Loess as a Collapsible Soil: Some Basic Particle Packing Aspects

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"The particles forming detrital sediments assume at deposition a certain mutual relationship, the geometry of which is their primary packing. A packing may be described either by reference to the relative amount of the particles and by its relative emptiness, or in terms of local variations in the amount of particles, or again by a statement of the average number of contacts between a particle and its neighbours."
J. R. L. Allen (1982)

Abstract

Loess is the most important collapsible soil; possibly the only engineering soil in which real collapse occurs. A real collapse involves a diminution in volume - it would be an open metastable packing being reduced to a more closely packed, more stable structure. Metastability is at the heart of the collapsible soils problem. To envisage and to model the collapse process in a metastable medium, knowledge is required about the nature and shape of the particles, the types of packings they assume (real and ideal), and the nature of the collapse process - a packing transition upon a change to the effective stress in a media of double porosity. Particle packing science has made little progress in geoscience discipline - since the initial packing paradigms set by Graton and Fraser (1935) - nevertheless is relatively well-established in the soft matter physics discipline. The collapse process can be represented by mathematical modelling of packing – including the Monte Carlo simulations - but relating representation to process remains difficult. This paper revisits the problem of sudden packing transition from a micro-physico-mechanical viewpoint (i.e. collapse imetan terms of structure-based effective stress). This cross-disciplinary approach helps in generalization on collapsible soils to be made that suggests loess is the only truly collapsible soil, because it is only loess which is so totally influenced by the packing essence of the formation process.

Key words: Loess; Structures; Packing transitions; Shapes.

1. Introduction

In the world of engineering geology and geotechnical engineering collapsible soils still present problems. These are usually metastable soils which can collapse when loaded and/or wetted. The original soil structure collapses to form a more stable soil structure. The initial packing of soil particles which produced the original structure is disturbed and a new, more stable packing is developed. Thus a study of soil collapse might be seen as a study of packings and the changes in the disposition of the particles comprising the packings.

Terzaghi et al. (1996) listed four types of natural collapsing soils; they were essentially: (1) loess and similar ground materials; (2) very sensitive soils, the so-called quick-clays; (3) residual sands with very weathered structures; and (4) submarine delta deposits of silty material. Of these the loess soils were seen as by far the most widespread and important; the other three are basically smaller more local deposits. The extent of collapsible soil systems has been shown in the map by Kriger (1986) - page 42 - which emphasises the importance of loess deposits. The world of collapsing soils research was surveyed by Derbyshire et al. (1995) and the status of collapsing soil studies has been reviewed by Rogers (1995) and Xie et al. (2015). There is an extensive literature on the testing of collapsible soils and this has recently been reviewed by Okwedadi et al. (2015). There is a very extensive literature on the development of collapsibility, much of this is in Russian and has been reviewed by Trofimov (1999-2001). See, in particular, important studies by Kriger (1986), Minervin (1993), Krutov (1974) and early work by Denisov (1953). The Soviet Union covered vast areas of collapsing loess ground and special institutes to study this problem were set up in various regions, in particular in Tashkent and Kyiv. The problem of the cause of collapsibility has proved remarkably resistant but recently some significant advances have been made, see, in particular, Milodowski et al. (2015) and Assadi-Langroudi and Jefferson (2013), see also Derbyshire et al. (1994), Smalley and Markovic (2014), and Xie et al. (2015).

Loess is the most important ground material in a collapsing soils context and the current studies are built around an appreciation of the nature and properties of loess; initially loess deposits as assemblages of loess material i.e. predominantly 10-50μm sub-angular coarse well-sorted quartz silt (Smalley et al., 2011), which then reworks to loess ground as a packing of loess particles i.e. clusters of silt bonded together directly and indirectly with clay, sesquioxides and carbonates. Loess is a collapsing/collapsible, metastable, unsaturated, macroporous with double porosity, silty soil/ground. It should respond to study as a packing; certain aspects should be able to be modelled via certain packing aspects and properties.

The science of particle packing, centred around sits the collapse mechanism, has made little progress in geoscience discipline - since the seminal work of Graton and Fraser (1935) - but is relatively well-established in the soft matter physics discipline. The difference is profound in part because the physics literature is mostly concerned with homogeneous laboratory-produced physical packings, and also because in this laboratory setting focus has settled on the various processes by which the packings are produced, and then examined/disturbed. In the granular matter literature the two most influential early works are those of Reynolds (1885), who introduced the notion of dilatancy, and Bernal (1959), who popularized the notions of random close packing (RCP) and random loose packing (RLP). Basically, it is found that granular matter exists with packing fraction between roughly 0.5 and 0.74. Arbitrarily low densities are mathematically possible, but the study of granular matter seeks to understand so-called `random' packings produced by simple bulk means, and it does not seem possible to get much below 0.5 (RLP) by such processes. Reynolds already noted that, when sheared, random packings collapse if their initial density is low and expand if it is high. The dividing point has been found, relatively recently, to be around 0.6 (Bratberg, 2003).

The aim of this brief (and rather subjective) cross-disciplinary review is to revisit the problem of sudden transition of packing from micro-physico-mechanical viewpoint (i.e. collapse in terms of structure-based effective stress), to complement the review of particle packing by Rogers et al. (1994a) and the studies on collapsible soils of Derbyshire et al. (1995) and the assemblage of material on hydroconsolidation in loess ground by Rogers et al. (1994b), and to propose some tentative generalizations. It might also serve as a link between speculative and imaginative packing studies and real observations on collapsing ground which now, at last, seem to be revealing the exact nature of the collapse mechanism see Assadi-Langroudi and Jefferson (2016), Milodowski et al. (2015), Smalley and Markovic (2014), and Xie et al. (2015).

2. Graton and Fraser Developed

Fundamental studies on particle packing commenced by Smith et al. (1929) who preceded Graton and Fraser (1935) and did, in fact, influence them. The study of particle packings in the geosciences begins with Graton and Fraser (1935). This was the seminal paper which defined some basic structures and introduced some useful terminology. It was not a particularly systematic treatment; the systematic approach was provided by Smalley (1971) who gave some rigorous definitions and set out the limits for the definable ‘simple’ packings. Pettijohn (1975) - Page 72 - in his classic study of sedimentary rocks has a section on particle packing and this is very much based on the Graton and Fraser (1935) work (see Fig.1). Pettijohn bases his entire section on this paper. He wrote that “The study of packing requires a closer definition of packing, the development of a suitable measure of ‘closeness’ of packing, and an assessment of packing in the post-depositional period”. This is still the aim of packing studies, it certainly informs the material in this paper.

Figure 1.

