A sandcastle is a complex entity – at least on the inside. That is where grains of sand, water and air combine to form an intricate structure. What holds them together is the subject of research being conducted by Stephan Herminghaus and his team at the Max Planck Institute for Dynamics and Self-Organization in Göttingen. Their work is also generating knowledge that can be applied in industrial processes, landslide prediction and oil production.

TEXT CHRISTIAN MEIER

At first glance, it’s not quite clear what sandcastles have to do with oil fields. However, as soon as Stephan Herminghaus and his team at the Max Planck Institute for Dynamics and Self-Organization in Göttingen had solved the long-unexplained mystery of the astonishing stability of sandcastles, the physicist received a phone call from oil giant BP.

But first things first: The story begins with pure scientific curiosity. Herminghaus was fascinated by an everyday wonder at the beach: the impressive alliance of sand and water. Out of an amorphous collection of grains that can trickle through the narrow neck of an hourglass or be scattered without the least resistance by a gust of wind, a liquid makes a stable and moldable building material for sandcastles and intricate sculptures. Stephan Herminghaus and his team were particularly puzzled by the following phenomenon: the firmness of the wet sand is largely independent of the quantity of water with which it is mixed. Sand that is barely wet is just as moldable and sta-
It’s all about the mixture. Only when water and sand come together in the right quantities do the grains of sand stick together. This picture shows water that has been dropped onto a dish of sand, dispersing and wetting the sand.
Diffusion of light in granulate: Stephan Herminghaus checks a vessel filled with tiny glass beads. The scientist from the Max Planck Institute for Dynamics and Self-Organization is studying the diffusion of light through granulate in this experiment.

Visible as sand that is almost saturated. This explains why no builder of sandcastles will ever be in need of a recipe for this building material.

In a bid to systematically get to the bottom of this phenomenon, the scientists in Göttingen studied a kind of model sand: glass beads with diameters of between 0.2 and 0.3 millimeters. Like most grains of sand, the glass beads consist of silicon dioxide. The model sand differs from the sand on the beach only in the fact that its grains form perfect spheres. The physicists wetted the glass-sphere granulate to different degrees and then measured the mechanical properties of the resulting paste, such as its tensile strength.

To achieve this, they formed a plug of the wet model sand in a cylindrical container, which they placed on a rotating plate. The scientists then gradually increased the speed of rotation until the granular plug was torn apart. From this rotational speed they were able to calculate the tensile strength. They also determined the granulate's resistance to shear forces. These are the forces that are at work when, for instance, a spoilsport attacks a sandcastle by pushing against the stronghold from the side, parallel to the ground. And finally, the scientists measured the strength of vibration the wet model sand had to be subjected to in order to make it flow.

**SOLID GRANULATE MORPHS INTO AN ALMOST FLUID SLUDGE**

The result: all three parameters are similarly dependent on the water content. Even the slightest addition of water causes them to rise abruptly, turning desert sand into paste. However, as the proportion of water rises further, they remain largely constant. Only when the water content accounts for around 20 percent of the volume do the three parameters decline again dramatically: the solid granulate becomes an almost fluid sludge. The granulate thus exhibits behavior similar to that of natural sand.

It thus really was suitable as a model, and not only for sand, but for what so often happens in landslides: when the material becomes too wet, it loses its stiffness. Why that sometimes happens very suddenly and also under widely varying water content, depending on the precise composition of the earth, is a complex problem. There is still a lot of work ahead for scientists who deal with such issues. The Göttingen-based Max Planck scientists started by devoting themselves to discovering just why it is that the sandy paste holds together so well with less water.

Investigating this matter was a fairly difficult business, as they had to look inside the granulate in order to understand the observations they made. “We wanted to know how the water distributes itself among the many narrow cavities between the beads,” says Herminghaus. An optical microscope was of no help because the many beads reflect the light in all directions.

X-ray tomography provided the solution. As with a computer tomograph at the hospital, the wet granulate is illuminated from all sides by an X-ray beam. Since water, glass beads and air absorb the X-rays to different degrees, each image produces a well-defined silhouette. From the combination of images, a computer calculates the spatial structure of the specimen, and also shows how the water is distributed...
throughout the space. Herminghaus’s team went to the electron synchrotron in Grenoble and took such three-dimensional pictures for a number of different water contents.

“When we looked at the images, we were astonished,” reports Herminghaus. As the quantity of water increased, the spatial structure of the water’s distribution between the grains of sand changed fundamentally numerous times, explains the scientist. “We asked ourselves how it could be that the mechanical properties didn’t appear to notice this.”

**CAPILLARY BRIDGES FORM A RING AROUND THE CONTACT POINT**

This is what happens in the granulate: Even with very little water added, “water bridges” immediately form between every two adjacent grains. The water attempts to cover as much glass as possible because the water molecules are attracted by the wall of glass. Consequently, the water moves to the places where it can touch two spheres at the same time: to the points of contact between two beads. The resulting liquid bond between two spheres is known by physicists as a capillary bridge. It forms a ring around the contact point.

