Sand: fluid or solid?

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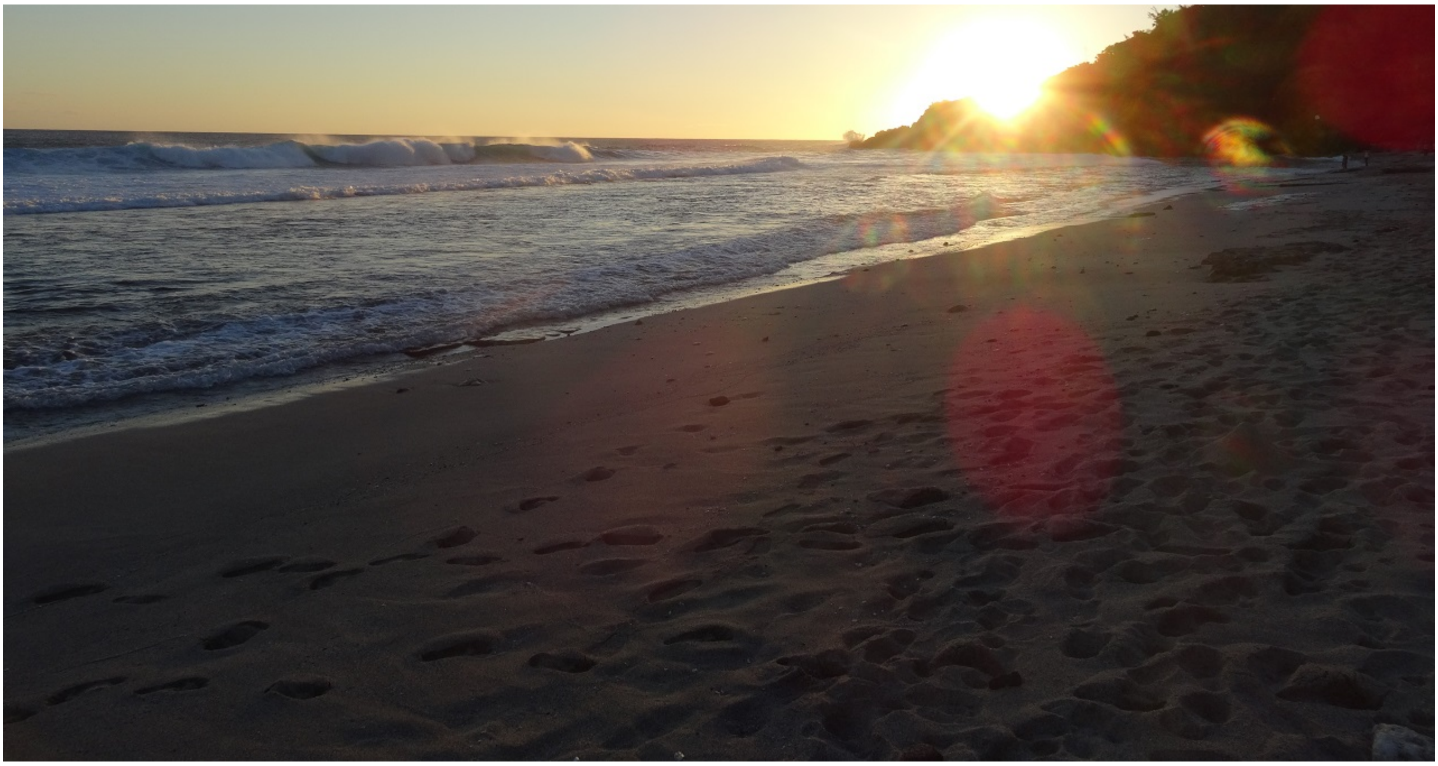

Sand is one of the common materials in our environment. Symbolically attached to the seaside frame, it is nevertheless one of the basic materials used to make concrete. In addition, it is one of the elementary components of soils, and as such it is familiar to any geotechnical engineer. Born from the decomposition of crystalline rocks, it is often presented as a particularly illustrative example of granular materials, where the disordered arrangement of its grains will give it quite unique properties. This article proposes to review some of these properties, after recalling the origin of sand.

1. Where does the sand come from?

Figure 1. Sand, as the ultimate state of alteration of certain rocks, is very present in the landscape of mountain ranges.

Sand is the ultimate state of degradation of many rocks, particularly *magmatic* rocks formed by deep crystallization, consisting of grains. Granitic rocks [1] are an excellent example, they are the main peaks of most high alpine massifs (Mont-Blanc, Ecrins, Ambin, Argentera). Erosion, an inevitable consequence of the ageing of the material under the influence of aggressive agents (mainly climatic), breaks down the rocks into smaller elements until they decompose into a granular assemblage, where the grains of the original rock are found (Figure 1). This assembly is called the *granite arena*. For example, for granite, we find mica crystals, feldspar crystals, and quartz crystals. Due to the ongoing physico-chemical alteration, only quartz grains often persist, forming the sand on riversides or beaches.

2. A story of grains

Figure 2. Example of a sand sample in laboratory. This handful of sand contains billions of grains of silica. [Source: By Daniel Ventura, Own work, CC BY-SA 3.0 (http://creativecommons.org/licenses/by-sa/3.0)], via Wikimedia Commons

Sand is therefore a granular material, constituted by an assembly of quartz grains (Figure 2). Symbolically, it can be represented mentally as a pile of balls, which collide with each other, slipping and rolling. But in addition, grains of sand are very rarely spheres like marbles. The grains are often irregular, sometimes angular or elongated; they may have flat facets or be rounded. Grain size is also an important parameter. Not all grains are the same size. Typically, in a sand, the grain size ranges from a few tens of micrometers [2] to a few centimeters. This is called *granulometry*. When spread out (i.e., when there are a multitude of different grain sizes), the medium will have few voids between the grains. The smaller grains are positioned between the larger ones, filling in the gaps, and so on. Dense sand will be used when, for a given sample volume, the proportion of the void volume between the grains is small. Otherwise, we'll talk about loose sands.

