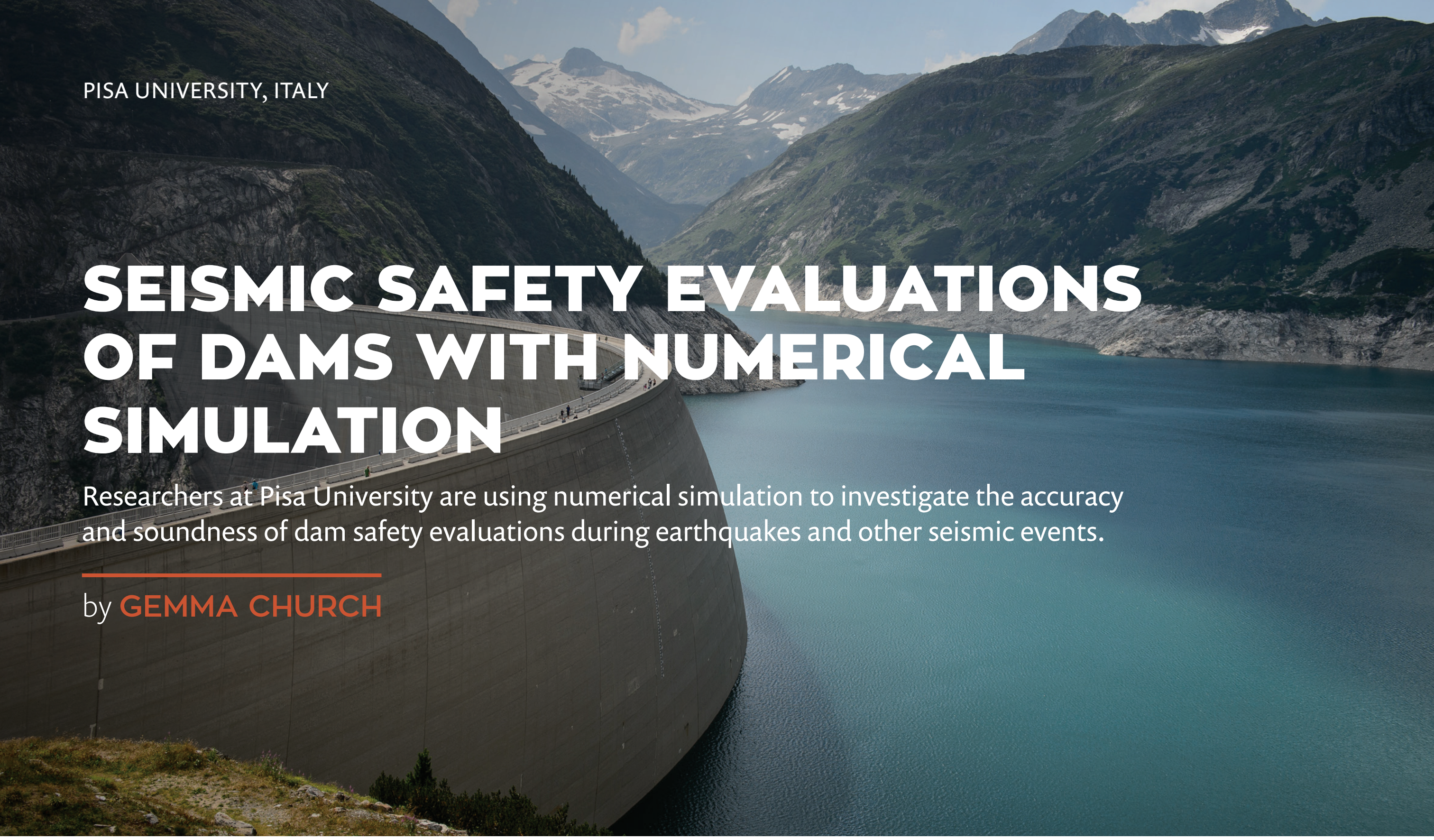

PISA UNIVERSITY, ITALY

SEISMIC SAFETY EVALUATIONS OF DAMS WITH NUMERICAL SIMULATION

Researchers at Pisa University are using numerical simulation to investigate the accuracy and soundness of dam safety evaluations during earthquakes and other seismic events.

by **GEMMA CHURCH**

Structural integrity and adherence to code requirements are paramount in the development of all types of large constructions and buildings. Numerical simulation can be of great help but is only as good as the assumptions that go into the mathematical model, and when it comes to the seismic safety evaluation of dams, there is a growing demand for a more rigorous approach. The failure of large structures poses serious safety concerns and often causes severe damage, with a higher risk during earthquakes.

