Mineralogical and geotechnical characterization of a clay unit that underlies the unstable flanks of Mount Etna - Sicily

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ABSTRACT: The mineralogical and geomechanical properties of a distinctive early Quaternary marine clay unit that underlies the eastern and southern flanks of Mt Etna, which may play a role in governing the style of instability on the edifice, have been determined. Preliminary clay mineral identification revealed the presence of interlayered illite-smectite and disordered kaolinite. The clay is heavily over consolidated (OCR≥32) and is a very stiff, extremely high undrained strength closely fissured, dark yellowish grey silty calcareous CLAY. Direct shear and ring shear tests measured peak shear strength parameters of $c' = 51$ kN/m^2 and $\phi' = 20^\circ$ and residual shear strength parameters $c'_r = 0$ to 3.0 kN/m^2 and $\phi'_r = 6.4$ to 9.7°. The mass strength of the clay will be influenced by the polished fissures, which are close to ϕ'_r, and may be a controlling factor in the style and rate of movement of the observed flank instability depending on fissure orientation.

INTRODUCTION AND GEOLOGICAL SETTING

Mount Etna is situated above the African – European plate boundary on the eastern margin of the Sicilian continental crust, a tectonic setting that imparts both structural and lithological discontinuities to the edifice substrate (Figure. 1). The volcano, Europe's largest and most active, has arisen rapidly to an elevation of over 3300 metres from a succession of overlapping central vents and associated flank eruptions in approximately the last 200 Ka (Romano, 1982; Calvari *et al*., 1994; Coltelli *et al*., 1994; Corsaro *et al*., 2002; Branca *et al*., 2004; and references therein). The northern and western parts of the volcano overlie and are buttressed against a pre-existing topography developed in metamorphic and sedimentary rocks within a southward verging system of thrusted nappes, the Apennine-Maghrebian Chain, at the southern margin of the Eurasian plate. By contrast, the southern and eastern flanks of the edifice overlie marine early Quaternary clays that accumulated in the foredeep created on the tectonically depressed northern margin of the northward-dipping downgoing African plate (Lentini, 1982; Figure. 1).

EDIFICE INSTABILITY

Numerous studies have proposed and elaborated large scale sliding of the eastern and southern flanks of the volcano (Borgia *et al.,* 1992; Lo Giudice and Rasà 1992; Rust and Neri, 1996; Garduño *et al.,* 1997; Borgia *et al*., 2000a, b; Froger *et al.,* 2001; Acocella *et al*., 2003; Neri *et al.*, 2004; Rust *et al*., 2005). The emerging picture is that the geological background outlined above sets the scene for complex edifice instability phenomena that are essentially unrecognised elsewhere. Most notable is the long record of relatively slow and stable sliding, albeit with limited accelerations associated with magma pressure, particularly from flank eruptions (Acocella *et al*., 2003; Rust *et al*., 2005). Movement on the northern boundary of the unstable mass, the Pernicana fault, averages up to about 20 mm a^{-1}, while the south-western boundary, the Ragalna fault system, averages about 25% of this slip rate (Neri *et al*., 2007). The variability in these rates reflects the inhomogeneous nature of the instability, which presents a nested pattern of movement in both map and cross section views, with a series of basal detachments extending to a depth of at least 5 km (Rust *et al*., 2005). The position and strike of the Ragalna fault system suggest that it is controlled by the rheological contrast between the juxtaposed rocks of the Chain and the sub-Etnean clays (Borgia *et al.,* 1992; Rust and Neri, 1996;) (Figure. 1). More recent work provides evidence that the structure continues across historical lavas, beyond its visible surface expression, towards the volcano summit, ultimately linking with the NE Rift and the Pernicana fault to encircle and define a zone of flank instability moving generally south-eastwards that comprises more than a third of the edifice (Neri *et al*., 2007;) (Figure. 1).

