European Journal of Soil Science, February 2005, **56**, 31–38 doi: 10.1111/j.1365-2389.2004.00652.x

Describing soil crack formation using elastic–plastic fracture mechanics

P. D. HALLETT[a] & T. A. NEWSON[b]
[a]*Plant–Soil Interface Programme, Scottish Crop Research Institute, Invergowrie, Dundee DD2 5DA, and* [b]*Division of Civil Engineering, University of Dundee, Dundee DD1 4HN, UK*

Summary

Crack development is predominant in soil structure formation. A number of fracture mechanics models have been applied to soil to describe cracking, but most are not applicable for soil in a wet, plastic state. We address this weakness by applying a new elastic–plastic fracture mechanics approach to describe crack formation in plastic soil. Samples are fractured using a deep-notch (modified four-point) bend test, with data on load transmission, sample bending, crack growth, and crack-mouth opening collected to assess the crack-tip opening angle (CTOA). CTOA provides a powerful parameter for describing soil cracking since it can be induced by soil shrinkage (an easily measured parameter) and can be used to describe elastic–plastic fracture in numerical approximations, such as finite element modelling. The test variables we studied were the direction of the applied consolidation stress, clay content, and pore water salinity. All samples were formed by consolidating soil slurry one-dimensionally with a 120-kPa vertical effective stress. Tests on pure kaolinite showed that the direction of the consolidation stress did not affect CTOA, which was $0.23 \pm 0.02\,\mathrm{m\,m^{-1}}$ for specimens cut both in a horizontal and in a vertical direction to the applied stress. Soil clay content had a marked influence, however, with silica sand:kaolinite mixtures by weight of 20:80 and 40:60 reducing CTOA to $0.14 \pm 0.02\,\mathrm{m\,m^{-1}}$ and $0.12 \pm 0.01\,\mathrm{m\,m^{-1}}$, respectively. These smaller values of CTOA indicate that less strain is required to induce fracture when the amount of clay is less. Salinity (0.5 M NaCl) caused a reduction in the CTOA of pure kaolinite from $0.23 \pm 0.02\,\mathrm{m\,m^{-1}}$ to $0.17 \pm 0.03\,\mathrm{m\,m^{-1}}$.

Introduction

Cracks dominate the structure of soil, forming the boundaries between incipient soil aggregates and major transmission pathways for water and chemicals. Considerable effort is placed in studying both transport and aggregation processes in soil, yet very little work has examined the fracture mechanisms that produce cracks (Hallett & Newson, 2001). This presents a major gap in understanding soil structural dynamics, restricting our ability to predict and explain the long-term physical behaviour of soil.

A complication with studying cracking in soil is that the mechanical behaviour changes considerably with water content. Various studies have described accurately the fracture of dry, brittle soil samples by using linear elastic fracture mechanics (LEFM) theory (Lima & Grismer, 1994; Hallett *et al.*, 1995). Other studies have applied the same theory to wetter, more plastic soil (Snyder & Miller, 1985; Konrad & Ayad, 1997), but the physical appropriateness of such an approach is questionable (Hallett & Newson, 1998). We recently applied a more robust approach, which accounts for plastic processes, to describe cracking in highly ductile, saturated soil samples (Hallett & Newson, 2001). The elastic–plastic theory we used was developed previously for the testing of highly ductile metal (Turner & Kolednik, 1997). It relies on describing the crack-tip opening angle (CTOA) at the front of an advancing crack as a measure of the strain energy field associated with ductile fracture. In conjunction with other mechanical properties of the material, CTOA analysis can be used to assess the crack resistance energy, D, which degrades to the classical J-integral at the point of crack initiation.

We extend on the previous study that applied CTOA to soil by improving the test and sample formation procedures, and examining a range of soil properties. The new test procedure allowed for data on force transmission to the sample to be measured from a load cell. Soils were formed by consolidating one-dimensionally soil slurries of kaolinite clay and fine sand with a 120-kPa vertical effective stress. This simulated the

Correspondence: P. D. Hallett. E-mail: p.hallett@scri.sari.ac.uk
Received 18 December 2003; revised version accepted 26 April 2004

influence of stresses from overburden soil or desiccation, which may influence soil microstructure formation in natural conditions. We investigated how the direction of the applied consolidation stress, soil clay content, and pore water salinity influenced the ductile fracture mechanics of soil. The tests used rectangular bar samples cut from the consolidated soil slurry. The bars were fractured using the deep-notch bend approach (four-point), with data on load displacement, applied force, crack opening and crack extension used to assess CTOA and the thermodynamic requirements for ductile crack extension.