The definitive reviews of particle packing in the earth sciences are those by Allen (1982) - p.137-177 - and Rogers et al. (1994a). Allen tackles the problems of description and nomenclature and concludes that the best descriptive system to apply to Graton and Fraser type packings is that defined by Smalley (1971). The Smalley (1971) system of ‘simple’ packings was designed to advance the Graton and Fraser approach and make it a little more rigorous. The Graton and Fraser packings are ‘simple’ packings; this means that they are composed of equal spherical particles which are arranged in regular packings such that every sphere is equivalent in terms of number and orientation of contacts. The number of contacts (on every sphere) gives the co-ordination number CN. Every packing has an associated Voronoi polyhedron VP which Rogers et al. (1994a) defined as the region formed by planes bisecting the lines linking the centre of the reference sphere to the centres of the nearest particles. In some ways a complex concept, reflecting the fundamental problem of representation - the problem at the heart of all particle packing problems. Every packing in the simple system is defined by a unit cell, essentially in the same way that crystals are defined, by a small representative part of the packing- the smallest part of the packing which truly defines the packing. The packings in Fig.1 are Graton and Fraser versions of unit cells of chosen simple packings. The unit cells can be described and defined by defining the type of cell side and recording the number of particular sides. The system is simple but slightly intricate, but Allen found it the best available; it allows the possible packings to be derived and described.

All (most) textbooks of soil mechanics describe two simple Graton and Fraser packings. The defining process depends on the unit cell; the sides of the unit cell are defined and, of course, given the constraints of packing spheres in three dimensions only three side definitions are required. The A side is a square side, the C side is a rhombohedral side, and the B side is in-between these two limiting cases. The three well-established varieties of non-overlapping, mono-sized sphere packings in 3D Euclidean spaces are the simple cubic (SC), the body-centred cubic (BCC) and the closely packed rhombohedral (CCP), also known as face-centred (FC). The cubic packing has six A faces and can be designated the 600 packing (six A faces, no B faces, no C faces; case 1 in Fig.1). The rhombohedral packing has two A faces and four C faces, its symbol is 204 (case 6 in Fig.1). Between 600 and 204 lies the whole world of simple packings; these define the Graton and Fraser approach to particle packing, designed for the study of sandstone reservoirs in petroleum geology but carried over into all aspects of the earth sciences.

3. The 600 and Body-Centred Cubic BCC Packings

A starting point for studies of regular packings, and the least dense of the simple packings (i.e. loosest stable), the 600 packing with a void ratio (e) of 0.91 (CN=6, n=0.48) models a classic loessic collapsing soil in terms of the packing density and porosity (Santamarina and Cho, 2004). Unit diameter spheres at co-ordinates 000, 001, 010, 100, 110, 101, 011, and 111 give the unit cell of the 600 packing (Fig.2). In co-ordinate terms this is the simplest cell, i.e. the simplest cell described by values of 0 and 1. The general 060 packing was the least rigorously defined of all the simple packings: six B faces with defining angles between 60˚and 90˚; it did not appear very interesting and since the derivation of packings in the simple system depended on moving A or C faces, structures with B faces were neglected. Except perhaps 024, the special case that Graton and Fraser called tetragonal-sphenoidal (case 5 in Fig.1); definitely is one of the most interesting of the simple packings. This is the one case from the nine defined packings (which covers a void ratio range from 0.91 to 0.35 and comprise 042, 402, 600, 240, 024, 222, 204, 060, 204/006 – see Smalley (1971)), where the VP has more faces than the CN, and where a B face was actually defined. The acute angles in the 024 cell are 60˚, 60˚and 75˚21'. Tsutsumi (1973) suggested that the 75˚21' angle was first listed by Smalley (1971) but in fact it was known to Morrow and Graves (1969). So 024 has two B faces, but they are locked into position by four C faces and thus the angles are defined and fixed.

Figure 2

The body-centred cubic structure is an apparently simple but actually remarkably complex packing (Fig.3). It has direct geotechnical interest because Molenkamp and Nazemi (2003) have used it as a basis for their micromechanical studies of unsaturated soils. Molenkamp and Nazemi (2003) adopted a 'homogenisation' approach to upscale inter-particle contact forces and contact-level displacements within the skeleton of a BCC packing - formed due to pore suction and surface tension in an unsaturated granular soil - to stresses and strains, respectively (see similar attempts by Oda and Iwashita, 1999, Cho and Santamarina, 2001, Chateau et al. 2002 and Assadi-Langroudi, 2014). They idealised the soil structure to a pyramidal packing in a periodic cell (Fig.4). The real problem with BCC, from the particle packing point of view, is that it does not fit into the 'simple' system of sphere packings; it is not one of the nine fundamental simple packings. It is very simple to produce a unit cell which contains two particles, as Molenkamp and Nazemi (2003) have done; but it is difficult to produce a unit cell which only contains one particle; Tsutsumi (1973) accomplished this difficult task.

Figure 3
Figure 4

4. Packing Formation: Genesis

The structures in particle packing would have been built with spherical particles, but the real world is occupied by particles with shapes far from 'perfect' spherical. Graton and Fraser could work nicely with equal spheres because they were mostly concerned with sand systems as reservoirs and an ideal sand could be considered as a collection of equal spherical quartz particles (also some aerosols like marine sulphate). The mode of formation of quartz sand (Smalley 1966a) tends to favour the formation of equi-axed particles with a very restricted size range. But loess is different. Krinsley and Smalley (1973) suggested that small sedimentary quartz particles should be distinctly blade shaped and Rogers and Smalley (1993) applied a simple Monte Carlo approach which indicated that the theoretical mode particle would, in fact, be a very distinctive blade with a side ratio of 8:5:2- this is a very flat particle (Fig.5). Earlier studies, using probability methods, had indicated that blade shapes should be favoured (Smalley 1966b) and the more rigorous Rogers-Smalley approach appears to confirm this. For more discussion on this topic see Domokos et al. (2010) and Howarth (2010, 2011). Assadi-Langroudi et al. (2014) simulated particle size reduction from sand to silt through a suite of coupled controlled grinding - optical and light transmission microscopy experiments. They suggested that quartz grain shape is a function of fragmentation force, which is controlled by particles' post-solidification fracturing-healing history and pronounced diameter. They brought an example of immature sub-rounded 50-55µm silt (5-6Ø), which – in a natural quartz assembly - enjoys a great number of contact points and hence confinement when fragmentation stress levels are not high enough to split the particles. This relevance of particle shape and size with silt origin was also reported in a set of SEM images of peridesert loess demonstrating a well- to sub-rounded shape for 4-6Ø sized silt grains (Karimi et al. 2009). Sub-angular silts from glacial abrasion (Moss, 1966, Moss and Green, 1975, Rogers and Smalley, 1993, Wright, 1995, Jefferson et al. 1997), continue to reduce in size on post-depositional modification and alter in shape to slightly sub-rounded, the degree to which relies on dominant post-depositional modifying system - fluvial or secondary aeolian (Assadi-Langroudi and Jefferson, 2013).