According to Di Stefano and Branca (2002), the sub-Etnean clay is marine in origin consisting essentially of a marley clay and is approximately 100m thick, with the most complete succession outcropping northeast of the Etna at Fiumefreddo (Figure 1). Here the sequence is composed of about 50m of bioclastic calcarenites passing up into about 30m of blue marly clays. The rheology of this early Quaternary marine clay unit, especially the marley clay is thought to play a role in governing the unusual slow-motion style of instability on the edifice. As part of on-going research to geotechnically characterize the edifice to enable deformation modeling using finite difference techniques to be made, a set of samples were taken of the sub-Etnean clay for geotechnical testing.

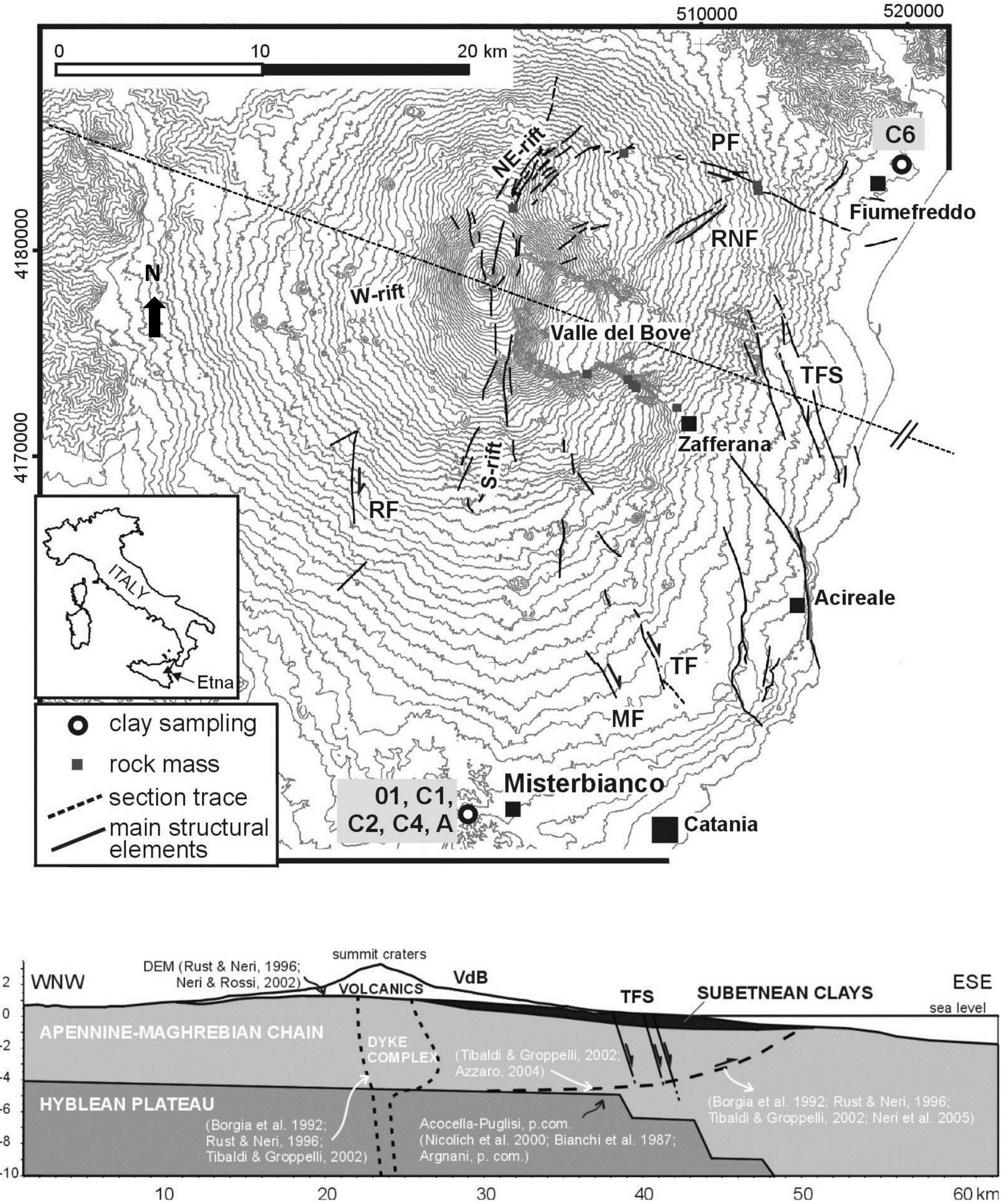

Figure. 1. Simplified geological map and cross section of Mt Etna showing the main structural features, including the three principal rift zones (NE, S and W) on the volcano, and highlighting the unstable eastern and southern flanks. The southern and eastern fronts of the spreading are evident from deformation of sediments on the southern margin of Etna (Borgia et al., 1992, 2000a, b) and inferred from bathymetric data in the Ionian Sea (Borgia et al., 1992). MFS = Messina fault system, MTFS = Mascalucia-Trecastagni fault system, PFS = Pernicana fault system, RFS = Ragalna fault system, TFS = Timpe fault system, VB = Valle del Bove. Cross section extends south of the map onto the Catania Plain underlain by the early-Quaternary clays (2). These overlie 'African' shelf carbonates of the Hyblean Plateau (4). Mount Etna volcanics (1) overlie the clays and the thrusted nappes of the Apennine – Maghrebian Chain (3).

SAMPLING AND TESTING PROGRAMME

Samples were collected in 2008 – 09 from outcrops newly revealed by quarry operations in the Misterbianco area to the south of the volcanic edifice (Figure 1). Samples were obtained from surface exposures with both block and thin walled samples being taken *in situ* for strength and compressibility tests (Figure 2). Irregular intact hand samples were obtained for index, mineralogical and residual strength tests.