Methods

Sample formation

The soils used for these experiments were mixtures of pure kaolinite clay and fine sand identical in grade and supplier to those in Hallett *et al.* (1995), where the properties are described in detail. Table 1 lists the various sand–clay mixtures, their initial water contents before consolidation, and selected physical properties. The saline kaolinite treatment was wetted with 0.5 M NaCl (equivalent to sea water; −2.5 MPa osmotic potential), rather than deionized water.

The mixtures were consolidated with a one-dimensional vertical effective stress of 120 kPa to form a cylindrical soil cake with dimensions of approximately 140 mm high and 150 mm diameter. Fracture mechanics test specimens were formed by cutting cuboid bars measuring 140 mm × 25 mm × 25 mm from the consolidated soil cake. Samples were cut so that the longest dimension was perpendicular to the direction of major principal stress, giving an assumed horizontal arrangement of clay platelets (Krizek, 1977). On one 100% kaolinite treatment, the fracture specimens were cut in an orthogonal (i.e. vertical) direction, to evaluate the influence of the applied stress direction. Based on the direction of applied stresses from overburden stresses or compaction in the field, the former specimens mimic vertical cracks and the latter specimens mimic horizontal cracks. The rectangular bar specimens were sealed to prevent evaporation and then allowed to equilibrate for 48 hours to minimize disturbance effects on water potential that may have resulted from cutting.

Fracture testing

Mechanical testing of ductile soil specimens is precluded by failure under self-weight. A conventional bend test was adapted so that the sample was supported during flexure, as illustrated in Figure 1. Before testing, a crack with a length a_0 equal to half the sample thickness W (i.e. $a_0/W = 0.5$) was cut into the sample using a razor blade (200 μm thick). The sample was then supported on glass slides that were free to move on the rolling platens of the test apparatus illustrated in Figure 1.

Testing was conducted using a mechanical test frame (Model 5544, INSTRON, Canton, MA, USA). The cross-head displacement and force transmitted to the loading platen was recorded using INSTRON Merlin software. In order to minimize the influence of viscous effects, the cross-head speed was set to 1 mm minute^{-1} for all samples (Hallett *et al.*, 1998). The load cell had a range of 5 N and was accurate to 1% at 1/250 maximum load. Video images were captured at regular intervals, generally in the range of 0.1–10 frames s^{-1}, depending on the speed of fracture. By analysing the crack in the images, information on crack-mouth opening displacement, V_{pl}, and ligament length in front of the crack, b, was obtained and related to load-point displacement, q (Figure 2). Combined with the data from the testing frame, sufficient information was collected using this simple approach to evaluate the elastic–plastic fracture behaviour of the various specimens tested.

Elastic–plastic fracture mechanics model

As in all other materials, the fracture of soil is a thermodynamic equilibrium process, meaning that fracture occurs when imposed mechanical energy equals the energy required for fracture. An applied increment in mechanical energy, $\mathrm{d}U$, transmitted to the soil increases its internal energy, w. When no crack growth occurs, the energy balance is

$$\mathrm{d}U = \mathrm{d}w. \quad (1)$$

If soil fractures under linear elastic conditions, w is entirely elastic and recoverable (w_{el}) resulting in $\mathrm{d}U = \mathrm{d}w_{el}$. Removal of the stress will cause the soil to return to its original state.

Table 1 Principal characteristics of the soil specimens tested. Unless specified, the specimens are cut to simulate a vertical crack in consolidated soil

Treatment	Initial water content /g kg^{-1}	Post-consolidation water content /g kg^{-1}	Linear shrinkage /cm m^{-1}	Plastic limit /g kg^{-1}	Liquid limit /g kg^{-1}	Plastic index
Pure kaolinite (100%)	1200	484	3.2	318	635	31.7
Pure kaolinite (100%) (Perpendicular cutting direction – simulated horizontal crack)	1200	519	–	–	–	–
Silica sand:kaolinite (20:80)	800	439	4.6	254	520	26.6
Silica sand:kaolinite (40:60)	600	541	5.7	203	405	20.2
Saline pure kaolinite (0.5 M NaCl)	1200	540	3.3	325	767	44.2