Figure 5

Loess has an open metastable packing structure because the initial sediment is formed by aeolian deposition of silt-sized particles. Some attempts have been made to model the airfall nature of loess ground and some interesting results have been obtained (Dibben et al. 1998a and b, Assallay et al. 1997) - see Figs. 6 - 9.

Figure 6
Figure 7
Figure 8
Figure 9

Two promising approaches can be identified: direct sedimentation of ideal loess material into an oedometer testing ring- for subsequent consolidation testing, and production of an ideal packing picture by a simple Monte Carlo particle dropping approach (Assallay et al. 1997). Particle dropping to form ideal packings was used to form packing of equal spheres in one-dimension (Smalley 1962), and it proved possible to adapt this very basic approach to the formation of two-dimensional structures that could model loess deposits. Dibben et al. (1998b) have produced the most developed view of the particle-dropping structure and have managed to adapt it to produce a simple view of collapse. The behaviour of the particles as they form the packing has been simplified. The metastable computer simulation considers the contact point of two rectangular particles in which the overlap is of variable widths. A pre-determined value of critical bonding is specified. If two particles overlap by more than the value of critical bonding then attachment will occur, cohesion will develop, otherwise the upper particle will move sideways and fall. Figure 13 is an example of the packing structure created. By choosing a suitable value of critical bonding void ratios of around 1.0 can be created. This is similar to loess in a metastable form where void ratios of between 0.9 and 1.1 are typically found (the loosest mono-dispersed packing of spheres adopt a theoretical maximum void ratio of 0.89 - see Dijkstra, 2001 - following an immediate collapse of the very open structure of initial aeolain deposit with e=2 - see Smalley et al., 2013). The hydrocollapsed structure forms when the bonding and cohesion mechanisms disintegrate on wetting and the system responds to collapse-causing stresses. As with the metastable structure in Fig.6 the system is a complex one and to model the collapse accurately is difficult. The collapse can be simulated in a simplified form in the same way as the metastable structure. If the critical bonding number is increased gradually form the metastable value, then the results show how the void ratio of the structure decreases until the dense collapsed structure is achieved as in Fig.7, where e is about 0.6. For more discussion on the particle dropping technique to construct packings see Lebovka et al. (2014).

5. Packing Transition: Collapse

5.1 Graton and Fraser Approach to Transition

Collapse is a transition; to understand collapse it is necessary to understand the nature of the transition from open soil structure to denser, collapsed structure. The transition is described in every oedometer test on a collapsible soil - it would be useful if the transition could be described at the single particle level, and this might be useful in establishing the basic mechanism of collapse.

A collapse transition can be illustrated by plotting packing density PD against void ratio e. Because of the relatively strange way in which *e* is calculated in soil mechanics this yields a curve. The curve has no dynamic significance but it does allow the various packings to be demarcated and the collapse route shown. It shows the relatively short route between 600 and 402, which essentially encompasses typical loess collapse or hydroconsolidation - and points to the large collapse potential left in a loess system after the initial classic ‘natural’ collapse.

The best diagrammatic version of collapse was produced by Morrow and Graves (1969) - Figs.10 and 11 - and their diagrams can be augmented with simple packing data to show possible transition routes. The work of Morrow and Graves was extremely elegant and was discussed at some length by Dijkstra et al. (1994) - Fig.12 - but by and large, like so much packing work, it has not been fully appreciated. They defined the cell shapes via dihedral angles and this is perhaps not so convenient as defining cell side shapes.

Figure 10

Figure 11

Figure 12

Kezdi (1979) studied the collapse of particle packings, but from an entirely different viewpoint. He was concerned with the construction of earth roads and he required efficient compaction of a granular highway material to produce maximum strength and durability. He produced graphs and equations to illustrate structure collapse from 600 to 402 and from 600 to 204 (Figs. 13 and 14). Not so elaborate as the Morrow-Graves curves but aiming for the same end. The packing process curves and diagrams do serve to indicate that perhaps loess collapse is a sort of intermediate process. It represents a position of comfortable collapse; the 402 position, the void ratio of about e = 0.6. A collapse position that is relatively easy to achieve with wetting and modest stress. Possibly the collapse from 402 to 204 needs to be more closely studied. It has been proposed, in a study of Venice and related collapsing soil problems, that maybe the continued slow subsidence of Venice is due to further loess collapse (Jefferson et al. 1998). Loess material from the Po basin was the underlying material for the construction of Venice but it was of course saturated and existed in a collapsed condition. Time and loadings and extraction of ground water have allowed the second-stage collapse to occur. It is more difficult to achieve than the initial collapse but under special conditions it can occur (Jefferson et al. 1998). Another situation where secondary collapse (402 to 204) might be considered is the failure of the Teton Dam. This was a large embankment dam, constructed largely of loess, which failed catastrophically. There was a major core failure. The core had been constructed of loess and energetic compaction methods had been applied; a particularly thorough treatment with sheeps-foot rollers was carried out. But the core failed; the compacted material still contained dangerous porosities (Smalley and Dijkstra 1991).

Figure 13

Figure 14

5.2 Structure-based Effective Stress Approach to Transition

A coupling between the mean normal effective stresses and shear stresses is fundamental to the onset of dilation or contraction, as the resistance to shear is proportional to the mean normal effective stress. In porous mediums with multiple fluids however, the effective stress is related to soil's packing state. Taking this relevance into account and to simulate the collapse, Khosravani (2014) and Assadi-Langroudi (2014) modelled cemented loess soil as a three-phase discontinuous medium composed of sub-rounded mono-dispersed R-diameter silt particles bridged with water menisci and bonding minerals, surrounding macro-pore spaces filled with liquid and/or gas. They adopted a homogenization framework to formulate the stress as a function of local micro-scale variables in an attempt to derive a tensorial effective stress for unsaturated collapsing soils. Taking the loess system as a representative elementary volume (REV) composed of distinct particles in interaction - via a suite of traction forces ($t_i(x)$) – the average inter-particle stress can be written as:

$$\bar{\sigma}_{ij} = \frac{1}{V}\int \sigma_{ij} dV = \frac{1}{V}\left(\int \sigma_{ij} dV^s + \int \sigma_{ij} dV^w + \int \sigma_{ij} dV^a\right) \qquad (Eq.1)$$

for $V^\zeta, \zeta = s, w, a$ indicating the volume of solids, water and air. The first and second terms refer to the partial pressures associated with solids and water, respectively, and V represents the REV's volume:

