Seismic preparation for nuclear plants

Lowering costs without compromising safety

Rethinking seismic design may be key for making nuclear plant construction affordable.

By Cory Hatch

Nuclear power plants not only provide the nation's largest source of carbon-free electricity, they also can operate 24 hours a day, 365 days a year to augment intermittent renewables such as wind and solar. Further, studies show that nuclear energy is among the safest forms of energy production, especially when considering factors such as industrial accidents and disease associated with fossil fuel emissions. All said, nuclear has the potential to play a key role in the world's energy future. Before nuclear can realize that potential, however, researchers and industry must overcome one big challenge: cost.

A team at Idaho National Laboratory is collaborating with experts around the nation to tackle a major piece of the infrastructure equation: earthquake resilience. INL's Facility Risk Group is taking a multipronged approach to reduce the amount of concrete, rebar, and other infrastructure needed to improve the seismic safety of advanced reactors while also substantially reducing capital costs. The effort is part of a collaboration between INL, industry, the Department of Energy's Advanced Research Projects Agency–Energy (ARPA-E), and the State University of New York–Buffalo (SUNY Buffalo).

The cost of nonstandardization

For reactors built in the 1970s or earlier, the large number of utilities, reactor design companies, and vendors involved in the nuclear power industry meant that U.S. nuclear power plants varied significantly in design. This meant that each new nuclear power plant was custom-built, which increased the probability of costly construction errors or last-minute design changes. Further, the lack of standardization increased the time and expense of the regulatory process.

The same is true for more recent projects. Two well-documented nuclear power projects using Westinghouse AP1000 reactors highlight the state of the industry. In South Carolina, a $9.8 billion expansion to the V. C. Summer Nuclear Station was abandoned in 2017 after costs spun out of control. Another project, adding two reactors to the Vogtle Electric Generating Plant in Georgia, has seen costs rise from the original estimate of $14 billion to more than $25 billion.

"The overnight capital cost of nuclear is four to five times too high," said Andrew Whittaker, SUNY Buffalo distinguished professor in the Department of Civil, Structural, and Environmental Engineering. "A lot of this work is focused on, how do we deliver sufficient safety and drive down overnight capital cost? How do we squeeze every penny we can out of new-build nuclear plants, recognizing that other industries have been doing this for a long time?"

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Earthquake mitigation expense

Utilities and nuclear engineers, going for economies of scale, have typically settled on building multiple large reactors at each power plant site. For a light-water reactor, that means a great deal of infrastructure—in the form of reinforced and prestressed concrete and steel—to contend with not only the high pressures required for operation, but also consequence mitigation in the event of a major earthquake or other natural disaster.

At some reactor construction sites, ensuring seismic stability starts with removing and replacing all of the soil at the site. Then the foundation, cooling towers, and other infrastructure are built with many tons of reinforced concrete, which is a composite of concrete and steel rebar.

This strategy of overbuilding nuclear power facilities to mitigate seismic risk has worked well. The World Nuclear Association estimates that 20 percent of the world's nuclear reactors are operating in areas of significant seismic activity, yet damage to nuclear reactors resulting directly from earthquakes is rare. Take the situation at Fukushima Daiichi: The magnitude 9.0 Great Tohoku Earthquake caused a 40-foot tsunami that damaged the cooling systems of the nuclear plant, causing the accident. According to the WNA, "Eleven reactors at four nuclear power plants in the region were operating at the time, and all shut down automatically when the earthquake hit. Subsequent inspection showed no significant damage to any from the earthquake. . . . The [Fukushima Daiichi] reactors proved robust seismically, but vulnerable to the tsunami."

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Still, the way we currently design nuclear power plants for seismic safety often makes new reactor construction prohibitively expensive, especially in the United States.

"For nuclear reactors in the U.S. and Western Europe, the capital costs are so high that very few utilities can afford [to build] one," said Rachel Slaybaugh, associate professor of nuclear engineering at the University of California–Berkeley, who recently served as ARPA-E program director and was a member of President Joe Biden's transition team. Slaybaugh added, "Right now, if you build a new reactor, the cost is 50 percent site preparation and concrete, in part due to earthquake mitigation."

