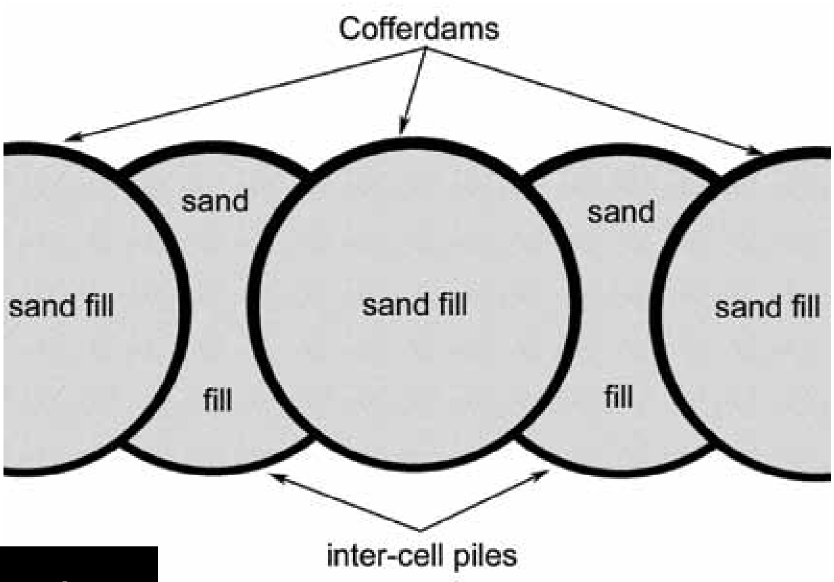
STRUCTURAL FORENSICS

investigating structures
and their components



The jetty consists of 35 sand-filled cylindrical cofferdams, or cells, each 39 feet in diameter. The space between them is bridged by additional steel piles that form sand-filled half-cells.

Inside Information Through Real Time Dynamic Structural Monitoring

Unique Method Allows Engineers to "See the Unseen" and Optimize Design

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An unusual investigation was recently conducted in a major European port. A vital structure, a jetty, was probed to assess its structural soundness using an innovative, cutting-edge structural health monitoring technology that allows engineers to "see" inside a structure and observe its performance in great detail. This technique, called "real time dynamic structural monitoring," uses some familiar tools and concepts, but in an unconventional way. Unlike other structural health monitoring systems, real time dynamic structural monitoring records entire structural performance, not just a measurement of the extent of movement of individual components. Performance data are used to derive a detailed picture of the inner life of the structure.

This process has been termed a structurocardiogram (SKG) because it detects the inner function of the structure by sensing its vibrational patterns, in much the same way an electrocardiogram (EKG) reveals the function of the human heart. The data is analyzed using sophisticated computer algorithms to resolve it into its individual component patterns. Interpretation of these patterns using 3-D computer models can determine how the structure and its component elements are performing, what condition led to that performance, and whether it is stable or changing.

This approach allowed the owner to assess conditions of the jetty that could not be seen, and measured current performance under real-world conditions. It gave engineers useful information about the location, nature, and extent of potential problems, information that could not be obtained by any other cost-effective means. It helped the owner to prioritize maintenance requirements; enabled engineers to design appropriate, cost effective solutions where they are needed; and reduced upgrade cost estimates by 90%.

The Jetty

The lead-in jetty helps guide ships into and out of port, sheltering them against a strong cross-current. It is vital to the continued operation of the port, which, in turn, is vital to the local economy. Extending its service life was a high priority for the owner.

The jetty, constructed in 1974, is 500 meters (1630 feet) long, built on a series of 35 cylindrical cofferdams or cells, each 12 meter (39 feet) in diameter. The cell walls are constructed of steel sheet piles and are filled with sand. Additional piles form arcs from one cell to the next, presenting a more continuous wall against the sea and creating additional "half-cells" between the main cofferdams. Large fenders are attached along the active side of the jetty.

The reinforced concrete deck that runs across the top of all the cells is 1meter (3.25 feet) thick. Over the center of each cell, there is a cut-out in the deck to allow access to the main sand chamber. This cut-out is separated from the main sand chamber by a 50-millimeter (2-inch) concrete cap, making the cut-out into a small upper chamber. The upper chamber is filled with sand and capped at deck level. Beneath the concrete deck, the main chamber of each cell is likewise filled with sand, approximately 19 meter (62 feet) deep. The half-cells between cofferdams are sand-filled, too.

The jetty is subjected to battering by both waves and ships. The tidal range is unusually high – in excess of 12 meter (39 feet) difference between low and high tide. The configuration of the structure makes the cofferdam walls largely inaccessible to inspection. The portions that are exposed on the exterior of the structure are mostly underwater or within the tidal zone. In addition, the water is extremely silt-laden, making it virtually opaque.

Under these conditions, visual inspection of the underwater sections was not feasible. Some steel sampling of cell walls was done by divers. Samples were used to assess corrosion levels. Ultrasound readings were attempted as well. However, the challenges of tides and visibility made a complete assessment by this method prohibitively expensive.

A New Form of Monitoring

To supplement the data they had been able to gather underwater, the owner engaged STRAAM Corp., New York, NY, to assess the jetty using real time dynamic structural monitoring. Readings were taken during one week in September, 2010. Each cell was monitored individually for 30 minutes.

Real time dynamic structural monitoring uses a single sensing device – the SKG – capable of measuring motion in three dimensions with highly sensitive accelerometers. Readings were taken simply by placing the SKG on the deck of the jetty. It was positioned at an optimum location over each cell, so response would be measured across the deck, along the deck and vertically.