$$V = V^s \cup V^w \cup V^a \qquad (Eq.2)$$

Within the framework of Cauchy's stress in closed domains and on expanding the water phase (in absence of the stress implications of inter-particle liquid bridge), equation 2 becomes:

$$\bar{\sigma}_{ij} = \left\{\frac{1}{V}\sum_{N^p}\int x_i t_j d\Gamma^p + \frac{1}{V}\sum_{N^p}\left(\int x_i b_j dV^p\right)\right\} + \frac{V^w}{V}u_w\delta_{ij} + \frac{V^a}{V}u_a\delta_{ij} \qquad (Eq.3)$$

whilst

$$x_i = x_i^c + R_i \qquad (Eq.4)$$

where hydrostatic pressures of water and air phases are represented, respectively, with $u_w\delta_{ij}$ and $u_a\delta_{ij}$, and δ_{ij} is the Kronecker delta. N^p is the total number of contact points (relying on the packing type in the Euclidean space), R_i is the location vector of the traction forces with respect to particle centroid (see Fig. 15), x_i indicates the position vector of traction (t_i) and body forces (b_j), Γ is the REV's boundary and x_i^c represets the position vector of particle's centroid.

Figure 15

In an open packing and upon formation of water menisci, particles are bridged through the contractile skin (Γ^m). The capillary forces form due to the gradient between the air and water hydrostatic forces (air pressure on dry proportion of particles surface Γ_d^p and wet proportion of particle's surface Γ_w^p), as well as the pressure difference between air and water phases at the two sides of the water menisci. Khosravani (2014) proposed an arithmetic formulation to incorporate the capillary effect into the average inter-particle stress equation. More recently, Assadi-Langroudi and Jefferson (2016) proposed a geometric solution to the Laplace equation and wrote the f_{cap} (capillary contact-level force) as a function of volume of the liquid bridge, contact angle between for the contractile skin, external and internal radius of the principal curvature, distance between particles, tensile strength, and the mean particle radius. Khosravani (2014) and Assadi-Langroudi (2014) both agreed to take the term in bracket in Eq.3 a representative of the inter-particle forces acting at contact points. The latter is an equivalent of the effective stress, σ'_{ij}, that applies to the solid skeleton in a soil. Khosravani (2014) then wrote the tensorial form of the effective stress equation as a function of χ_{ij} and B_{ij} effective stress parameters, and expanded the formulation for the benchmark REV. She assumed that the continuity of pore network is a valid simplification regardless of soil's structure and its dependence on the matric suction. For cemented BCC regular packings with varied volume (as a function of volumetric change in cementing agents on wetting-drying paths), Assadi-Langroudi (2014) built on the double-porosity theorem - double porositiness arises due to the post-depositional genesis of mineral buttress units at particle contacts in the light of regionally higher degrees of matric suction at contact points and upon seasonal evaporation - to develop a radically improved form of the tensorial effective stress equation. Despite similarities with the formulations offered in Khosravani (2014), Assadi-Langroudi (2014) suggested that the B_{ij} parameter is inversely proportional to χ_{ij} (the Bishop property - also see Alonso et al. 2010) and is a direct function of σ_{ij}^{d}, a periodic hydro-dynamic boundary level stress acting on buttress units during the flow of liquid between micro- and macro-pore phases.

Through a series of suction-controlled free oedometer tests on an artificially synthesised calcareous clayey loess ($CaCO_3$:20 wt%, silt: 70 wt% - 2R=10~20μm, Kaolin 10 wt%, e_0=1.4) - representing a BCC packing upon Aeolian lab-scale simulated deposition - Assadi-Langroudi (2014) used the proposed homogenisation framework to approximate the variation of stress state with wetting time and degree of saturation. In Fig. 16-a, $\left(\bar{\sigma}_{ij} - u_a\delta_{ij}\right) + \left(1 - \chi_{ij}\right)\sigma_{ij}^{d}$ represents the balanced summation of skeletal, buoyant, hydrostatic, body weight and hydro-dynamic forces at particle level. $\chi_{ij}(u_a - u_w)$ is taken as the capillary stress tensor, incorporated within is the contribution of matric suction and surface tension, $\bar{\sigma}_{ij}$ is the total stress, and u_a is the air pressure. In Fig. 16-b, f_{cap} is the capillary traction force which enhances the effective stress (and hence strength) and appear in tensorial form of $\chi_{ij}(u_a - u_w)$. Recognition that the χ_{ij} parameter has a marked control on the effective stress is vital to understanding the collapse mechanism (as it pertains in the packing science) in respect of the transition from BCC to Face Centred Packing FCP. The χ_{ij} parameter (also known as the effective degree of saturated) is itself a function of matric suction. Within the framework of the double porosity concept and for a REV consisting of an assembly of rigid particles interacting through buttress binding unit, Assadi-Langroudi (2014) showed that the water influx into loess first affects the buttress inter-particle units. On full saturation of bonds, water passes through the buttress bond units into the inter-particle macro-pore space. When matric suction drops below the air entry value, air pockets relocate from macro-pores into micro-pores within buttress units. In fact, macro-pore air commences to dissolve in micro-pore water (clay buttress units) prior to the water influx into macro-pore void spaces. Air bubbles form in micro-pore space as the degree of saturation of micro pores fall to a residual value. This eventually leads to the collapse of buttress units into macro-pore spaces.

Figure 16-a

Figure 16-b

6. Discussion

Packing studies have made remarkably little progress since the time of Graton and Fraser. There is always a nod to packing concepts in textbooks of soil mechanics and engineering geology but it has not proved possible to incorporate packing discussions into the mainstream. It may be that loess ground is the only engineering soil system in which it makes sense to invoke a packing parameter when engineering properties are considered. This would be because the formation of loess ground involves a uniquely ‘packing-based’ process in which constituent particles are delivered to form a special packing structure. It would be an exaggeration but it is tempting to state that all other soils are essentially more complex, have more complex mineralogies and more complicated formation processes. Within the sequence of events involved in the formation of loess deposit, the aeolian deposition is so totally dominant as a property determinant that the packing aspect dominates the entire soil system. This does not happen in other soil systems - hence the packing studies have been neglected.

The collapse from e = 1.0 to e = 0.6 can represent the extent of collapse in a classically collapsing soil such as loess. Particle movement is not extreme as indicated in the Morrow-Graves collapse curves where a move from 600 to 402 encompasses relevant collapse. In simple packings this can be a simple shear deformation, as Kezdi effectively demonstrated.