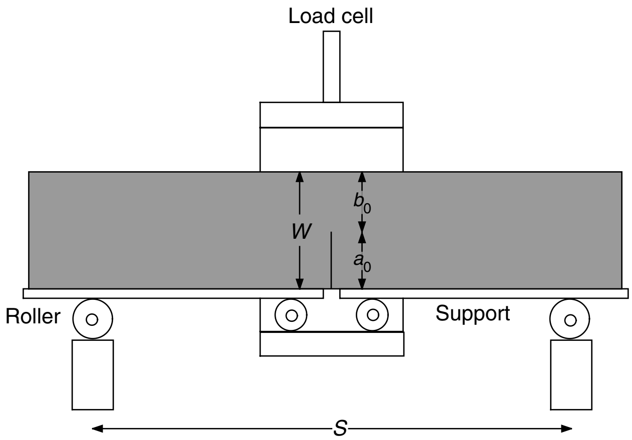

Figure 1 Four-point bend test apparatus. The soil sample is placed on supports that move freely on rollers attached to the load cell and the base of the mechanical test frame. A crack of initial length a_0 is cut to about 0.5 of the specimen width, W, with the remaining soil being the initial ligament length, b_0. S is the span distance between the furthest rollers.

These are the principles forming the basis of linear elastic fracture mechanics (LEFM).

Most work on soil fracture assumes LEFM behaviour. This fails to acknowledge the large amount of irrecoverable energy, w_{pl}, caused by plastic processes such as particle rearrangement, friction within the particle matrix, and bond rupture between particles not associated with fracture (Hallett, 1996). The energy balance for elastic–plastic materials is simply

$$\mathrm{d}U = \mathrm{d}w_{\mathrm{el}} + \mathrm{d}w_{\mathrm{pl}}, \tag{2}$$

which takes into account both recoverable and irrecoverable energy. For crack growth to occur, sufficient energy to break the particle surface bonds in advance of the crack, $\mathrm{d}\Gamma$, is also required, resulting in

$$\mathrm{d}U = \mathrm{d}w_{\mathrm{el}} + \mathrm{d}w_{\mathrm{pl}} + \mathrm{d}\Gamma. \tag{3}$$

How much energy is required depends upon the specific surface energy of particle bonds along the incipient fracture path, γ_0, and the incremental area of new crack surface formed, which is evaluated from the amount of crack growth, da, and the crack thickness, B, so that

$$\mathrm{d}\Gamma = 2B\gamma_0\mathrm{d}a. \tag{4}$$

Combining Equations (3) and (4) and transferring w_{el} to the left-hand side of the equation results in

$$\mathrm{d}(U - w_{\mathrm{el}})/B\mathrm{d}a = \mathrm{d}(w_{\mathrm{pl}} + \Gamma)/B\mathrm{d}a, \tag{5}$$

thus putting all irrecoverable forms of energy together on the right side. Equation (5) shows the balance between the applied energy and that stored in the system on the left-hand side of the equation, and the energy that is dissipated due to both crack formation and plastic processes on the right-hand side. The energy sink to crack growth is the energy dissipation rate, D, defined as

$$D \equiv \mathrm{d}(w_{\mathrm{pl}} + \Gamma)/B\mathrm{d}a, \tag{6}$$

and the energy source to crack growth is the crack driving force, C, defined as

$$C \equiv \mathrm{d}(U - w_{\mathrm{el}})/B\mathrm{d}a. \tag{7}$$

For fracture to occur the sink and source must be equal:

$$C = D. \tag{8}$$

This is the elastic–plastic criterion for fracture.

Obtaining data to assess elastic–plastic fracture behaviour can be difficult. Often it relies on examining the relationship between force and displacement under loading and unloading conditions. These tests allow D to be deduced from the difference between the energy applied to the system under loading and the amount recovered during unloading. Soil fracture surfaces re-bond during unloading, thus prohibiting the application of this type of testing.

An alternative approach, shown by Hallett & Newson (2001) to be effective for soil, uses the morphology of an advancing crack to estimate the strain energy associated with elastic–plastic fracture (Turner & Kolednik, 1994). The data needed can be collected using the deep-notch bend test described previously. Energy transmitted to the sample and its influence on cracking is determined from the bending nature of the test specimen (Figure 1) and how this affects crack opening and extension.

The basis for this approach lies in the thermodynamic equilibrium for material fracture outlined in Equations (1)–(8). Expressing Equations (6)–(8) in terms of the force transmitted in the bend test, F, results in

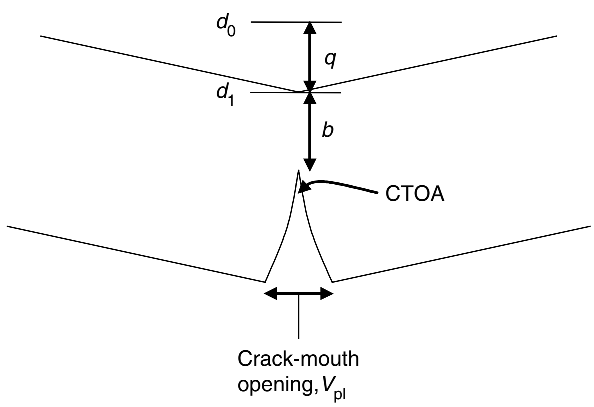

Figure 2 Image analysis of crack growth through the soil during the bend test was used to evaluate the crack-mouth opening, V_{pl}, ligament length of soil in advance of the crack, b, and displacement of the load-point, q, from the onset of testing, d_0, to the point of measurement, d_1. Ten sequential images were analysed to obtain the data. CTOA, crack-tip opening angle.

