

Research Article

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Problems with collapsible soils: Particle types and inter-particle bonding

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Abstract: A collapsible soil is composed essentially of a packing of mineral particles and a set of interparticle bonds holding the system together. Failure requires the bond system to fail and the soil structure to collapse. A natural hazard is presented. The soil structure may collapse inwards (consolidate), as in loess failure, or it may collapse outwards (disperse, disintegrate), as in the failure of quick-clays, some collapsing sands, some silty estuarine deposits, and in wind erosion of silty soils by saltating sand grains. Generalising about bonding systems allows two types of interparticle bond to be recognized: long range bonds and short range bonds. Long range bonds are found in clay mineral systems and allow the occurrence of plasticity. They are represented by c in the standard Coulomb equation. Short range bonds are found in inactive particle systems. These are soil systems where the constituent particles do not have a significant electrical charge. A slight deformation of a short-range bonded system causes much loss of strength. It is short range bonds which tend to dominate in collapsing soil systems, although in the complex case of loess the bond failure is initially mediated by long range bonds at the interparticle contact regions. A collapse failure involves a large scale re-making of the soil structure, and thus total failure of the bonding system.

Generalising again- it can be claimed that five types of particle make up engineering soils: A active clay mineral particles (the smectites), B inactive clay mineral particles (e.g. kaolinite, illite), C very small inactive primary mineral particles (close to the comminution limit in size- mostly in the quick-clays), D silt (usually quartz silt), and E sand (usually quartz sand). The nature of type D particles contributes to the collapse of loess soils, the most widespread

of the collapsing soil phenomena. The nature of type C particles controls the behaviour of quick-clays. C and D systems are essentially dominated by short-range bonds.

Keywords: Collapsible soils; sand, silt and clay-size; long and short range bonds; soil erosion; two basic types of soil collapse; loess

1 Introduction

Collapsible soils can be divided into two types: a) those in which an open structure collapses into a more compact structure (perhaps these are the classic, default collapsible soils), and b) those in which a soil structure disintegrates into a totally dispersed system. Type (a) is the widely accepted form of collapsible soil, and the most widespread, but since the NATO Conference on Collapsible soils in 1994 type (b) variants have been accepted within the definition of collapsible soil [1]. The particle packing structure of collapsible soils has recently been considered by Assadi-Langroudi *et al.* [2]. Here we are concerned with the interparticle bonds which have to be broken for the system to collapse; it would also be useful to clarify the nature of the various types of collapsing soil and to define some of the collapse actions and consequences. There have not been many studies of interparticle bonding in engineering soils, perhaps the most perceptive was that by Osipov [3]. This topic falls within the field of 'engineering soil science' which has always been more thoroughly pursued in Russia than in other countries, so most of the literature on engineering soil bonding and collapse problems in engineering soils is in Russian (see, in particular Sergeev *et al.* [4], Trofimov [5], Kriger [6], Kriger *et al.* [7] and for a review of early studies Drashevskaya [8] – which is highly recommended).

Loess collapses; loess ground possesses collapsibility; loess is the major collapsing soil and the development of collapsibility and the dynamics of loess collapse have been much studied. Perceptive investigations are still appearing, see, in particular, Xie *et al.* [9] and Milodowski *et al.* [10]. Loess collapses to form a more compact sys-

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tem; this may cause subsidence in the engineering environment. The terms subsidence and collapse have to be observed carefully, particularly in translated literature as subtle distinctions are often lost in translation. No doubt that loess is the critical collapsible soil. Terzaghi *et al.* [11] listed other soils in the collapsible category, these were quick-clays, estuarine deposits and collapsing sands. It should be noted that these additional systems tend to collapse by disintegration or dispersion, the initial, somewhat compact material is dispersed into a totally disaggregated mass with a much larger volume. In quick-clay failure solid turns to liquid and in the case of wind erosion by particle impact solid turns to vapour. That maybe a little exaggerated but this is the essence of the alternative collapsing systems. Perhaps the most important of the disintegrating systems is that operating when soil is eroded by saltating sand grains – the classic form of wind erosion – which reached it apotheosis in the ‘dust bowl’ of the nineteen thirties. Each impacting sand grain causes the collapse (disintegration) of a discrete volume of soil which is carried away by the wind. The impact + collapse event is the soil erosion event. The tensile strength of the material in the collapsing, impact zone is overcome [12].

