Left to right: Domniki Asimaki, José Andrade, and Nadia Lapusta

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 E. 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, or soil liquefaction. Thus one goal of the solid dynamics effort is to create new computational tools that can accurately model and even forecast such movements.

One critical application in this area is building safer structures and cities by better understanding and anticipating the types of potential motion and how artifacts and the ground they rest on will react to these motions. Another is making better concrete for various structures and in a more energy-efficient way.

The research of Professors Andrade, Asimaki, and Lapusta focuses on multi-scale, multi-physics, nonlinear problems, and the challenge for all is how to translate their fundamental science into triumphs of engineering. Fundamental science does not generate satisfactory solutions to many important problems: too many variables and unknown parameters are in play. Yet empirical understanding is highly limited; in the case of earthquakes, for example, there have not been enough large events to develop a robust empirical understanding of their effects. How does one create the best engineering solutions given empirical knowledge and our developing fundamental understanding? “Addressing such engineering challenges to positively impact people’s lives is central to the purpose of engineering as a whole,” says Ares Rosakis, Theodore von Kármán Professor of Aeronautics and Professor of Mechanical Engineering.

ENGenious sat down with the three faculty members to jointly discuss their work and the ties that link them. Nadia Lapusta, Professor of Mechanical Engineering and Geophysics, who has been at Caltech since 2002 after a start at the National University of Kiev and Harvard, focuses on the complex dynamics of solid interfaces and their 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 Athens and MIT a vision of understanding the reactions of surface features of the earth, ranging from hills and valleys to bridges and buildings, to the forces unleashed by subterranean players in the earth movement interactions analyzed by Lapusta.

José E. Andrade, Professor of Civil and Mechanical Engineering, who has been at Caltech since 2010, has been studying the properties of ground itself, of heterogeneous mixtures natural and artificial. Many materials—sand is one familiar example—are assemblies of particles of various shapes and sizes and chemical compositions with empty space between them. These do not have the neatly predictable behaviors of pieces of metal or crystal, but their behavior has to be understood both for industrial processes and for analysis of the natural world.

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 tomorrow.”

Asimaki agrees, supplying her own formulation: “For science, we want to understand why and create predictive models about the events that we experience. But engineers are trained to find practical solutions to problems. Sometimes the solutions are not perfect, but they’re good enough to build a building. Lots of the holes that they lack in understanding, they fill with empirical models. They extrapolate without complete understanding. Our studies aim to develop more fundamental-science–based approaches to such extrapolations.”

“I think it’s a difference in the philosophy between the way that we see things at Caltech and the way that usually the engineering world perceives things,” adds Andrade. “Our approach here at Caltech is more of an engineering science approach. As Nadia and Domniki explain, let’s find a solution that relies on fundamental science while explaining empirical ideas.”

The three have succeeded in applying this approach to their different but related problems. Working on the smallest scale is Andrade, who explores granular particle mechanics (GEM) using an analytical path called the discrete element method. As an abstract of one of his recent papers explains, “It has been determined that lack of sphericity, sharper angularity and increased roughness all lead to increased mobilized strength in granular materials. For decades engineers have used very rough approximations of shape irregularities to make quite inaccurate predictions about behavior of such materials.” But Andrade’s group has found ways to statistically specify the various sizes and shapes of the disparate granules seen in high-resolution X-rays and other imaging technology. Their technique then allows them to use these detailed quantifications to predict precisely the properties to be expected in masses of granules.

“GEM bypasses one of the current bottlenecks in computational discrete mechanics of granular materials by allowing discrete elements [of modeling] to take realistic and complex granular shapes encountered in engineering and science (e.g., sand grains),” says Andrade. “It is expected that, with the rapid advancement of computational power, combining high-fidelity characterization with physics-based computations will lead to more predictive modeling approaches. The granular element method may help transition from characterization to modeling and could lead to more realistic predictions at the grain scale.”

Humans create and use huge amounts of granular materials. Concrete, a key example, is mixed by the gigaton yearly for construction projects from skyscrapers to backyard patios. A better understanding of particulate behavior, Andrade believes, may allow for the formulation of more precisely and optimally shaped concrete particles, which will mix more completely and efficiently and produce stronger walls and foundations—and do so in a more energy-efficient fashion.

“The CO$_2$ footprint of concrete has to do with all the energy that has to be harvested in order to make concrete, from breaking stone all the way to making the actual concrete that makes buildings,” Andrade says. “The cement component goes into conveyor belts. It goes into trucks. It gets mixed with water. It gets mixed with sand. Each time you undertake one of those processes, you spend energy. It has been calculated that in all of those processes, we waste about 60% of the energy we use.” The right model could improve this, says Andrade. It could “enable you to decide on a better mixing technique, for instance. Instead of being only 40% efficient, maybe it would be 50% efficient or 60% efficient, and therefore waste less energy. So all of a sudden, your mixer needs to use less fuel to mix.”