Reducing those capital costs is a big part of the focus at INL, according to Chandu Bolisetti, Facility Risk Group lead at the laboratory. And none of that can happen without considering seismic safety infrastructure. "Recently, people have found that a lot of the economic problems in the nuclear industry are capital costs because of structural and construction engineering," he said. "A majority of the cost is from the structures you build around the core, not the core itself, and seismic hazard is one of the drivers of how you design these structures."

Reducing costs through innovation and standardization

Advanced reactor designs, which rely on a range of fuels and coolants, could help mitigate the cost dilemma. For example, most advanced reactor designs rely on natural circulation systems instead of pumps for coolant circulation and for safety systems in case of accidents. These passive safety features not only reduce the amount of infrastructure—electric pumps, valves, and overbuilt pipes are eliminated—but also make the reactors walk-away safe in case of an accident. In addition, most fast reactor designs operate at near-atmospheric pressure, so they don't require expensive containment domes and all of the associated concrete and rebar.

Further, some advanced reactors could be designed to be built in a factory and shipped to the construction site, as opposed to being custom-built. Standardizing reactor designs this way has the potential to dramatically reduce design errors and construction flaws seen in custom-built reactors. Once a reactor design is proven and approved, repeating the construction of that same reactor should reduce regulatory expenses and shorten the regulatory review time by several years.

But Bolisetti points out a major hurdle. "Right now, you have to build and license a different structure in California [versus] in New York," he said. "Seismic hazard is one big barrier to standardization. How can you use the same equipment everywhere and make it safe at the same time?"

Seismic isolation

Bolisetti and the Facility Risk Group have looked to other industries, especially those in earthquake-prone areas, and combined those technologies with state-of-the-art modeling and analysis to come up with different approaches to the seismic challenge.

One such solution, seismic isolation, makes use of a technology that has been successfully employed to protect all kinds of infrastructure projects—from schools to offshore drilling platforms to bridges. Examples of buildings in the United States that make use of seismic isolation include San Francisco City Hall, the Utah State Capitol building in Salt Lake City, and Apple's new headquarters in Cupertino, California.

Seismic isolators are essentially shock absorbers placed between a building and its foundation. There are a number of different types of seismic isolators, but one common design is made of alternating layers of rubber and steel with a lead core. Depending on the building, as well as the seismic characteristics of the site, engineers could place tens or even hundreds of seismic isolators under any given building.

"When an earthquake hits a nuclear power plant, seismic isolators absorb the earthquake's energy, and most of the energy will be dissipated," Bolisetti said. "It drastically reduces the shaking you see in the plant."

According to Slaybaugh, seismic isolators represent an important and relatively inexpensive technology for standardizing nuclear reactors. "With isolators, you're trying to get rid of doing this site-specific work," she said. "You're not customizing the building or the reactor, just the seismic mitigations for each site."