Laboratory tests were carried out at the Dipartimento di Scienze della Terra "A.Desio", Università degli Studi di Milano (Italy) and at the School of Earth and Environmental Sciences, University of Portsmouth (UK). Mineralogical and physical properties were obtained by SEM (Jeol JSM6100 Scanning Electron Microscope) and XRD (Philips X-ray diffractometer) analyses, and geotechnical identification procedures. Intact and residual shear strengths were obtained by direct and ring shear tests (Bromhead Ring shear apparatus). Compressibility properties were obtained by oedometric testing. Five samples (Etna 01, C1, C2, C4 & A) were tested.

GEOTECHNICAL CHARACTERISATION

The sub-Etnean clays form a distinctive geomorphology of soft rounded low hills (c. 260 m above sea level) with what appear to be areas of gulley erosion and shallow active landslide scars. The quarries where the samples were obtained were being excavated to win clay to be used as landfill liner and capping materials.

The clay at the quarry site is a very stiff, extremely high strength, thickly bedded, closely fissured, medium to high plasticity, dark yellowish grey silty calcareous clay. The well-developed fissures are steeply dipping in what appear to be conjugate sets. Their surfaces are highly polished and striated and often discoloured dark orangish-brown by iron oxide. Undrained strength measured *in situ* using a pocket penetrometer ranged between 300 and 400 kN/m^2. The results of the classification, shear strength and oedometer testing are summarized in Table 1.

Clay mineral identification made by SEM and X-ray diffraction analyses revealed the presence of interlayered illite-smectite and disordered kaolinite. The clay fraction makes up between 40 to 67% of the material which has a liquid limit in the range of 45-65% and plasticity index range of 20-40% classifying it as an inactive clay (A_c = 0.37 to 0.48). This suggests that the dominant clay mineral is kaolinite (Activity 0.4), with only small percentages of interlayered illite-smectite being present. Subordinate amounts of quartz and calcite were also identified in both the X-ray diffraction and SEM analyses. Marine micro-fossils were identified in the SEM micographs confirming the marine depositional environment of this clay.

