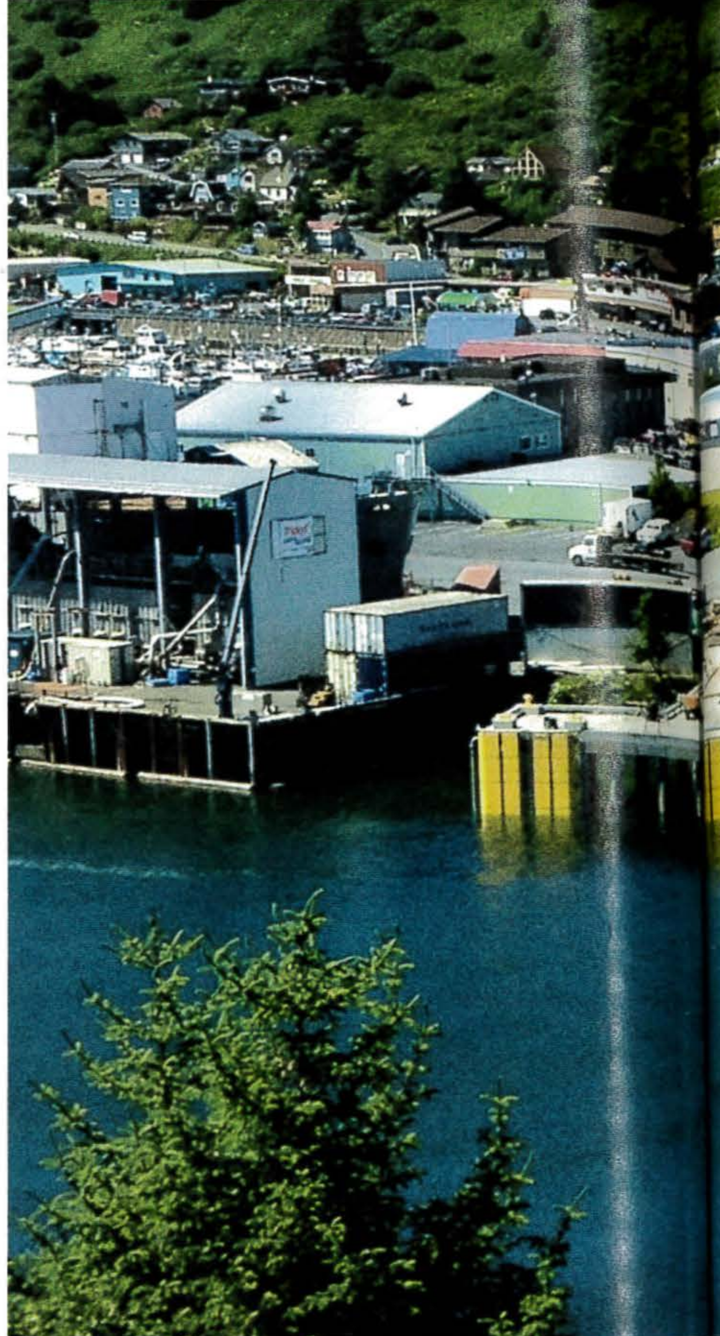

MARK STEEN, PACIFIC PILE & MARINE

A timber dock built in Kodiak, Alaska, in 1965 and used for ferry service, bulk fuel deliveries, and general cargo operations was recently reconstructed to meet current displacement-based seismic design standards. Unique challenges included the potential for large earthquake-induced displacements of the deck and the need to safeguard Steller sea lions that were suspected of being deaf and were protected under the Endangered Species Act.

By John Daley, P.E., M.ASCE, Robert Harn, P.E., S.E., M.ASCE, and Kimberly Nielsen, P.E., M.ASCE

THE ALASKA Marine Highway System is a marine ferry network that employs 11 ships and extends across 3,500 mi of the state's mainland and island coastlines to link more than 30 coastal communities, many of which are not accessible via roads. The ferry berths for this system are of crucial importance to communities, as they provide a physical transportation connection to the rest of the state. Last year, the Alaska Department of Transportation and Public Facilities, in cooperation with the Federal Highway Administration, reconstructed one of these docks in the city of Kodiak, located on the northeast coast of Alaska's Kodiak Island, the latter separated from mainland Alaska by the Shelikof Strait. The ferry terminal in Kodiak, known as Pier 1, is located in and owned by the city.

