Summer 2005

The BRIDGE

LINKING ENGINEERING AND SOCIETY

NATIONAL ACADEMY OF ENGINEERING
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Promoting the technological welfare of the nation by marshalling the knowledge and insights of eminent members of the engineering profession.

The
BRIDGE

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The BRIDGE

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LINKING ENGINEERING AND SOCIETY

Editor's Note

Features

NAE News and Notes

(continued on next page)

Editor's Note

George Bugliarello is President Emeritus and University Professor at Polytechnic University in Brooklyn, New York, and foreign secretary of NAE.

Systems Challenges on a Global Scale

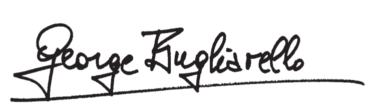
Human history has been punctuated by major natural disasters, from the Thera eruption of around 1600 B.C., which generated a tsunami some 100 meters high and devastated northern Crete, and the eruption of Mt. Vesuvius in 79 A.D. that buried Herculaneum and Pompeii, to the Lisbon earthquake and tsunami in November 1755 and the eruption of Krakatoa and the tsunami that followed in 1883. The tsunami event in December 2004, which devastated whole populations at the edge of the Indian Ocean, is a powerful warning, not only of how unprepared some areas of the world are for major catastrophes, but also that we must be aware of systems challenges on a global scale. These include tsunamis, volcanoes, global warming, the rise in sea levels, and the large meteorites that may hit Earth at some time in the future. The Indian Ocean tsunami reminds us that nature knows no political boundaries and that borders cannot stop the circulation of airborne pollution or limit the consequences of weapons of mass destruction and other anthropogenic disasters.

We can use the lessons we learn from disasters to try to mitigate the consequences of similar events in the future. The Indian Ocean tsunami might have been less deadly if sensors and a global warning system had been in place, if there had been local alert and evacuation systems for the populations at risk, if the global logistical support system for recovery had been more efficient, and if policies for coastal development had been more effective.

Clearly, we need better ways of assessing risks and better defense mechanisms against them. There is really no excuse for not having global systems in place to address technical and scientific challenges, as well as other challenges, such as the adequacy of first responders, communications to populations at risk, local emergency responses, the facilitation and coordination of international aid, and rapid decisions about the appropriateness of involving military organizations that have the logistic capabilities necessary to deliver assistance.

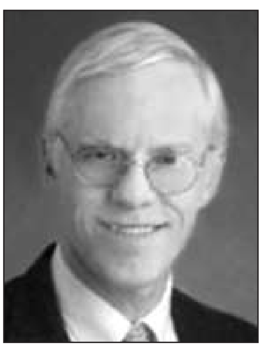
The papers in this issue of *The Bridge* focus on various aspects of the recent tsunami disaster. Philip Liu describes simulations of the propagation of the tsunami waves generated by the Sumatra earthquake and tsunami. Admiral Conrad Lautenbacher Jr. underlines the imperative of linking, integrating, and extending observational capacities. The paper by Robert Dalrymple and David Kriebel focuses on the survivability of structures hit by the tsunami waves. Costas Synolakis, Emile Okal, and Eddie Bernard address other factors that greatly exacerbated the human disaster last December, such as widespread ignorance of the phenomenon, shoreline configuration, lack of emergency preparedness, and inadequate evacuation plans.

Unfortunately, disaster prevention on a global scale does not have as high a priority as smaller-scale problems. For engineers to play an important role in global disaster prevention and mitigation, they must adopt a broad definition of engineering as a protector of our species from natural processes that are supremely indifferent to our plight and from the consequences of human follies on a global scale. In most engineering schools, however, global earth-systems engineering is the province of a few specialized departments (or even individuals). Knowledge of risk assessment, logistics, warning systems, and the prevention and management of disasters and their consequences put engineering in the proper context and should be a cultural requirement for engineering education.



The design of civil engineering structures in tsunami-prone areas can be critical.

Lessons in Engineering from the Tsunami in Thailand



Robert A. Dalrymple

David L. Kriebel

Robert A. Dalrymple and David L. Kriebel

Living near the sea means living with the risk of a tsunami. In some areas, such as the Pacific Rim countries, the risk is high: the possibility of a significant tsunami occurs on a decadal scale in Japan. In other regions of the world—the Mediterranean Sea and the Atlantic Ocean—the risks are much lower. In the Indian Ocean, the risks are lower still, although tsunamis have occurred there in the past. The National Geographic Data Center (NGDC, 2005) lists 63 tsunami events in the Indian Ocean since 1750, eight of which were major events, including the wave caused by the eruption of Krakatoa in 1883 in the Sunda Strait (for a good read, see Winchester, 2003). The Boxing Day Tsunami of December 26, 2004, which killed more than 200,000 people in 11 countries around the Indian Ocean, showed the catastrophic effects of a major tsunami in a low-risk, and consequently unprepared, region.