$$C = (F\mathrm{d}q - \mathrm{d}w_{\mathrm{el}})/B\mathrm{d}a = D, \qquad (9)$$

with $\mathrm{d}w_{\mathrm{el}}$ being insignificant for large amounts of ductile crack growth (Turner & Kolednik, 1994), such as in wet soils. The crack-tip opening angle, CTOA (or $\alpha_{\mathrm{g,pl}}$), describes the relationship between energy imposed by bending and crack extension. It depends on the span length of the loading rollers, S, the length of material that is being flexed, b, and the load-point displacement, q. By describing bending as a fully plastic hinge and taking into account the geometry of the test sample, $\alpha_{\mathrm{g,pl}}/r^*_{\mathrm{pl}}$ is evaluated as

$$\frac{\mathrm{d}q_{\mathrm{pl}}}{\mathrm{d}a} = \frac{S\alpha_{\mathrm{g,pl}}}{4r^*_{\mathrm{pl}}b}, \qquad (10)$$

where r^*_{pl} is dimensionless and defines the fraction of length b ahead of the crack tip to the instantaneous centre of rotation of the arms of the piece. The 'pl' subscript indicates fully plastic fracture, so w_{pl} is the dominant energy sink in Equation (5).

Evaluating $\alpha_{\mathrm{g,pl}}$ from Equation (9) is possible by calculating r^*_{pl} from the relationship between the crack-mouth opening, V_{pl}, and q_{pl} as

$$r^*_{\mathrm{pl}} = \{(S/4)(\mathrm{d}V_{\mathrm{pl}}/\mathrm{d}q_{\mathrm{pl}}) - a_0\}/b_0, \qquad (11)$$

where a_0 and b_0 are the initial values of the crack and ligament lengths, respectively. The CTOA (or $\alpha_{\mathrm{g,pl}}$) parameter provides a powerful measurement of the conditions required for ductile crack extension.

Results and discussion

Loading diagrams

Loading diagrams are presented in Figure 3 to illustrate the differences in mechanical behaviour between soil treatments. They illustrate a reduction in the peak applied force sustained by the sample with increasing sand content and salinity. From these data, the applied energy, C, can be derived from the area under the loading curve, as described in Equation (9). The curves suggest that the addition of sand or salinity lowers the energy required to cause fracture, whereas the direction of the consolidation stress appears to have minimal influence. A more exhaustive analysis of C is not reported herein since an accurate evaluation of the forces acting at the crack tip requires numerical modelling of the plastic hinge produced in the flexure specimen during loading. This will be the subject of a future paper.

All treatments have force-crack extension curves with a characteristic 'round-house' shape – evidence that they are low-strength high-hardening type materials (Turner & Kolednik, 1997). This behaviour is similar to the considerable amount of research on the compression and shear behaviour of soil that shows strain-hardening beyond the point of yielding (Mitchell, 1993). Chandler (1984) presented similar-shaped loading curves for tensile fracture tests on plastic soils. These curves identify immediately that a linear elastic approach, even with the Irwin–Orowan extension to account for crack-tip plasticity (Hallett *et al.*, 1995), is an inappropriate analysis tool.

Figure 4 provides an interpretation of the steps involved in fracture that may be deduced from the loading diagrams; Maugis (1985) discussed similar phenomena for other elastic–plastic materials. At the onset of loading, the relationship between the applied force and extension is linear, indicating the elastic region of fracture. Unloading of the specimen results in a return to the initial unloaded condition since the applied force is reversible. After a critical point, there is a transition from elastic to plastic behaviour. Increased plastic deformation in this region causes greater specimen extension with a lower increment of applied force. A tangent modulus drawn parallel to the elastic region of fracture provides a reasonable estimate of Young's modulus. Its intersection with the applied force is approximately the yield point of the material.

Once yield is exceeded, plastic processes cause the matric potential to become more negative at the crack tip and probably causes inter-particle bond rupture as particles become re-orientated (Hallett, 1996). Once these build up sufficiently with increasing applied force, crack initiation occurs, which is marked by a drop in the applied force. *J*-integral analysis, as employed by Chandler (1984) to soil, can be used to evaluate the energy requirements for the onset of ductile crack growth. This will describe only the conditions required for crack initiation, however, and not the conditions required for extensive crack growth. When the energy stored in the system is dissipated by crack growth, an equilibrium is reached at about the yield force. At this point stable ductile crack growth occurs. This is where the crack growth is greatest and can be described using the CTOA approach (Hallett & Newson, 2001).

