Advances in Life Science and its Applications (ALSA)
Vol. 1, No. 1, 2012

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The Architectural Basis of Soil Structure

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Abstract – Soil sustains all terrestrial life and is the heart of the Earth. In a handful of soil there are more organisms than the number of human on planet. Soil is the most complex systems known to science, and is vital to the existence of life on the planet. Yet no satisfactory geometrical model exists for soil structure. This paper will derive a new geometrical model using tensegrity. Using an evolutionary and holistic worldview literature, tensegrity is described as a physical principle for the mechanical functions of the soil system. Review of the principle shows soil structure as a hierarchy can be described as tensegrity. The tensegrity network is a stable, at the same time an adaptable construction. The whole system reacts to an outside force with an adaptive tension distribution. Soil can be described as a tensegrity structure with the following characteristics: Stability, Balance, Integrated, and Energetically efficient.

Keywords – complex system; entropy; soil, gas; water; structure.

1. Introduction

Soil that lies underneath our feet is a complex system made up of minerals, organic material, water, gasses, and living organisms[1]. Soil sustains all terrestrial and extraterrestrial life. Soil is the heart of the Earth, we constantly used and abused it yet know very little about how it works. In a handful of soil there are more organisms than the number of human on planet. There is more biodiversity found in soil than anywhere else. Soil allows plants to grow, supporting life on our planet, and a habitat for diverse biota. Given its importance and complexity, it is not surprising how little we know about soil and know very little about how it works[2-5]. Soil remains a mystery, but it presents us with the most important clues as to how complex ecosystems become capable of self-organization and sustaining functionality. Soil contains large numbers of living organisms and is the medium that supports life. The understanding and modeling of the most complicated biomaterials on the planet require an evolutionary and holistic worldview[6-12]. We have had many studies of the properties of the elemental materials in the soil. Its behavior has been fairly satisfactorily recorded. The nature of its acidity, its Base Exchange reactions, its flocculation, are well known [9, 10, 13-15]. Great efforts have also been made toward obtaining a picture of its mineralogical nature and crystal structure. We do not have as yet, however, satisfactory methods for giving quantitative characterization to the physical state of soils in the natural field condition. Practical students of soils have attached great significance to this field state of soils. They have recognized great differences in the productivity of soils having identical amounts and kinds of colloidal material. This difference has been attributed to differences in the arrangement of the particles or to the structure of the soil. The farmer refers to soils as varying in "tilth." Good "tilth" being defined as the optimum physical state for crop growth. It has long been recognized that tilth and structure are definitely associated with the presence of colloidal material. Soils devoid of colloidal material have what is known as single grain structure. Each grain acts as a unit. No compound particles are present. The soils will vary in physical state only as a result of variations in the closeness of packing of these single grains. Sands and silts are both soils having single grain structure. Because of the size of the grain, the tilth of sandy soils is seldom bad. They are well drained, but of course lack the capacity to store moisture. Soils containing very large amounts of silt often present quite a serious structure problem. The individual grains are so small that if they are forced into a position of close packing by beating rains or mechanical pressure, they become exceedingly hard and intractable and very slowly permeable to both air and water. Some of the most difficult soils to manage from the physical point of view are composed largely of fine silt having single grain. Current geometrical representation of soil is a sphere packed together in a closed configuration (Figure 1).

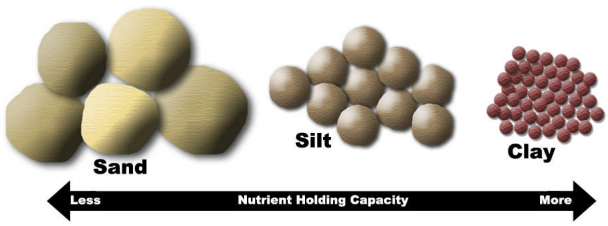

Figure 1. Current representation of soil aggregate as a packing spheres.

A significant challenge is in modeling soil aggregate, and to observe organisms as they live and interact in the soil. The current theories about soil aggregate formation and the development of soil structure proposed by Oades [15] more than thirty years ago. The aggregate hierarchy model conforms partly to the fractal theory. This theory states that no matter how complex a structure may be, it is built by repeating continuously, using a same pattern, a very much simpler structure or unit. Although aggregates of various sizes may all look similar, their composition is different. Microaggregates are tightly bound by stable organic matter and iron oxides, which are strong enough to remain intact even in soils. Macroaggregates, on the other hand, are held together by networks of fine roots and fungal hyphae that are readily disrupted by plowing. Soils containing high proportions of stable macroaggregates have undergone less physical disturbance than soils dominated by microaggregates.