Tsunamis are created in a variety of ways. Perhaps the best known generation mechanism is earthquake-induced displacement of the sea bottom, which causes a related sea-surface elevation that then propagates away from the generation area due to gravity. But submarine slumping of the offshore shelf or slope or the impact of a terrestrial landslide into the sea can also cause devastating tsunami waves. In fact, the highest known tsunami wave,

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caused by a large landslide in Lituya Bay, Alaska, is documented to have toppled trees growing 524 meters above the water level (Miller, 1960). Even higher tsunami waves are thought to have been caused by bolide impact—meteorites striking the ocean—during the millions of years of Earth's history. The height of the wave would be related to the size of the bolide, which could be comparable to the depth of the ocean.

Despite the infrequency of tsunami events, their severity and extreme consequences make the design of civil engineering structures in tsunami-prone regions critical. In Japan, efforts are under way, at great cost and expense, to ensure that ports are tsunami-proof and that populations living near the sea are protected through appropriate construction and alerted through warning systems. For example, on Okushiri Island, a seawall nearly 4.5 meters high was built to protect the Aonae peninsula. Yet this wall was overtopped by a tsunami in 1993, and more than 185 people were killed. Since then, the wall has been rebuilt, and there is an ongoing debate about the wisdom of the wall, which is so high now it obstructs the view of the sea and was extremely expensive to build. Today, nations around the Indian Ocean are trying to decide whether to allow rebuilding on the coast, which structures to rebuild and which ones to relocate, and how to rebuild to minimize losses in future tsunamis.

As they have done after other natural disasters involving the loss of many lives, the American Society of Civil Engineers (ASCE) sent teams of engineers to India, Sri Lanka, and Thailand to examine the effects of the December 26, 2004, tsunami on civil infrastructure and lifelines, such as ports and airports, residential and commercial buildings, roads and bridges, and water supply and wastewater systems. Composed of experts in earthquake damage to lifeline infrastructure and coastal engineering, these teams were asked to determine how well the civil infrastructure fared in the tsunami. The goal was to learn something new about mitigating future tsunami damage in the United States and around the world in other tsunami-prone areas (for a good summary, see NTHMP, 2001).

As part of the ASCE investigation, the authors[1] visited Thailand in early February 2005 to observe the tsunami's effects on the civil infrastructure, as well as on beaches and coastal structures. Because the southwest coast of Thailand has become an international tourist destination that now hosts more than 1.5 million visitors during the winter high season, this area provided an opportunity for the team to assess tsunami impacts on modern infrastructure that was designed and built to high standards. Lessons learned there are relevant to many coastal resort areas in the United States that are subject to tsunami hazards—notably, parts of Hawaii and the highly developed coastal regions of California, Oregon, and Washington.

Nations around the Indian Ocean are trying to decide whether to allow rebuilding on the coast.

The tsunami was generated less than 500 kilometers west of Thailand at 8 a.m. (local time) on December 26, 2004; it was caused by a magnitude 9.3 earthquake off the coast of Sumatra. Part of the tsunami propagated due east, and in 2 hours struck the populous southwest coast of the country at Phuket Island and nearby areas known for their beaches and tourist resorts. Unfortunately, because the wave arrived at high tide, the tsunami rode on top of the elevated tidal water level.

The tide-gauge at Ko Taphao Noi, an island about 7 kilometers southeast of Phuket City, is part of the Global Sea Level Observing System. Because the tide gauge was sheltered from the direct assault of the tsunami by Phuket Island to the west, the recorded wave magnitude was less than the magnitude that hit the western shorelines. The tide record (Figure 1) shows that the tsunami arrived as a negative wave that dropped the sea level to a level corresponding to low tide in a matter of 20 minutes; this was followed by two major wave crests in quick succession (20 minutes apart). These were followed by continuing oscillations of the water surface for the rest of the day due to the excitation of the entire Indian Ocean by the original tsunami (Figure 1).

