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ORIGINAL PAPER

Anisotropy of magnetic susceptibility analysis of deformed kaolinite: implications for evaluating landslides

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Abstract Plane strain tests were performed on seven kaolinite blocks, each of which developed shear bands. Anisotropy of magnetic susceptibility (AMS) analysis of the kaolinite reveals a threshold degree of magnetic anisotropy (P') exceeding which shear bands develop. Since P' is a strain-intensity gauge and soils are known to develop shear bands prior to landsliding, it is concluded that soil in every landslide-prone region must have its unique threshold P' exceeding which it develops shear bands before failing. Therefore, AMS monitoring of soil in landslide prone regions is proposed as a potential tool in the management of natural hazard zones.

Keywords Anisotropy of magnetic susceptibility · Kaolinite · Deformation · Shear bands · Landslide

Introduction

Every material has an ultimate strength exceeding which it cannot accommodate further strain and fails by fracture or ductile flow. This applies to rocks and soft sediments as well as to soils, which are presently undergoing strain and are subjected to landslides and similar phenomena. While structures such as faults and ductile shear zones have been widely reported and investigated in hard rocks, studies on Deep Sea Drilling Project and Ocean Drilling Programme cores of soft-sediments recovered from active plate margins have also shown the presence of similar structures (Lundenberg and Moore 1986; Knipe 1986a, b; Maltman 1987). Compression microstructures have been observed in natural clay samples from shear zones in landslides (e.g., Walton's Wood, Staffordshire; Tchalenko 1968). Shear bands, which are zones of high strain concentration, have commonly been reported from clays (e.g., Tchalenko 1968; Agar et al. 1988). These impart a scaly fabric to clays, and heterogeneous deformation due to cyclic shear movements has been inferred to be the cause of their genesis (Behrmann et al. 1988; Takizawa and Ogawa 1999). Recently shear bands have also been reported from clays in natural settings such as the Boom Clay in Belgium (Dehandschutter et al. 2004, 2005). In the past, several experimental studies on clays have investigated compressional structures (Tchalenko 1968) and development of shear bands in plane strain (Topolnicki et al. 1990; Viggiani et al. 1994; Lizcano et al. 1997) and under varying percentages of water content and strain rate (Maltman 1987; Arch et al. 1988). These experimental studies have confirmed that water-rich argillaceous sediments deform by the production of shear zones. SEM and TEM studies of shear bands in clays reveal reorientation of particles along failure surfaces, which implies rotation of particles in zones of strain localization (Hicher et al. 1994). Thus, it is clear that considerable knowledge exists about the genesis of shear bands in clays. Since clays comprise a majority of the areas that are susceptible to present-day natural hazards such as landslides and because they are known to develop shear bands prior to failure (Tchalenko 1968), the identification of zones of

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high strain concentration in clays prior to failure may help in taking steps that can prevent loss to life and property. The present study involves strain analysis of experimentally deformed clay using anisotropy of magnetic susceptibility (AMS) to gauge strain in zones of strain localization. On the basis of the experimental results, it is suggested that AMS monitoring of soil in landslide prone areas may lead to identification of zones of high strain concentration and prospective shear band development. This information can be useful in better management of natural hazard zones.

Strain analysis in geological materials

For identifying high strain zones in a geological material, it is essential to quantify strain using techniques such as $R_f - \varphi$ and Fry methods among many others (Ramsay and Huber 1983). However, rocks in areas prone to natural hazards such as landslides rarely possess strain markers that are essential to apply the above-mentioned conventional methods of strain analysis. In several previous studies, strain in rocks devoid of strain markers has been evaluated by carrying out AMS studies (Tarling and Hrouda 1993). This involves induction of magnetism in an oriented sample in different directions and measurement of the induced magnetization in each direction. The analysis yields magnitudes and directions of the three principal axes of the magnetic susceptibility ellipsoid K_1, K_2 and K_3 ($K_1 \geq K_2 \geq K_3$) using which the mean susceptibility (K_m), strength of magnetic foliation (F) and lineation (L) can be computed. The other parameters obtained from AMS analysis are the shape parameter (T) and the degree of magnetic anisotropy (P'). T quantifies the prolate/oblate shape of the ellipsoid and its value varies between -1 and $+1$. Positive values indicate oblate shape and negative ones prolate. P' is a measure of the eccentricity of the magnetic susceptibility ellipsoid and has been used as a strain-intensity gauge in previous studies (Hrouda 1993; Henry et al. 2004; Mukherji et al. 2004; Sen et al. 2005). Recently, triaxial laboratory tests on sedimentary rocks (marls) have revealed an increase in P' with increasing deformation that is related to increased reorientation of phyllosilicate grains in the rocks at higher strains (Kapička et al. 2006). Since clays are also devoid of strain markers, AMS data may provide a useful method of gauging strain in them and identifying regions of strain concentration and prospective failure. This has, however, never been attempted. The present study is targeted at highlighting the possible application of AMS in this direction by carrying out the analysis of experimentally deformed kaolinite and extrapolation of the results to the evaluation of present-day movements such as landslides.