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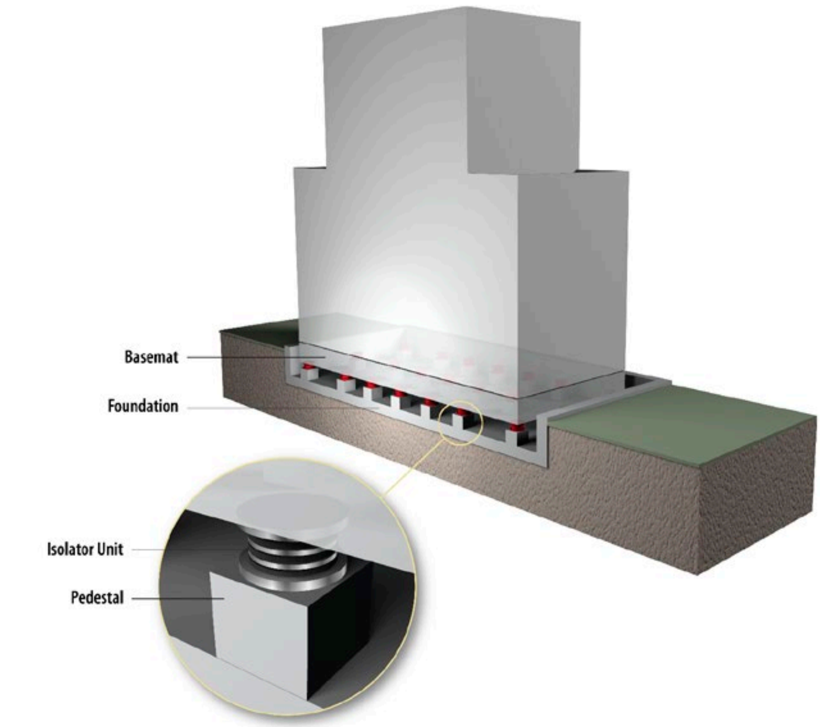
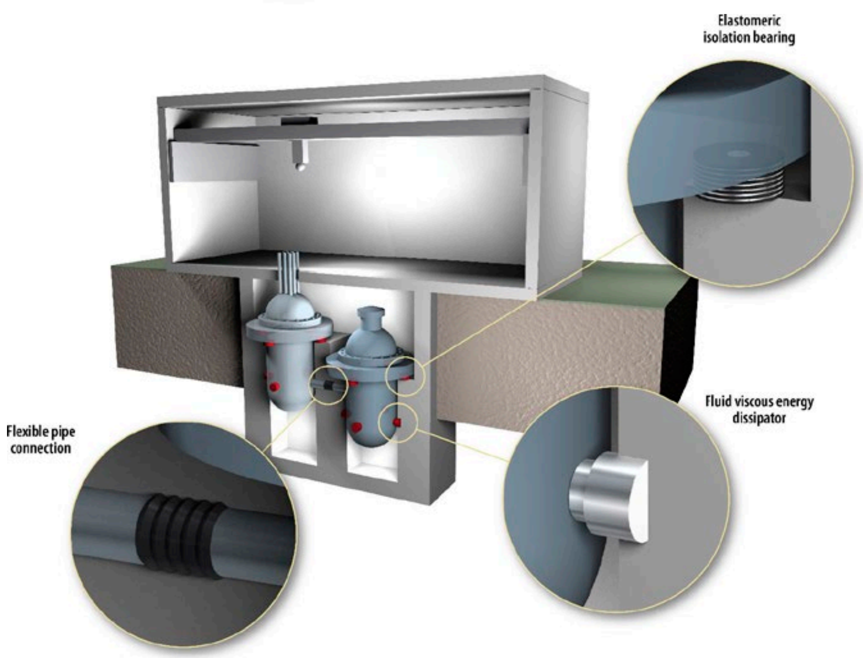
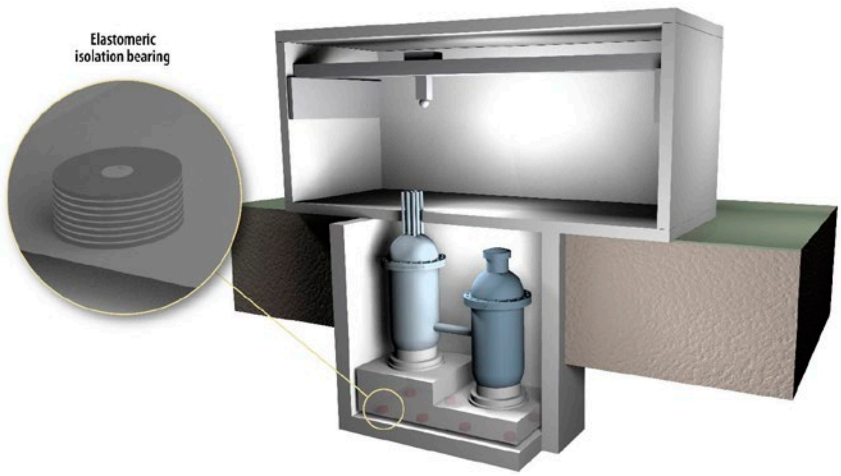






Seismic isolators can be used to provide seismic isolation for an entire structure. One application of seismic isolation is to individually isolate critical components like reactor pressure vessels and generators (center). Seismic isolation can be used to isolate systems within a nuclear power plant, like the reactor and electrical generator together (bottom). Images: INL

