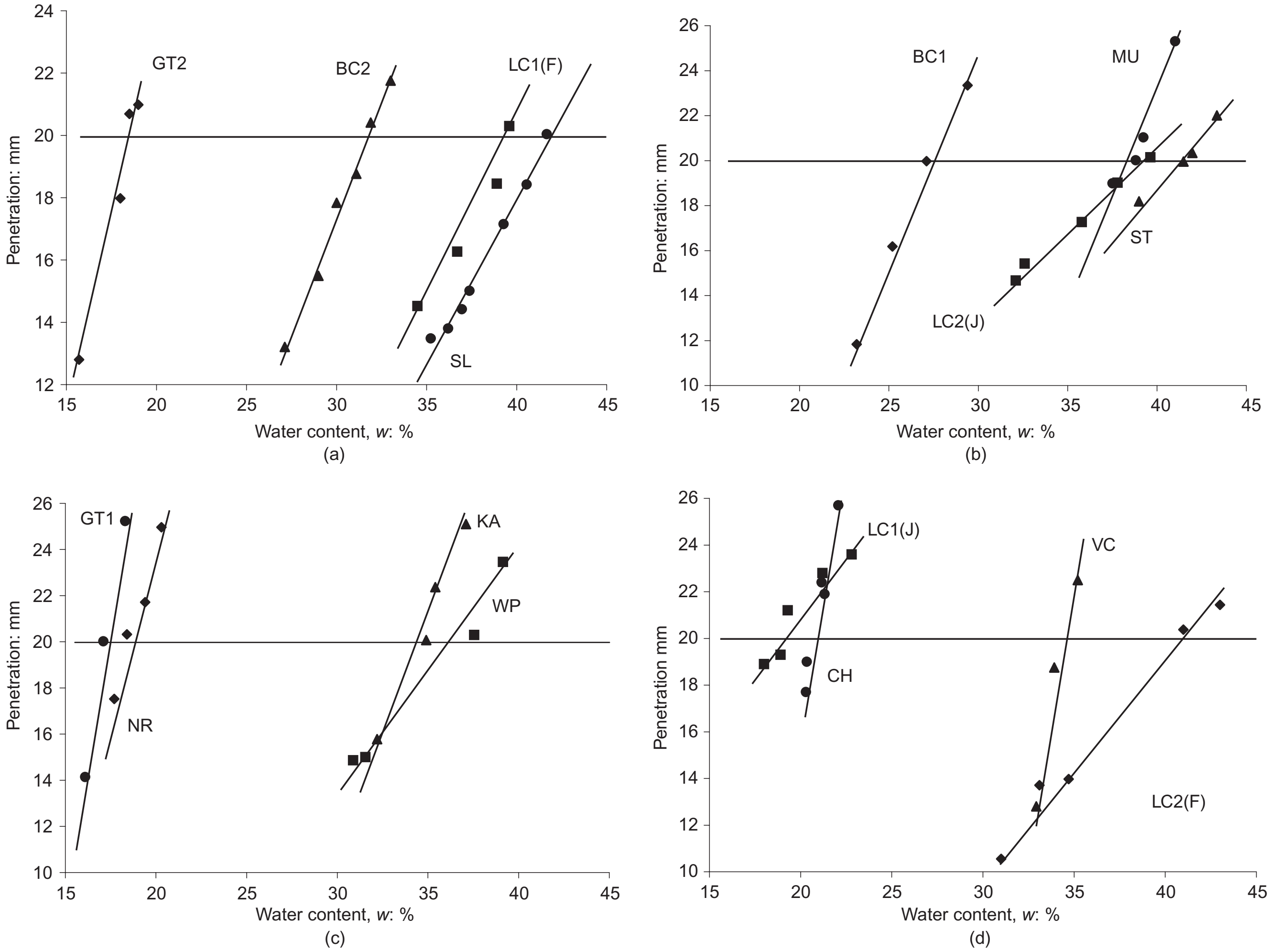

Fig. 6. Cone penetration against water content of soils close to plastic limit

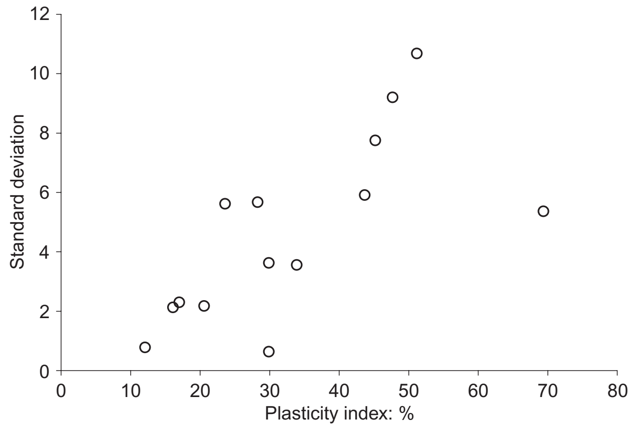

Fig. 7. Standard deviation of PL measurements made by four operators against plastic index

method (i.e. thread rolling) is perhaps not the most accurate way to assess the merits of the present approach. Nevertheless, the authors are well acquainted with the properties of Belfast clay and glacial till, and the PL values recorded using the revised procedure are in close agreement with previously published data on these deposits (Navaneethan & Sivakumar, 2002; Hughes *et al.*, 2007). PL values reported for sleech (SL) and Winnipeg clay (WP) vary between 78 and 110%, and 65 and 85% respectively (Graham *et al.*, 1988), and again agreement is good. The average PL of three London clay samples is 39%, with the remaining one recorded as 23%. The significant variation of index properties of LC is not untypical of this material (Pantelidou & Simpson, 2007).

Assessment and evaluation of the method

Six selected materials were prepared at target water contents of PL $-1{\cdot}5\%$, PL and PL $+1{\cdot}5\%$, where PL in this instance is the water content measured using the new method. An experienced operator was then instructed to 'roll out' threads for the various soil samples at the pre-established water contents using the standard PL test method. A series of photographs of the various soil threads is shown in Fig. 8. This visual evidence would appear to further substantiate the new procedure and its credibility as a reliable means of measuring PL, although it is possible that the PL obtained may be slightly on the wet side of the standard PL. Medhat & Whyte (1986) used Speswhite kaolin and reported a PL of 32%. However, the new device used in the present research is based on a PL of Speswhite kaolin of 34%. A possible $\pm 2\%$ error in the water content close to the PL can lead to substantial differences in undrained shear strength. In the case of Speswhite kaolin, the differences in strength would be as much as 30%, from typical values reported (e.g. Sivakumar *et al.*, 2002). This is compatible with Medhat & Whyte's (1986) postulation that the undrained shear strength of the clay between 110 and 170 kN/m^2 is sensitive to PL. Nevertheless, the authors acknowledge that the next stage in the development of the new method should be calibration of

