When the Soil Flows

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The puzzling phenomenon of soil liquefaction has led to many catastrophes - devastating earth dams, port quay-walls, marine structures, bridges, buildings, and roads, causing billions in economic losses, and costing thousands of lives

Water-saturated soils may undergo a phenomenon called liquefaction, when they experience a sudden shift from a state exhibiting macroscopic properties of a solid to a state with the consistency of a viscous liquid. Liquefaction is caused by shear stresses appearing in such soil as a consequence of strong shocks such as earthquakes, explosions, or storm surges. In connection with such events, residential buildings have repeatedly been seen to sink partially into the ground, some of them also tilting over as a result of uneven settlement due to subsoil liquefaction. People living on the second storey suddenly found their homes on the basement level. After the 1999 earthquake in Turkey, certain structures were discovered to have disappeared into the liquefied sea floor, while a seaside restaurant ended up on the sea bottom. The liquefaction phenomenon also poses a threat to marine structures such as drilling platforms or oil pipelines.

Courtesy of Dr. Robert Kayen, USGS

Surface craters indicate the appearance of the sudden dissipation of pore pressure, in the form of geysers of a water-soil mixture

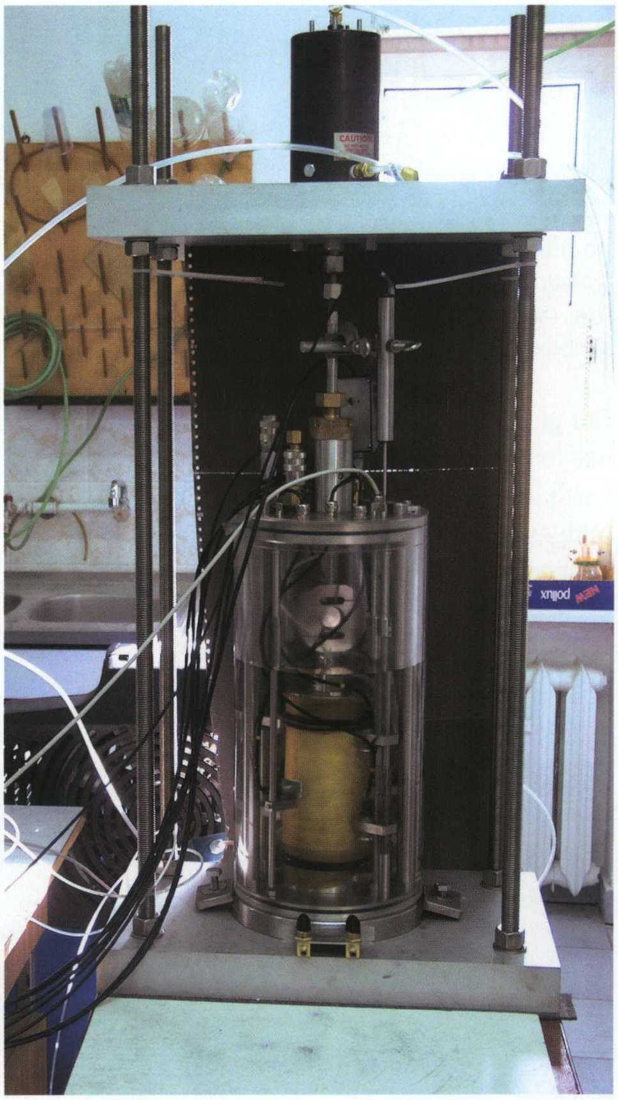
In Poland, although it is not a region particularly susceptible to seismic shocks, the liquefaction phenomenon also occurs. For instance, it was found to have been involved in the Dychów dam accident. Experts have identified the threats to Europe's largest waste disposal site, the post-flotation reservoir near Rudna (Legnica-Głogów Copper District, Silesia), to include potential liquefaction of the soils comprising the reservoir superstructure, stemming chiefly from potential para-seismic shocks caused by rock bursts in neighboring mines. Liquefaction may also be important along Poland's Baltic coast, in connection with plans to develop such infrastructure as artificial islands.

How does soil liquefaction work?

Saturated soil is a porous structure built of a soil skeleton, consisting of mineral grains of various sizes and shapes, plus water which fills the surrounding pores. Under normal conditions, those grains are in contact with one another and the whole structure can bear additional loads, such as overlying buildings, etc. The soil's own weight and external loads give rise to forces which act upon the contact surfaces between the grains, and are measured as effective stresses. These forces determine how solid the soil skeleton is and its capacity to bear additional loads. But should they disappear, the soil skeleton ceases to play its role. Effective stresses are therefore the key to understanding the soil liquefaction phenomenon, and are closely linked to the water pressure within the soil pores. Higher pore pressure reduces the effective stresses - and in extreme cases, if the pore pressure is great enough, effective stresses could disappear, which entails liquefaction of the soil. A building resting upon such ground will thus begin to sink and the process will continue as long as the ground soil remains liquefied - usually just few minutes, i.e. the duration of an earthquake. Once the event is over, the excess pore pressure dissipates and the ground returns nearly to its initial state.