Seismic analysis and risk assessment

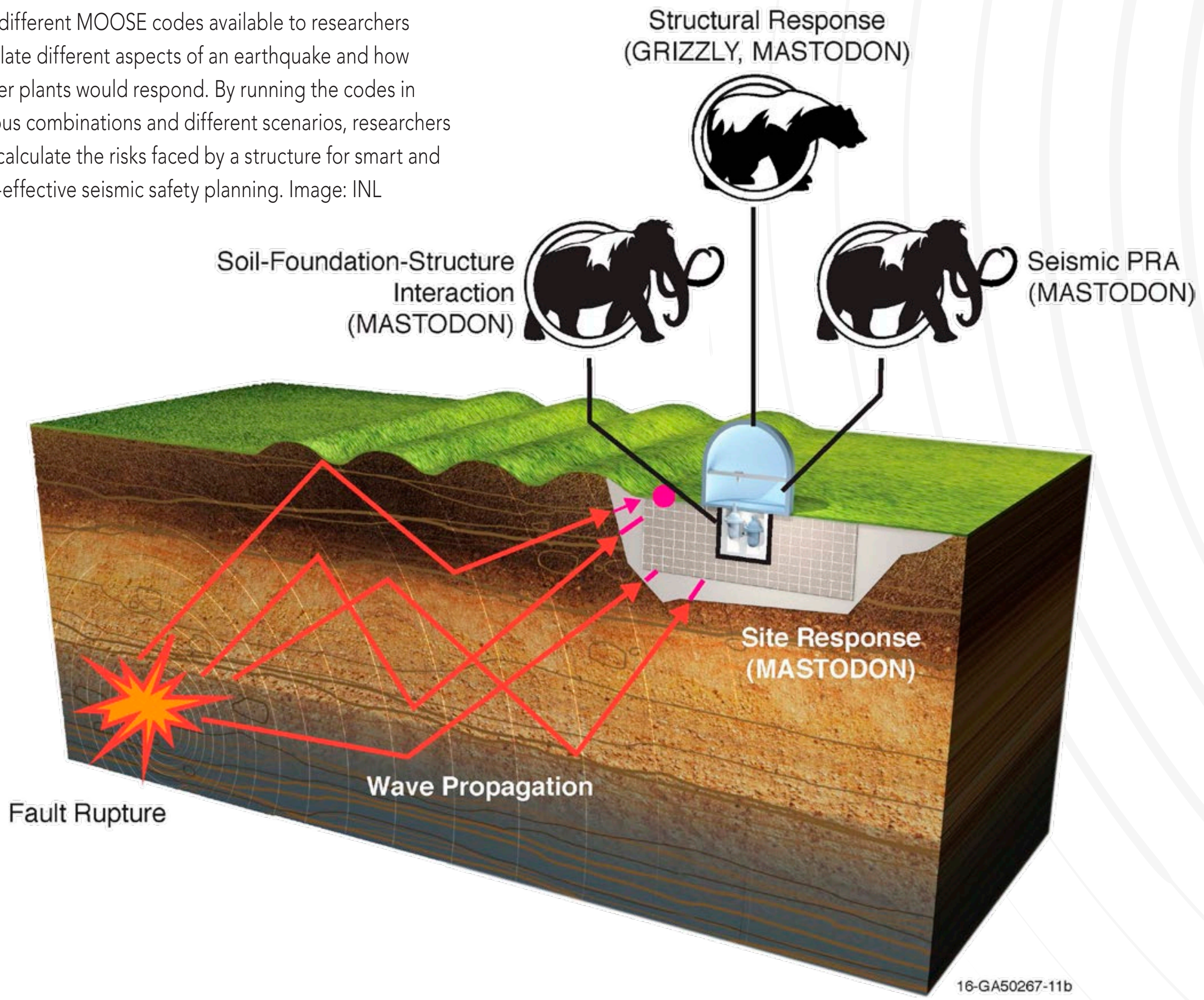
Another way to reduce costs of nuclear power facilities is to better assess the risk of earthquakes at a given site and then build the facility accordingly.