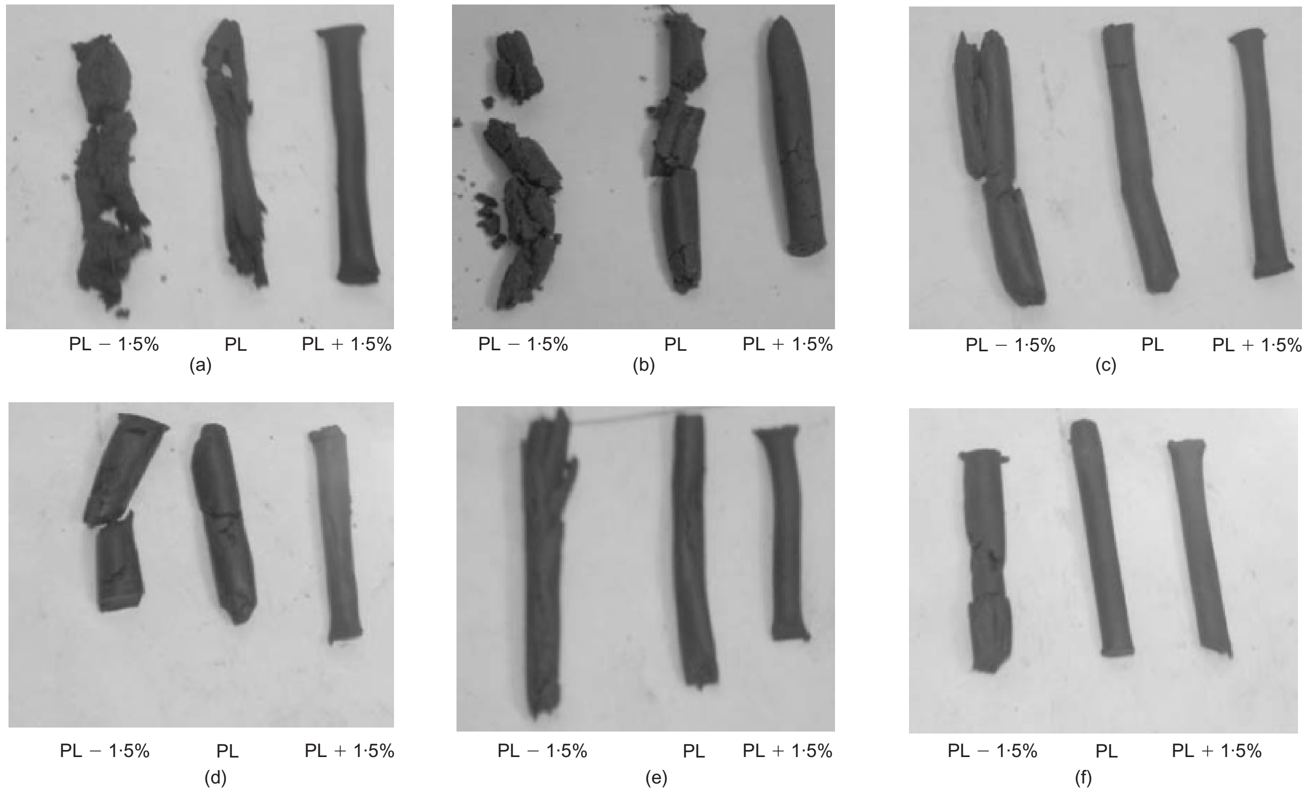

Fig. 8. State of soils prepared at water content close to plastic limit: (a) Norway clay; (b) mudstone; (c) London clay; (d) Belfast clay; (e) China red clay; (f) Winnipeg clay

the device based on the PLs of a variety of soils that have been carefully assessed and agreed by experienced operators working in one or a number of leading site investigation laboratories in the UK.

In a limited exercise, three site investigation laboratories operating in the UK were asked to participate in the present study as a means of seeking external and independent validation for measuring PL using the new method. Five soil samples were obtained from testing laboratory A, two samples were obtained from testing laboratory B, and a single sample was tested from testing laboratory C. The water content necessary to achieve a penetration close to 20 mm was determined for the samples from laboratory A and B. The material was initially prepared at water contents equivalent to the standard PL. However, if penetrations close to 20 mm were not achieved, the material was either wetted or dried (using a heat gun) in order to increase or reduce the water content as necessary. No attempt was made to determine water contents for exactly 20 mm penetration, as the quantities of material supplied by the testing laboratories were insufficient for this purpose. Table 4 lists PL values reported by the participating laboratories. Also listed in the table are the final water contents of the samples, together with the corresponding penetrations. With the exception of sample 1 (from laboratory A), the PL values reported by the testing laboratories A and B are in fairly good agreement with the values determined using the new approach. The reported PL of sample 1 from laboratory A was 29%; however, when the material was later prepared at this water content, the structure of the specimen appeared fragile and dry. This suggests that the PL was actually higher than the value reported. Using the new method, a penetration of 17 mm was achieved at a water content of 33% for sample 1 from laboratory A. Based on the typical penetration–water content slopes observed in Fig. 6, it is estimated that the true PL lies between 33 and 35%. In other cases the penetration was higher than 20 mm and, accordingly, the water content was deemed higher than the reported PL. In the case of sample 1 from laboratory C (locally known as Ampthill clay), an exact PL value documented by the site investigation company could not be reported here for confidentiality reasons. However, it can be reported that the clay used in this case is being used as a liner material with PL values in the range 30–36%, at a landfill site in the Midlands, UK. The value of PL recorded using the new method falls in the upper end of the range stipulated by the supplier, confirming the earlier comment that the new method measures water content slightly over wet of actual PL.