We have reached a situation where the need to model and study collapse is perhaps less pressing than it was. Advances in electron microscopy (as demonstrated by Milodowski et al. 2015, Xie et al. 2015 and Assadi-Langroudi and Jefferson 2013) have enabled the real soil system to be examined. The interest in soil collapse should perhaps shift from the nature of the packing to the nature of the inter-particle bond. It is the packing that provides metastability, and thus it must remain of some interest, but it is the bonding which controls collapsibility. A rigid open structure can be as strong as a rigid compact structure, but both can vary in interesting ways if there are changes in the bonding systems. Assadi-Langroudi and Jefferson (2016) measured - for the first time – a suite of particle level forces on the dry-to-wet stress state surface for an artificial collapsing calcareous clayey Aeolian loess specimen. Their findings lend evidence to the double porosity concept and led to a new form of the principle of effective stress for unsaturated collapsing soils in which shear strength is a function of water retention, which is a function of hydrodynamic stresses, dominantly influenced by packing.

In the study of packings there is the transition from regular to random to be negotiated. An attempt was made to describe a random packing in the geoscience discipline by using a radial distribution function (Smalley 1964) but this did not lead to any real progress. Nolan and Kavanagh (1992) produced more interesting results- which can be applied to soil collapse situations, see Dijkstra et al. (1995).

It may be that now that there is some understanding of the ‘natural’ collapse of loess ground, that some attention be focused on problems related to further consolidation and compaction. The focus on 600 to 402 should perhaps now shift to 402 to 204. Oda (1972) made a careful study of particle packing with a special emphasis on grain orientation. He invoked some fundamental studies by Smith et al. (1929) who proposed defining packing as a combination of the 600 and 204 packings; they offered an equation:

$$CN = 26.4858 - \frac{10.7262}{PD} \qquad (Eq.5)$$

This has been called the SFB equation (after Smith, Foote and Busang 1929), it was an early attempt to describe the actual nature of ideal packings. Description is a large problem, and a laudable aim. Oda (1972) - see Page 17 - was eloquent on this topic: “ .. in order to realize the mechanical properties of granular materials, one must first study in detail morphological and physical properties of granular particles and their configuration relations” (a point emphasized by Farouki and Winterkorn 1964). It might be possible to offer some generalizations and connectivities. Alfred North Whitehead made some relevant observations on generalizations: “Too large a generalisation leads to mere barrenness. It is the large generalisation, limited by a happy particularity, which is the fruitful conception.” The happy particularity that we move towards might be the recognition that loess is the only real collapsing soil; there are fringe alternatives but these are small and local. Loess is the particular collapsible soil because it is the only one in which the mode of formation is so packing-related. The aeolian particle deposition produces a metastable packing, and this is the basis of all packing studies. Hence the relative neglect of packing studies; hence the large focus on packing studies in the Soviet Union. Loess relates to packing, which relates to collapsibility.

7. Conclusions

Early particle packing models - Graton and Fraser, 1935 and Smalley, 1971 – and the more recent developments in experimental micro-mechanics – Santamarina, 2013, Khosravani, 2014 and Assadi-Langroudi and Jefferson, 2016 - have provided unique insight into the formation and transition of packing state in collapsible soils, most widespread important of which is loess. The original Graton and Fraser (1935) approach to particle packing can be improved. The rigorous approach to the 'simple' packings produces nine definable packings which cover a void ratio range from 0.91 to 0.35.
Collapse usually reduces the void ratio from about 1.0 to about 0.6 (roughly 600 to 402). This can be modelled in two-dimensions using a simple Monte Carlo technique to produce the initial packing, the same reduction in void ratio is observed. Collapse produces a more stable system but a considerable pore structure remains; loess material has the potential to form relatively unstable deposits even when remoulded. The great lurch towards stability represented by classic hydroconsolidation represents the great increase in entropy in loess ground but problems remain. The entropy in granular systems can be further reduced (Morgenstern 1963). Further compaction may be possible/desirable (Kezdi 1979), and should be investigated.
In the loess world there is some impact of packing considerations on to the 'proportionality' discussion. The dominant causative factor in loess deposit formation is the aeolian sedimentation of the silt particles, which forms the open packing; but there is a subsequent event - a 'loessification' type event in which the particle contacts are modified and collapsibility is enhanced. The proportionality discussion concerns the relative importance of the two events; which event controls the collapsible nature of loess and therefore which event is most critical in a geotechnical sense? Actually the packing factor is critical; this produces the initial open packing - which can lead to eventual collapse.

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Figure captions

1. Packings by Graton and Fraser (1935 p.796). These are unit cells from the seminal paper as reproduced by Pettijohn (1975 p.74). Four definable packings are shown: Case 1 is the ‘cubic’ packing, 600 in ‘simple’ notation; Case 6 is ‘rhombohedral’ 006 packing; Cases 2 and 4 are the same- 402; Case 3 is 204- essentially the same as Case 6; Case 5 is 024.

2. The 600 cubic packing opened out. The centre points of the unit cell defining spheres are indicated.

3. The body-centred cubic packing; the unit cell as described by Tsutsumi (1973); does not fall within the definition of a ‘simple’ packing; contains one sphere.

4. The body-centred cubic packing as deployed by Molenkamp and Nazemi (2003). This forms a basis for their studies on the interaction between their BCC packings and pore water; contains two spheres.

5. The shape of loess particles; the 8:5:2 particle as calculated by Rogers and Smalley (1993). The Monte Carlo method suggests a very flat particle with particle side ratios 8:5:2; this is a Zingg class 3 particle (see Smalley 1966b for Zingg definitions).

6. The Dibben random structure, formed by random particle dropping of 4:1 particles, where 4:1 represents the side view of the modal 8:5:2 particles of Rogers and Smalley (1993).

7. A variant of the Dibben et al. (1998b) structure using elliptical particles.

8. An ideal Dibben structure before collapse (after Dibben et al. 1998b); void ratio e is 0.996.

9. The Dibben structure after collapse (Dibben et al. 1998b) in which the void ratio has reduced to 0.575. The pore pattern is similar to that in Fig.14 but the pore size is reduced. Note that considerable porosity remains; further consolidation might be possible.

10. The Morrow and Graves (1969) transitions from 600 to 006; this is essentially the original Morrow and Graves diagram, as reproduced by Dijkstra et al. (1995).

11. The Dijkstra et al. (1995) modification of the Morrow and Graves diagram to indicate the positions of simple packings and the routes of critical transformations. Note two stages of compaction: 600 to 402, 402 to 204/006.

12. Representation of loess collapse (after Dijkstra et al. 1995). Within the boundaries of the random packing system, based on Nolan and Kavanagh (1992), a conjectural route for loess collapse is indicated.