Due to the offshore bathymetry, the height of the tsunami that struck along the southwest coastline varied by nearly a factor of three, with 4-meter high waves striking Nai Yang Beach (near the Phuket International Airport), 6-meter high waves hitting the populous Patong Beach on Phuket Island, and 11-meter high waves inundating the popular Khao Lak resort area,

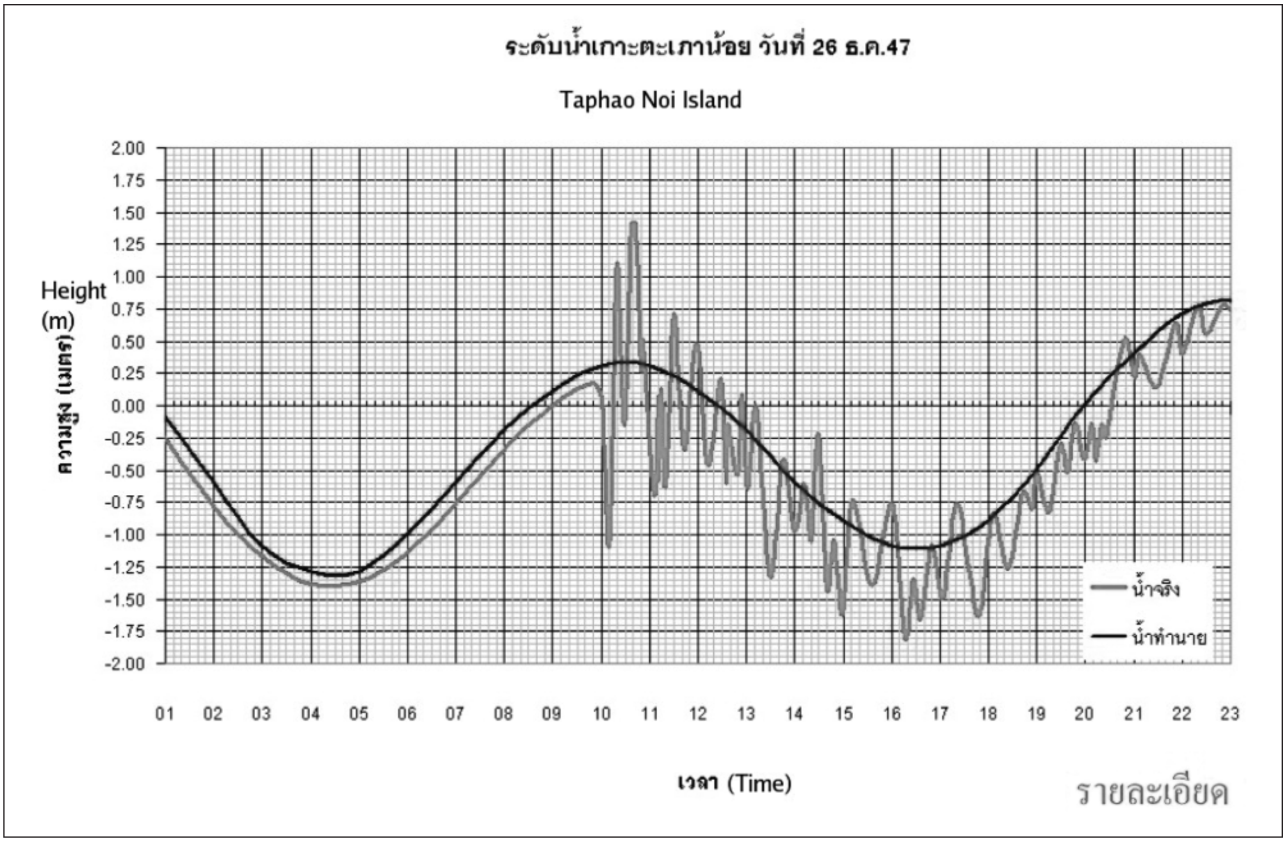

FIGURE 1 Tide-gauge record for December 26, 2004, showing the arrival of the tsunami at about 10 a.m. The tide gauge is on Taphao Noi Island, which is east of Phuket Island and is sheltered from direct tsunami impact.

65 kilometers north of Phuket City. These run-up and inundation elevations were measured by Japanese-Thai survey teams just after the wave attack (RCDRS, 2005). The variations in wave height resulted in corresponding differences in the number of fatalities and injuries. The official total death toll in Thailand was more than 5,000 people, and about 3,000 more are still listed as missing. Surprisingly, only about 250 people were lost at the densely populated Patong Beach on Phuket Island. In contrast, nearly all resorts in Khao Lak, a jumping-off point for diving in the Andaman Sea, were destroyed or severely damaged, and thousands died there.

At Phi Phi Don Island, 40 kilometers southeast of Phuket Island, each wave struck the crowded tourist area twice, because the geography of the island is comprised of two high rocky islands connected by a low sandy isthmus that has a maximum elevation of about 1.5 meters and a width of several hundred meters. Approximately 10,000 people were celebrating the holidays on this finger of sand when the first wave struck. The H-shaped island, with the isthmus running roughly east-west, was struck from the west, which forced the tsunami to refract and diffract into the north- and south-facing beaches (on Loh Dalam Bay and Ton Sai Bay, respectively). From the photographic evidence, the shallowness of Loh Dalam Bay and the deeply indented southern Ton Sai Bay caused the northern beach to be struck first and experience the largest wave heights (about 5 meters), which overtopped the isthmus. Immediately after, another part of the same wave struck from the south, washing the debris back over the island. Nearly 2,000 people died that day from drowning or being hit by debris (Figure 2).