Organic matter is perhaps the blood life of the soil. One of the reasons why the model "C-P-OM" has gained wide acceptability is this model links the two most important soil constituents: organic matter (OM) and clay (C)[14]. Together with clay, organic matter forms the seat of soil reactions. Organic matter and clay, either directly or indirectly, influence various chemical, physical and biological reactions. It was once said that just as photosynthesis is important to a plant, the same is organic matter to a soil. Although this statement was considered excessively sensational by some, nevertheless, it does highlight the importance of organic matter (Figure 2).

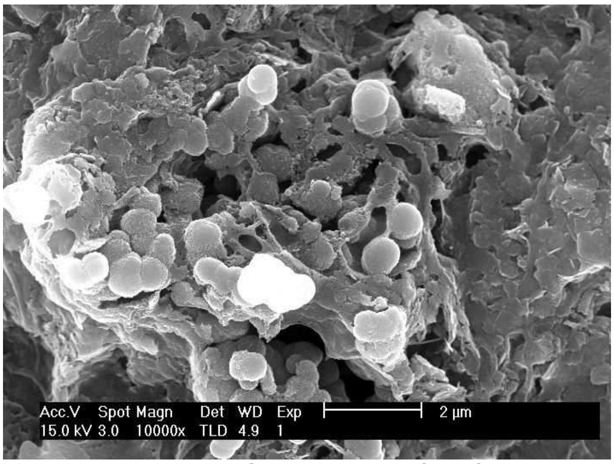

Figure 2. A scanning electron micrograph with 10000 times magnification, showing mineral phase of soil structure as a tensegrity. Picture courtesy of Prof. Silvapalan (URU).

Despite this model, no advanced geometrical model exists for soil aggregates. While we have successfully applied geometry to galaxies and atoms, the geometry we have applied to soil structures has been generally limited to levers, angles, and inclined planes, based on the 'isolated ped' theory we outlined in our introduction. Though we have learned much from the Newtonian force mechanics that underlie our current understanding of soil mechanics, this line of inquiry has still not produced convincing models of soil structure as whole.

The concepts of tensegrity have become increasingly recognized over the last thirty years as a useful model for understanding some of the structural properties of living organisms. The term tensegrity was coined by an American architect, engineer and philosopher Richard Buckminster Fuller (1895-1983). It is a combination of the words 'tension' and 'integrity'. These are technical structures consisting of a continuous system of tension elements and a discontinuous system of compression elements

"Tensegrity describes a structural relationship principle in which structural shape is guaranteed by the finitely closed, comprehensively continuous , tensional behaviors of the system and not by the discontinuous and exclusively local compressional member behaviors"

This paper introduces for the first time of soil structure as a tensegrity structure.

2. Tensegrity structure

Complexity is the state or quality of being intricate or complicated, a factor involved in a complicated process or situation. A great many quantities have been proposed as measures of soil's complexity. In fact, a variety of different measures would be required to capture all our intuitive ideas about what is meant by complexity and by its opposite, simplicity. Thus it is important to give a definition of the term tensegrity as accurately as possible, as precisely this definition will play an important role in the expert discussion. The problem is that an exact definition of the term is still difficult [16-30].

Buckminster Fuller defines the term tensegrity in his main work "Synergetics" and describes the relation between continuous tension elements and discontinuous compression elements, which are responsible for a structure, as follows: "The word tensegrity is an invention: it is a contraction of tensional integrity. Tensegrity describes a structural-relationship principle in which structural shape is guaranteed by the finitely closed, comprehensively continuous, tensional behaviours of the system and not by the discontinuous and exclusively local compressional member behaviours. Tensegrity provides the ability to yield increasingly without ultimately breaking or coming asunder. The integrity of the whole structure is invested in the finitely closed, tensional-embracement network, and the compressions are local islands." In this work he also explains the balance between tension and compression. In his opinion these are only two aspects of one and the same thing. They only function in interdependence. Compression elements cause tension and vice versa.

Stability is defined as the ability of the system to return to its original balance after an external force has had an impact on it. It is not determined of which type of „components“ the system is made of. They can be lines, surfaces or volumes, they can be cables, rods, a membrane or an air volume. The components can even be a combination of various elements combined to a component of a higher order. Moreover, it is not determined of which material these components consist.