Table 4. Assessment of the new method using reported PL values from other testing laboratories in Northern Ireland

Sample ref.	LL: %	PL: %	Penetration: mm	Water content: %
Testing laboratory A				
1	88	29	17·0	33
2	41	21	19·2	22
3	39	19	20·8	21
4	30	15	20·4	17
5	28	16	21·8	19
Testing laboratory B				
1	N/A	17	24·5	18·4
2	N/A	21	22·7	22·2
Testing laboratory C				
1*	N/A	30–36	19·5	35·5

* Ampthill clay

The response or observed behaviour of soils under fast-static loading significantly diminishes the argument that 100 times higher cone weight is required to determine the water content (i.e. in order to achieve the requisite penetration to overcome the theoretical hundredfold increase in shear strength) and hence the PL of fine-grained soils. On the same note it is not unreasonable to expect reduced shearing resistance, even though the soil is close to PL, resulting from a natural decrease in χ and the frictional effects between the stainless steel cone and the soil. Of course, this particular aspect needs further investigation.

The main difference in the proposed approach compared with the standard approach is in having a 'feel for the material'. It is believed that this should be an essential ingredient in deciding non-plastic materials. As part of this experimental study, and to explore this hypothesis further, well-crushed quartz passing 0·06 mm (i.e. silt-size granular particles) was prepared at various water contents, and cone penetration tests were subsequently performed. The results reveal that water content has little effect on the magnitude of penetration insofar as penetrations in excess of 22 mm were observed for the range of water contents considered. This implies that the new method can correctly identify plastic, as well as non-plastic, materials.

Correlation between LL and PL

For the final phase of this study, the LL of the various clay materials was measured using the falling cone approach, with the results shown in Figs 9(a)–9(d). Also included in the figures are the relevant penetration–water content relationships close to the PL. It appears that the trend lines for PL and LL are generally parallel, or slightly steeper in the case of PL, although the general assumption that strain lines have linear relationships is made for simplicity's sake. On the other hand, Muir Wood (1990) postulated that linear relationships exist between water content and natural logarithm of penetration under different masses of cones, and suggested that the slopes of the lines describing these relationships are, in fact, identical. The data presented in Fig. 8 were re-analysed in terms of w against $\ln(d)$. A typical case is shown in Fig. 10 for LC2 (Jarwick). The gradient or slope of the lines for the soil close to LL and PL are represented respectively as $\psi_{(LL)}$ and $\psi_{(PL)}$. The ratio of these slopes (for each soil type) is plotted against the activity of the relevant soil specimen and presented in Fig. 11. The results suggest that the relationship between water content and penetration (plotted in terms of the natural logarithm) may become parallel only when the soil in question becomes significantly active – that is, the plasticity of the clay fraction significantly influences its behaviour – although further research is necessary to properly validate this statement.