Collapse is allowed because the bonds are breakable, and in most cases this is a ‘short-range’ bond, which needs to be defined and discussed. And to provide a reasonably comprehensive setting we need to discuss the various soil particle types which are involved in the relevant collapsible soils. The aim of this paper is to provide a simple recognition and definition of soil particle types, and of the basic bond types that operate in soil systems. Mechanisms of soil collapse can be described in terms of particle type and bonding type and the various collapsible soils described and discussed.

2 The bond/weight ratio R

The strength of the interparticle bond divided by the weight of the particle gives the bond/weight ratio, sometimes called R [13–15].

This is a useful concept and it allows the various types of particle in engineering soils to be identified. Figure 1 shows the variation of R with particle size for ideal soil systems.

Five ideal soil materials are demarcated on Figure 1: region A, with a very high R value, is the active clays, the smectites, very small particle size, very high surface area $c.800\text{m}^2/\text{g}$. Region B is the inactive clay zone, clays with a low activity, kaolinites, illites, halloysite etc. Region C is a

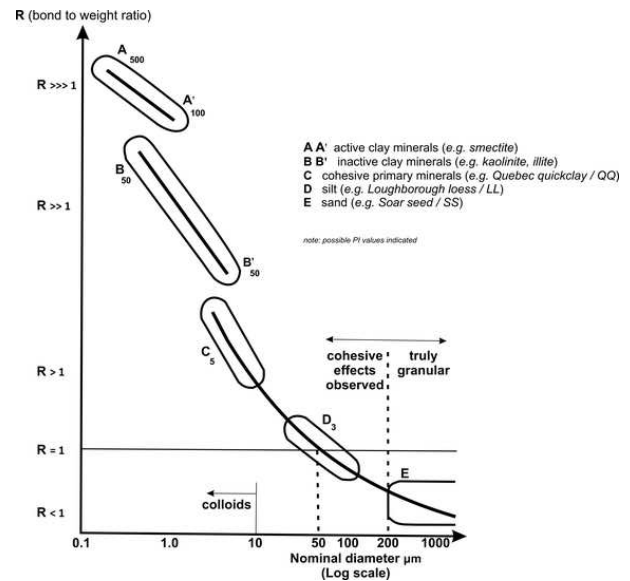


Figure 1: The R-size diagram. The bond/weight ratio R is plotted against particle size. The demarcated regions are A active clays, B inactive clays, C very small primary mineral particles, D silt, E sand. At $R = 1$ the interparticle bond force is equal to the weight force. At $R > 1$ cohesive; at $R < 1$ cohesionless (ideally). Typical values of PI plasticity index are shown.

contentious region, one which is not traditionally defined but this is where the very fine primary mineral particles, often very fine quartz, occur; the material for quick-clays. Region D is silt, the region where $R = 1$, where the transition from cohesive to cohesionless occurs, where strange properties are observed, where loess is. Region E is sand, quartz sand by default, where R is very small, where the gravitational force represented by the weight of the particle far outweighs the short range interparticle bond force.

To generalise: particles A and B have electrical charges and are involved in long-range bonding – action at a distance; particles C, D and E do not have electrical charges and are involved in short-range bonding – contact bonds which lose strength on disturbance. Soil systems with charged particles have plasticity – the ability to deform without a significant loss of strength. By and large it is the short range bonded systems which can respond to stress by great losses of strength, and by structural collapse.

3 Quartz sand

Most sand is quartz sand. Since ‘sand’ is an accepted size range definition in most systems of soil classification it is inevitable that other minerals falling within the definable range will be classified as sand – but the ‘de-

fault' sand is quartz sand. There is an large amount of quartz sand in the systems we know as sediments and soils, its very ubiquity has led to its scientific neglect and a widespread failure to appreciate many interesting qualities and properties. There are a few perceptive general studies on sand; Moss [16] is pre-eminent but there are offerings from Siever [17], Welland [18], Pettijohn *et al.* [19], Kuenen [20] and Krinsley & Smalley [21].

The default crustal rock is granite, and it is the weathering and breakdown of granite which delivers sand into the sedimentary system.