Damage

Despite the high water levels, there was surprisingly little permanent damage to major civil infrastructure. At Patong Beach, despite the flooding, most of the structural damage was confined to beachfront structures, and within weeks, much of the town had reopened for business. The Phuket International Airport suffered no damage to the runways, despite its seaside location. Water supply and waste treatment plants were largely intact, except for seaside pumping stations and pipes in waterways that were damaged by scour. Most of the major bridges, roadways, and civil buildings survived the inundation from the wave well. However, low-lying coastal resorts, businesses, and private homes were severely damaged, as were fishing villages, such as Baan Nam Kem, which were visited by the ASCE team and, subsequently, by former Presidents Bush and Clinton.

After visiting a variety of beaches, ports, and fishing villages, the team was able to draw some very clear conclusions about structural design in a tsunami-prone region. Most of the well designed, reinforced concrete buildings with good foundations survived the wave attack. The survival rate was even higher for buildings that were elevated, allowing the water to flow under the structure. In addition, if the structure was constructed so water could flow through the first floor, structural damage was minimized, despite the loss of interior contents. This was actually part of the (accidental) design of many resorts in Thailand, which had reinforced concrete buildings that contained resort apartments with sliding glass doors facing the sea and the backs of the buildings. These buildings suffered little structural damage as the force of the tsunami broke through all of the doors and windows, thus reducing the force of the water on the building itself. By contrast, concrete buildings with solid masonry in-fill walls and no flow-through capability often experienced destruction of the walls and, in many cases, damage to the load-bearing structural frame.

At Kamala Beach, on Phuket Island north of Patong Beach, the Hotel Benjamin was one of the few buildings we saw that was constructed on concrete pilings that allowed water to flow under it. There was no obvious structural damage to the hotel, but the non-elevated buildings on either side of this shorefront hotel sustained considerable damage. Interestingly, the next row of non-elevated buildings landward showed a surprising pattern of damage because they took the brunt of the wave force from the water that flowed under and through the Hotel Benjamin. From this observation, the team concluded that if a seaside building is elevated to reduce damage from wave impact, the landward buildings behind it should also be elevated (Figure 3).

Many building failures occurred as the tsunami floodwaters scoured building foundations, as shown in the picture of Yumei Wang (ASCE team member) and an exposed footer (Figure 4). Unlike hurricane-prone coastal areas of the United States, where coastal buildings are now elevated on deep foundation piles, buildings in Thailand are often elevated on shallow spread footings embedded less than 1 meter below ground level. Our team saw dozens of examples of sediment scour down to, and under, these shallow footings. Interestingly, the scouring appeared to occur mainly as the tsunami receded and floodwaters returned seaward. Thus, many damaged buildings may have survived the incident tsunami wave only to be damaged as the floodwaters ebbed.

Khao Lak, with its low-lying coastal plane and numerous tourist resorts, suffered tremendous damage and loss of life as the result of the 1-meter high turbulent bore that raced 1.5 kilometers landward (Figure 5). The height and bore-like nature of the wave were likely due to the much shallower shelf offshore of the beach

FIGURE 2 View of the thin, low-lying isthmus on Phi Phi Island looking westward. Several hotels survived the wave, but most of the wooden homes on the near end of the isthmus were destroyed.

FIGURE 3 Two views of the Hotel Benjamin, Kamala Beach. The elevated structure escaped significant damage by allowing water to pass under it. The water level during the tsunami event was at the level of the exterior light fixture.

compared to the shelf off Phuket Island. Tourist videos and pictures[2] show that the waves in this region broke far offshore (in fact, well offshore of two coastal patrol boats) and came ashore as a nearly vertical wall of water moving at high speed (probably on the order of 40 to 60 kilometers per hour, based on measurements made after other tsunamis). This rapidly moving tsunami bore destroyed much of what was in its path. All timber structures, with few exceptions, were destroyed, creating hazardous floating debris.

Reinforced concrete structures fared somewhat better, and structures that were flow-through, such as the microwave tower and the Andaman Scuba shop shown in Figure 6, did very well. The scuba shop fortuitously had a trapezoidal footprint and was oriented so that the short side faced the sea, streamlining the building. The first floor was a shop lined with display windows that were broken out by the wave, which further reduced the hydrodynamic load on the building. The building on the right shows the typical type of damage to concrete buildings with masonry in-fill walls. The garage-door size holes broken through by the water on both the seaward (to the left in the photograph) and landward sides of the building illustrate the need for flow-through design. (The building between these two was apparently under construction; the skeletal nature of the building is not likely due to tsunami damage.)