Experimental deformation of kaolinite and AMS analysis

In the present investigation, a commercially procured homogenous kaolinite [$Al_2Si_2O_5(OH)_4$] was used. Its liquid limit, plastic limit and plastic index were 57.6, 28.5 and 29.0%, respectively, and according to the American Association of State Highway and Transportation Officials (AASHTO) system of classification, it falls under the A-7-6 group. Kaolinite blocks having dimensions of 140 mm × 70 mm × 25 mm were obtained from a kaolinite slurry after consolidation under static loads for 15 days. Plane strain tests under undrained conditions with varying confining pressure and axial stress were carried out on seven such blocks in a biaxial cell at the Indian Institute of Technology (IIT Kharagpur, India). The cell consists of two Perspex platen 226 mm × 146 mm × 25 mm in size that are bolted together with the kaolinite clay specimen sandwiched between them (Supplementary data 1). The bottom end platen is fixed with the two Perspex platen by bolts and is restrained from movement. The top end platen is attached to the assembly in such a way that it can slide smoothly in the vertical direction only between two fixed guides. Before each test a 10 mm × 10 mm square grid made of oil-based paint was imprinted on the kaolinite to enable visualization of shear band development. The adopted test configuration generates very negligible friction between the surfaces of the sample and the walls of the Perspex platen. A stationary digital camera was utilized to record the deformation of the grids with the progress of the tests. The whole-plane strain test device, with the clay specimen in it, was mounted on a strain controlled loading frame. The clay sample was compressed by lowering the top platen at a constant strain rate of 0.22 mm (0.16%) per minute. Three linear variable differential transducers (LVDT) were used, for measuring the vertical and the horizontal deformations. The axial load was measured with the help of a load cell while average pore pressure in the sample was measured with the help of a pressure transducer. The stress and strain conditions of each test are tabulated in Supplementary data 2 and Fig. 1a is a sketch of shear bands developed in one of the experiments.

After each test, at least five cylindrical cores, each 25.4 mm in diameter and 22 mm in height, were extracted from different locations of every deformed sample for AMS analysis. Reference lines with half arrows (Fig. 1b and Supplementary information 3b) were marked on each deformed sample prior to extraction of the cores to maintain a uniform orientation of different cores during AMS analysis. The cores from each deformed sample could be grouped into two categories—cores containing shear bands (Position A) and those without them (Position B). Since a grid had been marked on the samples prior to deformation,

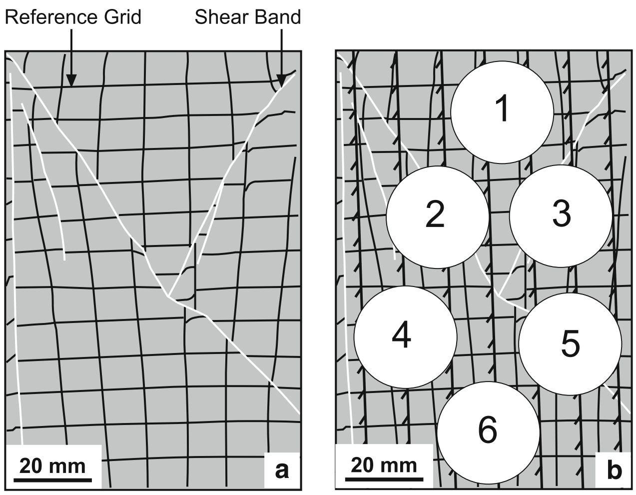

Fig. 1 **a** Explanatory sketch showing development of shear bands in deformed kaolinite (test 3). **b** Positions of *cores 1–6* that were taken from the deformed kaolinite for AMS analysis. The photographs of the deformed sample from which the sketches were made are shown in supplementary data 3