Before the renovation, Pier 1, built in 1965, was a 12,150 sq ft timber dock. In plan the dock was somewhat U shaped, comprising two access trestles, one located on each side of a city-owned building, connected by a 200 ft long dock face. The dock's primary purpose was for berthing the 296 ft long Alaska Marine Highway System ferry *Tustumena,* although it was also used by the city for the transfer of freight and fuel by barge.

The primary focus of the renovation project was to replace the aged timber structure and improve the ferry's mooring and vessel-loading operations. To accomplish this, a new, 19,570 sq ft steel pile and concrete deck structure with a U shape in plan similar to that of the timber dock was designed and built as a replacement. The new iteration of the structure increases the dock face by nearly 30 ft and the deck area by approximately 60 percent, which will allow additional ferry-related vehicle staging on the pier.

There is significant seismic risk for all structures in Kodiak. The city overlies the Aleutian megathrust zone, located approximately 18 mi underground, while the Narrow Cape Fault, a major high-angle oblique slip fault, is located about 17 mi southwest of the city. The latter is understood to produce major earthquakes every 1,000 to 2,000 years. Indeed, the history of Kodiak is intertwined with earthquakes and tsunamis. Most significant was the Great Alaska Earthquake, which had a magnitude of 9.2 and struck on March 27, 1964. During that event the ground around the city subsided vertically by as much as 6 ft, the Pier 1 site subsiding vertically approximately 5.8 ft. The ground shaking was described as "slight" according to the modified Mercalli intensity scale, and very little ground failure was documented (for example, there were local areas of differential settlement and spreading in unconsolidated soils). However, the city sustained significant losses, resulting primarily from a series of tsunamis that inundated the low-lying areas, including the Pier 1 waterfront area. Before 1964 the site

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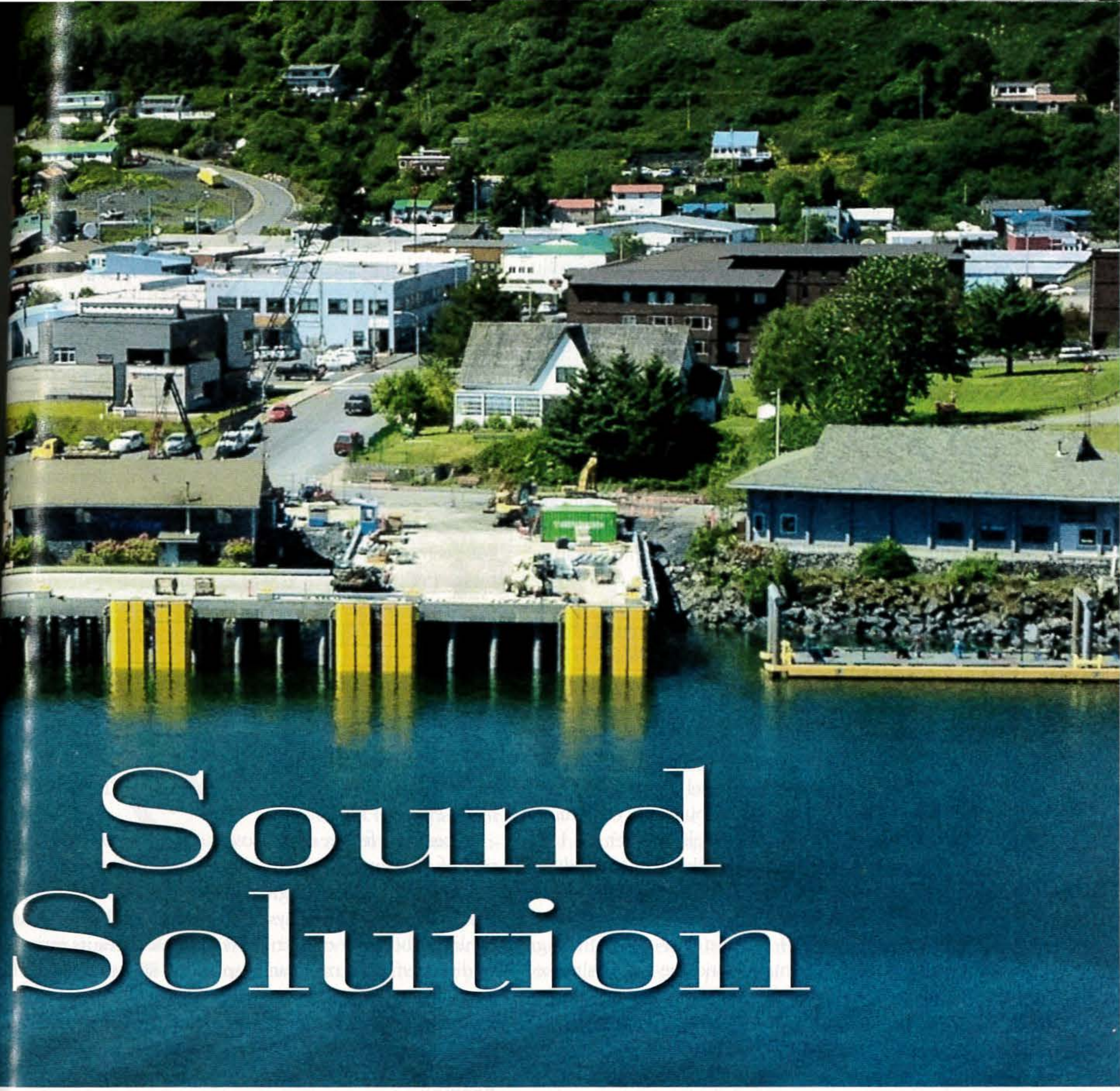