CTOA analysis

The description of stable ductile crack growth by the CTOA isolated the impact of the direction of the applied consolidation stress in relation to the crack, clay content, and salinity on fracture behaviour (Table 2). Crack-tip opening angle dropped with decreasing clay content as would be expected. Sand acts as a rigid inclusion and serves as a nucleus to failure due to its low surface energy (Mitchell, 1993) compared with clay. This was also reflected in the plastic and liquid limits (Table 1), which, as in natural soils, increase as clay content increases (Mitchell, 1993). The CTOA values were smaller than those reported by Hallett & Newson (2001) for remoulded soils with a smaller clay content and larger water content. A larger water content would be expected to increase plasticity and hence CTOA, but consolidation increases soil stiffness as particles become more closely packed and the effective stress increases (Mitchell, 1993). Crack-tip opening angle is consequently

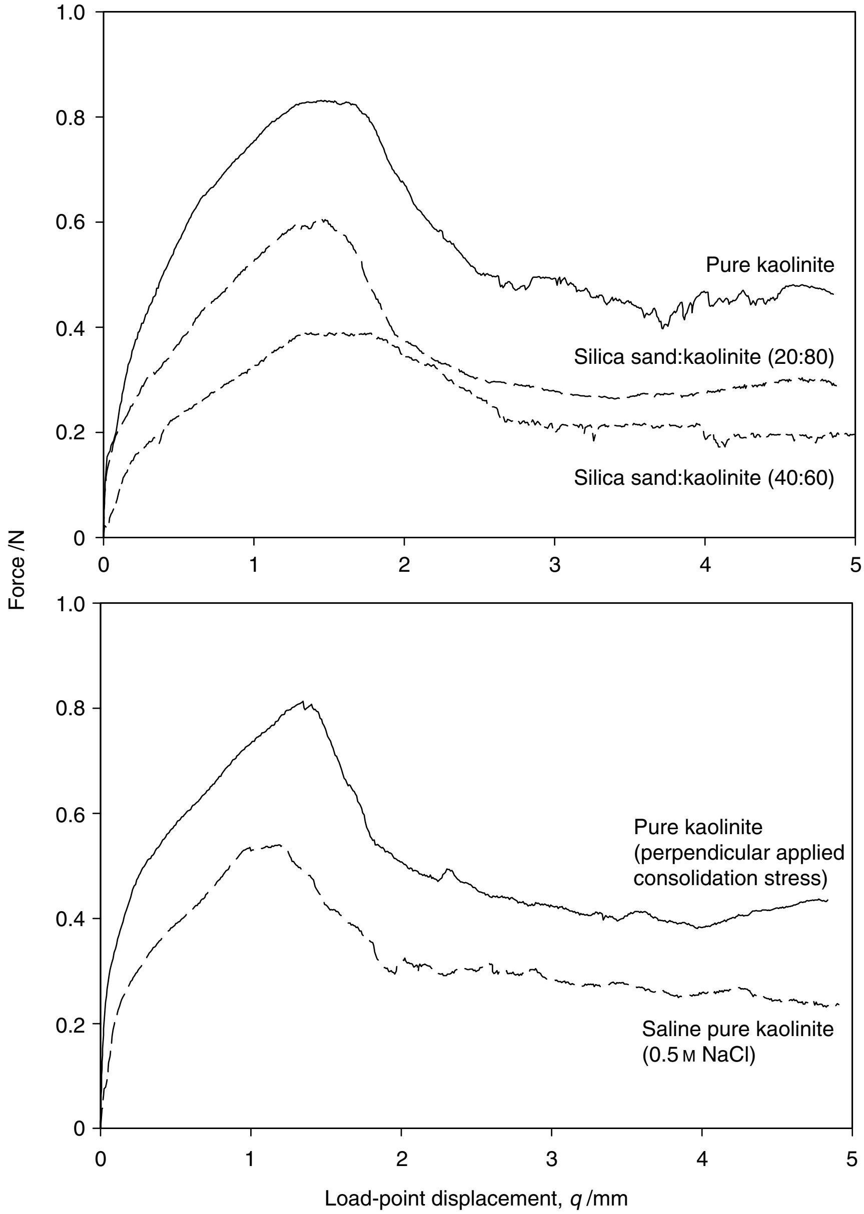

Figure 3 Loading diagrams showing the change in applied force versus load-point displacement, q, as the soil sample flexes and the crack grows.

smaller than for remoulded soils because more energy is transmitted to the crack tip following bending. Metals and other engineering materials tend to have even smaller CTOA values (Turner & Kolednik, 1997) because they are far stiffer than the wet soils discussed previously.