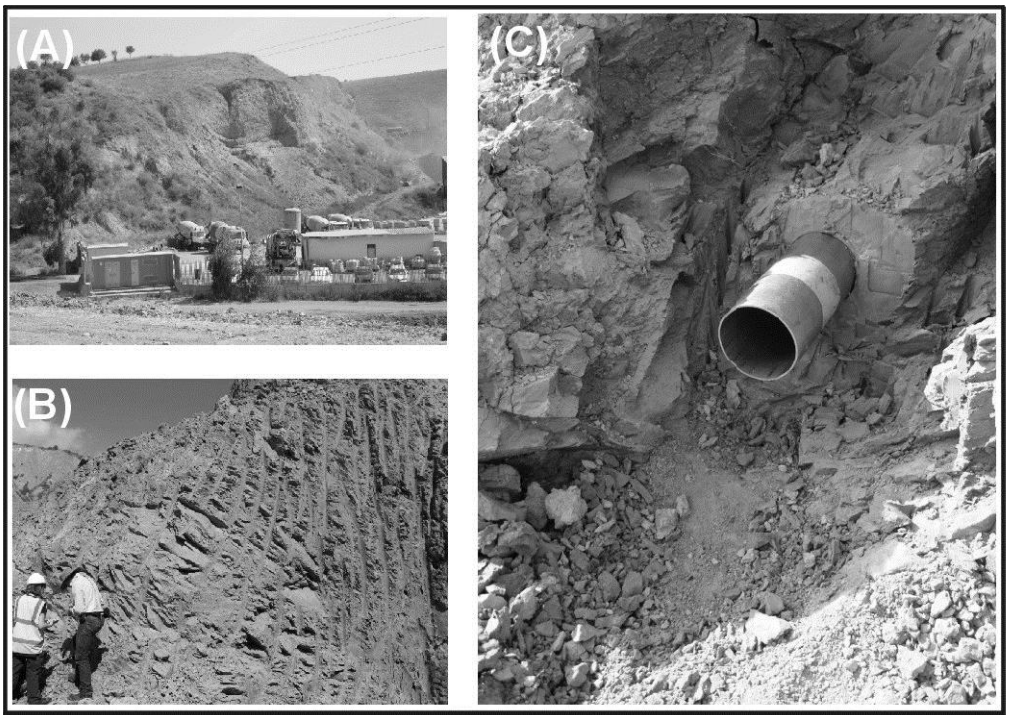

Figure. 2. Sampling site: (A) The Misterbianco quarry. (B) In outcrop well developed fissures in the clays with an apparent dip out of the face (C) Horizontal tube sampling of C1.

Table 1. Summary of Geomechanical Laboratory Testing of Sub-Etnean Clay.

Parameter	**C1**	**C2**	**A**	**C4**	**Etna 01**
Sand (%)	2	2	3	1	-
Silt (%)	36	31	54	34	-
Clay (%)	62	67	43	65	-
Liquid Limit (%)	48	49	46	53	-
Plastic Limit (%)	22	24	26	22	-
Plasticity Index (%)	26	25	20	31	
Activity (A_c)	0.42	0.37	0.46	0.48	-
Bulk Unit Weight (kN/m^2)	20.7	21.6	-	20.7	-
Dry Unit Weight (kN/m^2)	17.6	17.8	-	17.1	-
Internal effective angle of friction (peak) (ϕ_p') (°)	-	-	-	-	20
Effective cohesion (c′) (kN/m^2)	-	-	-	-	51

Parameter	C1	C2	A	C4	Etna 01
Residual angle of friction (remoulded) (ϕ'_r) (°)	9.3	8.0	-	9.7	6.4
Residual cohesion (c'_r) (kN/m^2)	1.4	0.0	-	1.3	3.0
Coefficient of compressibility (m^2/MN)	0.02	-	-	-	-
Coefficient of consolidation (m^2/year)	0.98	-	-	-	-
Material permeability (m/sec)	$6.6x10^{-12}$	-	-	-	-
Overconsolidation Ratio (OCR)	>32	-	-	-	-

