Virtual Dams Subjected to Strong Earthquakes

Morrow Point Dam in southwest Colorado. (Image courtesy of the U.S. Bureau of Reclamation.)

THE U.S. Bureau of Reclamation (USBR) has constructed more than 600 dams in the western U.S. over the past several decades. USBR's Dam Safety Program ensures the safety of these structures and protects the public by using computer simulations to identify those dams that pose a potential risk to the public. With the help of Livermore computer codes and the expertise of civil engineer Chad Noble, USBR has advanced its computational and analysis capabilities for studying the response of dams to earthquakes.

"We want to help the Bureau of Reclamation study these structures using advanced computational methods," says Noble, who works in Livermore's Engineering Directorate. Realistic computer analyses of dams' vulnerabilities to Earth movement are critical because overestimating a dam's response can lead to unnecessary and expensive modifications, while underestimating its response could put nearby communities at risk. Furthermore, it is practically impossible to conduct small-scale experiments for determining the anticipated behavior of dams under strong seismic motions.

USBR asked Noble to simulate the seismic response of Morrow Point Dam, which was constructed from 1963 to 1968 in a 750-meter-deep gorge of the Gunnison River's Black Canyon in southwest Colorado. The Cimarron Fault is located about 1 kilometer from the dam. Morrow Point Dam impounds approximately 144 million cubic meters of water in the Morrow Point Reservoir, which extends about 7 kilometers upstream. The dam structure is 143 meters high with a crest (top of the dam) length of 221 meters. The dam ranges in thickness from 3.7 meters at the crest to 16 meters at its base.

Morrow Point Dam is a relatively thin, double curvature arch dam. An arch dam is curved upstream to transmit the major water load to the dam's abutments (the part of a dam that supports the ends) and to keep the structure in compression. A double curvature arch dam is curved vertically as well as horizontally.

Livermore Family of Codes

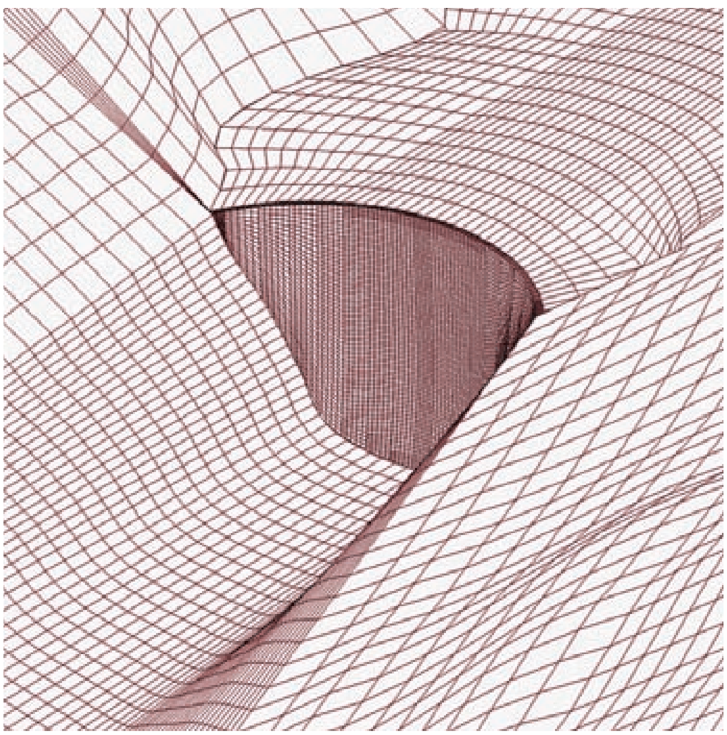
Noble was tasked with modeling the general area of the dam as realistically as possible and computing as accurately as possible the response of the dam to seismic forces. To accomplish the detailed seismic analysis, he turned to a family of codes developed at Livermore and now widely used by academia, private industry, and other government laboratories. These codes are the mechanical deformation codes NIKE3D and DYNA3D (and its variant for massively parallel supercomputers, PARADYN), as well as the thermal code TOPAZ3D. Noble previously used these codes in blast-effect analyses for homeland security applications, biomechanical applications, and a nonlinear seismic analysis of the Bixby Creek Bridge in northern California. The bridge analysis was part of a continuing Livermore effort to simulate the effects of destructive earthquakes. (See *S&TR,* September 2006, pp. 4–12.)

The Livermore codes use finite-element analysis, a method for analyzing engineering problems. In this approach, a solid object is divided into an assemblage of simple elements for which the computer calculates structural behavior. Visually, the collection of elements resembles a wire mesh. The element boundaries are defined by lines that intersect at junctions called nodes. The nodes at each corner define the movement and deformation of the elements. Each corner can move in any direction, depending on the stresses and strains it experiences. Finite-element analysis has been used to simulate car crashes, train accidents, nuclear waste containers falling off transportation vehicles, blade failures on aircraft, and biomedical interactions. (See *S&TR,* May 1998, pp. 12–19.)