At least 5 meters of water flooded the Phang Nga (Thai) Navy Base near Khao Lak, causing scour, grounding a Navy frigate, and killing 80 land-based sailors. Buildings at the base of the major pier were destroyed as the wave attempted to plane off the pier structures. At Baan Nam Kem, the fishing village north of Khao Lak, the uplift pressure of the water displaced the concrete pier decks. Fishing boats broke their moorings and were found clustered in the inland swamps and among the residences in the town. By contrast, boats and ships at sea suffered no damage because the tsunami was small in amplitude offshore. (We also heard that scuba divers were unscathed by the wave, although they were scared by the sudden powerful surge as the wave passed.)

On Phi Phi Island, major resorts on the isthmus constructed of reinforced concrete were not structurally damaged by the wave; most of the wooden homes in the inundation zones were destroyed. The resorts' foundations were designed well enough to prevent the scour from overpassing waves at the corners of the building from being deep enough (a meter or so) to create foundation problems. These multistory, reinforced concrete resorts also played a lifesaving role by providing a vertical evacuation route that enabled some people to find safety above the floodwaters.

In almost all cases, it was clear that buildings in the inundation zone, piers, and harbor support buildings should have scour-resistant foundations, small projected areas exposed to the horizontal flow of the wave, and good anchoring to their foundations. Flow-through

FIGURE 4 Example of scour below a shallow footing in the Khao Lak area. The building was several hundred meters from the ocean.

structures are critical to reducing hydrodynamic forces on structures. Designing buildings with habitable areas on upper floors and using the ground floor for less vital space can also reduce fatalities.

However, structural engineers must be aware that buildings able to withstand wave attacks, as suggested above, might not survive the earthquake that triggers the tsunami. Earthquake resistance and flow-through lower floors are not obviously compatible. Therefore, in active earthquake-tsunami-prone regions, the design of structures is a multi-hazard exercise.

Seawalls

At a number of beaches, low seawalls were in place, presumably to protect against high perigean tides and storm waves. Most of these walls were not damaged by the tsunami, and, despite the fact that the walls were overtopped by the much higher tsunami waves, structures landward of the walls were somewhat protected. At Patong Beach, the most populous beach on Phuket Island, where a low seawall stretched across most of the beach front, the steep offshore bathymetry caused the leading crests of the tsunami to break close to shore as plunging breakers, much like large surfing waves in Hawaii, except that they were backed by a step increase in water level. When these plunging breakers hit the beach, they broke into tongues of water that jetted into the community. The low seawall deflected much of the momentum of the waves skyward, reducing the forces on landward structures.[3] Although the wave flooded more than half a kilometer inland into the business district, completely flooding first floors in some areas, the loss of life was very low.

All along the business district of Patong Beach, the seawall had regularly spaced openings for pedestrian access to the beach (Figure 7). Damage to inland shops appeared to correlate to these openings.[4] Scour of the beach berm also appeared to be related to these openings, probably because of the draining of the receding tsunami floodwaters seaward through the openings. If access had been provided by cross-over access paths over the wall, instead of openings in the wall, the constant wall elevation along the beach would presumably have reduced damage significantly.

At the north end of Patong Beach, the design of a masonry seawall created a problem (Figure 8). Rather than having a vertical seaward face, the wall sloped inland, creating a ramp for the tsunami run-up jet that essentially launched the water into the attic of the building the wall was supposed to protect. This surprising phenomenon reinforces the idea that seawalls should be vertical or concave seaward.

Located at the north end of Phuket Island, the Phuket International Airport has one runway, running east and west; the western end of the runway is located at the shoreline. However, because the runway was protected by a vertical concrete wall set high up on the beach face, the airport was shut down for only two hours from flooding of 100 meters of the seaward end of the runway. The wall suffered no damage and probably prevented significant damage and scour at the airport.

At Kamala Beach, south of the Hotel Benjamin, a vertical seawall fronted the playground of a school.

FIGURE 5 Structural damage at a Khao Lak resort, illustrating both foundation failure due to scour and direct wave impact. This level of devastation was observed in many areas.

FIGURE 6 Buildings at Khao Lak. The wave came from the left and broke through the masonry walls of the building on the right. The Andaman Scuba building was relatively untouched by the wave because of the large number of display windows that broke out and the streamlined footprint of the trapezoid-shaped building.

Although the vertical wall was damaged, the playground and the school buildings were not seriously damaged. Fortunately the school was closed on the Sunday of the tsunami.