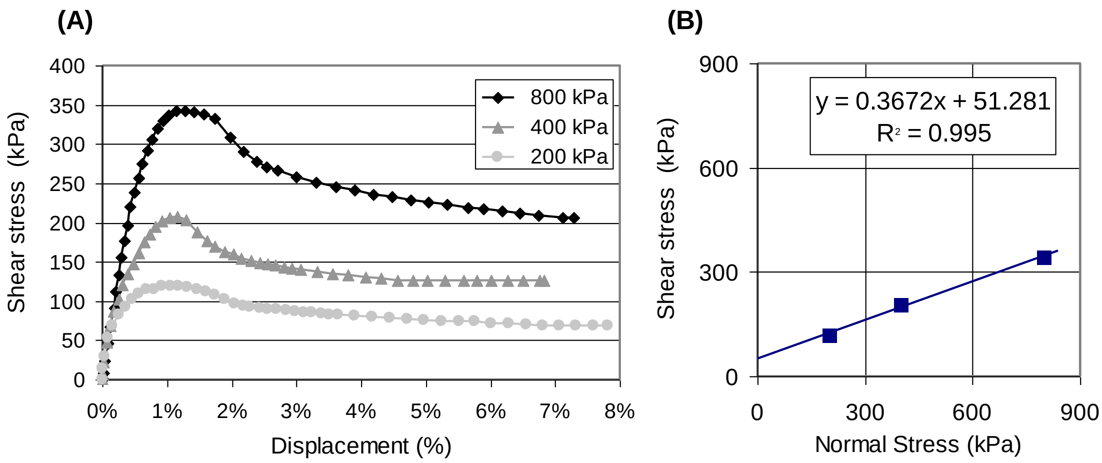

Figure 3. Direct shear test results (sample C4). (A) stress vs displacement curves. (B) Shear stress vs normal stress.

Direct shear tests measured peak shear strength parameters of c′ = 51 kN/m^2 and ϕ' = 20° (Figure 3). The testing was on an intact specimen at loading rate of 0.001 mm/min. The high cohesion intercept for the peak strength is due in part to the over consolidation of the clay but also to the presence of calcite within the soil lattice that is possibly acting as a weak cement. Residual shear strength parameters, measured using completely remoulded samples at water contents close to the liquid limit and at shearing rates of 0.001 mm/min gave c'_r = 0 to 3.0 kN/m^2 and ϕ'_r = 6.4 to 9.7° (Figure 4).

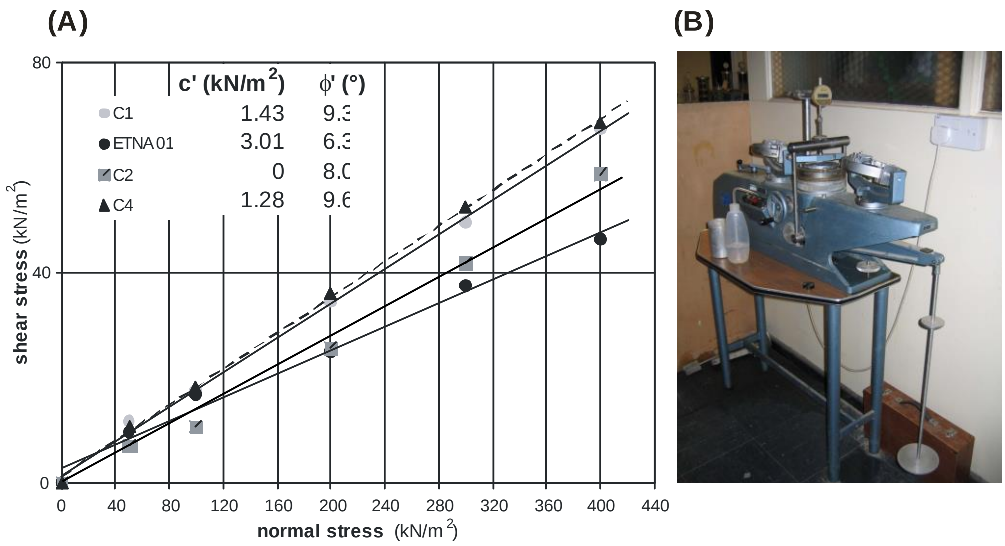

Figure 4. Ring shear test results. (A) shear stress vs normal stress (x and y scales are different). (B) Bromhead apparatus used for testing.

Oedometer testing confirmed the low compressibility low permeability of the deposit and measured a coefficient of compressibility (m_v) of 0.02 m^2/MN, a coefficient of consolidation (c_v) of 0.98 m^2/year, and a coefficient of material permeability (k) of 6.6x10^{-12} m/s (all measured over an effective vertical stress (σ_v') range of 1.6 to 3.2 MN/m^2) (Figure 5). The clay is heavily over consolidated (OCR≥32), based on apparent pre-consolidation pressure of approximately 9 MPa and depth of exposure of about 15m.