Early work using electron microscopy (e.g. Krizek, 1977) suggests that clay platelets will orientate themselves perpendicular to the major principal stress during soil formation and any subsequent applied loading. It was therefore expected that the direction of the applied consolidation stress would influence CTOA, since the crack surface charge, Γ, Equation (4), should be greater if the crack direction is perpendicular to the platelets. However, there was minimal influence of the direction of the applied consolidation stress on CTOA. More recent investigations of the coupling of mechanical and structural anisotropy (Anandarajah, 2000) suggest that there is much less correspondence between the applied loading and the soil fabric (i.e. platelet orientation). Much of the observed mechanics of anisotropic clay soils may be due to groups of platelets (i.e. clusters or clay domains), thus the average platelet orientation may be less affected by the principal stress directions than previously thought. This view may also explain why previous work by Chenu & Guérif (1998) found that platelet orientation did not influence the rupture stress of soil.

Crack-tip opening angle may be smaller for NaCl-treated soil because sodium disperses the clay domains, thereby reducing the particle bond energy (Barzegar *et al.*, 1996). More evidence is provided by the loading diagram presented

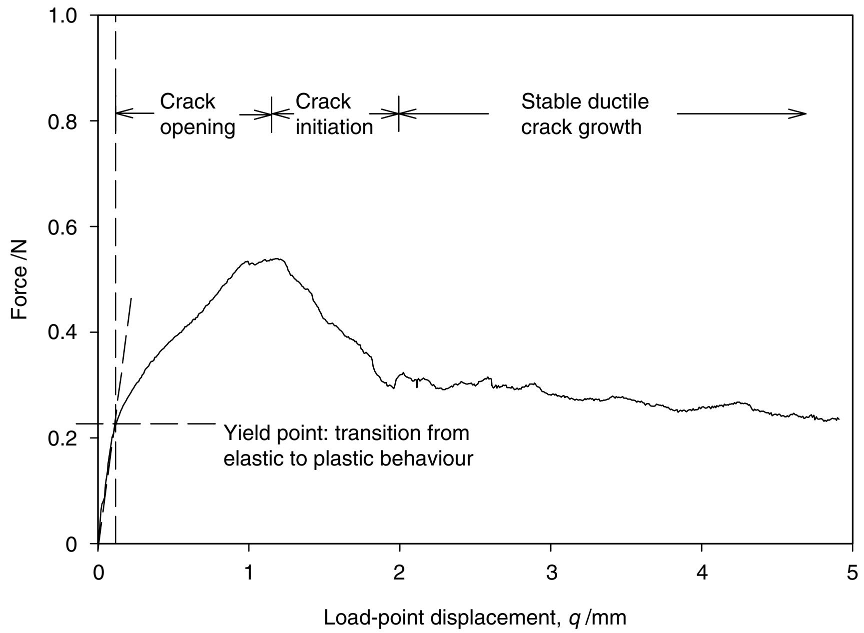

Figure 4 The stages of crack growth in wet soil during the flexure test. After the yield point the crack opens, causing strain energy to build up at the tip. Energy is then released as crack growth initiates. Steady-state conditions occur once ductile crack growth becomes stable. Based on the conditions defined in Turner & Kolednik (1994).

previously (Figure 3). Given the conditions defined in Equations (4) and (8), these data also suggested that the crack surface charge, Γ, was decreased by the addition of salt. Nichols & Grismer (1997) used linear elastic fracture mechanics to evaluate the influence of salinity on cracking. Their results, with soil drier than that tested here, suggested that increased salinity causes a small decrease in Γ. It was postulated in this paper that the effect on Γ would be more pronounced at higher water contents, as suggested by our results. In dry soils, Lima & Grismer (1994) found that salinity increased Γ.

Other physical properties of the soil that will influence crack development were also influenced by salinity. The liquid limit, plastic index, and water content at testing in the pure kaolinite samples were greater if wetted with 0.5 M NaCl solution (Table 1), as observed by a number of researchers (e.g. Torrance, 1974). These parameters describing the current state of the soil indicate the range of water contents over which cracking may occur. Chertkov (2002) argued that cracking initiates at about the liquid limit and continues until shrinkage ceases at about the plastic limit. The CTOA and increased liquid limit of the saline soils suggested that they will crack more easily when wet, which is often observed in clay-liner systems and clayey mine-wastes contaminated with saline solutes (Newson & Fahey, 1998). Increased fracture toughness in dry samples, as reported by Lima & Grismer (1994), may result in fewer cracks developing below a critical water content. In an earlier study, Lima & Grismer (1992) reported that salinity causes a blocky structure to develop in soil, with fewer small cracks present.