There are controls that operate on the nature of sand particles and the majority of these operate within the natal granite. There are two significant events which take place while the granite is forming that have great influence on the eventual sand grains. These are a eutectic like reaction (Figure 2), essentially between feldspar and quartz, which produces a typical eutectic type product of small individual units of quartz and feldspar. This reaction sets the size of the sand particles- this is the important size control, much more important than any post-weathering activity. The quartz particles are formed as high quartz, the less dense variety of quartz, but as the system cools they undergo a displacive change into low quartz, with a higher density (Figure 3). This change occurs within the solid matrix of the granite rock and since the low quartz has a higher density than the high quartz there is an essential mechanical constraint. The quartz unit wishes to contract, some defects are formed and some internal tensile stresses are introduced. The eutectic reaction controls the size range and the high-low transformation introduces the stresses which enable the sand grains to weather efficiently from the decomposing granite [22]. This accounts for the limited size range of quartz sand particles in sediments and soils; the mode size range is around 200-500 μm , the classification size range is usually 60-2000 μm .

4 Quartz silt

There are large amounts of silt in the soil/sediment system [14]. How the silt was made is still being discussed, largely because in loess deposits the amount of silt required is so vast. The other interesting question is: why is silt silt? What are the controls which restrict quartz silt to a size range where the particle mode is around 20-50 μm ?

Quartz silt is controlled by the defects introduced into the quartz crystals at the sand stage [16, 23–25] For convenience these are called 'Moss' defects after A.J.Moss a ma-

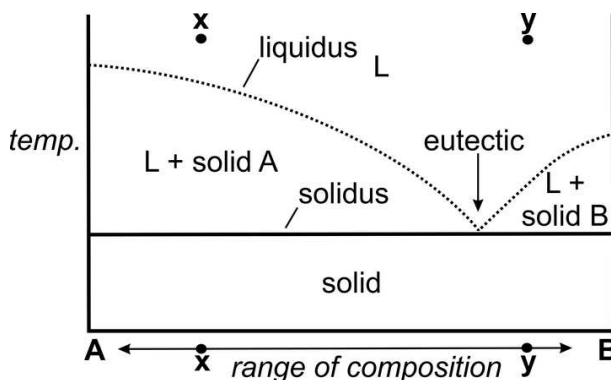


Figure 2: Sand. The essential eutectic phase diagram. The end members here are feldspar(F) and quartz(Q), T is temperature; the dotted line is the position of a model granite. The granite structure will be primary feldspar crystals and a eutectic mix of quartz and feldspar. The quartz particles become sand.

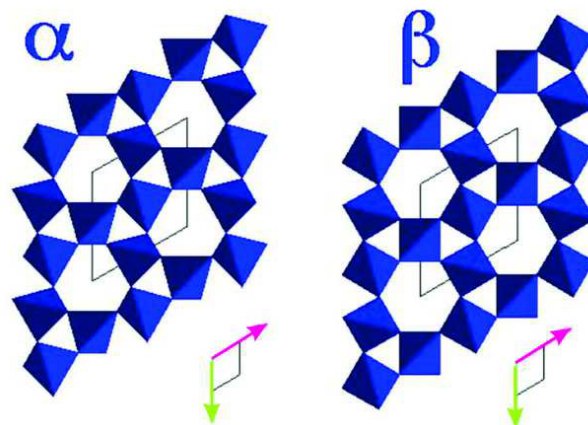


Figure 3: Sand. The high/low transition in quartz. As the temperature falls the low density high quartz is transformed into the more stable high density low quartz. In a granite system this causes widespread tensile stresses to develop. The c/a ratio in quartz changes significantly as the high-low transition proceeds.

for investigator. The distribution of the Moss defects controls quartz silt production and establishes the limits on the size distribution. The initial size control introduced by the eutectic reaction at the sand stage influences the level of stress which is developed at the high-low transition. To generalize – each sand particle in the granite system is about the same size so that as the high-low transition occurs roughly the same amount of stress is developed in each sand grain, and thus the breakage control which is exerted has the effect of producing roughly the same size of silt particles in each instance of silt formation.