Starting from about 3 percent water content, these capillary bridges begin to fuse with one another, resulting in the creation of individual “water nests.” If more water is added, the little nests merge to form bigger nests. At around 10 percent water content, they become so large that they form waterways within the specimen, reaching from one end to the other. “A paramecium could swim from one end of the specimen to the other,” says Herminghaus.

“We couldn’t intuitively understand why these complex transformations caused no changes in mechanical stability,” explains the physicist. The only thing the scientists found easy to understand was what happened when just a little water was added, provided there were only individual water bridges in the granulate. The interface between the capillary bridge and the air is concave, arching down into the water. This creates a negative pressure in the water, which draws the beads together.
Complex experimental setup: Doctoral student Frank Rietz watches the package of spheres compact in a shear chamber – a type of open-top aquarium whose glass walls periodically tilt back and forth, “shearing” the glass spheres between the plates.

If more water gets into the granulate, it flows into the capillary bridge, making it larger. The concave arch of the water surface thus becomes less pronounced and the negative pressure decreases. However, the drop in suction is balanced out by the increase in the area in contact with the glass spheres with which it interacts. The force of attraction between the beads as exercised by the capillary bridges thus remains constant – and with it, the stability of the granulate.

“But things get exciting when two growing capillary bridges blend into one,” says Herminghaus. This happens whenever two neighboring capillary bridges touch. In this case, they merge and fill the whole of the cavity between three spheres with water. Given that the three spheres are usually in contact with each other, there is a third capillary bridge, which inevitably merges with the other two: a trio of capillary bridges results. Because the spheres involved are about the same size, the trio always forms when the capillary bridges reach a very specific size, in other words always with the same amount of negative pressure – what scientists call fusion pressure.

A similar thing occurs when the capillary bridge trio combines with other bridges or other trios to form larger nests. “All of this can be very nicely tracked and confirmed with tomography,” says Herminghaus. The scientists thus understood what happens when more than 3 percent water is added: no new bridges are formed, but rather, the existing bridges grow together to form nests.

**THE PRESSURE ACTS FROM ALL SIDES**

But one mystery remained unsolved: Why does the negative pressure have the same effect on the stability of the material when the majority of the grains appear to be surrounded by water? In this case, the pressure on the spheres floating in the water acts from all sides and should be completely equalized. All things considered, there would be no suction left to hold the granulate together.

Here too, it was X-ray tomograms that provided the crucial clue. What they showed was that many air-filled cavities still remained. “The granulate is soaked, not in a nest, but in an intricate water sculpture,” explains Herminghaus. All of the grains are in contact with water surface and are mechanically stabilized by its surface tension.

A beaker full of glass spheres is, of course, not the same as natural sand, because grains of sand are anything but perfect spheres. Nevertheless, the physicists from Göttingen are convinced that their explanatory model also applies to sand. Not only did they discover that the mechanical properties of wet natural sand depend on the volume of liquid to an almost equal extent as do those of model sand, but as the X-ray tomogram showed, their water nests also form a very similar structure.

Manufacturers of tablets have long been aware of the fact that the mechanical properties of wet granulates do not change – even when their liquid content varies. Pharmaceutical producers use mixing machines to blend the carrier powder and the active ingredient with a liquid in order to make pills. “Over a broad moisture range, the mixers always consume about the same amount of power,” re-
ports Herminghaus. The resistance that the mixture exerts on the mixers does not change significantly as it becomes wetter.

Herminghaus stresses that his research results are important for more than just sand sculptors and pill manufacturers. “The findings can probably be applied to most sands that occur in nature and a large number of other sediments,” says the physicist. This is because most natural sediments are fairly well “sorted,” as geologists say, by their lengthy transportation in water and wind. In plain text, this means that all of the grains are approximately the same size. For instance, the flow velocity of a river determines the size of the grains that settle on the riverbed. “This being the case, our findings could contribute to a better understanding of landslides and perhaps even enable them to be predicted,” says Herminghaus.

Herminghaus’s research also fits into another context, which is an area of burning interest to physicists the world over: namely the question of whether there are overriding, universal laws for complexity and self-organization. Or, putting it another way: are completely different systems, such as wet granulates, ant colonies and the human brain, governed by the same rules of complexity? Such rules, many physicist hope, would make it easier to understand the physics of highly complicated phenomena.

**THE RIGHT QUESTIONS PRODUCE SIMPLE ANSWERS**

The physics world is split on this question. “I’ve spent a lot of time on this issue and have come to the conclusion that there are no such universal laws,” says Herminghaus. He believes the search for generally valid formulas merely serves to hold people back. “Each complex system is a case in itself that we, as scientists, must consider anew,” he says.

Herminghaus has nevertheless developed a kind of methodology for getting closer to complex systems. He approaches them rather like a criminologist: “I put myself inside the system, as it were, and try to visualize how it works,” explains the physicist.

The right questions are key. “If you ask a complex system the right questions, it gives you surprisingly simple answers,” says Herminghaus. He goes on to explain that it often shows you very simple rules by which it works. The job of the scientist is to find the right questions.

