The Underwater Way .............................. 48
When stringent surface water runoff regulations forced the Los Angeles Department of Water and Power to construct a bypass system for part of its Stone Canyon Reservoir Complex, the engineering solution included two tunnels and a 4,200 ft (1,280 m) long underwater pipeline constructed of high-density polyethylene. The innovative approach helped to reduce the final cost of the project by more than $10 million.

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A large portion of the destruction from Hurricane Katrina was caused not only by the storm itself but also by problems with engineering and engineering-related policies, problems exposed by the storm. This article is a distillation of some of the major findings of ASCE’s Hurricane Katrina External Review Panel report, The New Orleans Hurricane Protection System: What Went Wrong and Why.

The Millstones of Barbegal ...................... 62
By Wayne F. Lorenz, P.E., and Phillip J. Wolfman, S.M.ASCE
Millstones and millstone fragments discovered within ancient ruins in southern France indicate that the Romans may have used the site to test designs that would enable them to develop more technologically advanced flour mills—powered by water—that increased production and quality.
Since the time of early man, stones have been used to refine plants into digestible foodstuffs. Hand grinding of wheat and barley has occurred for at least 23,000 years, and humans may have even used stones for this purpose as long as 45,000 years ago, according to the article “Processing of Wild Cereal Grains in the Upper Palaeolithic Revealed by Starch Grain Analysis” (D.R. Piperno, E. Weiss, I. Holst, and D. Nadel, *Nature* 430 [2004]: 670–73).

Hand milling of grain was almost certainly a time-consuming chore in an ordinary ancient household. The eventual use of animal and water power for milling grain made life considerably easier for ancient humans.

The heart of the milling process, the millstone, was designed by ancient engineers with notable differences depending on whether the mills were to be powered by water or by humans or animals. An ancient Roman milling installation at Barbegal, in the south of France, reflects a change in milling technology from earlier hand- and animal-powered millstones to water-powered millstones, a change that may prove that the ancient Romans were even more technologically advanced than was previously believed.

Ancient Roman engineers had extensive milling knowledge and refined the technologies of both animal-driven and hydraulically driven millstones. The hourglass-shaped millstones used in the bakeries at Pompeii and Ostia, for example, reflect millstone designs common throughout the Roman Empire, according to “The Mills of Pompeii” (D.P.S. Peacock, *Antiquity* 63 [1989]: 205–14). These Pompeian-style millstones ranged in diameter from 45 to 64 cm and were driven by horses and donkeys (or humans) at low rotational speeds. The stones required a steep grinding plane in order for gravity to carry the grain from the inside of the stone, where the grain was fed, to the stone’s outside edge.

The ancient Roman engineers designed water-driven millstones to take advantage of the benefits of hydropower, doing away with the brute force required by the milling techniques used at Pompeii and Ostia. Using...
power from a waterwheel, the millstones were driven by gears that turned the millstones at much higher rotational speeds. The resulting centrifugal force was sufficient for the grain to pass from the inside of the millstone to the outside edge.

The Barbegal mill operated from the second through at least the fourth century AD and was located near Arles (see the figure on page 64). This region’s waterwheel-driven mill site had 16 millstone vaults and 16 water-powered millstones. As such, Barbegal is the largest known milling installation of its kind from that era. In his article “A Roman Factory” (Scientific American [1990]: 106–11), A. Trevor Hodge, Ph.D.—a professor of classics at Carleton University, in Ottawa, who specializes in Roman waterworks—posits that the Barbegal site “is significant because it calls into question what may be termed the technological theory of the decline of the Roman empire,” that theory being that the Romans did not fully develop power-driven machinery for manufacturing because they were able to rely instead on ubiquitous slave labor, and this lack of technological knowledge eventually led to the decline of their civilization. However, Hodge writes, the Barbegal site was indeed a power-driven manufacturing plant. The facility’s 16 waterwheels were arranged in two parallel rows, each wheel located downhill from the previous one so that the same water source could power each wheel in turn. He adds that a nearby Roman-engineered aqueduct seemed to have been dedicated to this water-driven manufacturing plant.

Millstone fragments discovered at the Barbegal site are distinguished by specific design differences. These differences could have been intended by the Roman engineers to test various designs in an effort to develop the most efficient millstone for mills using hydropower. With respect to rotational
speed and millstone shape, the technology that was engineered and refined at Barbegal could have helped to greatly advance the knowledge of the mass production of flour, making possible larger quantities and greater quality control. Although there is no written record, the knowledge obtained at Barbegal was clearly passed down from master to apprentice until the Industrial Revolution.

The general concept of rotary millstone technology remained roughly the same from pre-Roman times through the Roman era and even through the Middle Ages and into the industrial age. Animal-driven or hydraulically driven millstones were generally composed of two pieces: a movable top stone, known as the runner stone or, in Latin, *catillus*, and a stationary bottom stone, known as the bed stone or, in Latin, *meta*. The runner stone was supported 1 to 2 mm above the bed stone, the entire assembly generally situated on a stone or timber base.

Grain to be ground was fed into the millstone assembly via a hopper that was located on the top of the runner stone. The hopper was shaped roughly like a funnel, facilitating a constant supply of grain to the millstone. In mills of the Pompeian type, the hopper was built into the runner stone, forming a hollow, hourglass shape (see the figure opposite). Fernand Benoit, a French archaeologist, suggested that the integrated hopper at Barbegal was augmented by a wood extension (“L’usine de Meunerie Hydraulique de Barbegal [Arles],” *Revue Archéologique* 15 [1940]: 19–80).