On Phi Phi Island, a seawall on the south beach built with a core of sandbags and a hard outer covering was supposed to protect shops. The wall failed in numerous spots because of scour, hydrostatic force of the waves, and, in one spot, because a house dropped on it. It is not clear how much protection this poorly constructed wall afforded.

Coastal Features

The tsunami removed an immense amount of sand from the beaches in Thailand. Presumably, most of the sand was carried landward by the wave and deposited as a thin lens across the wave-inundation zone. (Geologists use lenses of sand in the geological record to determine the occurrences of paleo-tsunamis.) Figures 9 and 10, taken from the IKONOS satellite, show the beaches of the Khao Lak region of Phang Nga province one year before the tsunami and just after the event. The wide beaches (in the low tide image, Figure 9) prior to the tsunami disappeared along with most of the vegetation between the sea and the limit of wave incursion (up to 1.5 kilometers inland). The images document the flushing of sediments from tidal creeks and streams. The incoming wave run-up and subsequent seaward draining of the floodwaters produced abnormally high streamflow rates and sediment transport in these streams. This sand was apparently carried into the nearshore area.

The loss of the beaches, if prolonged, would have been devastating to tourism, because the beaches are a major attraction to the millions of tourists who visit southwestern Thailand. However, one month after the tsunami, we found that the beaches had recovered remarkably. In most places, the new beaches were more than 30 meters wide and showed no obvious permanent damage from the tsunami, suggesting the existence of significant offshore and nearshore sources of beach sand to replenish the destroyed beaches. Some of this sand was probably the very material that was flushed from

FIGURE 7 Pedestrian opening in the Patong Beach seawall (the short wall to the right of the figure). Tourist videos show that this wall deflected the tsunami run-up skyward, reducing forces on the seafront buildings.

creeks and rivers. (This is not to say that there was no permanent damage—the northwest tip of Cape Pakarang at the top of the pictures was still missing.)

Although there are few sand dunes along the Thai coast, in locations with wide, elevated, vegetated sand dunes, damage was reduced. In the Kata-Karon area of Phuket, residential and commercial development was set back behind a sand dune that had been preserved by local authorities. Although the dune was overtopped by the advancing tsunami, interviews with local inhabitants and observations of residual damage suggest that the dune dramatically reduced flow velocities. Damage in this area was limited to direct flooding and did not convey the kind of impact-related structural damage that was seen elsewhere.

Debris

As the waves came ashore and flowed across streets and through structures, they generated an immense amount of debris. Demolished wood buildings, cars, furniture, clothing, and objects of day-to-day life were picked up by the waves and carried inland (Figure 11). As the waves receded, the debris receded with them; subsequent waves then returned the debris to shore once again. Numerous photographs after the tsunami of downtown Patong Beach reveal automobiles in shops, piled on top of one another, and on rooftops. This flotsam was a major source of injury and death as it struck people struggling in the water or trying to hold on to fixed objects.

In flood-prone areas, it makes good sense to locate potential debris-producing objects and structures as far landward as possible. For example, parking lots should not be seaward of hotels, because floating cars are very destructive. At Patong Beach, local officials are even limiting the number of beach umbrellas allowed on the beach; nearly 7,000 umbrellas were transformed into projectiles that washed inland during the tsunami.

Rebuilding in a Tsunami Zone

Because beach tourism is the prime economic driver for southwest Thailand, a major tool of hazard reduction—prohibiting people from living in now known inundation areas—is not really a viable option. Thus tsunami-proof structures with flow-through designs, stronger buildings, and deeper scour-resistant foundations are mandatory. In addition, evacuation strategies must be part of the re-design. Although horizontal evacuation routes provide clear escape routes leading inland from inundation areas, vertical evacuation routes that ensure easy access to the upper floors of tsunami-resistant structures, may be better, given the lack of warning time. In all cases, public education about tsunamis and warning systems are critical.

Cost is one of the most difficult impediments to tsunami-proofing structures. Although the tsunami showed that Thailand is not immune to these disasters, historically, they have occurred infrequently. In addition, because this most recent earthquake relieved much of the stress in the fault, it may be more than 100 years before the next major tsunami occurs. With such a low level of risk, calculating acceptable investments for elevating structures, refitting buildings to reduce damage, and zoning people out of inundation regions may be difficult.

The wisest choices may be to revive the tourism industry by tsunami-proofing tourist resorts to reassure patrons they will be safe (or safer) and to dedicate remaining public funds to public education about tsunamis. Public knowledge about tsunamis, in this case

FIGURE 8 This seawall, which slopes inland, apparently acted as a ramp that launched the tsunami run-up into the attic of this building located at the north end of Patong Beach.