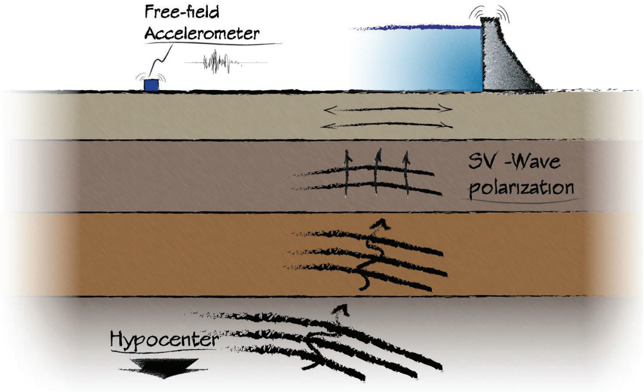

FIGURE 1. Schematic of the waves generated in the terrain by an earthquake.

Dams are huge barriers built across rivers and streams to restrict the flow of water for purposes such as irrigation and the production of hydroelectricity. Because of the unique interactions with both soil and water, modeling techniques used for conventional buildings are not directly applicable to dams. Assessing the behavior of these dam-reservoir-soil systems is complex and has been approximated and simplified for years. But through new efforts led by a team of researchers at Pisa University in Italy, a renewed accuracy and soundness of dam simulations has been developed and looks to make the future of these gargantuan structures much safer.

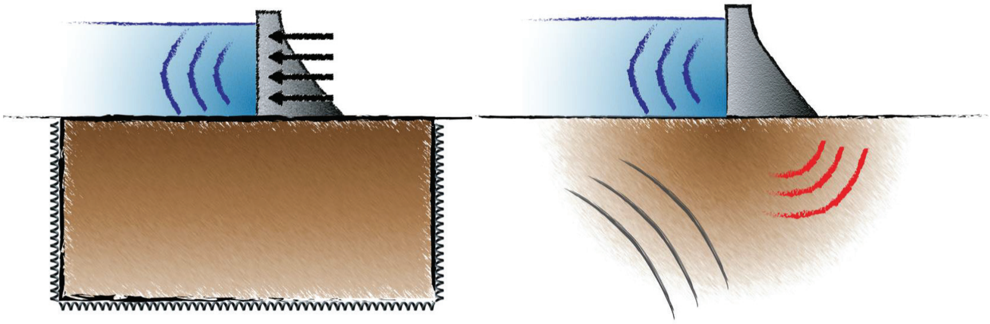

FIGURE 2. Comparisons of the direction of energy transfer between the massless foundation (left) and the infinite terrain model (right).

Under the influence of earthquake excitation, the concrete gravity dam, water reservoir, and soil foundation behave as a coupled system.

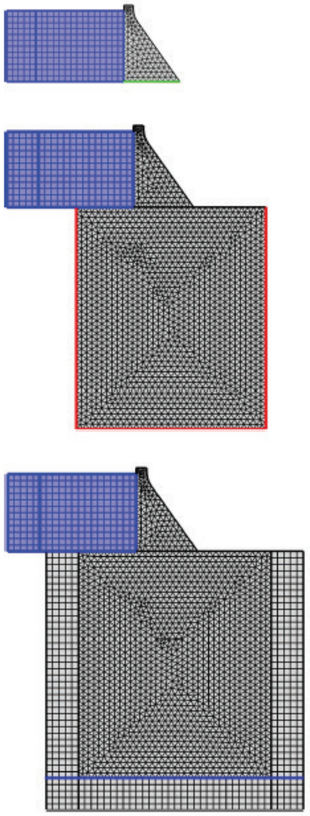

FIGURE 3. Geometry adopted for the three modeling techniques: rigid base (top), massless foundation (middle), and infinite terrain (bottom).

Due to the high complexity involved, the computational sophistication required has not been readily available; thus, the soil-structure interaction is frequently neglected or roughly estimated via simplified assumptions. The risk in not considering these interactions is the possibility of unexpected stress amplifications within the dam body.