Table 1 AMS data of deformed and undeformed kaolinite samples

Test	Position	*n*	K_m (μSI)	P'	*T*
1	A	3	68.380	1.459	0.310
	B	3	38.280	1.112	0.709
2	A	2	39.990	1.185	0.799
	B	3	58.373	1.324	0.597
3	A	2	48.325	1.351	0.597
	B	4	41.370	1.220	0.628
4	A	1	42.110	1.312	0.664
	B	4	38.365	1.159	0.500
5	A	2	43.695	1.160	0.263
	B	3	38.877	1.135	0.415
6	A	3	31.677	1.255	0.614
	B	2	42.735	1.079	0.541
7	A	2	41.260	1.433	0.846
	B	3	55.243	1.326	0.580
Undeformed sample		2	26.785	1.060	0.773

The values of AMS parameters are averages of cores for each position from every test

A and *B* refer to cores with and without shear bands, respectively; *n* = number of cores

the extent of modification of the grid helped identify the above positions. In parts where shear bands developed, the grid shows displacement while locations distant from shear bands show minimum modification of the original square grid. As an example, Fig. 1b and Supplementary data 3c show locations of cores extracted after test 3. AMS was measured in a field intensity of 300 A/m in a spinning specimen using the KLY-4S Kappabridge (AGICO, Czech Republic) in the magnetic laboratory of the Department of Geology and Geophysics, IIT Kharagpur. The data generated are listed in Table 1. The magnetic data from the undeformed kaolinite are also listed.

It is observed that K_m and P' of deformed kaolinite are higher than the values for the undeformed sample. The shape parameter (*T*) of the undeformed sample is 0.773. *T* value in most of the cores from deformed samples is less than the above value. An important observation is that in all the tests, except test 2, P' values of cores containing shear bands are found to be higher than the cores that do not have shear bands. Further, all the cores from deformed samples have P' greater than 1.06, which is the P' value for the undeformed sample.

Discussion

It is known that high strain concentration/strain localization leads to the development of shear bands in clays (Tchalenko 1968; Dehandschutter et al. 2004, 2005). This implies that the magnitude of strain would be higher in the vicinity of shear bands than away from it. AMS data from the deformed kaolinite (above) reveal a higher P' value in cores with shear bands as compared to those devoid of them. Therefore, it may be concluded that AMS data are useful in gauging strain-intensity variations in the investigated kaolinite clay. This is also supported by the fact that the P' value is greater in the deformed samples as compared to the undeformed sample (Fig. 2). It is also noted that a minimum P' value of 1.16 is needed for the development of shear bands in the kaolinite under investigation. This is highlighted by the dashed line in Fig. 2 and represents the threshold P' for the kaolinite for development of shear bands. Thus, all the samples with $P' \geq 1.16$ develop shear bands after which they fail. Even in experiment 2, where the cores with shear bands have lower P' than those devoid of them, P' in the former is >1.16. Thus, it is suggested that

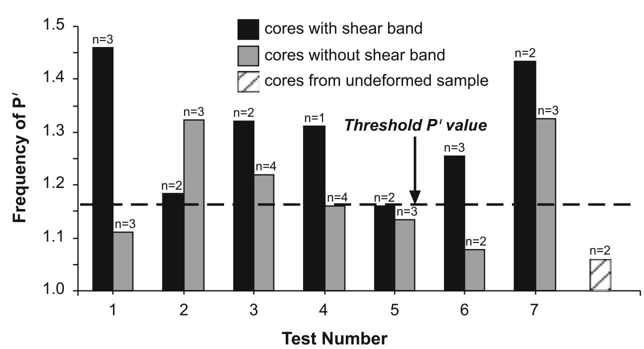

Fig. 2 Frequency diagram of P' measured in the cores from each experiment. *Dashed line* highlights the threshold P' value in the present experimental study that must be exceeded for shear bands to develop. *n* = number of cores

this threshold P' value of 1.16 is critical for the kaolinite used in the present experiments and can be considered analogous to the ultimate strength of the material beyond which it fails.