Sound Solution

was occupied by a timber wharf that housed a seafood-processing plant operated by the Alaska Packers Association, as well as several commercial and warehouse buildings that were washed away by the tsunamis.

Most existing pile-supported piers and wharves in Alaska today were designed using a "force-based" approach that typically included vertical and battered steel pipe piling, steel pile caps, and a precast-concrete deck. However, because battered piles tend to create a relatively stiff dock with a short-period dynamic response during earthquakes, large lateral loads often result, and the force transfer at the battered piling connections tends to be eccentric, which is undesirable. Recent testing has shown that this is because battered piling and welded connections between steel piles and pile caps are typically not ductile. This results in a design in which the performance of

The rebuilt and expanded Pier 1, in the city of Kodiak, on Kodiak Island, is part of the Alaska Marine Highway System, which connects more than 30 coastal communities, many of them inaccessible via roads.

the structure in a major earthquake cannot be accurately predicted.

To create a state-of-the-art seismic design for the new dock, the team adopted the 2014 edition of ASCE's standard 61 (*Seismic Design of Piers and Wharves*) as a governing document, along with the 2012 edition (with 2013 interim revisions) of *AASHTO LRFD Bridge Design Specifications* (the acronyms denoting respectively "American Association of State Highway and Transportation Officials" and "load and resistance factor design"). Implementation of these standards enabled the design team to utilize a displacement-based design approach centered on achieving a controlled, ductile response to seismic forces. A central design goal was to provide a ductile moment frame using vertical piling, caps, and precast-concrete panels. The pile-to-cap connection is designed to yield in a controlled, ductile manner, while the pile cap and deck panels are to remain elastic under seismic forces. A pushover analysis was used to confirm that these goals were achieved.

THE GEOTECHNICAL profile across the project site consists of loose to moderately dense gravel and sand with nonplastic silt overlying steeply sloping bedrock. The deep portion of the soil unit is interpreted to be colluvium, and the thickness of the soil column ranges from 15 to 25 ft. The bedrock ranges from cretaceous, hard, slightly weathered bedrock to fresh, vertically bedded graywacke interlayered with soft phyllite.

The surface of the dock and the parking area at the base of the piers are elevated approximately 20 ft above mean lower low water and are approximately 16 ft above mean sea level; the seafloor along the face of the dock is about –20 ft with respect to mean lower low water. The seafloor under the dock slopes toward the channel at 10 to 15 degrees. The side slopes of the parking area embankment are covered with riprap.

