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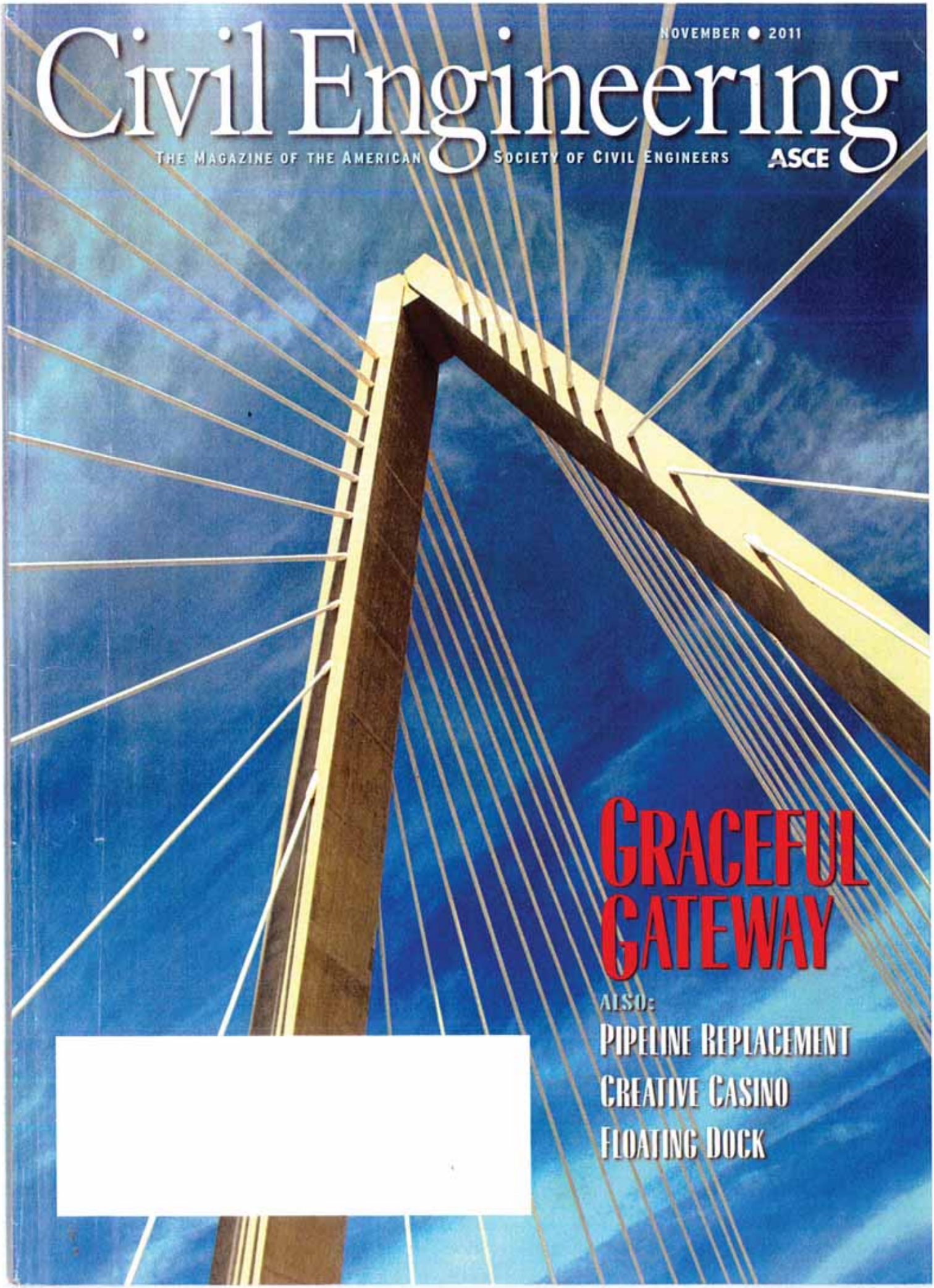

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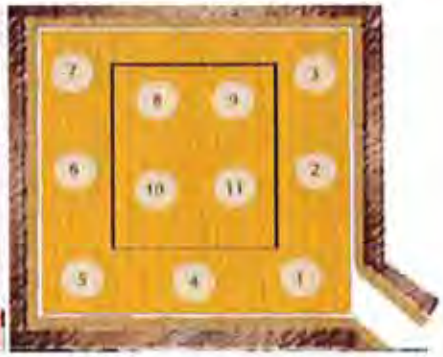


Air Bags and Stainless Steel Anchors and Mesh Help Preserve Egyptian Pyramid

AN EFFORT TO PRESERVE and protect the oldest pyramid in Egypt involves the use of air bags and stainless steel anchors and mesh to secure the ancient structure's burial chamber and prevent any additional seismically induced collapse. Located in the Saqqara (Sakkara) burial complex – the necropolis of the ancient city of Memphis – roughly 30 km south of Cairo, the 4,700-year-old Step Pyramid of Djoser is considered by Egypt's Supreme Council of Antiquities to be the earliest example of large-scale stone construction in that country. Its name derives from its terrace profile, and it has been damaged by earthquakes throughout its history, most recently in 1992.