The difference in the shape parameter (T) between the undeformed and deformed samples is also revealing. T value of 0.773 for the undeformed sample (Table 1) indicates a strong oblate shape of the magnetic susceptibility ellipsoid in the sample. This is due to the flat orientation of kaolinite in the blocks that were obtained from the kaolinite slurry after consolidation under static loads for 15 days. Thus, this T quantifies the shape of the pre-deformational kaolinite block and is similar to a fabric that natural clay would acquire when it is under its own load. On plane strain deformation, T of the kaolinite generally falls below 0.773, which is T for the undeformed sample. This indicates that on deformation of the kaolinite, there was a superimposition of prolate strain over the original oblate fabric of the kaolinite block, which led to reduction of the T value. Similar superimposition has also been interpreted and modeled for sedimentary thrust sheets (Hrouda 1991) as well as for deformations associated with diagenesis (Hrouda and Ježek 1999). In two tests (numbers 2 and 7), cores containing shear bands have $T > 0.773$, which indicates further flattening of the original oblate fabric. It is known from the experimental work of Kapička et al. (2006) on marls that an increase in strain leads to greater reorientation of phyllosilicates in them. Moreover, Hicher et al. (1994) also documented reoriented particles along shear bands and failure surfaces in clays. In light of these studies, it is inferred that T value of kaolinite after deformation would eventually depend on the direction in which reorientation of the clay minerals took place. A reorientation in a direction perpendicular to the original flattening fabric would be equivalent to superimposition of prolate fabric over the original oblate one, thus leading to $T < 0.773$. In contrast, if the deformation was to lead to reorientation in a direction parallel to the original oblate fabric, then there would be a further flattening of the initial fabric, thus resulting in $T > 0.773$. Because shear bands have developed in the deformed clays, it is obvious that strain at the scale of observation was heterogeneous and strain partitioning took place. It is thus concluded that the reorientation of the minerals was different in different parts of the clay block and this led to differences in the T values. However, despite this, P', which measures the eccentricity of the magnetic susceptibility ellipsoid, is higher in the cores that contain shear bands as compared to those without them, which is an indication of the usefulness of AMS data as a strain proxy in clays.

These results have an important bearing on the evaluation of strain in clays occurring in natural situations that are presently undergoing deformation. An important geological situation to which the results of the present laboratory experiments could be extrapolated is landslides. It is known that clays are the main constituent of soil that undergoes land sliding and shear bands are known to develop in clays from landslides. It is envisaged that just as a threshold P' of 1.16 was identified in the experimentally deformed kaolinite, every soil in an area prone to present-day movements (e.g., landslides) must have a threshold P' that must be exceeded prior to failure. If AMS analysis is carried out in different parts of such a soil, then it can help in mapping P' values, which can provide vital information about areas where higher strain is being accommodated. These areas can then be monitored regularly and over a period of time the database can lead to determination of the threshold P' value exceeding which failure and land sliding takes place. Figure 3 is a flowchart highlighting the envisaged guidelines for AMS monitoring in hazard prone zones. With the threshold P' value already known for a soil in an area, efforts can be made to take measures that can either reduce the build-up of strain in the region or the area can be evacuated prior to failure in order to prevent loss of life.

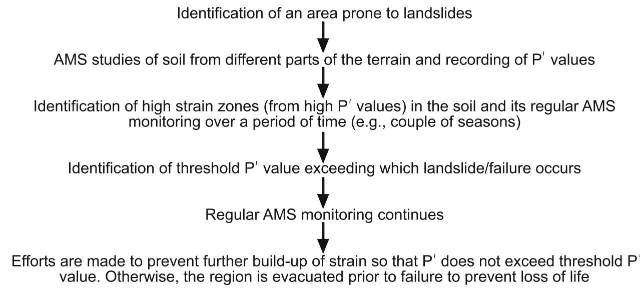

Fig. 3 Flowchart of the proposed guidelines for AMS monitoring of areas prone to natural hazards such as landslides

Conclusions

Considerable damage to life and property takes place due to present-day movements such as landslides and therefore identifying zones of high strain accumulation in soils is an important aspect of hazard management. The present study has explored the use of AMS as a potential tool in this regard. Following are the main conclusions from the investigation.

1. Cylindrical cores of experimentally deformed kaolinite which contain shear bands have a higher P' than those devoid of them. Therefore, P' can be used as a strain intensity gauge in clays.
2. A threshold P' is identified for the deformed kaolinite, exceeding which it develops shear bands.
3. Clay minerals are the dominant component of soils that undergo landslides in nature and these soils are also

known to develop shear bands prior to failure. Therefore, it is concluded that AMS monitoring of soil in a landslide-prone region can help in (a) recognition of zones of high strain localization within the soil and (b) identification of a threshold P' value for that particular soil exceeding which it develops shear bands.

From the present study and the above conclusions it is clear that AMS can provide information about zones of strain localization prior to failure. This calls for AMS analysis of soil from a landslide zone to test the feasibility of using AMS as a tool in natural hazard management.

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