This simple set-up is in sharp contrast to traditional strain-gage monitoring used to assess structural health. Strain gages require more numerous instrument locations and longer monitoring periods to establish a structure's complete range of motion. Conventional static monitoring of the jetty would have been difficult due to the inaccessibility of much of the structure.

The SKG senses standing waves that are generated in the structure when it is excited. The physical dimensions and material properties of any structural unit will tend to favor certain frequencies of vibration, because their wavelengths fit within the dimensions of the structural unit in neat, whole-number multiples. Vibrations at these special frequencies reflect back and forth from the ends of a structural unit in synchronization, reinforcing each other, allowing the frequency to persist or resonate for an extended period. They are thus called the "resonant frequencies" of the structure. Other frequencies reflect chaotically and cancel out quickly.

Excitation of the structure, which induces the vibrations to be recorded, was supplied constantly by wind and waves. Additionally, there were two instances of ships impacting the jetty during monitoring, lucky circumstances that allowed the jetty's response to such impacts to be recorded from different points on the structure.

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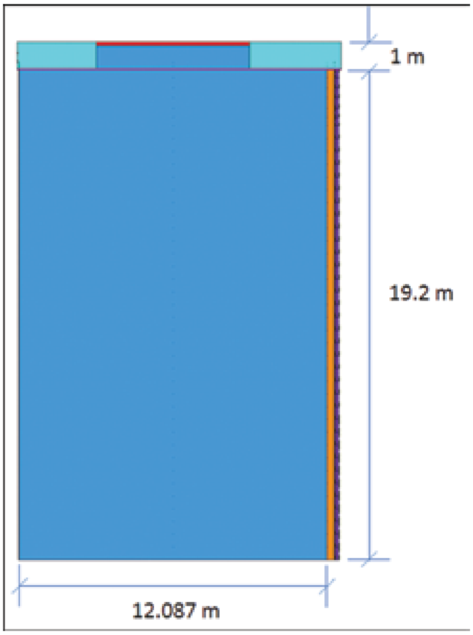
From Data to Decision

The SKG records all the resonant frequencies produced by a structure, or portion of a structure. That data must then be separated into individual frequencies that can be traced to different elements of the structure. This is performed using proprietary algorithms coded into specialized software.

Monitored patterns are then evaluated and compared in several different ways. The resonant frequencies are one aspect. Changes in frequency in response to changes in amplitude (the impact-force of the excitation) can reveal much about structural health. Damping – the ability of a structure to absorb energy and resolve oscillations after impact – is also useful in tracing structural response.

The measured response patterns can be compared with a huge database of patterns from other structures, to enhance understanding of their meaning. The database was collected over a period of 30 years by one of STRAAM's three founders, Dr. Alan Jeary, a global expert on structure instrumentation and diagnosis.

To utilize the data from the jetty readings, two computer models were built. A finite element (FE) model of a single cell was made to analyze the individual performance of each cell. A global matrix model of the entire structure allowed the STRAAM team to model the behavior of the jetty as a whole, and determine the effects of any individual cell's behavior on the entire jetty.



This cross-sectional drawing shows the cell configuration. The 1 meter concrete deck has a cut-out in the center to allow access to the main chamber. The cut-out is separated from the main chamber by a 2 inch concrete cap, and capped on top flush with the deck. Both the main chamber and the small upper chamber are filled with sand.

Steel piles form the cylindrical cofferdams. Between the cofferdams are additional arcs of steel piles, making much of the cofferdam piles inaccessible.

Many different types of information were derived from this data. For example, using the measured responses of selected cells in conjunction with steel sampling data from those cells, they were able to determine the effect of steel thickness on vibrational response. They could also differentiate a steel-like response from a soils-like response, indicating the relative participation of sand or steel in resisting loading.

In addition to assessing the condition of each cell, they were able to show that the cells were well isolated from each other structurally, and the behavior of one had little influence on the response of the rest of the jetty.

The most relevant indicator of a cell's structural health was damping. In this case, however, the meaning of damping was the opposite of usual.

In most above-ground structures, low damping values, with oscillations continuing to resonate for longer periods of time, mean that a structure is responding more like a single element that is structurally cohesive. High damping values indicate that energy is being dissipated within the structural system, and that dissipation is often taking place in structural connections that are being pulled apart bit by bit.

In the case of the jetty, however, the desired response is for the sand fill to absorb and dissipate most of the impact energy, a high damping response. Low damping would be an indication that the sand fill was not absorbing energy optimally.

Cost Effectiveness

Monitoring data was used to generate assessments of each cell. The engineer used these assessments as a tool in their analysis, to confirm the safe stability of the lead-in jetty, and to determine its residual design life. It is estimated that they will be able to cost-effectively extend the life of the jetty by 20-30 years.

"Using real time dynamic structural monitoring," explains STRAAM chairman Charles H. Thornton, Ph.D., P.E., "we could see the exact condition of the jetty. That allowed the engineer of record to eliminate unneeded repairs, and prioritize areas that were eligible for upgrading. The owner could do what was needed in a highly cost-effective manner with minimal disruption of operations."

Previous estimates for preserving the jetty had been made in the absence of complete data, so they were based on very conservative assumptions. Potential upgrade costs approached $24,000,000. Prioritization, based on real time dynamic structural monitoring data, lowered the cost estimates to under $2,400,000, 90% less than original estimates.

As work began on the jetty, the conditions of the first cells that were opened proved to be exactly as predicted using real time dynamic structural monitoring. As of this writing, work is on-going and confidence is high.▪

Photos courtesy of STRAAM Corp.