FIGURE 9 IKONOS satellite image of the Khao Lak Region, Phang Nga Province of Thailand, before the tsunami. Note the wide beaches and sediment-filled tidal streams. This image was taken December 13, 2003. Source: Centre for Remote Imaging, Sensing, and Processing, National University of Singapore.

FIGURE 10 IKONOS satellite image of the Khao Lak Region, Phang Nga Province of Thailand, after the tsunami. Note the absence of beaches, the damage to Cape Pakarang (upper left), and flushed tidal streams. This image was taken December 26, 2004. Source: Centre for Remote Imaging, Sensing, and Processing, National University of Singapore.

about the association of tsunamis and earthquakes and the import of a large initial drop in water level, can play a major role in saving lives. In Thailand, astute coastal residents, visitors, and some local lifeguards recognized the hazard and evacuated the beaches just minutes before the tsunami hit.

Some of the tsunami protection solutions are available at reasonable cost. For example, the presence of a coastal sand dune at Karon Beach, just south of Patong Beach, reduced the force and velocity of upland flooding. However, today coastal dunes are nearly nonexistent along the southwestern Thai shoreline. If they existed at all, they have been removed either for construction or to provide a better view of the sea. Dunes are a simple, low-tech construction that can be implemented fairly easily. In addition, replanting mangrove swamps at appropriate locations can reduce the intensity of the waves.

Although it is impossible to guarantee safety in the event of another disaster of the same magnitude, the prudent implementation of the knowledge gained from this tsunami could dramatically reduce the loss of life the next time, whenever it occurs.

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FIGURE 11 A rural area with typical debris composed of small trees and natural vegetation, structural lumber and building components, and interior contents of buildings.

D.C.: U.S. Government Printing Office.

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Notes

1. Other team members were Robert Lo, Yumei Wang, Curt Edwards (team leader), Robert Barnoff, Martin Johnson, and Anat Ruangrasseme.
2. The video Tsunami2004-Tsunami-Hits-Khao-Kak-by-German-Tourist-Uncut.wmv (available online at *http://www.waveofdestruction.org*) shows the waves and the two patrol boats being struck by the wave. One of the ships may have been the police patrol boat, which was surfed ashore and deposited upright 1.5 kilometers inland, along with other flotsam.
3. The tourist video taken from the Novotel Coralia Phuket of the beach at Patong and the inundation of the shorefront Franco Roma Restaurant shows the waves striking the seawall (evidenced by the splash-up) and the inundation of the business district. Available online at: *http://www.waveofdestruction.org/download.php?f=www.waveofdestruction.org-patong_beach.wmv*.
4. Team member Robert Lo first noticed this correlation.

Computational models of tsunamis can be used to design and operate early warning systems.

Tsunami Simulations and Numerical Models

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Philip L.-F. Liu

The Earthquake

At 00:58:53UTC on December 26, 2004, a strong earthquake struck southwest of Banda Aceh in northern Sumatra (3.30°N, 95.78°E). The earthquake, which occurred near the junction of the Indian, Australian, and Burma plates, was caused by the sudden release of tectonic strain built up by the subduction of the Indian plate under the Burma microplate (at roughly 60 millimeters [mm]/year) along a fault line stretching from Indonesia in the south to the Andaman Islands in the north. The original earthquake and aftershocks indicate that approximately 1,200 kilometers (km) of this fault ruptured along the northern Sunda Trench (Figure 1).

The initial estimate of the magnitude of the earthquake was $M_W = 9.0$ based on the Harvard University centroid moment tensor (CMT) solution. The seismic moment released on the fault plane (strike = 320° and dip =11°) was estimated at 3.57×10^{29} dyne-cm (Ji, 2005). The duration of the associated total rupture was 200 seconds (sec), and the peak slip was about 20 meters (m). The rupture propagated northwestward for nearly 400 km at a speed of 2.0 km/sec. In the seismic body-wave analysis, only the first 220 sec of seismic data were used to constrain the slip. Hence, the body-wave analysis cannot resolve the later, smaller slip if it occurred further north.

Analyzing the normal modes excited by this earthquake, Stein and Okal (2005) estimate that the seismic moment was as large as 1.0×10^{30} dyne-cm

(M_W = 9.3). They also suggest that the larger moment can be accounted for by 11 m of slip on a fault 1,200 km long and 200 km wide (down-slip dimension). This would indicate that the slow slip probably occurred over the northern part of the 1,200-km long rupture zone indicated by the aftershocks (Figure 1).

It has also been suggested that the rupture propagated to the north relatively slowly, producing a long source duration of approximately 30 minutes (Dr. Kenji Satake, Active Fault Research Center, National Institute of Advanced Industrial Science and Technology, Japan, personal communication). However, the entire rupture process, including the cause of the suggested slow rupture propagation, remains unresolved.