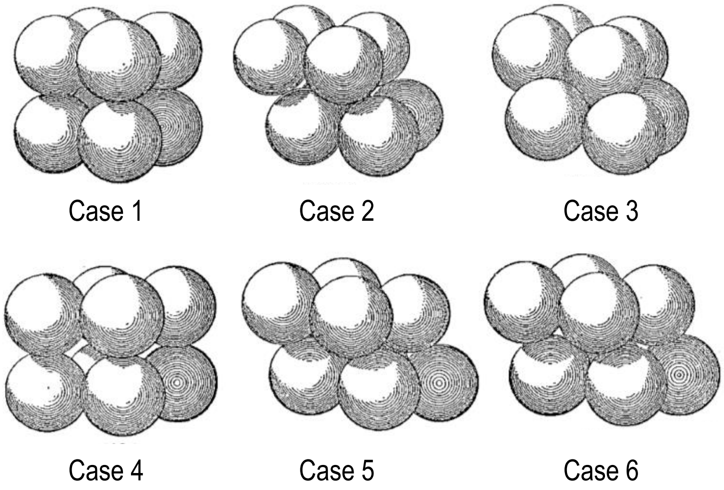
13. The Kezdi transition 600 to 402; this is the loess collapse process described by a simple equation. This shows 'natural' consolidation.

14. The Kezdi transition 600 to 204; the totality of collapse within the simple sphere packing system, a desirable situation in the construction of earth roads. Consolidation beyond the 'natural' point.

15. Assembly of rigid mono-dispersed spherical particles (Representative Elementary Volume REV) of Radius R interacting through buttress units / asperity contacts with relatively smaller dimension i.e. non-conformal contact conditions

16. (a) variation of total stress ($(\bar{\sigma}_{ij} - u_a\delta_{ij}) + (1 - \chi_{ij})\sigma_{ij}^d$ in 8E+06 scale) with degree of saturation (S_r) on timed wetting (t); (b) variation of capillary stress at particle level ($f_{cap} \equiv \chi_{ij}(u_a - u_w)$ in 8E+06 scale) with degree of saturation (S_r) on timed wetting (t)

Figures



Case 1 Case 2 Case 3

Case 4 Case 5 Case 6

Figure 1.