Thus there is an obvious mode in the size distribution of quartz silt particles, probably at around 20–50 μm . The 'official' size distribution of silt is 2-60 μm .

5 Clay size; clay mineral

For convenience of classification it was decided that all soil particles less than 2 μm should be called clay (this is the case in most soil classification systems). This size barrier does effectively separate the clay minerals from the primary minerals, but there are exceptions which have caused problems. It would be useful to clearly distinguish between clay-size and clay-mineral. A clay mineral particle has an electrical charge and this determines its special nature and influence on ground properties. The distinction of soil particles into charged and uncharged is fundamental. It essentially establishes the division into cohesive and cohesionless. It is where there is straying across these arbitrary barriers that soil problems can arise.

The possession of electrical charge by clay mineral particles confers on relevant systems the remarkable property of plasticity. In general plasticity is the consequence of long-range bonding. A system dominated by short-range bonds will have a low plasticity. Some values of plasticity index PI are indicated on Figure 1.

6 Bonds

The 'long' and 'short' range bonds were first thoroughly demarcated by Cabrera & Smalley [26] in their study of quick-clays. They needed to describe a system where strength was lost on disturbance, which could account for the behaviour of quick-clays. Quick-clays are very sensitive soils where the undisturbed strength is vastly greater than the remoulded strength [27, 28]. Some confusion was caused in the investigation of the quick-clays by the semantic accident of their being referred to as clays. This tended to focus thought in the direction of clay minerals and clay mineral properties when, in fact, the quick-clays are composed mostly of primary mineral particles. Exceptional geological circumstances deliver very fine primary mineral material which forms a clay size soil but one without clay mineral properties. The quick-clay, by and large, has short range bonds, the sort of bonds that lose strength on disturbance, which nicely explains the high sensitivity. The validity of the short range approach depended heavily on a mineral analysis of a typical quick-clay and this was provided by tests on the St Jean Vianney quick-clay [29]. The St Jean Vianney slide of 1971 was a classic quick-clay event causing much damage and some loss of life. The first application of thermogravimetric analysis to quick-clays showed convincingly that the clay mineral content was low, less than 10%, and that the small amount of clay min-

eral material was of a low-activity nature (point B) on Figure 1. The bulk of the St Jean Vianney material was very fine primary mineral material produced by glacial grinding, at point C on Figure 1. The required glacial connection means that quick-clays have a limited geographical distribution; there is a glacierization requirement so northern Canada (Quebec), parts of Scandinavia, Alaska are typical quick-clay regions.

Quick-clays were reviewed by Maerz & Smalley [28]; for more recent views see L'Heureux *et al.* [30].

7 Short-range bonds

In a sand dune there are interactions between the particles; these are classic short range bonds. The bond/weight ratio R is very small; the weight of the sand grains is a much more significant force than any possible attraction between the sand grains- if the system is dry. In a wet sand system considerable cohesion develops because of meniscus bonds between the particles. But a dry sand system is very close to a cohesionless state.

There are forces between dry quartz particles but they only become apparent when the particle size is greatly reduced, when R is increasing towards 1.0.

The development of cohesion can be demonstrated by determining the flow-stick transition in the granular system [31, 32]. The graphs in Figures 4 & 5 show the change in flow rate for granular materials flowing through an orifice; the experiments were variations on the original Bingham & Wikoff [33] studies on the rheology of granular sys-

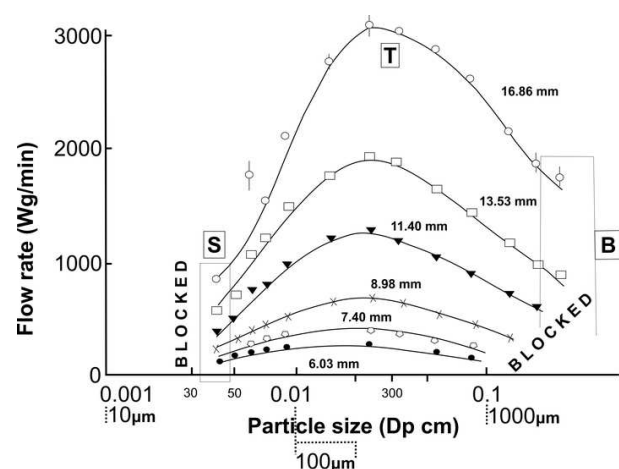


Figure 4: Flow-stick. The Jones-Pilpel [32] results; flow of dry magnesia powder through a variety of orifices. Cohesion becomes dominant at about 50 μm ; cohesion starts to become effective at about 250 μm . The interparticle bonds are classic short range bonds.