⇨ SOIL-STRUCTURE INTERACTION

Both kinematic and inertial effects are part of the soil-structure interaction, but the inertial effects are rarely accounted for. While the kinematics are governed by soil flexibility and are influenced by the structure's stiffness, the inertial effects are influenced by the structure's and the soil's density properties. Under excitation, the concrete wedge making up a dam moves back and forth in the soil, but the soil is not massless and does not simply move along with the slab. The soil and structure both directly influence each other, and this interaction generates elastic waves that travel through the soil, carrying energy away from the system (Figure 1). This is known as "radiation damping."

Currently, simulating soil effects on seismic behavior consists of a couple of methods, but they all leave something to be desired. Soil effects are considered in conventional building models by using code-provided response spectra based on the type of soil. However, structural differences between conventional buildings and dams render these methods inappropriate. Furthermore, for dams specifically, a technique called the "massless foundation" model (Figure 2) has been extensively implemented in dam-foundation analysis, modeling the soil solely in terms of flexibility and displacement at its boundaries. By disregarding the inertial effects and assuming the soil is "massless", all of the kinetic energy in the system is transferred to the base of the dam, which is unrealistic and results in substantial overestimates of the seismic response.

⇨ UPPING THE COMPLEXITY WITH NUMERICAL SIMULATION

Numerical simulation allowed Matteo Mori of the Department of Energy Engineering of Systems of Land and Construction at Pisa University to explore the full soil-structure interactions in his simulations. "The flexible nature of COMSOL® makes it the most straightforward software to work with, and in our case, we appreciate the breadth of features available for the study of elastic, or acoustics, waves," Mori says. "It is comprehensive in nature and a powerful tool for our research."

The viability of any new technique to model concrete gravity dams needs to be considered in context, so Mori decided to run three different models under multiple scenarios. He investigated the dynamic response of each system under earthquake excitation and compared the findings. The three models, rigid base, massless foundation, and (full) infinite terrain analysis, are shown in Figure 3; each has an additional degree of sophistication beyond the former.

The blue rectangular area represents the water reservoir, the triangular region represents the dam, and the large rectangular region represents the soil. The soil domain in the massless model is simply that, massless soil with only flexibility and displacement.

To ensure consistency across the model types, the horizontal harmonic acceleration boundary condition at the base of the dam (green, red, and blue lines), which simulates the earthquake excitation, is set up such that the base acceleration at the dam is the same for all three models. A global equation feature, available in COMSOL, is used in the third model to ensure that the boundaries allow for waves to pass through.

A key aspect of the infinite terrain model is the perfectly matched layer (PML) surrounding the soil. A powerful feature in the COMSOL Multiphysics® software, PMLs absorb all incident waves, regardless of angle and frequency, preventing them from returning back into the medium after incidence at the boundaries. This feature helps incorporate radiation damping and energy dissipation, treating the unboundedness of the soil domain as a perfectly absorbing material and creating a decaying oscillation of the concrete slab without any reflection of the energy waves.

"COMSOL offers the suitable tools to perform accurate multiphysics simulations, including fully coupled fluid-structure interaction (FSI) analysis and infinite domains," Mori

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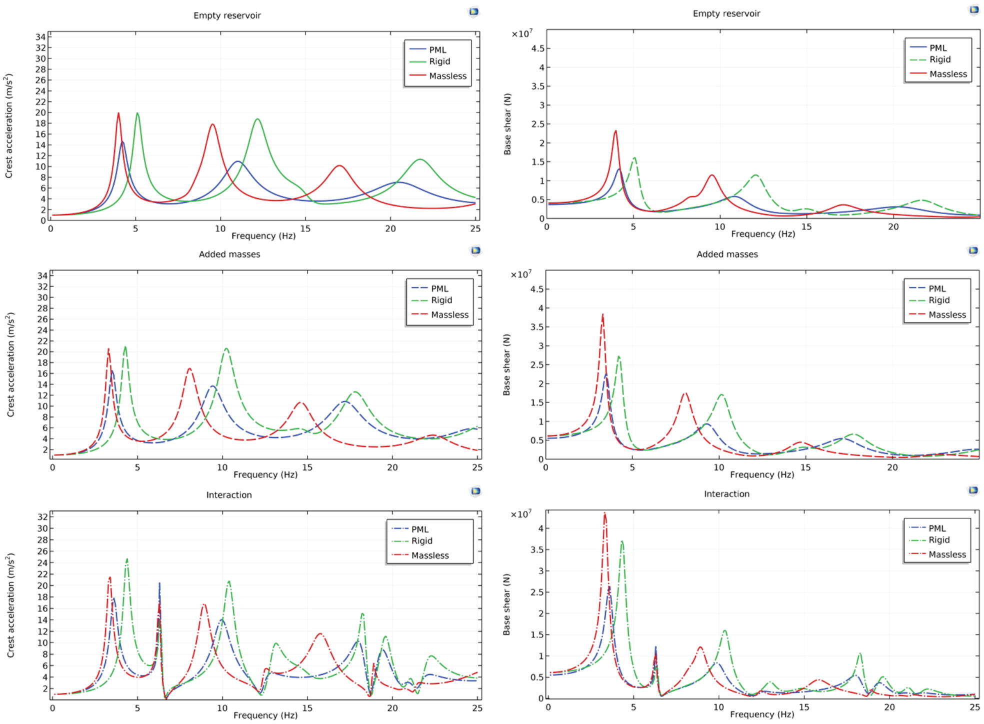