CONCLUSION

The currently accepted 'standard' method for determining the plastic limit of a soil, widely known as the 'thread

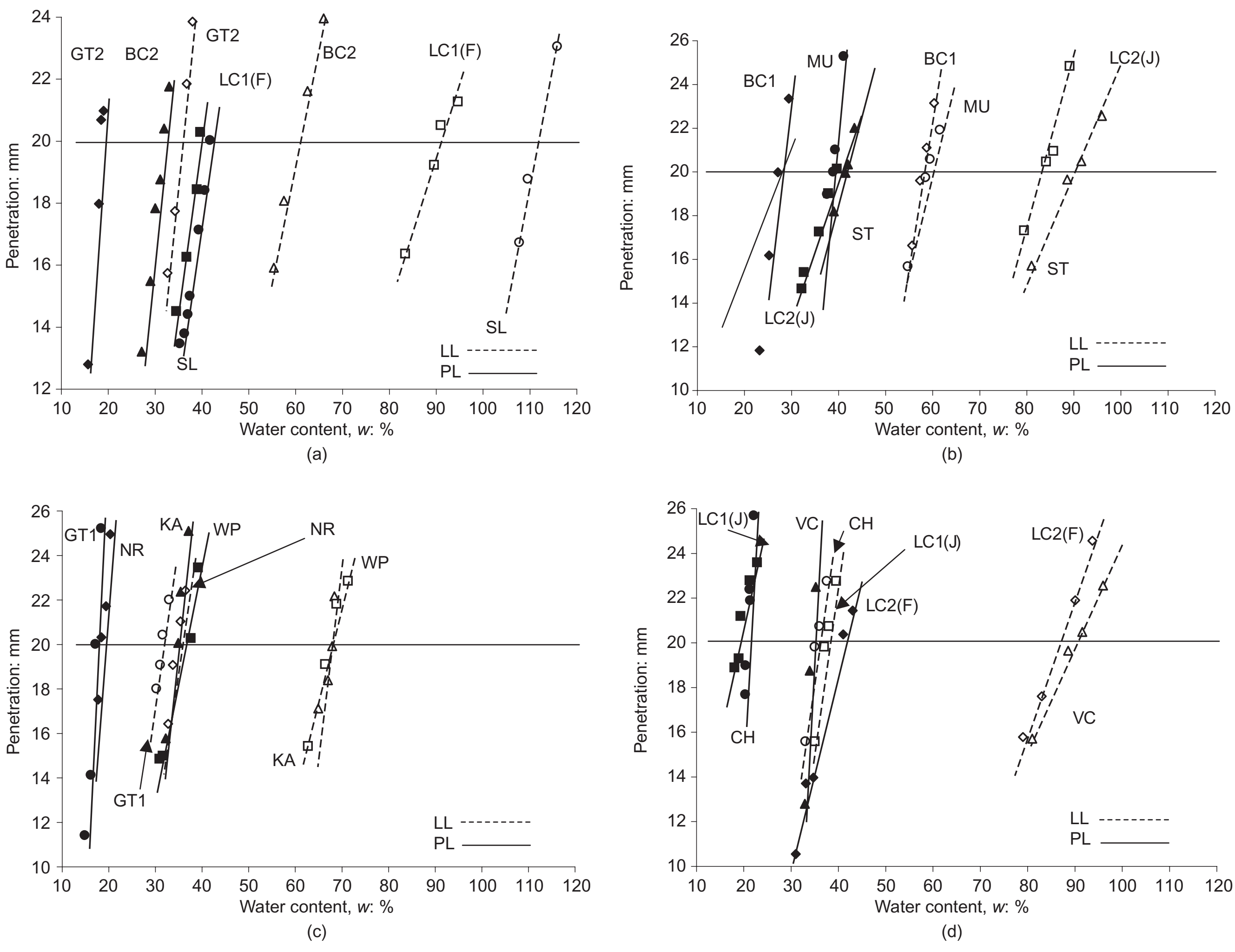

Fig. 9. Cone penetration against water content of soils close to liquid limit and plastic limit