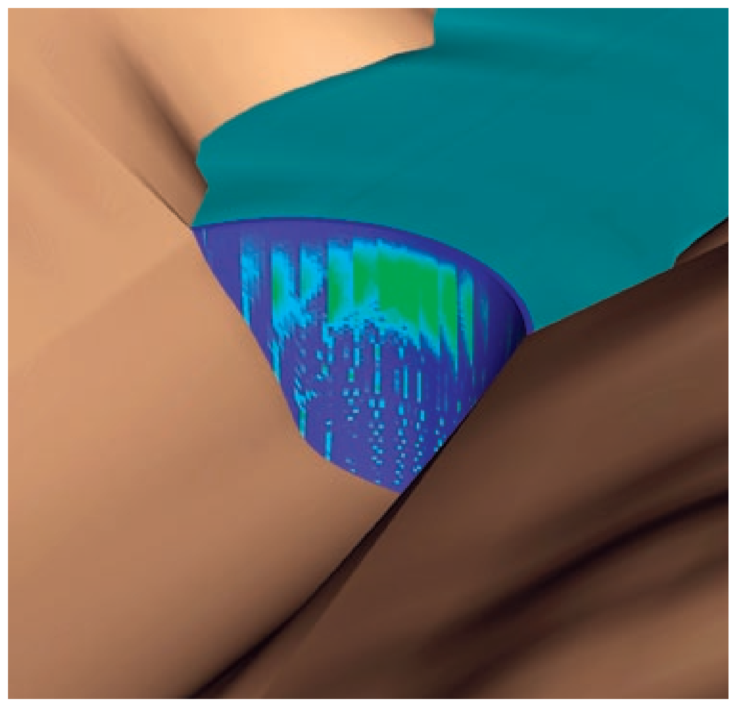
For the Morrow Point Dam study, Noble simulated a 2.6-kilometer area that included the dam and its foundation, part of the reservoir, and the surrounding canyon. An accurate representation of the region's geology and topography were required to study the effects of seismic waves traveling through the canyon.

Noble transformed the area into a mesh of 1 million brick-shaped elements of different sizes that extended 520 meters underground. A three-dimensional (3D) mesh of fluid elements was developed to represent the water in the reservoir and permit hydrodynamic interaction, which is the interaction between the reservoir and the dam during an earthquake. Hydrodynamic interaction can have a significant effect on the dam's response and must be considered in any dynamic analysis. In particular, hydrodynamic interaction has a larger influence on thinner, less massive dams such as Morrow Point. The simulated dam was composed of a much finer mesh of 30,000 elements. An increased mesh density produces results that are more accurate but requires additional computer time.

In addition, the simulation included the movement of the dam's 17 vertical contraction joints, which were incorporated in the dam's design to help relieve stress under different loading environments such as thermal changes and earthquakes. Livermore engineer Jerome Solberg developed a contraction-joint-contact algorithm that allowed simulated movement of the dam's contraction joints. These concrete contraction joints have shear keys, similar to beveled teeth, that allow contraction joints to open 0.25 centimeters during the simulated earthquake response.



A regional simulation of the Morrow Point Dam region, including the dam, part of the reservoir, and the surrounding canyon, was transformed into a mesh of 1 million brick-shaped elements of different sizes that extended 520 meters underground. The dam itself was composed of a fine mesh of 30,000 elements.



This simulation shows a fringe plot of the principal tensile stresses on the downstream side of the dam structure at 6.55 seconds in the earthquake simulation. The time of 6.55 seconds correlates with a peak upstream dam displacement of approximately 6 centimeters. Blue correlates with a stress value of 0, and green correlates with a stress value of approximately 2,400 kilopascals.

Noble used TOPAZ3D to perform thermal analysis. “It is important to account for temperature differences between the dam and the water as well as temperature differences throughout the dam,” he says. For example, temperature is a factor in the movement of the contraction joints.

Noble subjected the 3D mesh to realistic ground motion generated from the Cimarron Fault. The ground motion data were supplied by USBR’s Seismotectonics and Geophysics Group. The motion, which lasted about 25 seconds, was equivalent to a 6.5-magnitude earthquake. The seismic forces were applied to the dam’s foundation, and simulated seismic waves propagated upward through the dam.

The seismic analysis was nonlinear, meaning it modeled nonlinearities in materials and geometries. Nonlinearities in the dam included those from contraction joints and concrete cracking. They also included those from the extensive contact surfaces between the dam, reservoir, foundation, and abutment. In contrast, most USBR concrete dams have been analyzed using linear dynamic finite-element analysis. Linear analyses can determine levels of stress and movement that indicate potential damage in a structure. However, they cannot predict failure. High stresses computed in linear analyses do not take into account the redistribution of stress when cracks form or when contraction joints open and close.

Animation Shows Dam Motion

One of Noble’s simulations was performed on Livermore’s Multiprogrammatic Capability Resource supercomputer. This simulation, which obtained the greatest amount of detail, required 32 processors and two days to complete. An animation showed the structure moving up and down, side to side, and back and forth as the water in the reservoir sloshed against the dam and the sides of the canyon. The greatest displacement occurred in the middle top as it moved back and forth in the upstream–downstream direction, covering a distance of nearly 6 centimeters. The simulation showed no significant damage occurring from the earthquake. Only minor cracking of the dam was observed. “This structure is very robust,” says Noble.

Building on experience gained in the Morrow Point Dam study, Noble plans to study the seismic integrity of levees in northern California’s Sacramento–San Joaquin River Delta region. “We can use many of the same techniques to study levees,” says Noble. Livermore’s Energy and Environment Directorate is providing the geologic modeling required to accurately study levee damage. Noble is also hoping to study the seismic vulnerability of structures in the Midwest, an area that could be devastated by an earthquake on the New Madrid Fault. As long as Earth keeps shaking, advanced finite-element analysis seems certain to play an important role in analyzing the likely response of structures.

—Arnie Heller

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