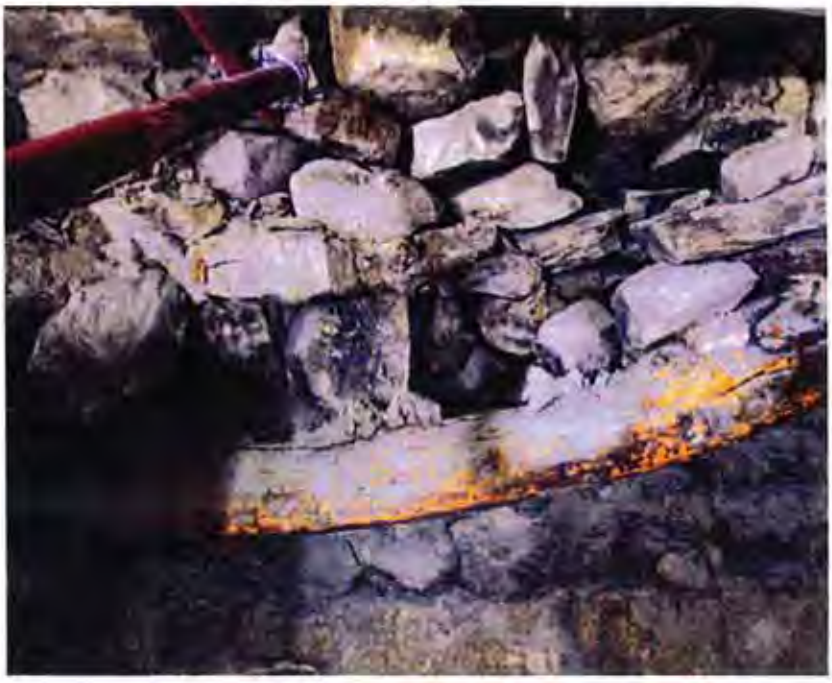
Believed to have been designed by an official named Imhotep, the pharaoh Djoser's chancellor and chief architect, the pyramid was constructed in stages during Egypt's Third Dynasty and ultimately reached a height of 60 m above the surrounding plateau. The structure contains 330,400 m³ of stone and clay. It originally featured a limestone outer casing, but that has since disappeared, explains Peter James, the managing director of Cintec International, Ltd., an international structural engineering firm based in the United Kingdom in the Welsh city of Newport. Since 1997 Cintec has helped restore several other pharaonic and Islamic monuments in Egypt, and in 2006 the Supreme Council of Antiquities selected it to shore up the roof of the Step Pyramid's crumbling burial chamber. The 1.8 million (U.S. $2.8 million) project is now nearing completion but has been plagued by challenges ranging from additional rockfalls within the chamber to the chaos arising from Egypt's recent political changes, notes James.

The burial chamber is an open space roughly 8 m tall. At the bottom of the chamber is the pharaoh's enormous

sarcophagus. The mummified body of Djoser disappeared long ago, and any valuables that were in the tomb were removed by robbers who entered the site in antiquity. Located mostly below grade, the burial chamber can be accessed through a stone passage that is one of the original tunnels and is roughly 36 m long. It is referred to as the high tunnel because it enters the chamber near the top of the space, explains James. The chamber can also be reached through a network of other original tunnels beneath the sarcophagus as well as

The 4,700-year-old Step Pyramid of Djoser – so named because of its terraced profile – was damaged over the centuries by repeated earthquakes, most recently in 1992. Located in the Saqqara (Sakkara) burial complex roughly 30 km south of Cairo, the structure is considered the oldest pyramid in Egypt. At a maximum of 8 psi, each air bag, left, can support 3 metric tons of stone. Thin blocks of high density, semi- rigid foam carefully cut and shaped to fit around the hanging stones were used atop the air bags. Over the centuries the burial chamber's flat timber roof deflected and collapsed. The chamber was closed to the public after an earthquake in 1992 caused as much as 200 metric tons of loose stone and rubble, as well as the supporting timber props, to fall from the roof onto the sarcophagus.

through tunnels dug by the robbers. Although the burial chamber originally featured a flat timber roof, a design that was not repeated in subsequent pyramids, James says, the roof beams deflected and collapsed over time. The roof is now a jumble of jagged rocks wedged tightly together that form a concave done roughly 3 m in height. Various attempts to repair the structure, primarily with more timber supports, were made in the past, but there are no exact records of what was done or when, James notes. In the 1992 earthquake, however, the chamber suffered further damage, and as much as 200 metric tons of loose stone and rubble, together with the supporting timber props, fell from the roof onto the sarcophagus. At that point the chamber was deemed by the Supreme Council of Antiquities



to be too dangerous for visitors and was closed except for occasional inspections by council personnel, James says.