FIGURE 4. Base shear and crest acceleration for an empty reservoir (top), an added mass approach (middle), and a full elastic wave coupling approach (bottom).

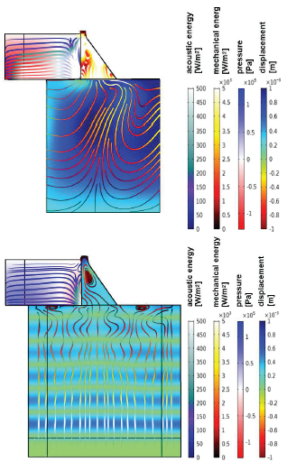

FIGURE 5. Plot of the mechanical displacement, fluid pressure, and mechanical energy flux streamlines for the massless foundation (top) and infinite terrain (bottom).

says. The fluid subsystem is solved using the Helmholtz equation in the hypothesis of small vibrations and neglected viscosity, the soil and dam subsystem is solved with solid mechanics, and the unbounded terrain is modeled with the PML functionality.

⇨ OBTAINING RESULTS IN CONTEXT

The soundness of the infinite terrain model is assessed by applying multiple scenarios to a 65-meter-tall concrete monolith, namely both empty and filled reservoirs. Furthermore, the filled basin is simulated in two ways: with a full elastic wave coupling and a simplified "added mass" model. Added mass is a way to simulate the hydrodynamic effect of the basin, also known as "virtual mass." As the slab accelerates, it must also move the neighboring water, as the two cannot occupy the same physical space simultaneously. This adds inertia and essentially increases the effective mass of the slab.

The results obtained from these simulations are calculated with each technique (rigid base, massless foundation, and infinite terrain) for each basin scenario (empty reservoir, added mass, and full interaction). Compared to the rigid base and massless foundation models, the infinite terrain technique (blue curves, Figure 4) noticeably reduces and smooths the peak responses in all three cases. This smoothing is, as expected, due to the newly implemented considerations of radiation damping. As this phenomenon dissipates energy from the system into the unbounded earth terrain (simulated with the PMLs), a smaller and more realistic amount of kinetic energy is thus transferred to the slab. The other two modeling techniques fail to account for this.

There are also noticeable differences in the mechanical displacement, fluid pressure, and mechanical energy flux, as shown above in Figure 5. Whereas the massless model displays circulatory streamlines (which represent the acoustic energy flux) without a defined incoming wave front, the infinite terrain model's energy flux is clearly directionally defined. This is both visually and qualitatively indicative of the radiation damping that transmits energy away from the system, and it confirms that lower amounts of energy are transferred to the dam.

⇨ FINAL STEPS AND FUTURE WORK

"The fidelity of the model is the biggest challenge in our work because this is not a mathematically perfect problem and accurate predictions are difficult. The infinite terrain model is one method that can be considered a good solution, but there are still some developments required, which we are working on right now," Mori says. "Concrete is a brittle material," Mori explains. "We would like to be able to identify cracks in the dam structure."

They plan on implementing deconvoluted experimental data from accelerograms that monitor seismic activity to set more accurate boundary conditions in their models. This would yield tremendous power and accuracy for dam modeling in Italy as well as all over the world. ❖