The former Pier 1 facility was supported on timber piles that bore directly on bedrock. In 1965 the embankment under the dock's approach trestles and the adjacent parking area was raised with imported fill to its present elevation. The fill thickness ranges from approximately 5 ft along the edge of the existing roadway to roughly 20 ft at the base of the approach piers. Sometime before 1977 additional fill was placed between the two approach trestles, extending that portion of the embankment 50 ft into the channel. It is on this made ground that the existing city-owned building, constructed in the mid-1980s, was built. The fill placed after the 1964 earthquake may be susceptible to nonliquefied ground failure during another large earthquake, whereas the sediments under the fill are liquefiable.

Despite the shallow soil column, the seismic design ground motions were determined, and the site was ranked as class B (rock) as defined in the 2010 edition of ASCE's standard 7 (*Minimum Design Loads for Buildings and Other Structures*) because the new pier's piles are socketed directly into bedrock. The Department of Transportation and Public Facilities specified that the new dock had to be designed using seismic ground motions determined in accordance with *AASHTO LRFD Bridge Design Specifications* to have a return period of 1,033 years. The project design acceleration response spectrum was developed using short-period (S_{DS}) and long-period (S_{D1}) spectral ordinates of respectively $1.29g$ and $0.57g$.

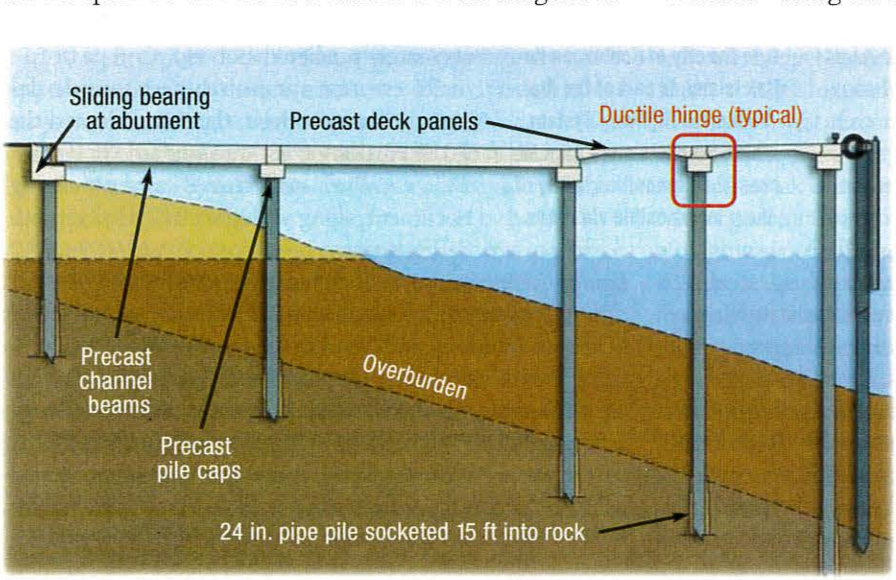
All the existing soils below the waterline have the potential to liquefy or at least weaken significantly during the two assumed design earthquakes, and there is a high potential for significant ground displacements from lateral spreading.