For the geotechnician, who is interested in soils in anticipation of future civil engineering works (construction of a road structure, a building, a dam, an offshore structure), the density of the sand that constitutes the soil is of paramount importance, because the mechanical behaviour (i.e. the way in which the soil deforms under the action of a given load) will not be at all the same whether the sand is dense or loose. And for most civil engineering works, it is essential to avoid that the ground deforms beyond a very strict limit!

3. Solid, air and water

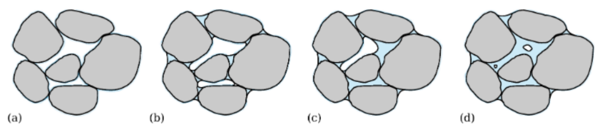

Figure 3. Diagram of the different water states in soil: (a) hygroscopic regime, (b) pendulum regime, (c) funicular regime, (d) capillary regime. [Source : Based on Luc Scholtes (2008): Micromechanical modelling of partially saturated granular media. Doctoral thesis, Engineering sciences[physics], Institut National Polytechnique de Grenoble]

Sand in soils is rarely composed only of solid grains and air. Indeed, voids between grains can be filled by a fluid (often water, but sometimes also hydrocarbons as in Canada's oil sands). This fluid can fill all the voids (the sand is then said to be saturated), or only part of the voids (Figure 3). The presence of a fluid profoundly modifies the mechanical behaviour of sandy soil. If the voids between the grains contain some water, then forces (called *capillaries*) develop between the grains, exerting between them an attractive effect, responsible for the *cohesion* of the sample. That's how you can build a sand castle, with vertical walls! If the material is saturated (which happens when the tide rises), the castle collapses, due to the disappearance of capillary forces, and thus the cohesion of the material.

In addition, the presence of a fluid in the sand can promote alteration and physico-chemical transformation processes, leading to the formation of solid bridges between the grains. A kind of cement appears between the grains, which improves the *mechanical resistance* of the soil. When this phenomenon of *consolidation* continues over very long periods of time on a geological time scale, we will speak of *diagenesis*, leading to the formation of a rock called *grès*.

4. In confidence of a granular material

Sand, as an example of granular material, has been a constant concern for soil mechanics since the 18th century with the founding work of C.A. Coulomb (see What is the Coulomb friction law?). Three centuries later, the light remains partial on all the mysteries that this material holds for us. Sometimes resistant like a "real" solid, sometimes fluid like a liquid. Think of the quicksand! More catastrophically, we keep in mind the major disorders that occur during an earthquake on sandy soils: the soils liquefy, no longer allowing the stability of the structures they support, leading to their ruin.

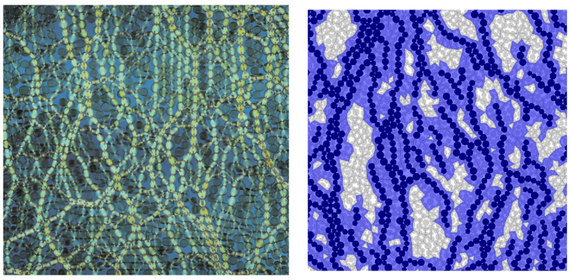

Figure 4 Existence of a microstructure within a granular assembly. Preferential grain chains develop when the assembly is subjected to mechanical loading (left, laboratory test from photo-elastic particles; right, results obtained by numerical calculation using a Discrete Element Method). [Source : Based on Huaxiang ZHU (2015): Consideration of an intermediate scale in micro-structural modelling of granular soils. Doctoral thesis, Engineering sciences[physics], Institut National Polytechnique de Grenoble]

Without going into all the details, the complexity of sands, as a granular material, comes from two aspects:

On the one hand, rearrangement between grains, which can slide or roll relative to each other, modifying the granular structure (by decreasing or increasing voids between grains). This relative movement between the grains is controlled by the coefficient of friction between the grains (through Coulomb's law), and the shape of the grains.

On the other hand, the colossal number of grains contained even in a small volume (a handful of sand can contain billions of grains!). This results in a geometric complexity (effect of large numbers, observable in any large population, living or material), which can be perceived in the variety of entanglement patterns formed by the grains in contact, drawing kinds of grain chains in the middle of highly variable clusters, sizes and shapes (Figure 4). One of the most singular properties of sands, and which results in part from a collective effect, is *dilatancy* (see What is sand dilatancy?), reflecting the ability of a sand sample to increase in volume when subjected to shear stress.

One of the major current challenges for sand soil engineering is to pursue this fruitful path of understanding the behaviour of sands, by returning to their granular structure at the most elementary scales: that of the grain, or an elementary cluster of a few grains. Between the scale of the engineer, which extends to a few dozen metres, and that of the researcher, which goes down to the heart of the assembly of the grains, there is a disjunction whose resolution constitutes an authentic intellectual challenge.

References and notes

Cover photo: Reunion Island [© François Nicot]

[1] Granitic rocks refer to a family, of which granite is a representative. The gneiss or amphiboles of the Belledonne massif (Isère) belong to this family.

[2] A micrometer is a thousand times smaller than a millimeter : 1 mm = 1000 µm

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