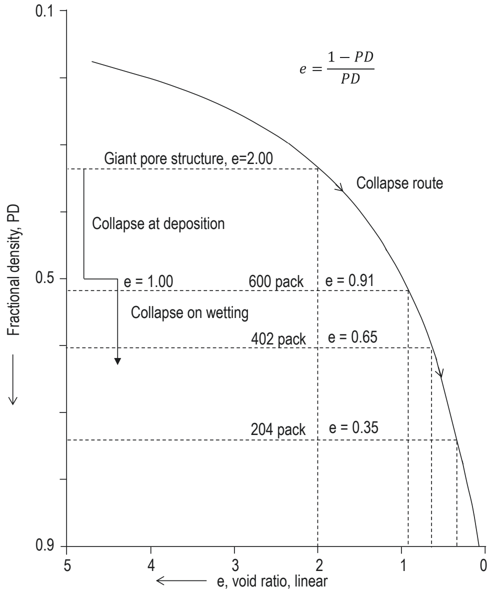


Figure 2

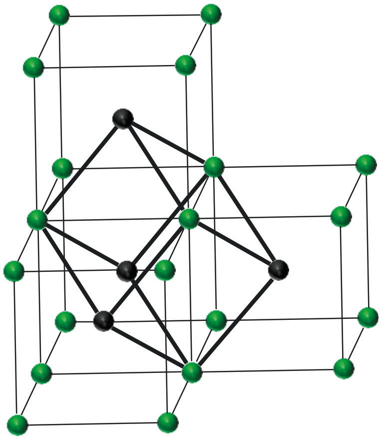


Figure 3

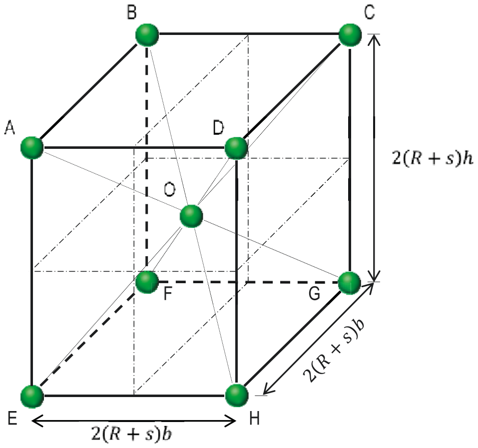


Figure 4

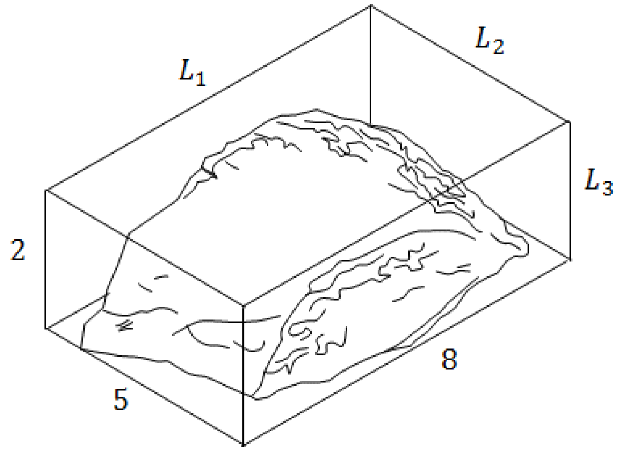


Figure 5

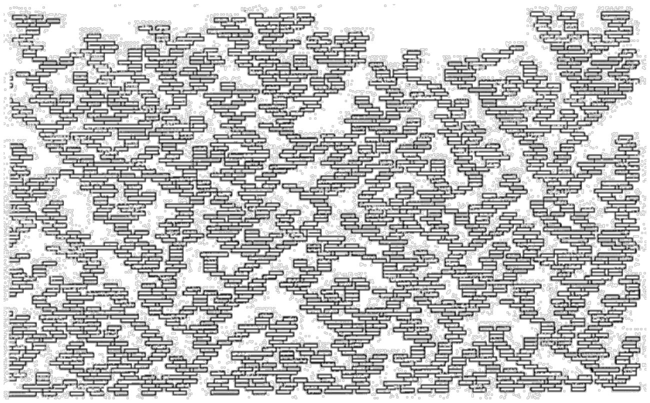


Figure 6

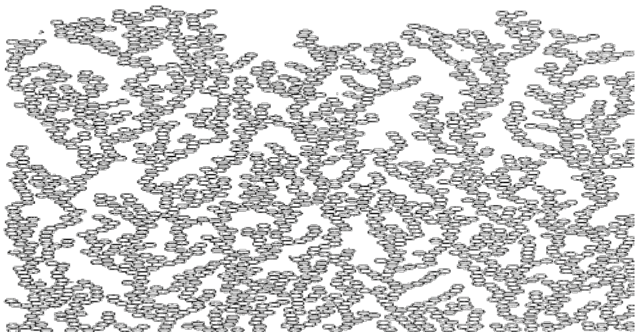


Figure 7

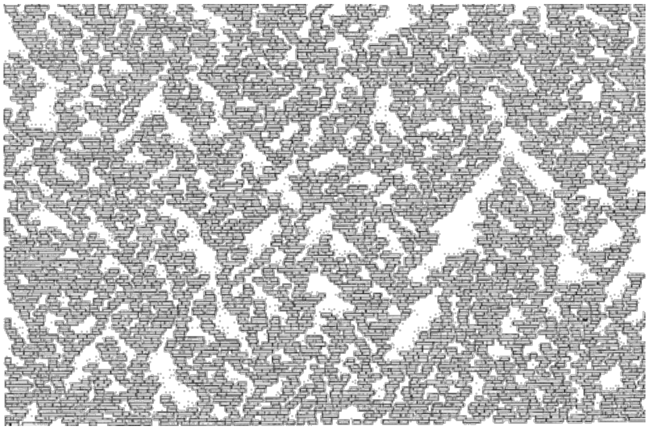


Figure 8

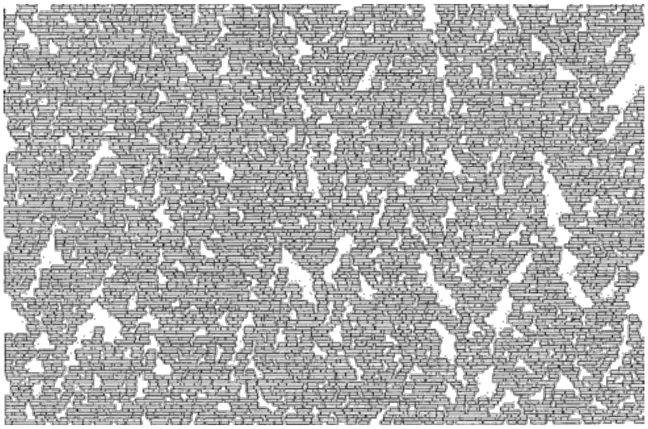


Figure 9

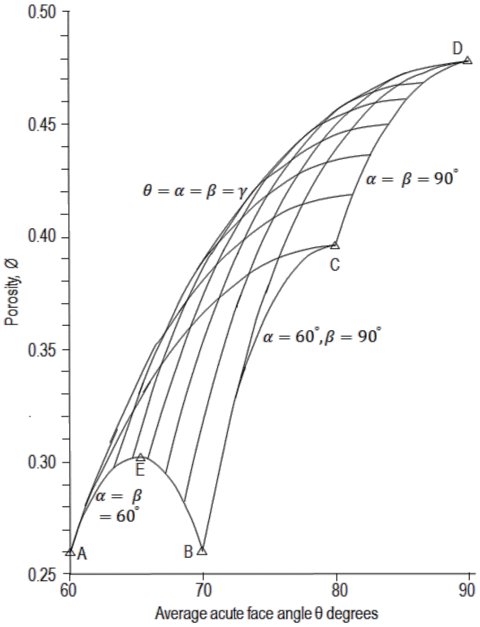


Figure 10

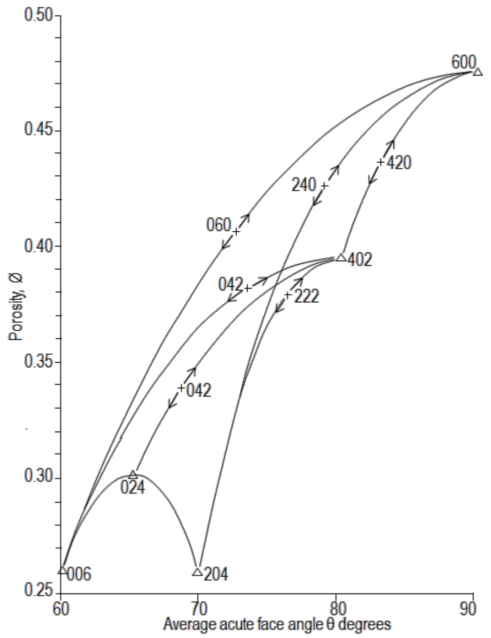


Figure 11

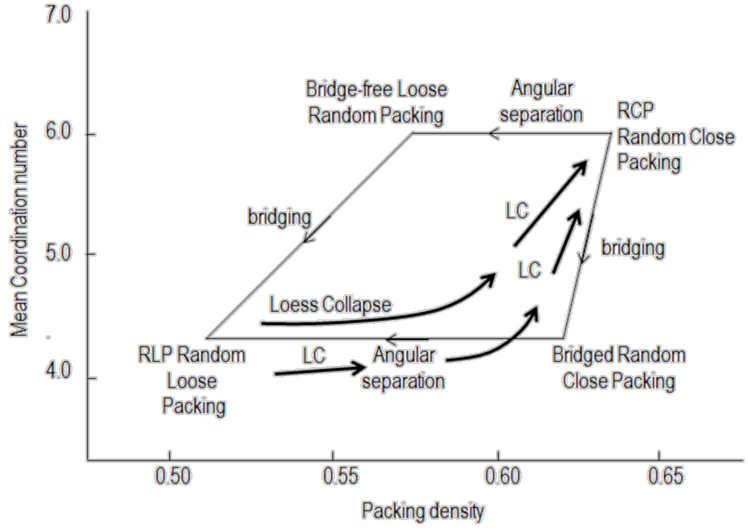