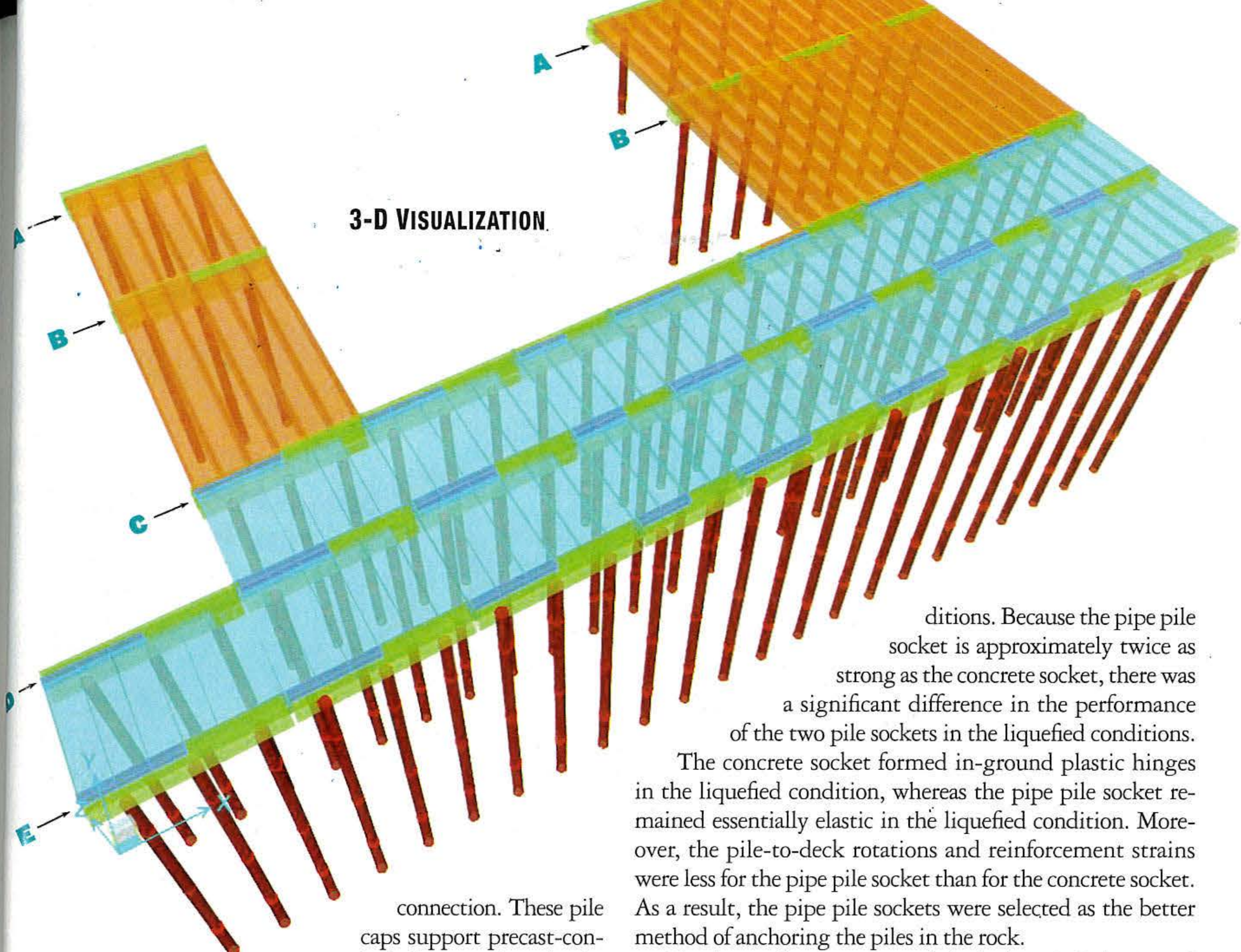
Until the late 1990s the seismic design of pile-supported piers and wharves in the United States was governed by building and bridge codes using a lateral force method often described as force-based design. In this type of design the expected inelastic response of the structure and the displacement demand on it during ground motion are accounted for by response factors (R) and are often not specifically examined or well considered in an overall design strategy. As a result of this approach, many docks built in Alaska over the past 30 years commonly consist of a precast-concrete deck supported by steel pile caps and a grid of plumb piling, with battered piling arranged to take the lateral berthing and seismic loads.

Initiatives in the United States to reduce damage to port structures led to the passage in 1990 in California of the Lempert-Keene-Seastrand Oil Spill Prevention and Response Act. This ultimately led to the creation of the Marine Oil Terminal Engineering and Maintenance Standards, followed by seismic codes for the ports of Los Angeles and Long Beach, and, most recently, by the 2014 edition of ASCE's *Seismic Design of Piers and Wharves.*