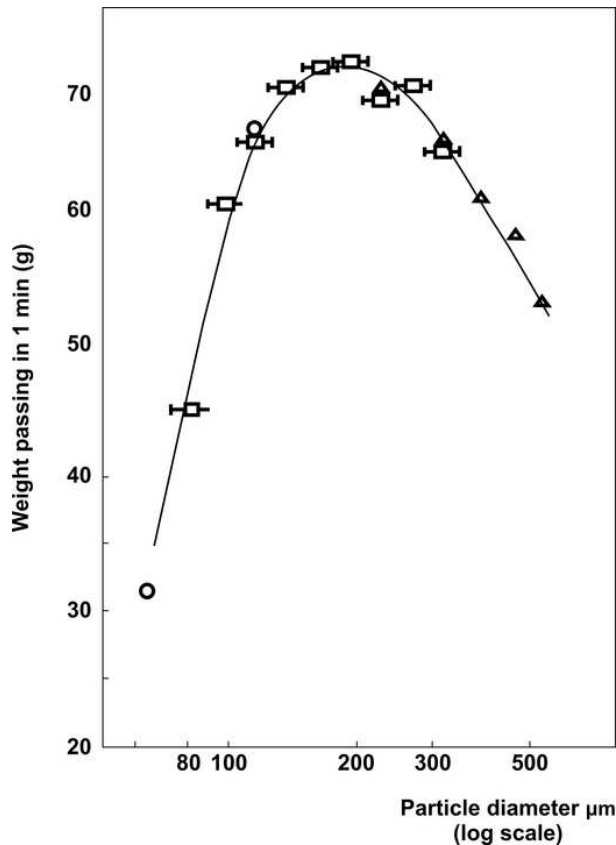


Figure 5: Flow-stick. The flow-stick transition for granular quartz, after Smalley [31]. Dry quartz powder flowing through a 3mm orifice: B is blockage, T is turnover from free-flowing towards cohesive, S is flow failure due to dominance of cohesive forces- at about 50 μm .

tems. The first determination of the flow-stick transition point is shown in Figure 4; here the orifice had a 3mm diameter and the granular material was crushed quartz sand. When the particles are large the orifice is blocked and no flow is possible, point B on Figure 4. As the particle size is reduced flow begins and grows quicker as the particle size is reduced, the smaller grains flow more quickly. The flow rate increases until cohesive forces start to be felt; at point T, at about 150 μm , flow reaches a maximum rate and then decreases as the particle size is further reduced until flow stops at about 50 μm , point F. At this size the flow forces and the stick forces balance and flow stops. This would be at $R = 1$ on the R/size diagram (Figure 1).

These original flow-stick experiments were repeated on a larger scale by Jones & Pilpel [32] using magnesia powder and a variety of orifice diameters (Figure 5). Flow-stick forces equated at about 50 μm as in the original experiments but the enlargement of the orifices showed that the turnover point where cohesive forces began to be apparent was at about 250 μm . At the smaller orifice sizes there

was a distinct 'orifice' effect which affected the turnover point. The Smalley [31] and the Jones & Pilpel [32] results were totally reconcilable and appear to establish 50 μm as a reasonable setting for the $R = 1$ point; nicely in the silt range in Figure 1. (see Castellanos [34] for more, perceptive discussion on this topic).

8 Types of collapse

Figure 6 is a cartoon version of types of collapse; L is loess, where the original soil suffers from hydrocollapse and the collapsed material occupies a smaller volume than the original; collapse as compaction. QC is quick-clay where the failure is a total dispersion of the original material, the solid ground turns into a liquid flowslide. S is sand, a small scale part of the collapsible soil collection, residual material, highly weathered sands in which the structure can collapse when loaded or disturbed. Es is estuary- silty deposits usually in estuary situations; and Er is soil erosion by sand grain impact – classic wind erosion.