Figure 12

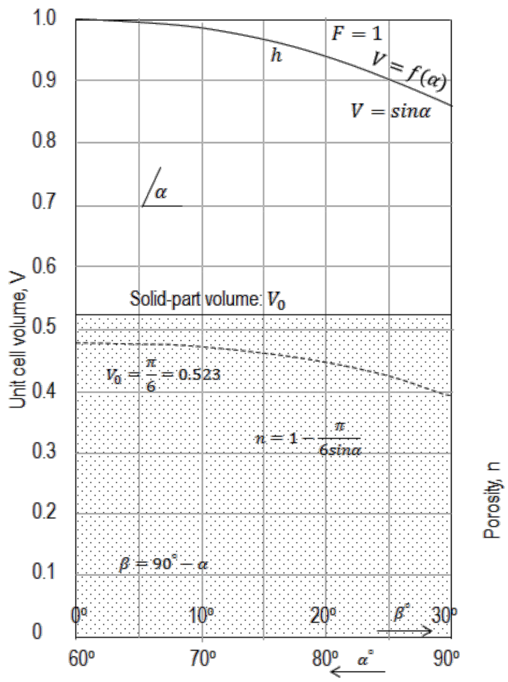


Figure 13

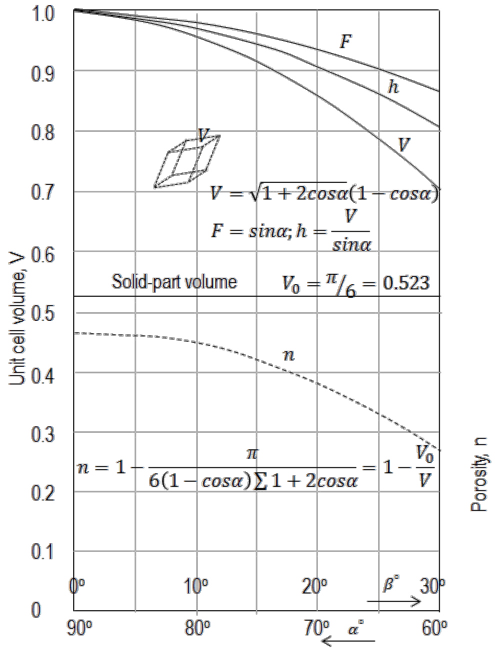
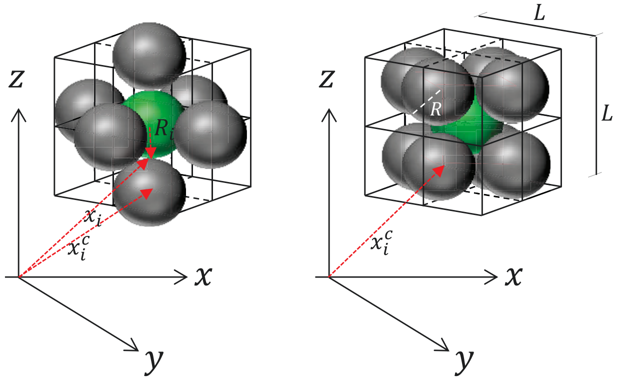


Figure 14



$(a)\ SCP\ Packing$ $(b)\ BCC\ Packing$

Figure 15

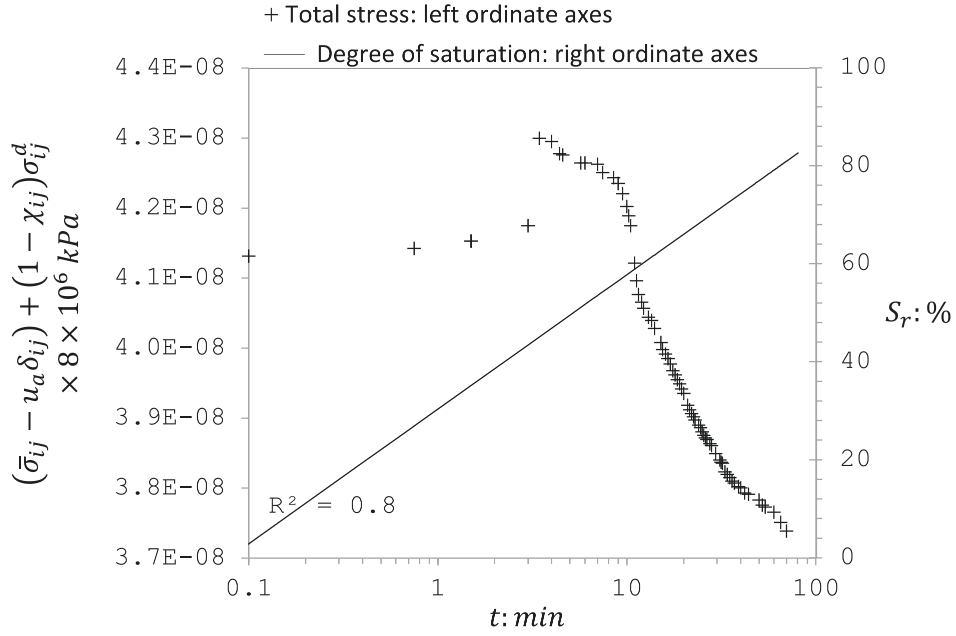


Figure 16a

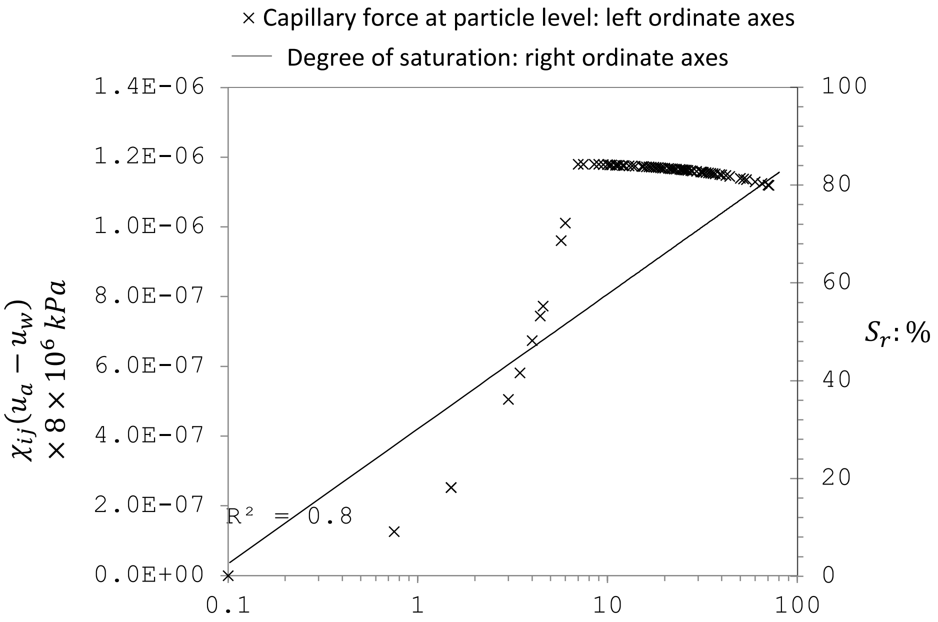

× Capillary force at particle level: left ordinate axes
Degree of saturation: right ordinate axes
$\chi_{ij}(u_a - u_w) \times 8 \times 10^6\ kPa$
1.4E-06
1.2E-06
1.0E-06
8.0E-07
6.0E-07
4.0E-07
2.0E-07
0.0E+00
R² = 0.8
0.1
1
10
100
100
80
60
40
20
0
S_r: %

Figure 16b