A common feature of these codes and standards is the adoption of a performance-based design approach that includes multiple levels of design ground motions and associated performance goals. The analysis includes the evaluation of the nonlinear behavior of a structure and calculates its estimated displacement demand and capacity. A structural hierarchy is established that accounts for the yielding that occurs in a controlled and ductile manner. Under this approach, the new Kodiak dock is designed as a "strong" beam to "weak" column ductile moment frame, the deck being the former and the piles the latter. Capacity protection principles are applied to the deck and pile caps to prevent the occurrence of brittle modes of failure. Special attention is paid to the connection between the pile and the deck. The vertical dowels in this joint are designed to act as a ductile plastic hinge, and performance is evaluated with allowable strain limits for the reinforcing. To meet these design needs, the new dock is composed of galvanized steel pipe piles 24 in. in diameter that are installed vertically into sockets drilled into bedrock. Reinforcement extending from the piles is cast into steel sleeves in the precast-concrete pile caps to form the ductile seismic

DOCK SECTION





connection. These pile caps support precast-concrete deck elements that take the form of either 36 in. deep precast channel beams or 24 in. haunched precast deck panels. Cast-in-place concrete is used to integrate the deck elements and create a continuous pile cap. The abutment includes sliding bearing pads for the precast-concrete channel beams.

The pushover analysis of the design was performed using the capacity spectrum method. The model utilized frame elements and nonlinear links to represent the predicted nonlinear lateral behavior of the structure. The moment-curvature behavior of the pile hinges was analyzed and converted to a moment-rotation plot in accordance with ASCE's *Seismic Design of Piers and Wharves.* The fixity of the base of the piles was modeled using lateral springs to represent the stiffness of the rock sockets and soil above the rock.

There are five pile bents, labeled A through E (see the figure above), bent A located on land and each of the subsequent bents located progressively farther offshore. Because the abutment includes a sliding bearing and is therefore disconnected from the lateral-load-resisting system, the pilings at bent B were recognized as the critical elements, since they were the shortest and therefore the stiffest and had the highest lateral loads.

Initially, the pipe piles were designed to be partially embedded in a concrete socket, but based on constructability and performance concerns of the owner, an alternative design was developed that fully embedded the pipe piles in bedrock. Pushover analyses were performed for both the concrete socket and the pipe pile socket in liquefied and nonliquefied conditions. Because the pipe pile socket is approximately twice as strong as the concrete socket, there was a significant difference in the performance of the two pile sockets in the liquefied conditions.

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The concrete socket formed in-ground plastic hinges in the liquefied condition, whereas the pipe pile socket remained essentially elastic in the liquefied condition. Moreover, the pile-to-deck rotations and reinforcement strains were less for the pipe pile socket than for the concrete socket. As a result, the pipe pile sockets were selected as the better method of anchoring the piles in the rock.

The design for the new Kodiak dock included polished stainless steel sliding bearings bonded to an elastomeric pad at the abutment to release the forces from the relatively short and stiff abutment piles from the rest of the dock. This effectively lengthens the period of the dock and thereby reduces seismic forces. The bearings can accommodate thermal movements without sliding and can accommodate sliding movement of approximately 16 in. in any direction. Testing revealed that these bearings would experience significant galling and scratching under large movements. This damage, while not ideal, would not affect the ability of the dock to support loads after an earthquake.

TO MITIGATE THE effect of noise on marine mammals during pile driving, environmental permits originally required the construction team to monitor the area and stop work when a marine mammal was observed within 1,150 ft of the site, the distance within which the work is seen as potentially harassing or harmful to an animal. Challenges arose, however, because Pier 1 is located just 40 ft from a seafood-processing dock. Unbeknownst to those who sought or issued the original permit, the plant was attracting Steller sea lions that are part of the western distinct sea lion population segment protected under the Endangered Species Act. Because the construction contractor mobilized to the site in October, when the seafood plant is very active, sea lions were consistently observed. The team soon realized that pile driving would be impossible given the permit's shutdown requirements.

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The new dock's steel pipe piles are installed vertically into sockets drilled into bedrock. These piles support precast-concrete pile caps, which in turn support precast-concrete deck elements. Cast-in-place concrete was used to integrate the deck elements and create a continuous pile cap.

Because sea lions congregate at the nearby seafood-processing dock and often board fishing vessels as they unload their catch, the team realized that reconstruction of Pier 1 would be impossible without an incidental harassment authorization (IHA), issued by NOAA Fisheries (the acronym denoting "National Oceanic and Atmospheric Administration"). Such a permit would authorize pile driving while sea lions were nearby. However, it limits the number of "takes," that is, harassment, injury, or killing of animals, during construction to protect the local population as a whole.