The QC and Er events have certain similarities. In each case a soil composed of an open structure of primary mineral particles is disturbed, perhaps by an earthquake or an impacting sand grain, and the rigid short range bonded system disintegrates, the particles are dispersed into a fluid medium which supports them in suspension, in water and in air. The QC failure mechanism was explained by Cabrera & Smalley [26]; the early studies on QCs have been gathered by Maerz & Smalley [28]; the Er erosion event was described and discussed by Jefferson & Smalley [15]. The S and Es events are minor events in the collection of collapsible soil occurrences, for adequate outlines see Terzaghi *et al.* [11].

The most significant form of collapse is loess collapse. This has been discussed to a great extent and over a considerable time (see Rogers *et al.* [35] for review, also Kriger [6], Trofimov [5], Xie *et al.* [9], Milodowski *et al.* [10]).

It has turned out that loess collapse is a complex process, and to provide a proper explanation it is necessary to invoke both long and short range bonds. Milodowski *et al.* [10] have produced a vision of a stepwise process which can explain the formation of bonding in loess ground and subsequent collapse (see also Smalley & Markovic [36]). Soon after the initial deposition of the loess material there is deposition of calcium carbonate needles (calcite and aragonite) at particle contacts. The short range contacts are reinforced by carbonate deposition. The networks of carbonate needles serve to trap clay mineral particles so the nature of the bond region changes again, and the

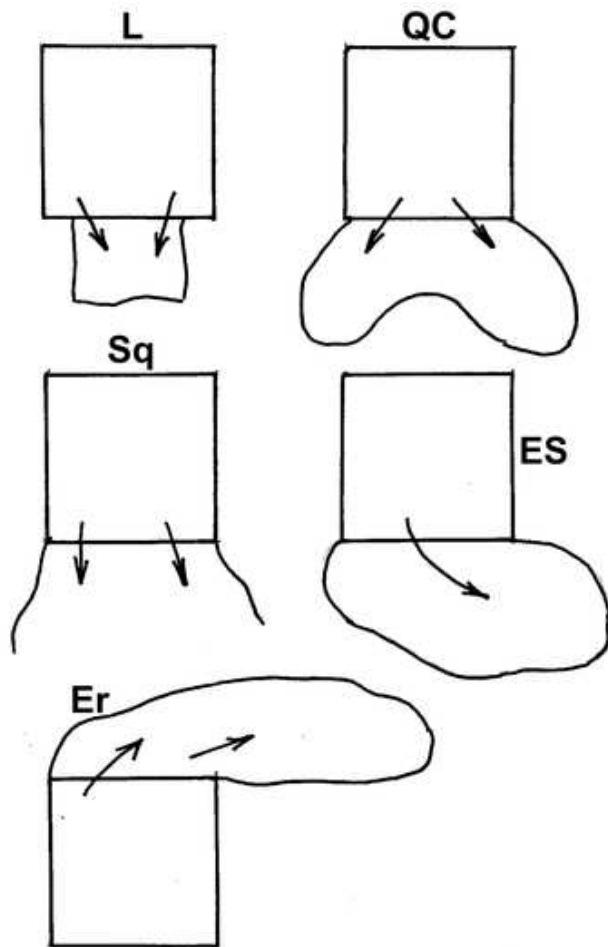


Figure 6: Five types of failure in collapsible soil systems; a very simple cartoon overview. L loess, QC quick-clay, S sand, Est estuarine silts, Er wind erosion of a silty soil. L fails by compaction, the others are disintegrative, dispersive failures.

bonding takes on a long-range aspect. So the essential metastable loess ground is in place but the properties are mediated by the presence of clay mineral material at the interparticle bond points. When the system is loaded and wetted failure develops by the weakening of the long range regions; eventually there is enough initial deformation for the metastable structure to collapse. Once the bonds lose enough strength the system is in effect a simple short range bonded system, which can undergo proper loess collapse, as voids ratio changes from about 1.0 to about 0.6.