The behavior of sand, earth, and other granules is also important for problems with larger spatial scales, such as in the assessment of the effects of geological forces. Asimaki explains: “At these scales, computational constraints prohibit us from using detailed models composed by individual grains. Instead, we combine the understanding from these models with empirical data from laboratory experiments and field studies of

Domniki Asimaki (left) and Nadia Lapusta

near-surface geology characterization to develop 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 name a few—we cannot characterize the material properties as well as we could 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. And now, 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 blanks. "Where exactly are the quake-prone areas, with what kind of buildings? What areas will be more prone than others? 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 where they lie in the valley of Los Angeles as well as the buildings and pipelines." We still need better modeling tools for the effects of earthquakes in general on soils and geological structures and buildings, Asimaki says. This is achievable, she adds, if we make the effort: "At least for the Los Angeles basin, we will be able to improve near-surface land deformation predictions on these large scales so that we can have physics-based assessments of the risks if an earthquake falls on the distributed system."

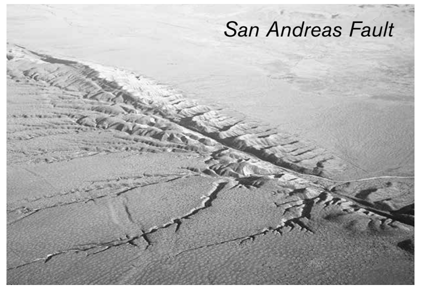
A crucial element in achieving such physics-based assessment is the work being done in her colleague Professor Lapusta's computer simulation laboratory. Lapusta's methods probe the detailed underground dynamics of the stresses induced by tectonic motion and create models that reveal how the materials and their interfaces behave in response. Under the large compressive forces in the earth's interior, failure of solids that produces earthquakes is localized to extremely narrow zones, less than a tenth of an inch wide. Inside such zones, the resistance to motion is determined by micro- and nano-sized particles. Lapusta's group includes in its models insights into how such materials behave from various sources, including micro-modeling from Andrade's group and Lapusta's own micro- and continuum modeling of localized shear.

In some cases, Lapusta notes, "as loading increases, the material resists until it experiences a catastrophic failure, a high-magnitude earthquake. But sometimes it accommodates the loading by gradually sliding and releasing the stored energy less violently. This understanding, as it increases, opens intriguing possibilities of both forecasting different types of behaviors and new action alternatives."

There are limits, of course, but Lapusta also sees great potential. "To predict that there is going to be an earthquake on Tuesday at 2 p.m. will not be possible," she says. "But what else can we do about it? Our models are realistic enough at this point that we can start using our modeling and the increasing array of observations to understand the potential future earthquake scenarios and their effects. It may also be feasible to find a way to avoid a large earthquake altogether. Might we find a way to modify the behavior of the fault so that, instead of one large event, we get much smaller events or slow slip that does not generate shaking? This is quite futuristic and far-fetched but conceivable. But we first need to understand in detail what the physics of the process is, and then we can ask if we can modify it."

The beginnings of this striking vision took the form of a graphic portrait of a segment of the San Andreas Fault, imaged from an array of instruments on the surface. A range of motion of the segment was reproduced in the simulation, from almost none in some parts of the fault to active slippage corresponding to the known movement—a stop-action movie of the earth in motion. Then Lapusta and colleagues modeled in detail earthquakes in Taiwan and Japan, trying to find the subterranean differences leading to massive, violent slips, as opposed to gentler, more gradual slides. In these studies, the researchers combined all known fault behaviors—earthquake nucleation, dynamic rupture, post-seismic slip, interseismic deformation, and patterns of large earthquakes—in a single dynamic model. The construction of such a model was facilitated by extensive collaborations and consultations across campus with a number of EAS and GPS (Geological and Planetary Sciences) faculty.

One message that came out of this work has disturbing consequences for California: creeping segments can participate in large earthquakes, and hence much larger events than seismologists currently anticipate in many areas of the world are possible. That means, Lapusta says, that the seismic hazard in those areas need to be reevaluated—including around the San Andreas Fault.



San Andreas Fault

A creeping segment separates the southern and northern parts of California's San Andreas Fault. Seismic hazard assessments assume that this segment would stop an earthquake from propagating from one part to the other, limiting the scope of a San Andreas quake. However, Lapusta's models suggest that a much larger event may be possible than is now anticipated—one that might involve both the Los Angeles and San Francisco metropolitan areas.

Lapusta and Asimaki say we still need to have a much deeper understanding of exactly what we have along our faults in California, both to make estimates of possible damage and perhaps—not tomorrow, but someday—to take action to create prophylactic miniquakes or slow slip to relieve accumulating stress, such as by manipulating fluid effects. But to do this, much better information is required.

In the meantime, the hope of these researchers is more modest but still ambitious: a research valley. They visualize an area along an active fault zone 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 materials science theories. "Not today," says Lapusta, and "maybe not even in 20 years. But eventually we may learn enough to understand and modify 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 for my 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 she first arrived, "It's gorgeous! I've never had the opportunity to live in a place that reminds me so much of Greece."

José Andrade is Professor of Civil and Mechanical Engineering. Domniki Asimaki is Professor of Mechanical and Civil Engineering. Nadia Lapusta is Professor of Mechanical Engineering and Geophysics.