Compression and tension are, mechanically described, the effects of a force. This means that the material is either exposed to compression or tension effects. A component that is compressed requires rigidity in compression, however, a component that gets under tension requires rigidity in tension. It is a known fact that cables and membranes do not possess rigidity in compression. The words discontinuous and continuous are closely related to the words. Each compressed component represents an island. If a system has several compression elements, i.e. several islands, these must not be in contact otherwise the system may not be defined as tensegrity system (Figure 3).

An astonishingly wide variety of natural systems, including carbon atoms, water molecules, proteins, viruses, cells, tissues, and even humans and other living creatures, are constructed using tensegrity. All structures are compromises between stability and mobility. Biological structures lie in the middle of this spectrum, strung between widely varying needs for rigidity and mobility, which can change from second to second. The efficiency, adaptability, ease of hierarchical assembly, and sheer beauty of tensegrity structures would recommend them to anyone wanting to construct an earth system. Explaining the structure, interconnection, responsiveness and strain patterning of the soil without tensegrity is simply incomplete and therefore frustrating. With tensegrity included as part of our thinking and modeling, its compelling architectural logic is leading us to re-examine our entire approach to how soil initiated structure, develop, grow, move, stabilize, respond to stress, and repair damage.

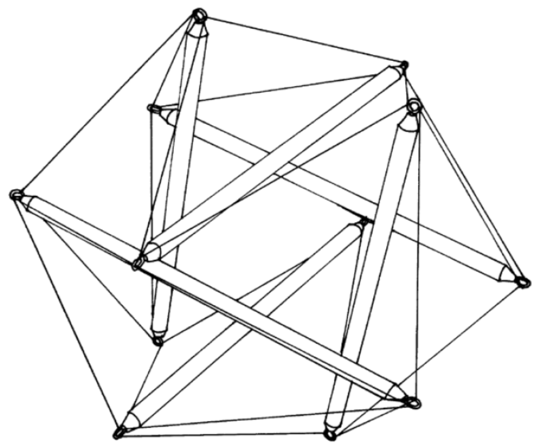

Figure 3. A simple tensegrity system. Tensegrity structures contain a continuous system of tendons and a discontinuous set of compression members called struts. The various ligaments form 'slings' that are capable of supporting the weight of the body without applying compressive forces. In other words, the soil structure is not, as it is usually portrayed, a simple stack of blocks.

3. Theory

There are but two ways to support something in this physical universe - via tension or compression; brace it up or hang it up. No structure is utterly based on one or the other; all structures mix and match these two forces in varying ways at different times. Tension varies with compression always at 90°: tense a rope, and its girth goes into compression; load a column and its girth tries to spread in tension. Blend these two fundamental centripetal and centrifugal forces to create complex bending, shearing, and torsion patterns. A brick wall or a table on the floor provides an example of those structures that lean to the compression side of support. Only if you lean into the side of the wall will the underlying tensional forces be evident. Tensional support can be seen in a hanging lamp, a bicycle wheel, or in the moon's suspended orbit. Only in the tides on earth can the 90° compression side of that invisible tensional gravity wire between the earth and the moon be observed[15, 18, 20].

The tensegrity principle underlies geodesic domes, tents, sailing vessels, and various stick-and wire sculptures. A tensegrity system is characterized by a continuous tensional network connected by a discontinuous set of compressive elements. A tensegrity structure forms a stable yet dynamic system that interacts efficiently and resiliently with forces acting upon it. Tensegrity opens new avenues of holistic strategy for understanding how soil structure works, how it compensates, and how to understand some otherwise incomprehensible behaviors. "Tensegrity" derives from collapsing the words "tension" and "integrity" and means that the integrity of these class of structures depends on the balance of tension within it. Tensegrity forms a class of truss structures with tension in cables and compression in bars. In cell physics, some biologists utilize tensegrity models for cells to investigate the mechanotransduction involving cytoskeleton. Tensegrity structures self-assemble under pre-stress and exhibit mechanisms without pins and gears. All structures in the earth are supported by a balance between tension and compression, between "push" and "pull". Shear, bending, and other forces are just combinations of basic tension and compression. We are very used to looking at and building structures that rely primarily on compression for support. The brick wall is the classic example: one brick is piled on top of the other. This is a "continuous compression" structure - where the compression created by gravity is carried from one brick to another, all the way to the ground. The bottom brick has to be compressively strong enough to carry all the bricks above it. Nobody asks what a brick wall, or a house, which is similarly constructed, weighs. Weight is rarely a consideration in continuous compression structures. Soils, however, are constructed with strict evolutionary limits on weight, so continuous compression is not a good model for building a soil structure.