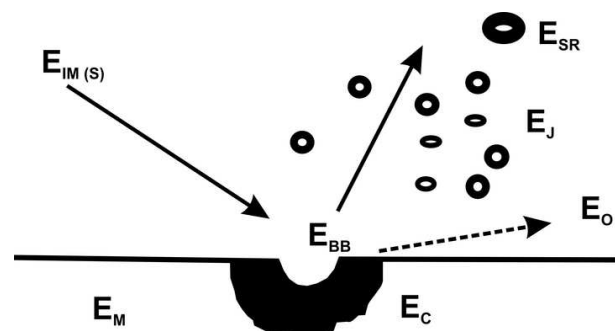


Figure 7: Erosion Er. Factors involved in wind erosion by saltating sand grains impacting into an ideal loess soil. For explanation see text. The particles in a small volume are completely dispersed; all the bonds are broken, it is a total tensile failure (Smalley [12]).

9 Soil erosion as a collapse process (Figure 7)

Many soils, but in particular loess soils, suffer from wind erosion. Saltating sand grains transfer energy from the wind to the ground and the impacting sand grain disrupts a region of ground which is dispersed in suspension. The soil erosion event is essentially a collapsible soil phenomenon, and the failure of a local part of the ground surface can be seen as a tensile failure, the breaking of a certain number of interparticle bonds, plus of course, particle-particle energy transfer which lifts and disperses the eroded particles [15].

The soil collapse = soil erosion event can be portrayed by a simple functional equation:

$$E_{IM}(s) + E_M = E_{BB} + E_J + E_{SR} + E_C + E_O$$

$E_{IM}(s)$ is the impact energy delivered by the moving sand grain; this combines with E_M , the metastable energy (potential energy) of the open structured loess soil system to cause disruption in the impact zone (the collapse region). $E_{IM}(s)$ delivers the trigger energy which makes the metastable stored energy available. The type of soil which suffers from wind erosion is likely to be a soil in which the E_M value is significant.

The impact energy (plus metastable component) is dissipated into breaking interparticle bonds (E_{BB}); injecting eroded particles into the airstream (E_J); carrying the sand particle on its way (E_{SR}) and disturbing and compacting the soil around the impact zone (E_C). It can be seen that E_{BB} and E_J are the important factors and the trade off between these two factors affects the nature of the erosion.

E_{SR} and E_C are minor factors, in the consideration of the impact event, and there may be other minor factors to

be eventually included. A compromise between Ebb and Ej is needed for wind erosion to proceed. If the bonding is too strong a large Ebb requirement makes erosion impossible; if the particles are too large the Ej requirement also inhibits particle movement and soil collapse. This is the compromise which is illustrated in the flow/stick studies.

10 Discussion

Classification and nomenclature have played a role in obscuring the true nature of collapsible soils and the true mechanisms of the collapse process. It needs to be established that the range of particles and particle sizes in the engineering soil universe is not a continuum. Certain definable processes produce certain characteristic products. The soil world is complex and sometimes the modes fail to be distinguished. Lithological processes control the production of quartz sand, because of its abundance it gained a named size range – but it is a material in its own right; not just a size interval. The same applies to quartz silt, lithological processes determine the mode size and again abundance dictates nomenclature. Because the zone C particles are not produced in great numbers or are produced in particular circumstances (*e.g.* desert dust) they have not been named. In the world of dust and loess studies these are called ‘small dust’ and a mode of around $3\mu\text{m}$ is observed [37]. Actually small dust will include some clay mineral material of an inactive nature so its use for type C systems should be done carefully.

Quick-clays are not clays in the sense that few clay minerals are involved. They were called clays originally because of the small particle size, and, of course, size determined nomenclature. Perhaps they should be referred to as very sensitive soils.

11 Conclusions

The classic soil collapse is the hydrocollapse of loess ground under the right conditions of loading and wetting. Also included as collapsing soil systems are the very sensitive soils known as quick-clays, silty estuarine deposits, some types of collapsing sand systems, and soil erosion by wind action. Of the disintegration type of collapse failures the soil erosion is the most significant. The discontinuous nature of soil size distribution needs to be understood, as an aid to understanding collapsing soil problems. The division into active clays, inactive clays, small primary particles (small dust), silt and sand provide a useful set of ini-

tial distinctions. Interparticle bonds can be divided simply into long-range and short range bonds, observed between clay mineral particles and primary mineral particles; it is the short range bonds which have the major role to play in events involving collapsible soils.

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