Table 2 Summary of the parameters of stable ductile crack growth

Treatment	$\alpha_{g,pl}$ (CTOA) /m m^{-1}
Pure kaolinite (100%)	0.230 ± 0.025[a]
Pure kaolinite (Perpendicular cutting direction – simulated horizontal crack)	0.230 ± 0.018
Silica sand:kaolinite (20:80)	0.136 ± 0.018
Silica sand:kaolinite (40:60)	0.123 ± 0.014
Saline pure kaolinite (0.5 M NaCl)	0.171 ± 0.027
Saline pure kaolinite (0.5 M NaCl) (Perpendicular cutting direction – simulated horizontal crack)	0.159 ± 0.015

[a]Mean ± SE.

Implications for soil structure research

Further research is needed to investigate the relationship between soil fracture mechanics and shrinkage characteristics over a range of water contents. Moreover, the impact of the mechanical history of the soil also needs to be considered, as was highlighted by the differences between CTOA for the consolidated samples tested here and the remoulded soils tested in an earlier study (Hallett & Newson, 2001). Although the addition of sand decreased CTOA, indicating that the soil is more susceptible to cracking, sand will also decrease shrinkage (Groenevelt & Grant, 2001), which means less fracture energy, C, Equation (7), from shrinkage-induced strain. Combined shrinkage and fracture mechanics models could provide a fundamental understanding of soil pore structure genesis. This has practical relevance to the understanding of temporal changes in water transport, bypass flow of solutes through macropores, and structure regeneration in degraded soils. It may help in the development of realistic soil pore structure models to describe a diverse range of processes such as water transport and retention (Bird & Perrier, 2003), structure influences on microbial processes (Rappoldt & Crawford, 1999), and soil fragmentation by tillage and natural processes (Dexter, 1988).

Soil fracture mechanics and shrinkage are both complex processes, however, so a combined model of these processes would benefit from numerical modelling. Finite element packages (e.g. ABAQUS) can account for both shrinkage and the influence of CTOA on crack growth. We are currently investigating the development of a single crack in soil by shrinkage-induced strain energy. Existing models of soil cracking based on crack dimensions and assumed linear elastic behaviour (Chertkov, 2002) may be improved by accounting for the physical conditions of ductile crack growth using CTOA. Spring-lattice models or new advances in discrete element modelling may allow for more complex crack pattern development in soil to be predicted with physically realistic input variables obtained using the test procedures described in this paper.

Conclusions

The CTOA approach appears to be sensitive to different soil properties and provides a powerful measurement of the fracture mechanics of wet soil samples. Increased sand content and salinity both decreased CTOA, suggesting fracture under a lower imposed energy. Changing the ratio of silica sand: kaolinite clay slightly from 0:100 to 20:80 caused the CTOA almost to halve, from $0.230\,\mathrm{m\,m^{-1}}$ to $0.136\,\mathrm{m\,m^{-1}}$. Salinization of pure kaolinite with the equivalent of sea water (0.5 M NaCl) resulted in a 26% drop in CTOA. Although the direction of the applied consolidation stress, which has been postulated to influence clay platelet orientation, did not influence CTOA, this may be due to microstructural heterogeneity at the clay domain level. In comparison to linear elastic fracture mechanics approaches applied previously to describe soil cracking, CTOA is applicable to wet, plastic soils where considerable energy loss occurs due to plastic processes.

This work has direct relevance to a physical understanding of soil structure genesis. Considerable research is conducted in this area, but it tends to be either highly empirical or simply observational. Future research needs to consider fracture mechanics over a range of water contents and the influence of strain energy imparted by shrinkage. Temporal shifts in the soil pore structure caused by cracking could then be predicted.

Research is also needed to quantify the impact of soil management and biological processes on the fracture mechanics of soil. This will help to describe soil structure genesis and the impact of different management practices on soil sustainability. Our research has already illustrated the potential impact of soil degradation through salinization on fracture mechanics and hence soil structure.

Acknowledgements

We thank Yilong Chen for his help with the fracture tests. Dr Blair McKenzie and an anonymous reviewer provided valuable and insightful suggestions that greatly improved our script. The research was funded by Grant-in-Aid from the Scottish Executive Environment and Rural Affairs Department to the Scottish Crop Research Institute.