Construction had to be suspended for a year to obtain the IHA. Biologists conservatively estimated that 40 unique animals might be affected each day of pile driving.

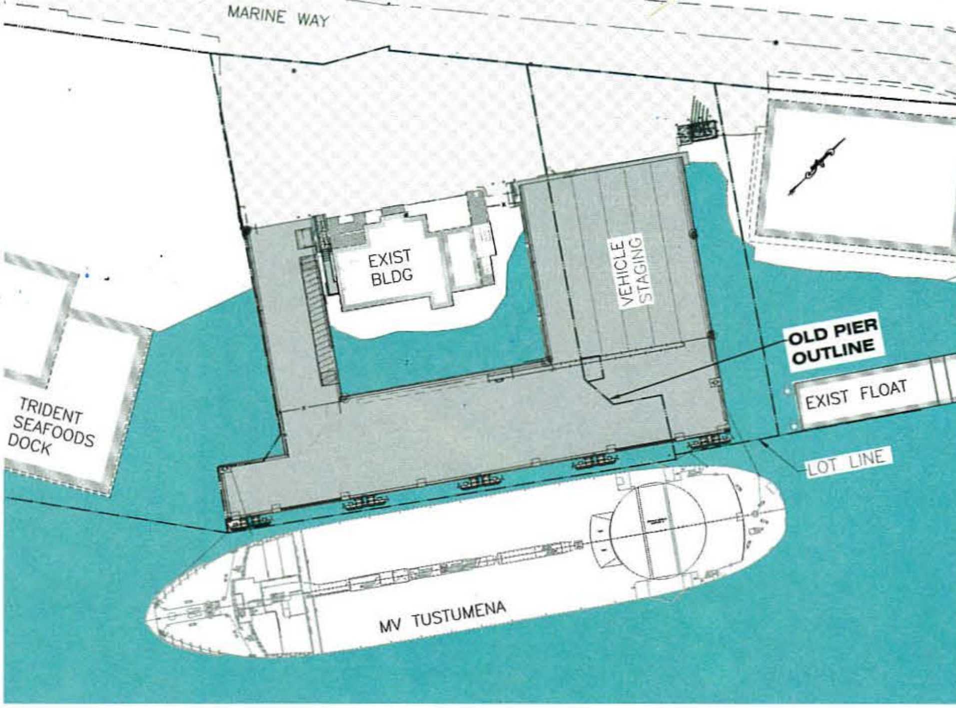
There are different levels of takes under the IHA. Level A is defined as the distance from a sound source at which injury, such as hearing damage, is likely to occur. Level B is defined as the distance within which "harassment" leading to modification of animal behavior is likely to occur. For this project, level A was defined as 4 m or less, whereas level B extended to 300, 350, or 1,150 m, depending upon whether downhole drilling, impact driving, or vibratory driving of steel piles was being undertaken. Adhering to the IHA was complicated because many of the animals were suspected of being deaf as a result of the use of deterrent seal bombs by fishermen (which is no longer permitted). Therefore, such typical mitigation measures as warning strikes or the "ramping up" of pile driving would not be efficacious in causing the sea lions to disperse.

As a result, the construction team implemented alternative mitigation measures to reduce the number of takes at the site. One involved working with the fish processor to berth vessels with their sterns away from Pier 1. This seemingly small change increased the sea lions' distance from Pier 1 by a boat length, approximately 50 ft, potentially reducing the number of level A (injury) takes.

Additional challenges included establishing the appropriate observation and shutdown zones for the types of construction taking place. Noise from pile installation varies greatly, depending on, for example, the size and type of pile, the pile installation method, the equipment used to install the pile, the geotechnical conditions, the water depth, the strength of currents, and the surrounding topography (that is, constricted channel or open ocean). What is more, the effect of noise on a particular species depends on biological factors, made more challenging in this case because of the suspected deafness of the sea lions. It also depends on the extent to which the species is accustomed to existing background noises. Since there was limited published information applicable to this project, very conservative assumptions had to be made to ensure that the sea lions would be protected in accordance with the law.

