Exploring the Unstable World of Geomaterials

From Fundamental Science to Engineering Solutions

The study of the materials and structures that appear solid and reliable but can fail or move violently—including the ground under our feet and buildings—is of great interest to Engineering and Applied Science (EAS) professors José Andrade, Domniki Asimaki, and Nadia Lapusta. They develop sophisticated, data-intensive models to computationally investigate solid dynamics and understand how forces move both tiny particles and large-scale geologic formations within the earth.

Some of these now-unpredictable movements are potentially catastrophic—earthquakes, for example, and the complex interactions analyzed by Lapusta.

José E. Andrade, Professor of Civil and Mechanical Engineering, who has been at Caltech since 2010, focuses on the complex dynamics of solid interfaces and the friction properties, both within the earth’s interior and in the lab. She develops friction laws and computational tools to analyze how confined materials and their interfaces behave under stress, some failing suddenly and violently and others moving more gradually and less destructively.

Domniki Asimaki, Professor of Mechanical and Civil Engineering, joined the EAS faculty last year, bringing from Harvard and MIT a vision of understanding the reactions of surface features of the earth, ranging from hills and cities to bridges and buildings, to the forces unleashed by subterranean players in the earth movement interactions analyzed by Lapusta.

The methods of study overlap for the three EAS faculty members, and for each of them, that means using sophisticated modeling that combines scientific understanding and empirical data. Says Lapusta, “People have to build buildings and make decisions now mostly based on the empirical models they have. We are developing models that agree with the empirical observations but extend them to the situations and environments that have not or cannot be easily tested, using fundamental science. We are building models that will enable more science-based engineering solutions for problems—new faces and bases.”

Asimaki agrees, supplying her own formulation: “For science, we want to understand why and create predictive models that we can test in the lab that have not or cannot be easily tested, using fundamental science. We are building models that will enable more science-based engineering solutions for problems.”

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near-surface geology characterization to scale up to continuum mechanics models of soil behavior. These models are complex because the physics of the problem in hand are complex: deformation of soft sediments, liquefaction of saturated granular soils, slope stability failure, landslides, and the effects of all of these on the civil infrastructure of urban regions—buildings, transportation networks, and pipeline distribution systems. She emphasizes that “the challenge, however, is that, exactly because the models we are building are large—basins, hills, and ridges, to do a few—we cannot characterize the material properties as well as we could have had the model been of a scale small enough to be tested in the lab. So while our models need to be complex to represent the complex behavior of geomaterials and how they affect the ground shaking, during strong earthquakes, they at the same time need to be simple—that is, based on parameters that we estimate using simple field tests, satellite imagery, or empirical models. Of course, this abstraction introduces uncertainty that we also seek to quantify: uncertainty from the phenomena that our complex-simple models cannot capture, uncertainty from the errors involved in the parameter estimation, and uncertainty related to the fact that geomaterials are very heterogeneous—that is, their physical properties (stiffness, strength) can change dramatically over the distance of a few tens of meters, and the characterization of this variability also involves uncertainty.”

Asimaki is working to develop models that can improve the currently limited state of the art of evaluating vulnerabilities to phenomena such as liquefaction, landslides, and ground deformation, and also estimating the forces that these so-called earthquake effects impose on the buried and surficial infrastructure (e.g., pipelines, tunnels, and foundations) that can help to determine the risk of urban environments to earthquakes. This is a critical area in cities all over the world, particularly in California, Domniki Asimaki explains, there is a window of opportunity, in the wake of the release by the Los Angeles mayor’s office of the Resilience Assessment Overlay. “It’s basically an attempt,” she says, “to prioritize spending for public infrastructure (pipelines, buildings), so that in the occurrence of the next big earthquake, the amount of human losses and the economic loss will be minimized, and the city will improve its capability to pick up and start functioning again.” But to do this, she adds, we have to fill in knowledge gaps. In this context, not only are there the quake-prone areas, with what kind of buildings? What areas will be replete with buildings? Or is it a mountainous area? Where will the most deformation be induced on the pipelines?”

To get useful answers to these questions, according to Asimaki, we cannot just “rely on faith and our understanding of soils, beams, and pipelines from other cities and other earthquakes. We need to use new methods and mathematically model future scenarios in the specific fault system under consideration. But even then, how can we estimate the uncertainty?”

A crucial element in achieving such physics-based assessment is the work being done in her colleague Professor Lapusta’s computer simulation laboratory. Lapusta’s methods probe the detailed underground dynamics of the stresses induced by tectonic motion and create models that reveal how the materials and their interfaces behave in response. Under the large compressive forces in the earth’s interior, failures at the plate boundary that produces earthquakes is localized to extremely narrow zones, less than a tenth of an inch wide. Inside such zones, the resistance to deformation modeled by micro- and nano-sized particles. Lapusta’s group also characterizes the mechanical properties at various depths, in order to visualize an area along an active fault that can be minutely, meticulously instrumented, with boreholes extending to various depths, in order to obtain unique and currently unavailable data on actual fault structure and properties at various depths, factors that are currently incorporated in models mostly based on material science theories. “Not today,” says Lapusta, and “maybe not even in 20 years. And yet, the amount of information and data that we are gathering is clearly enough to understand and modulate the behavior of these faults.”

She adds that Caltech is the ideal place to try: “It has the best solid mechanics faculty in the world and also the best geophysics faculty in the world,” she says. “Hence it is the best place in the world to work, which uses solid mechanics to understand earthquakes and their effects.”

Andrade finds Caltech’s relative smallness to be a particular benefit: “The energy barrier to communicate across campus is essentially zero. So at Caltech my group has been able to do things and to think of things that were not possible somewhere else.” He notes, too, that “the JPL connection would never have happened somewhere else. JPL is like a great playground for us engineers!” “It’s an inspiring place to work,” Asimaki agrees. “Scientific discoveries across campus motivate you to keep asking questions.” Plus, as she noted when we met last year, “I’ve never had the opportunity to live in a place that reminds me so much of Greece.”"