References

Anandarajah, A. 2000. Numerical simulation of one-dimensional behaviour of kaolinite. *Géotechnique*, **50,** 509–519.

Barzegar, A.R., Oades, J.M. & Rengasamy, P. 1996. Soil structure degradation and mellowing of compacted soils by saline sodic solutions. *Soil Science Society of America Journal*, **60,** 583–588.

Bird, N.R.A. & Perrier, E.M.A. 2003. The pore–solid fractal model of soil density scaling. *European Journal of Soil Science*, **54,** 467–476.

Chandler, H.W. 1984. The use of non-linear fracture mechanics to study the fracture properties of soils. *Journal of Agricultural Engineering Research*, **29,** 321–327.

Chenu, C. & Guérif, J. 1998. Mechanical strength of clay minerals as influenced by an adsorbed polysaccharide. *Soil Science Society of America Journal*, **55,** 1076–1080.

Chertkov, V.Y. 2002. Modelling cracking stages of saturated soils as they dry and shrink. *European Journal of Soil Science*, **53,** 105–118.

Dexter, A.R. 1988. Advances in characterization of soil structure. *Soil and Tillage Research*, **11,** 199–238.

Groenevelt, P.H. & Grant, C.D. 2001. Re-evaluation of the structural properties of some British swelling soils. *European Journal of Soil Science*, **52,** 469–477.

Hallett, P.D. 1996. *Fracture mechanics of soil and agglomerated solids in relation to microstructure*. Unpublished PhD thesis, University of Birmingham, Birmingham.

Hallett, P.D. & Newson, T.A. 1998. Desiccation of a sensitive clay: application of the model CRACK: Discussion. *Canadian Geotechnical Journal*, **35,** 1109–1110.

Hallett, P.D. & Newson, T.A. 2001. A simple fracture mechanics approach for assessing ductile crack growth in soil. *Soil Science Society of America Journal*, **65,** 1083–1088.

Hallett, P.D., Dexter, A.R. & Seville, J.P.K. 1995. The application of fracture mechanics to crack propagation in dry soil. *European Journal of Soil Science*, **46,** 591–599.

Hallett, P.D., Bird, N.R.A., Dexter, A.R. & Seville, J.P.K. 1998. Application of fractals to the scaling of aggregate structure and strength. *European Journal of Soil Science*, **49,** 203–211.

Konrad, J.M. & Ayad, R. 1997. Desiccation of a sensitive clay: field experimental observations. *Canadian Geotechnical Journal*, **34,** 929–942.

Krizek, R.J. 1977. Fabric effects on strength and deformation of kaolin clay. In: *Proceedings of the 9th International Conference on Soil Mechanics and Foundation Engineering, Tokyo*, Volume 1, pp. 169–176. A.A. Balkema, Lisse.

Lima, L.A. & Grismer, M.E. 1992. Soil crack morphology and soil-salinity. *Soil Science*, **153,** 149–153.

Lima, L.A. & Grismer, M.E. 1994. Application of fracture mechanics to cracking of saline soils. *Soil Science*, **158,** 86–96.

Maugis, D. 1985. Review: Subcritical crack growth, surface energy, fracture toughness, stick-slip and embrittlement. *Journal of Materials Science*, **20,** 3041–3073.

Mitchell, J.K. 1993. *Fundamentals of Soil Behavior*, 2nd edn. John Wiley & Sons, New York.

Newson, T.A. & Fahey, M. 1998. *Saline tailings disposal and decommissioning*. Report Project M241, Volume 1, Department of Minerals and Energy of Western Australia, Perth.

Nichols, J.R. & Grismer, M.E. 1997. Measurement of fracture mechanics parameters in silty-clay soils. *Soil Science*, **162,** 309–322.

Rappoldt, C. & Crawford, J.W. 1999. The distribution of anoxic volume in a fractal model of soil. *Geoderma*, **88,** 329–347.

Snyder, V.A. & Miller, R.D. 1985. Tensile strength of unsaturated soils. *Soil Science Society of America Journal*, **49,** 58–65.

Torrance, J.K. 1974. A laboratory investigation of the effects of leaching on the compressibility and shear strength of Norwegian marine clays. *Géotechnique*, **24,** 155–173.

Turner, C.E. & Kolednik, O. 1994. Application of energy-dissipation rate arguments to stable crack growth. *Fatigue and Fracture of Engineering Materials and Structures*, **17,** 1109–1127.

Turner, C.E. & Kolednik, O. 1997. A simple test method for energy dissipation rate, CTOA and the study of size and transferability effects for large amounts of ductile crack growth. *Fatigue and Fracture of Engineering Materials and Structures*, **20,** 1507–1528.