In the end, the IHA authorized the project to affect a limited number of Steller sea lions to construct the project. This was controlled by observing the specified level A and level B distances for the various types of pile installation, including vibratory, drilling, and impact, and counting the number of animals that came within level B. Operations were then shut down before the sea lion came within level A. As noted above, it was estimated that 40 unique animals would be affected on each day of pile driving, for a total of 3,290 authorized takes over the course of the project. The actual number, however, was much lower. Some of the sea lions coming within level B may have had impaired hearing and thus would not move away from the noise source. It is therefore likely that some sea lions were counted multiple times per day. In the end, marine mammal observers documented level B takes at less than 40 percent of the authorized limits, and there were no level A takes.

In the future, projects like the reconstruction of Pier 1 should include the collection of pile-driving noise data for particular conditions, pile sizes, and installation methods, as well as animal reactions to the noise, since the hearing thresholds for various marine species are not well documented. With more data, observation zone distances could be better adjusted to match individual sites, and dock pile designs could be chosen to better protect marine species at a site by taking into consideration site conditions, pile types, pile sizes, and installation details. Indeed, the Department of Transportation and Public Facilities initiated a program to collect pile installation noise data on this and future projects that will then be used for waterfront structure design and construction planning in Alaska.



The new, 19,570 sq ft dock has, like its predecessor, a U shape, but the dock face has been increased by nearly 30 ft and the deck area by approximately 60 percent.

KODIAK'S Pier 1 was completed in October 2016, although the first ferry was able to berth there a few months earlier. The use of displacement-based design methods for the reconstruction of the pier gave the team a better understanding of the postyield performance of the structure. An engineered plastic hinge mechanism was provided in the pile-to-cap connection, and the capacity of the deck was protected by designing for greater strength than the yielding elements. In all cases analyzed under the design earthquake, the strains to the structure were within acceptable limits, although accommodating the necessary large displacements at the abutment by means of sliding bearings proved challenging.

Two significant limitations remain for Pier 1. The first is that while the piling would be able to resist some amount of lateral spreading from liquefied soils, the dock would be unable to resist significant soil movements above water at the base of the piers. Because of the risk of such a condition, the design team has recommended upland soil improvements as a follow-up project. The second is that because there are currently no well-established tsunami design procedures, tsunamis were not considered in the design, even though there is a significant history of them at the site. ASCE has a committee that is currently working to produce such standards. **CE**

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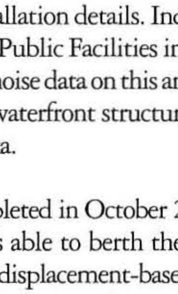
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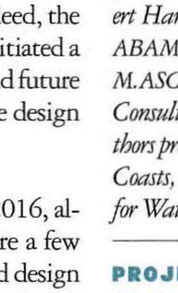
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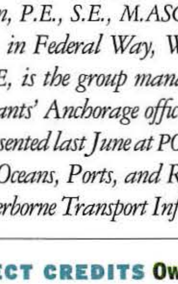
Nielsen

R&M CONSULTANTS, INC.

PROJECT CREDITS **Owner, design reviewer:** City of Kodiak, Alaska **Client/project management, design reviews, permitting, and construction administration:** Alaska Department of Transportation and Public Facilities **Prime consultant/engineer of record for condition assessment; alternatives analysis; geotechnical investigation; waterfront, structural, geotechnical, and civil engineering; cost estimating; environmental coordination; and bidding and construction support:** R&M Consultants, Inc., Anchorage, Alaska, office **Pier seismic consulting, pushover analysis, pile cap details:** BergerABAM, Federal Way, Washington **Contractor:** Pacific Pile & Marine, Seattle and Kodiak, Alaska **Historical/cultural resources:** Cultural Resources Consultants LLC, Anchorage, Alaska **Electrical engineering (power and lighting):** Haight & Associates, Inc., Juneau, Alaska **Mechanical engineering (fuel systems):** Great Northern Engineering, Palmer, Alaska **Environmental permitting support:** HDR, Inc., Anchorage, Alaska, office **Marine mammal observation:** ABR, Inc., Anchorage, Alaska, office