First inroads

Soil liquefaction is preceded by rising pore pressure, accompanied by a reduction of the effective stresses. Under ordinary conditions, i.e. where there are no extreme events, the water pressure within the pores can be calculated easily. But calculating the excess pore pressure generated by additional shocks like earthquakes, explosions, or storm surges poses a significantly more difficult task. Moreover, other problems also arise, such as greater macroscopic weakening of the soil skeleton the greater the pore pressure becomes, manifesting itself in reduction of the soil



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Samples of saturated soils tested in a cyclic triaxial compression apparatus at a laboratory of the Institute of Hydro-Engineering of the Polish Academy of Sciences

skeleton stiffness and the material appearing to soften. Modeling these phenomena poses a great challenge to soil mechanics and engineering researchers. Overall, researchers now seem to be making only our very first inroads here.

Modeling liquefaction

It is very difficult to observe the liquefaction phenomenon in real time, as it occurs mainly during extreme events that are mostly unpredictable and moreover highly dangerous, and therefore not favorable for scientific research. It is only when we study the aftermath of such an event that we can ascertain whether soil liquefaction has occurred or not. Aside from obvious indicators like sunken buildings, liquefaction also leaves behind other signs like craters on the surface of the ground which served as exits for the generated pore pressure, in the form of ground water geysers. Empirical research has identified factors favouring liquefaction (fully saturated and loose soils) and identified the shear stresses - mainly cyclic, but also sometimes monotonic - as the causative factor. Such empirical knowledge has enabled the first theoretical models describing the phenomenon to be formulated, including models proposed by the Institute of Hydro-Engineering of the Polish Academy of Sciences.

The models developed at the Institute are based on an analogy between the compaction of dry or saturated soil allowing for the free flow of water through pores, and the generation of pore pressure without water outflow from the pores, as occurs during short-term dynamic loads. First a theory was built to model the compaction of granular soils subjected to cyclic loads, which was subsequently supplemented with a model describing soil deformation before failure. Next, drawing upon the analogy mentioned above, a model was developed to describe the generation of pore pressure within saturated soil and the degradation of the mechanical properties of the soil skeleton, for both cyclic and monotonic loads. These models were verified in the laboratory, and next used to describe and analyze a range of problems of great practical significance: the settlement of foundations under turbogenerators, soil settlement as a result of earthquakes, phenomena which occur when piles are driven into the ground, the compaction and liquefaction of soils during explosions, pore pressure generation in the sea floor during storms, the liquefaction of the ground under breakwaters, the phenomenon of objects sinking into liquefied ground, the process of pore pressure generation in dams during earthquakes, and the dissipation of pore pressures.

A fifth state of matter?

This paper has looked at just one spectacular phenomenon that is characteristic for soils. Granular media are also a subject of study for physicists dealing with natural complexity and self-organization. A growing number of papers on the topic are being published even in such prestigious journals as *Nature* and *Physical Review Letters*. Some authors, definitely going to extremes, are even beginning to treat loose media as a fifth state of matter.

The mechanics of granular media, including soil mechanics, is no longer a closed specialization. Many fundamental problems are still waiting to be solved. We must hope that the authorities responsible for the development of science in Poland will support the further advancement of the field, while we do our utmost to ensure that the research done continues to be of world-class caliber. ■

Further reading:

Sawicki A., Mierczyński J. (2006). Developments in modeling liquefaction of granular soils, caused by cyclic loads. *Applied Mechanics Reviews (Am. Soc. Mech. Eng.), 59*, 91-106.

Groot de M.B., Bolton M.D., Foray P., Meijers P., Palmer A.C., Sandven R., Sawicki A., Teh T.C. (2006). Physics of liquefaction phenomena around marine structures. *Jnl Waterway, Port, Coastal, and Ocean Engng (Am. Soc. Civil Eng.), 132*, 227-243.

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Damaged and shifted quay-wall at the port of Derince (Turkey) caused by soil liquefaction

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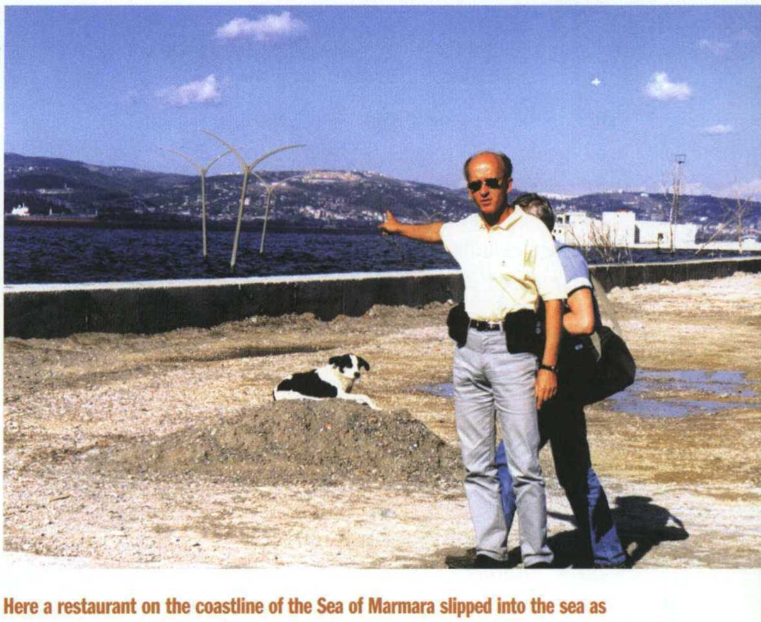

Here a restaurant on the coastline of the Sea of Marmara slipped into the sea as a result of soil liquefaction. Emerging from the water are the tips of lamp posts which once lit the road leading to the restaurant before the earthquake struck