Engineers now rely on probabilistic seismic hazard analysis and seismic probabilistic risk assessment—methods of quantifying the intensity of potential earthquakes and the risk of damage to a facility, respectively—to design and maintain nuclear power facilities so they are built to withstand the largest earthquakes expected at a given location. But the existing methodology means that engineers are often overdesigning structures for earthquakes. For instance, nuclear power facilities in France are designed to withstand an earthquake twice as strong as the 1,000-year event calculated for each site, according to the WNA. That may be an appropriate level of seismic safety in some locations, but at other sites, it may be overkill.

Earthquake loads are incredibly challenging to predict and involve a certain amount of uncertainty. "We currently overdesign because we tend to be very conservative and use large safety factors when calculating the seismic load," said Bolisetti. "We are trying to be more accurate in our predictions of seismic loads, so engineers don't have to use such large safety factors."

At INL, Bolisetti and his colleagues are using powerful modeling and simulation tools to better understand the risk from earthquakes at different types of safety-critical facilities such as nuclear power plants and dams. Bolisetti's team is using the Multiphysics Object-Oriented Simulation Environment (MOOSE), a framework developed at INL that allows researchers to build their own simulation

The different MOOSE codes available to researchers simulate different aspects of an earthquake and how power plants would respond. By running the codes in various combinations and different scenarios, researchers can calculate the risks faced by a structure for smart and cost-effective seismic safety planning. Image: INL



applications by plugging in the right physics equations.

Though INL's computer scientists originally designed MOOSE to model how nuclear fuel performs in a reactor, the open-source software is flexible enough to simulate many physics problems, including seismic analyses. One MOOSE application—MASTODON (Multi-hazard Analysis for STOchastic time-DOmaiN phenomena)—is specifically designed to simulate, in 3D, the risks that natural and human-caused hazards such as earthquakes and floods pose to structures such as nuclear reactors.

This modeling and simulation technology can be used to answer complex questions: How does the molten salt/fuel mixture found in some advanced reactors behave when the "fluid" shakes during an earthquake? How might that molten salt mixture respond to an earthquake motion that is damped by seismic isolators?

Another question relates to some advanced reactor designs that would embed the reactor underground. "We know that the seismic load will be smaller when something is embedded," Bolisetti said. "But we don't know by how much. We're using the simulation tools to predict seismic loads on deeply embedded structures."

He added, "If you use more accurate tools to show that a facility has a good safety margin, you don't have to spend $100 million to strengthen something that doesn't need to be strengthened."

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Design optimization

Engineers could also reduce costs by optimizing the design of a nuclear facility to concentrate protection on the pieces of equipment that need it the most.

"Previous work focused on isolating the entire reactor building," said Whittaker. "That's certainly viable, but some reactor developers are looking to isolate specific pieces of equipment for ease of construction, for safety, or to protect an expensive asset."

For instance, the designer of a nuclear power facility may choose to use seismic isolation or some other earthquake mitigation infrastructure for the reactor vessel and the steam generator, since those two pieces of equipment would be expensive to replace and could pose safety hazards.

"How do you design a nuclear power plant in such a way that you are spending the money where you need it?" Bolisetti said. "We want to know how much each component is contributing to the risk so that the money is spent where the risk is the highest."

Not compromising safety

In the end, Bolisetti said, the goal is to make sure that safety is not sacrificed for cost. "We know how to achieve safety," he said. "But, if we want nuclear in the mainstream energy space, we need to make it cheaper."

Whittaker agreed. "We're not going to compromise seismic safety at all, but you also don't need a product that is a hundred times safer than it needs to be. We must meet all safety goals while recognizing that the industry must be commercially viable." Whittaker added that tackling these big-picture questions is where INL's leadership is invaluable.

Most advanced reactor developers understand the need to take a holistic approach to designing and constructing new plants. INL is making important contributions in a number of areas and disciplines for the construction of next-generation reactors, with its work encompassing not just Bolisetti's Facility Risk Group but also the National Reactor Innovation Center and the DOE's Advanced Reactor Demonstration Program.

"At the end of the day," Whittaker said, "it's dollars that are going to drive decisions to build, and the industry must develop a pathway to commercial viability, including minimizing the financial risk to potential customers."

Modern seismic preparation techniques—from seismic isolator technology to advances in modeling and design—can play a role.

Cory Hatch (matthew.rodgershatch@inl.gov) is a science writer for Idaho National Laboratory.