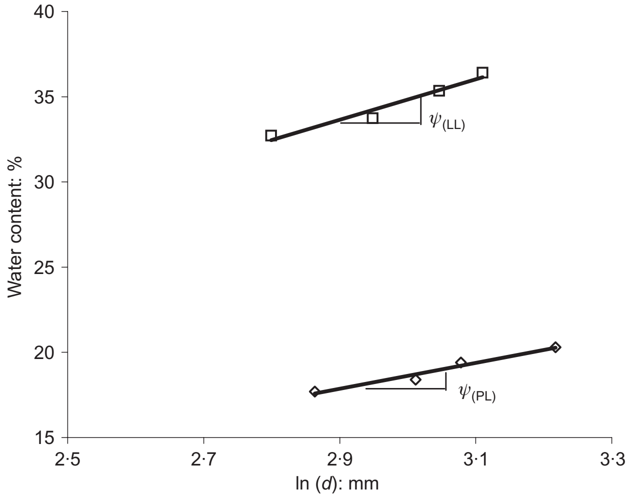

Fig. 10 Water content against natural logarithm of cone penetration (Ampthill Clay)

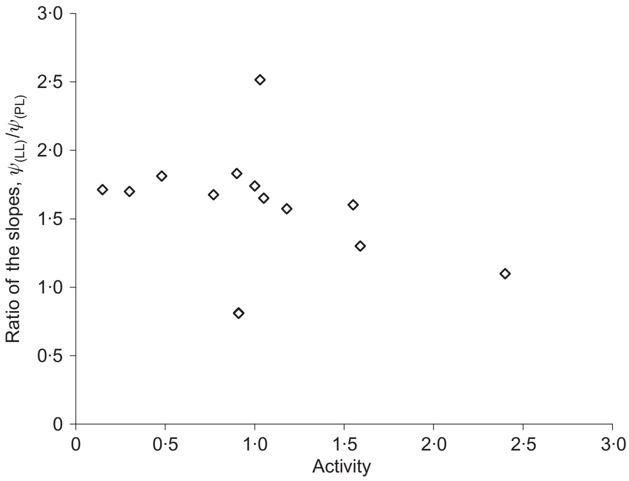

Fig. 11. The ratio of the slopes, $\psi_{(LL)}/\psi_{(PL)}$, against activity

rolling procedure', has been the subject of much criticism in recent years. This method is non-mechanical, and so brings with it major drawbacks, most notably its subjective nature and the fact that considerable judgement is needed on the part of the operator. The present paper reports the usefulness of a new device developed at Queen's University Belfast that can be used to measure PL with reasonable accuracy. The study is based primarily on an approach that utilises the standard falling cone apparatus (as used in the LL test) and requires a 54 N force to be externally applied to the existing cone used in LL investigation. Some 16 different soils were examined, along with a further eight soils for assessment purposes. The results show that the new method can be used to evaluate PL with reasonable confidence. The research also found that the force required on the cone to achieve a penetration of 20 mm is considerably less than the 8 kg suggested by many researchers working in this area. The present study suggests the reason for this is primarily the interaction between cone and clay.

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NOTATION

c_u	undrained shear strength
$c_{u(LL)}$	undrained shear strength at liquid limit
$c_{u(PL)}$	undrained shear strength at plastic limit
d	depth of cone penetration (dynamic loading)
F	non-dimensional factor (quasi-static loading)
h	depth of cone penetration (quasi-static loading)
k_α	cone factor (dynamic loading)
P''	force on cone (quasi-static loading)
PL_{100}	water content at which soil undrained shear strength is 100 times that at the liquid limit
w	weight of cone
α	cone factor
χ	measure of frictional factor between cone and soil
$\psi_{(LL)}$	slope of water content against ln(d) with soil close to LL
$\psi_{(PL)}$	slope of water content against ln(d) with soil close to PL

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