4. Soil as a tensegity structure

Much of the interest in the subject of soil structure may be ascribed to the fact that many important soil phenomena, such as aeration and the movement and storage of water, are frequently determined by the nature of the soil structure. The number, size-distribution, and configuration of the voids in the soil are all intimately associated with these phenomena. In fact, most methods of evaluating soil structure consist either in the direct measurement of some characteristic of the soil pore space or in the conscious or unconscious evaluation of such pore spaces from other data. Our paradigm determines what we are able to see, how we think, and what we do. Soil structure can be viewed as a tensegrity structure (Figure 3). The mineral phase is the ‘tension member’ - pulling in. The organic matter is the ‘compression member’ pushing out. The minerals pull in until they balance the organic materials pushing out, and that determine the size and form of the structure.

The extraordinary and beautiful microscopic world of soil miscrostructure of an alluvial soil in Canada (Figure 2) shows the larger inhabitants of the soil. There is a whole world of activity in the soil by organisms visualized by a Scanning Electron Microscope. It is important not to miss that soil is a vibrant and dynamic habitat even at these tiny scales. Microorganisms are extremely important because of their numbers (billions in just a spoon full of soil), the fact that they break down the organic remains, the dying vegetation, deposited on and in soils, to release nutrients for the next generation of plants, and they also play a big part in creating the tensegrity structure or architecture of soils. The tensegrity structure shown in figure 3 soils from an alluvial soil displays the tensegrity of structures and life within the soil microstructure.

Tensegrity provides a conceptual link between the structural systems and the energy/ informational systems. Soil structure as a whole can usefully be described as a tensegrity system. In soil structure, the soil particles act as discontinuous compression elements and the organic materials act as a continuous tensional system. Together the minerals and organic materials elements permit the structure to change shape, move about and transport water (Figure 4).

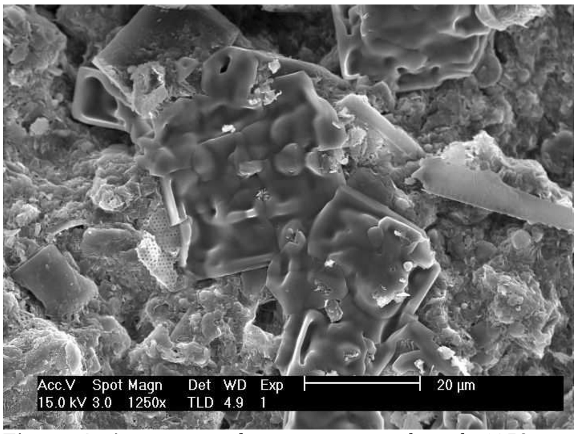

Figure 4. A scanning electron micrograph with 1250 times magnification, showing mineral phase of soil structure as a tensegrity. Picture courtesy of Prof. Silvapalan (URU).

Tensional forces naturally transmit themselves over the shortest distance between two points, so the elastic members of tensegrity structures are precisely positioned to best withstand applied stress. For this reason tensegrity structures offer a maximum amount of strength for any given amount of material. Additionally, either the compression units or the tensile members in tensegrity structures can themselves be constructed in a tensegrity manner, further increasing the efficiency. These nested hierarchies can be seen from the smallest to the largest structures in our universe. This is known as aggregate hierarchy.

When applied to the soil structure system, the tensegrity concept explains the ability of the soil to absorb impacts without being damaged. Mechanical energy flows away from a site of impact as an elastic shock wave in the tensegrity network. The more flexible and balanced and communicative the network, the more readily it absorbs shocks. This is important in understanding how flexible and organized organic material continuities can reduce the incidence of damage to structure.