When the current repair project began, Egyptian engineers inspected and strengthened the supports for the sarcophagus itself as well as for the tunnels beneath the tomb, installing stainless steel pins to anchor the stonework where necessary. Work crews removed the debris from atop the sarcophagus, carrying the material out in small loads through the narrow, lower tunnels. Archaeologists from the Supreme Council of Antiquities carefully monitored this work, inspecting each rock as it was removed to determine its possible historical significance, the council also monitored all subsequent efforts by Cintec, James notes.

All electric power for lights and equipment within the chamber was supplied via cables that ran through the tunnels to outside generators; even the air inside the chamber was carefully controlled for humidity by equipment on the outside, James adds.

To perform the work on the chamber roof, Acrow Misr, a Cairo-based metallic scaffolding and framework designer and manufacturer, erected a steel scaffolding system that spans the space containing the sarcophagus. The scaffolding was erected in such a way that no loads were imposed on the sarcophagus or the tunnels beneath it. Next, a work platform was raised to the underside of the chamber roof, and Cintec constructed a second level for this scaffolding. This smaller "mezzanine' section, in the center of the main scaffolding and the mezzanine section provided the bases from which Cintec's engineers installed a series of 11 custom-designed air bags, each roughly 1.5 m long and 1 m diameter. Adapted from a Cintec product known as the Waterwall – a structure made of a tough synthetic fabric that can be filled with water to provide protection against explosive blasts – the systems used in the Step Pyramid featured thin layers of poly-vinyl chloride and were filled with air rather than water. The thinner polyvinyl chloride fabric was easier to control during the inflation process and thus could
accommodate the tight and delicate tolerances at the chamber roof, James notes. As he explains, it was essential to "Support the dangerous hanging stones without applying any upward pressure that might unlock the stone jam and further release an avalanche."

Air was preferable to water because of the weight that the water would have imposed on the scaffolding and chamber floor, to say nothing of the potentially disastrous consequences of a leak inside a space that has been bone dry for millennia. Like the Waterwall structures, the air bags are heavily reinforced internally with a special stitching system that helps them maintain shape and stability.

Connected to a common manifold and pressurized either individually or in groups, as the site circumstances dictated, the bags were gently inflated, initially at a low pressure of 1 psi, to form the shape overall dimensions required, James says. The pressure in each bag was then gently increased to a maximum of 8 psi, at which point each bag could support 3 metric tons of stone. The tops of the bags were adjusted to provide the optimal support to the roof's jagged profile. Timber shims were used to support the undersides fo the air bags, and thin blocks of high-density, semi-rigid foam were carefully cut and shaped to fit around the hanging stones. These foam blocks were used atop the bags to ensure "a gentle kiss with no compression" between the bags and the surfaces of the stones, James notes. "We just want to hold the stones where they are," he says.

As the first air bags were being installed this summer, it became obvious that additional support would be needed along the perimeter of the roof, James says. So a second set of air bags that were smaller and narrower also were designed, at press time, these perimeter bags were being installed.

Once all of the bags are in place, Cintec engineers with spend about a month or so using a lime grout to fill in gaps around the stones. Then, using a diamond drill, they will carefully create a series of 52 mm diameter holes at roughly 2 to 4 m intervals along the perimeter of the roof and at varying angles in the stones. The drilling will be conducted under dry conditions, and a dust extraction system will be used throughout the process, James adds.

Stainless steel anchors generally 2 to 4 m in length will then be installed in the drilled holes and secured with additional grout by means of a proprietary Cintec process featuring a vacuum tube that applies the grout under low pressures. This process is also designed to prevent any negative buildup of pressure that might prevent the anchor from being properly installed. The anchors will create what is essentially a three-dimensional archlike support at the roof to stabilize the stones and prevent further collapses, James explains.

A second series of holes that will have diameters of 32 mm will be drilled and filled with 750 mm long anchors. These smaller anchors will secure a stainless steel mesh tightly against the ceiling to prevent smaller stones from falling. The mesh will also be attached to the ends of the main anchors.

A total of about 60 anchors will be used to secure the stones and mesh. Given the limited space and dangerous conditions within the burial chamber, the work crews will probably be able to install the anchors at a rate of only about one per day, James Notes. Although the air bags will be removed when the project is completed, he explains that they will be repositioned as needed while the anchors and mesh are being installed. This will ensure that the roof remains supported throughout the process.

Earlier this year, at least two more large stones fell from the chamber roof, James adds. Fortunately, no one was inside the chamber at the time because work had been temporarily halted in the aftermath of the political crisis that led to the ouster of Egypt's longtime president, Hosni Mubarak. Still, it was a reminder of why James describes the Step Pyramid work as "probably the most incredible and dangerous job" he has ever performed. When working on the air bags or the anchors from atop the scaffolding, he explains, "you sit there with sixty meters of stone right above your head and you think, "Let's hope there's no earthquake now or any movement of the stones, because a hard hat won't help!" – ROBERT L. REID