How surprisingly simple the answers can be was demonstrated by the group in Göttingen, again using a wet granulate of glass spheres. They examined how it reacted to different degrees of vibration. The scientists poured the granulate into a flat, cylindrical, plastic container and placed it on a shaker. They then changed the energy and the acceleration of the vibration by varying either the shaker’s amplitude or its frequency.

The behavior the wet granulate exhibited was highly complex. It went through similar phase transitions as those experienced by a solid that is melting as a result of heating, and whose particles ultimately evaporate into a gas. Similarly, at low acceleration, the grains lay closely packed together and remained motionless, which corresponds to the solid state.
As the acceleration increased, they transitioned into a sort of liquid phase in which the particles moved faster and migrated through the granulate.

Things got really interesting when the scientists increased the energy input during the stage of high acceleration. In this case, a third gaseous phase manifested itself in which the grains moved very fast and free. This gas phase existed in the middle of the plastic dish. Around it, a ring of the liquid phase remained, where the particles moved much slower. Since the median particle speed provides a measure of the temperature, this dual phase had two temperatures. A truly complex occurrence, and one that is unlikely to be faced when boiling water on the stove.

THE COMPUTER BRINGS LIGHT TO COMPLEX SYSTEMS

The obvious assumption is that such behavior depends on many different properties and details of the wet granulate. However, the scientists in Göttingen showed in computer simulations that this is not the case. “We asked ourselves how the phase transitions depended on the behavior of the force with which a capillary bridge pulls on the beads when they move apart,” explains Herminghaus. The bridge is like a spring that pulls tighter and tighter as the glass spheres try to move further apart, and that ruptures at a certain tensile force.

The scientists simulated this behavior on the computer and obtained a phase diagram that corresponded fairly well with what they had observed. They then made a bold assumption: they conjectured that the behavior of the system did not depend on how the tensile force of the capillary bridge changed as a function of the distance of the spheres, but that it depended solely on the energy one had to input in order to pull the bridge apart.

And they were right: when they repeated the simulation using this assumption, the scientists obtained the same phase diagram as they had from the previous simulation. In the energy that was needed to break the capillary bridge, they had found the crucial lever that described the behavior of the wet, shaken granulate.

As far as Stephan Herminghaus is concerned, this example shows where one of the keys to understanding complex systems lies: in identifying the fundamental properties of the system and blanking out the many irrelevant details. “In its fundamental aspects, every system is simple,” says Herminghaus. “The art of finding this fundamental aspect is not something that can be learned through schooling – it can come only through years of experience.”

NEW KNOWLEDGE TO MAKE EXPLORATION MORE EFFICIENT

“I believe that it is this ability that convinced BP to fund our research,” says the physicist. The oil conglomerate has a problem, namely: oil fields contain residues that are impossible or at least difficult to exploit. When the oil stops bubbling up to the surface on its own, the oil producers give it a helping hand by pumping water into porous rock in a bid to force the oil out. “Nests” of oil form in the underground rock and no longer reach the conveyor pipes – roughly half of the oil stays in the depths.
“These nests have a very similar structure to the water nests in a wet granulate and should follow similar principles,” says Herminghaus. The situation becomes even more complex when it comes to storing carbon dioxide in empty oil fields. In this case, it is not two but three components – carbon dioxide, water and residual crude oil – that need to be squeezed in between the grains. “There is an enormous amount of research still to be done here,” says Herminghaus.

BP SUPPORTS THE RESEARCH FINANCIALLY

“Ensuring sustainable supplies of energy for the world is a multifaceted problem,” says Herminghaus. “It is our job as scientists to deliver the knowledge that can provide the basis for the right decisions to be made.” BP is now funding the work of his department for a period of ten years to the tune of USD 1 million per year. However, the Göttingen-based scientists have agreed with the oil company that they will continue to determine their research program themselves.

“We did not want to have a research agenda imposed on us,” says the physicist. “It’s nice and actually encouraging that even major industrial corporations like BP accept this.”

And so the research at the Max Planck Institute in Göttingen continues as planned. The next thing that Herminghaus wants to study is new types of model sand. These consist of tiny platonic bodies, such as tetrahedrons and octahedrons. “The objective is to understand how the grains’ shape influences the properties of the wet granulate,” says the physicist. In the process, he and his team are moving closer to a precise understanding of how moisture behaves in natural sands whose particles differ in shape. And they may also learn more about how oil behaves in the irregularly shaped pores of rocks.

GLOSSARY

Silicon dioxide
General term for compounds with the chemical formula SiO₂; subsumes modifications of silicon oxides. There is crystalline and amorphous SiO₂; the best-known crystalline form is quartz.

X-ray tomography
An imaging process for generating three-dimensional images of a specimen. X-ray absorption images are taken of the specimen at a large number of different angles. A powerful computer can then reconstruct the three-dimensional structure from these images (computer tomography).

Capillary bridge
A liquid bond that causes the grains to interact through the force of the surface tension.

Platonic bodies
Completely regular bodies consisting of equally sized, equilateral and equiangular polygons. Exactly the same number of surfaces meets at each corner of such bodies.

Phase diagram
A schematic representation of phases and their phase boundaries as a function of temperature, pressure and composition. Such diagrams can describe materials in their solid, liquid and gaseous states.