SEM micrographs of the polished fissures indicate that at least two phases of movement have

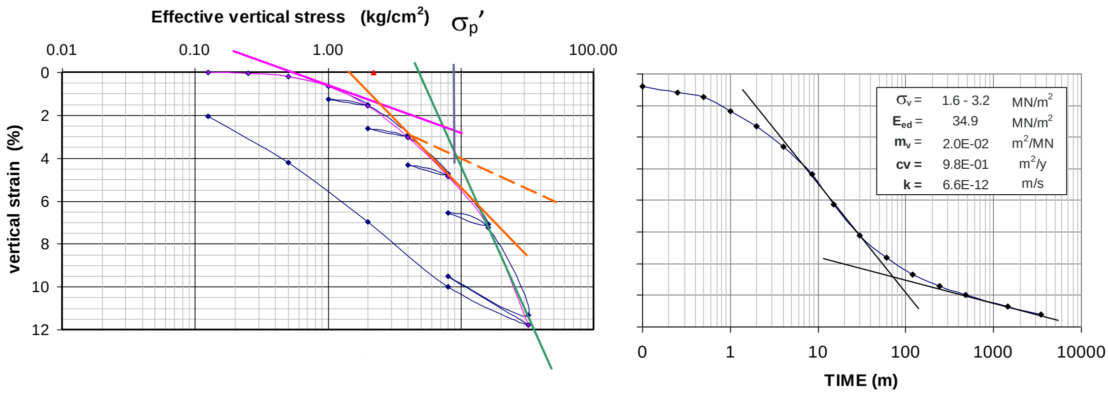

Figure 5. Oedometer test results. (A) Vertical strain vs vertical effective stress. (B) Gauge readings vs Log time curve (effective vertical stress range σ'_v 1.6-3.2 MN/m^2).

occurred along these discontinuities. The structure of the clay close to the fissures appears undisturbed (no visible re-alignment) indicating that shearing is confined to “paper-thin” zones within the clay material. It is not clear from the SEM micrographs the amount of movement that has taken place along these fissures. Further work is however underway to analyse the relationship between these discontinuities and structures that appear to control edifice movement. This work may give some indication as to the amount of shear displacement the sub-Etnean clays have under gone. This is important as the amount of movement that has occurred along these surfaces will dictate if residual strengths operate or if further movement is required to reduce the strength to the lowest possible values.

Although the intact strength of the sub-Etnean clay is relatively high, the mass strength could be controlled by the presence of the highly polished fissures. These surfaces will be at or very close to the residual angle of friction (ϕ'_r) of the clay (depending on the amount of movement already taken place) and will therefore act as surfaces of weakness within the clay mass provided that their orientation forms a surface along which movement can take place. It should be noted that only a small number of samples have been collected and tested to date, and the above results are not expected to fully represent the variability and mass characteristics of this lithological unit. However, they do provide the basis for a dataset of the physical and mechanical properties of a clay unit that may mediate the distinctive Etnean flank instability process, and help constrain a geotechnical ground model for subsequent numerical stability analyses. Sampling and testing continues so that characterization of this unit can be refined. It is the intention to carry out drained triaxial tests on undisturbed samples to fully characterise peak strength characteristics but such samples are as yet not available. Direct shear box tests on cut samples may also help determine the strain required to reach residual strength but samples for this are also not available at present.

CONCLUSIONS

The sub-Etnean clay underlying the eastern flank of Mt Etna is a heavily over consolidated very stiff, closely fissured, dark yellowish grey silty calcareous CLAY with a medium to high plasticity. Preliminary clay mineral identification revealed the presence of interlayered illite-smectite and disordered kaolinite, initial geotechnical testing of the highly overconsolidated clay has peak shear strength of $c' = 51$ kN/m^2 and $\phi' = 20^\circ$ for the intact clay from direct shear box testing and residual shear strength parameters $c'_r = 0$ to 3.0 kN/m^2 and $\phi'_r = 6.4$ to 9.7° from ring shear testing. Refinement of the parameters will lead to an enhanced geotechnical model for the assessment of flank instability.

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