A tensegrity model of soil paints an altogether different picture - forces are distributed, rather than localized. An actual tensegrity structure is difficult to describe - we offer several pictures here, though building and handling one gives an immediate felt sense of the properties and differences from traditional views of structure - but the principles are simple. A tensegrity structure, like any other, combines tension and compression members, but here the compression members are islands, floating in a sea of continuous tension. The compression members push outwards against the tension members that pull inwards. As long as the two sets of forces are balanced, the structure is stable. Of course, in a body, these tensile members often express themselves as membranes, not just as tendinous strings. The stability of a tensegrity structure is, however, generally less stiff but more resilient than the continuous compression structure. Load one 'corner' of a tensegrity structure and the whole structure - the strings and the dowels both - will give a little to accommodate. Load it too much and the structure will ultimately break - but not necessarily anywhere near where the load was placed. Because the structure distributes strain throughout the structure along the lines of tension, the tensegrity structure may 'give' at some weak point at some remove from the area of applied strain, or it may simply break down or collapse.

Applying pressure to any point of a tensegrity structure causes force to be transmitted around the edges, with both compression and tension operating within different parts of each strut, which means that they must be made of a material that can deal with both types of loading. Prestressed tensegrities, on the other hand, have these two components separated, optimizing the material properties of each.

The organisation of soil structure cannot proceed without observing certain rules. The whole matter creates a chaotic impression, however, these structures, which are mainly polygons, can be converged towards icosahedra and other geometric shapes despite their chaotic distribution. These tensegrity shapes, for example the icosahedron, allow, from a mathematical point of view, filling a space under optimal conditions. The final shape is not obtained by chance and the construction is carried out according to rules and instructions. The elements have to be pre-stressed and stabilisation has to be effected by balanced opposed tension and pressure forces, whereby the shape, the firmness and the adaptability in many directions as well as the independence of gravity are maintained. Therefore, all soil structures distributed in a given space react to the smallest increase in tension in one of the elements which is then passed on to the even most distant elements. Each local compression changes the global tension. This global organisation, which forms the framework of the living matrix, enspires a holistic view. Perhaps one could wonder whether it is a basic structural architecture of living forms.

The tensegrity network is a stable, at the same time an adaptable construction. The whole system reacts to an outside force with an adaptive tension distribution. This happens due to the arrangement of the stable and elastic elements. Pressure and tension are distributed evenly in this arrangement. Then follows a self-stabilisation through the distribution of tension and pressure forces in the whole construction. As a response to a locally working force all structures of the tensegrity model re-arrange themselves. The elements arrange themselves towards the tension force. This causes a linear stiffening of the tissue in this direction. This three-dimensional arrangement and the even distribution of force cause the largest possible strength with as little input of energy and material as possible.

5. Conclusions

Soil is a major part of the natural environment, alongside air and water, and is vital to the existence of life on the planet. Without healthy soil, life on Earth is unsustainable. Sustainable land use is a prerequisite for lifting billions from poverty, enabling food and nutrition security, and safeguarding water supplies. It is a cornerstone of sustainable development. Inasmuch as the amount, size distribution, and configuration of the soil pores are significant features of a soil's structure, it appears that the evaluation of soil structure can best be made by the direct measurement of one or more of these characteristics rather than by the measurement of other soil features which must then be interpreted in terms of pore size distributions. Galileo once said 'the book of Nature may indeed be written in the characters of geometry.' This paper proposes a novel idea of soil as a tensegrity structure. To summarize the significant aspects of this type of structure:

1. Stability – achieved through the configuration of the whole network, and not because of the individual components. It is also omnidirectional, with the different elements maintaining their respective properties regardless of the direction of applied load.
2. Balance – the tension and compression components are separated and balanced mechanically throughout the entire structure, which will optimize automatically so as to remain inherently stable.
3. Integrated – a change in any one tension or compression element causes the whole shape to alter and distort, through reciprocal tension, distributing the stresses to all other points of attachment.
4. Energetically efficient – giving maximum stability for a given mass of material. In mechanical terms it cannot be anything other than in a balanced state of minimal energy throughout.

Since its discovery, the tensegrity concept has developed in four main areas – sculpture, building, space research, and structural biology. Space research has shown a great deal of interest in tensegrities because of their lightness and other unusual structural properties. Defining structure as tensegrity and their complex mathematics will probably lead to new developments in soil research, with physical and computerized modeling becoming valuable tools for exploring their potential in the future.

Acknowledgements

The Author thanks Prof. Lal and Sivapalan for the discussion and validation of this concept. Dr. Ingber and Buckminster Fuller provided help when I got into potholes and inspiration when I need relieve.

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Vitae

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