The best-preserved Barbegal millstone is a bed stone that has a diameter of 76 cm and a depth of 44 cm at the axle. The diameter of this bed stone falls within the range (55 to 85 cm) of most rotary powered millstones that
have been discovered from Roman antiquity, according to Orjan Wikander (“Exploitation of Water-Power or Technological Stagnation? A Reappraisal of the Productive Forces in the Roman Empire,” *The Classical Review [New Series]* 36, number 1 [1986]: 177–78).

Fragments of a complementary runner stone that could have fit this bed stone also have been discovered at the Barbegal site, according to Henri Amouric, who was interviewed for this article by the author and has written a paper (not yet published) on the grinding stones of Barbegal. Notches in the top of the runner stone—which are evident in the fragment—may have been used to anchor metal fittings to an axle used to turn the runner stone.

The diagram of a section of the Barbegal runner and bed stones shown in the figure on this page includes millstones of the Pompeian type and typical millstones used in the Middle Ages and colonial America. As can be seen in the figure, the Pompeian millstones typically have grinding plane surface angles of 60 degrees to the horizontal, as noted by O. Williams-Thorpe in “Provenancing and

This figure is based in part on a drawing that appears in the book *The Ancient Engineers*, by L. Sprague De Camp (New York: Ballantine, 1993, page 227).
Archaeology of Roman Millstones from the Mediterranean Area” (Journal of Archaeological Science 15 [1988]: 253–305). The Pompeian hourglass millstones were operated at a relatively low speed, probably 3 to 5 revolutions per minute. At this low rotational speed, the centrifugal force was negligible. Therefore, the grinding plane needed to be at a great enough angle so that gravity could bring the grain to the bottom of the runner stone and exit.

The best-preserved Barbegal bed stone has a straight, linear grinding plane surface angle of approximately 30 degrees to the horizontal. In contrast, millstones from late antiquity through the Middle Ages and into the industrial age typically had flat grinding plane surfaces. Therefore, the Barbegal millstones represent an intermediate step between the conical designs of earlier millstones (like the Pompeian millstones) and stones that are essentially flat. With the advent of water power and gearing, the millstones could be operated at a much higher rotational speed, a speed 10 to 20 times greater than that of an animal-powered millstone. The centrifugal force acting on the grain to push it from the center of the millstone is dependent on the square of the velocity. So the centrifugal force of a water-powered millstone was several hundred times greater than that of an animal-powered millstone. In fact, the centrifugal force was much greater than the gravitational force and therefore a higher angle was unnecessary. Barbegal could well have been the place where these flatter millstone grinding planes evolved.

Other millstone fragments from the Barbegal site have diameters that range from 66 to 76 cm. Two other examples have much smaller diameters (48 and 54 cm) and have a different design. Apart from the diameter, one of the differences had to do with the shape of the grinding plane surfaces. The figure on the opposite page is a schematic of both concave and convex grinding plane surfaces that were used at Barbegal, as noted by Amouric.

The differences in the diameters and the grinding plane surfaces of the millstone fragments from Barbegal indicate the variability in the design of the millstones.

Based on surveying and field observations, the millstones were gear driven from the waterwheels and were housed in separate rooms. The overall configuration of the mill shows that some millstones were driven from gearing located above the millstones and others from gearing below.

Wikander and others have proposed that the period of operation of the Barbegal mill was, in general, the time of the water mill technological breakthrough. This breakthrough included the waterwheels and gearing as well as the new millstone designs characteristic of Barbegal. Millstone fragments discovered at the site suggest that Barbegal was a type of research facility for grinding grains.

The discussion of the Barbegal millstones cannot end without at least some mention of the composition and origin of the stones. There have been some studies regarding the composition and origin of the stones discovered at Barbegal. Williams-Thorpe performed a petrologic analysis on a fragment discovered at the site and concluded that the sample was composed of trachyandesite, an extrusive igneous rock. The fragment was reported to be from the lava fields of the Volvic area, located 270 km the north of Barbegal near Auvergne. Other studies performed on millstone fragments that are believed to be from Barbegal show several groups of basaltic type rock (see “Les moulins de Barbegal [1986–2006],” by Phillipe Leveau, http://traianus.rediris.es). The studies also demonstrate that the stones do not come from the same quarry locations. None of the other samples show a
source from the regions of southern France. Since the city of Arles, located nearby, was an important port city in Roman times, it has been suggested by Leveau that the Barbegal millstones could have been brought as ballast in ships from unspecified Mediterranean locations.

Even though the origins of the stones are in question, they all are of basaltic type, a type favored by Roman millers because of the small cavities, or vesicle texture, that provide the cutting and grinding edges needed for processing the grain.

The site at Barbegal essentially proves that Roman engineers took hand- and animal-driven milling technologies to more advanced operations based on hydraulic power. A major factor in this transition was the greater rotational speed of the millstones, which directly resulted in a different grinding plane angle. Millstones of varying sizes and designs at this site suggest that the Romans may have used the Barbegal mill as a research facility. Regardless of the exact purpose of the mill, Barbegal contains important evidence of the Romans’ evolving milling engineering.

Wayne F. Lorenz, P.E., is the president of Wright Water Engineers, a civil engineering firm based in Denver, and a research associate with the Wright Paleohydrologic Institute, a nonprofit body that studies how ancient man used water. Phillip J. Wolfram, S.M.ASCE, is working as an intern at Wright Water Engineers while pursuing a civil engineering degree at the Colorado School of Mines. He is also a recipient of the Kennedy/Jenks Consultants Scholarship, awarded by the American Council of Engineering Companies.