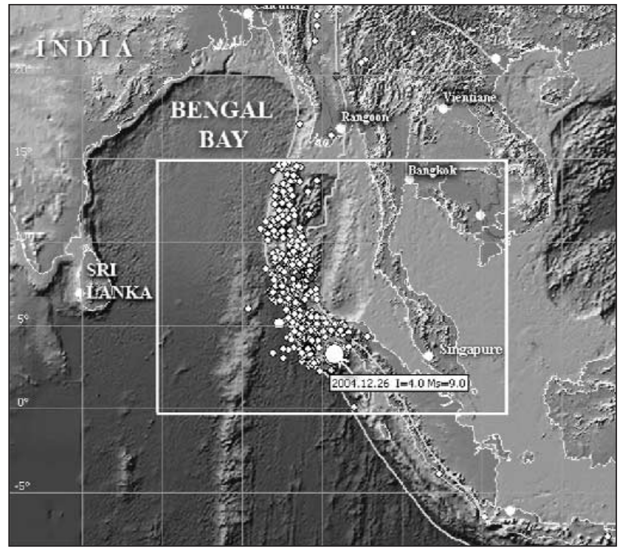

FIGURE 1 Epicenter and aftershocks associated with the December 26, 2004, earthquake.

The Tsunami

The earthquake triggered giant tsunami waves that propagated throughout the Indian Ocean, causing extreme inundation and destruction along the northern and western coasts of Sumatra. Within hours, the tsunami devastated the distant shores of Thailand to the east and Sri Lanka, India, and Maldives to the west. The tsunami also caused destruction in Somalia and other nations of east Africa. The highest recorded tsunami run-up occurred on the west coast of Sumatra, where the height of the water reached almost 35 m. In Indonesia alone, more than 230,000 are dead or missing. The death toll in Sri Lanka and India is more than 50,000. More than 1,500,000 people are believed to be homeless as a result of the tsunami.

Post-Tsunami Survey

In response to the Indian Ocean tsunami, the international community quickly initiated and organized post-tsunami survey plans. Scientists and engineers from Japan, Korea, New Zealand, and the United States participated in this effort. Within three days of the earthquake, three U.S. survey teams were organized and dispatched to Indonesia, India, and Sri Lanka and Maldives. Later, a small team was sent to east Africa. Most of the team members from the United States were supported by the Earthquake Engineering Research Institute (EERI), National Science Foundation (NSF), and U.S. Geological Survey (USGS). The U.S. teams included researchers from Cornell University, Georgia Institute of Technology, Oregon State University, Portland State University, Texas A&M University, University of Arizona, University of Southern California, and University of Washington; they were joined by researchers from USGS and local scientists from India, Indonesia, and Sri Lanka.

The primary objective of the post-tsunami surveys was to collect physical evidence and eyewitness accounts on maximum tsunami heights, maximum run-up heights, inundation distances, areas of inundation, and tsunami deposits. These data are essential for validating numerical models for tsunami-wave propagation over the ocean and run-up/inundation in coastal areas and for improving our understanding of the fault-plane mechanism.

Maximum tsunami height is defined relative to sea level and is measured by watermarks on buildings, scars on trees, and rafted debris. Inundation distance is the distance from the shoreline to the inland limit of tsunami flooding; maximum run-up height is the elevation at the inundation distance. Every mark used for these measurements was photographed and its location identified by GPS. Wave heights were plotted for Sri Lanka (Figure 2), the east coast of India (Figure 3), and the north coast of Aceh, Indonesia (Figure 4).

Soil samples from tsunami deposits were also collected. The tsunami in India and Sri Lanka deposited sand from the beach and ocean floor in buildings, on top of boulders, and on the ground. Tsunami sand deposits were found at every visited site. The width of the tsunami deposit varied, depending on the characteristics of the deposit and the wave height. The thickness and grain size distribution of tsunami deposits will be correlated to the wave height and flow velocity associated with the tsunami to provide a scientific basis for analyzing paleo-tsunami deposits. These data will also be added to the database for estimating recurrences of tsunamis at given sites.

Damage to houses and buildings was also recorded and documented. In general, most wood-framed structures and straw houses were totally destroyed. Some masonry buildings survived, as did almost all reinforced concrete houses (Figure 5). One of the prominent effects of the tsunami was extensive scouring around the foundations of buildings (Figure 6). The scouring appeared to be the result of both incoming and returning flow and was significant enough to undermine foundations. More detailed reports on field surveys can be found in EERI Special Earthquake Report (March 2005) and Liu et al. (2005).

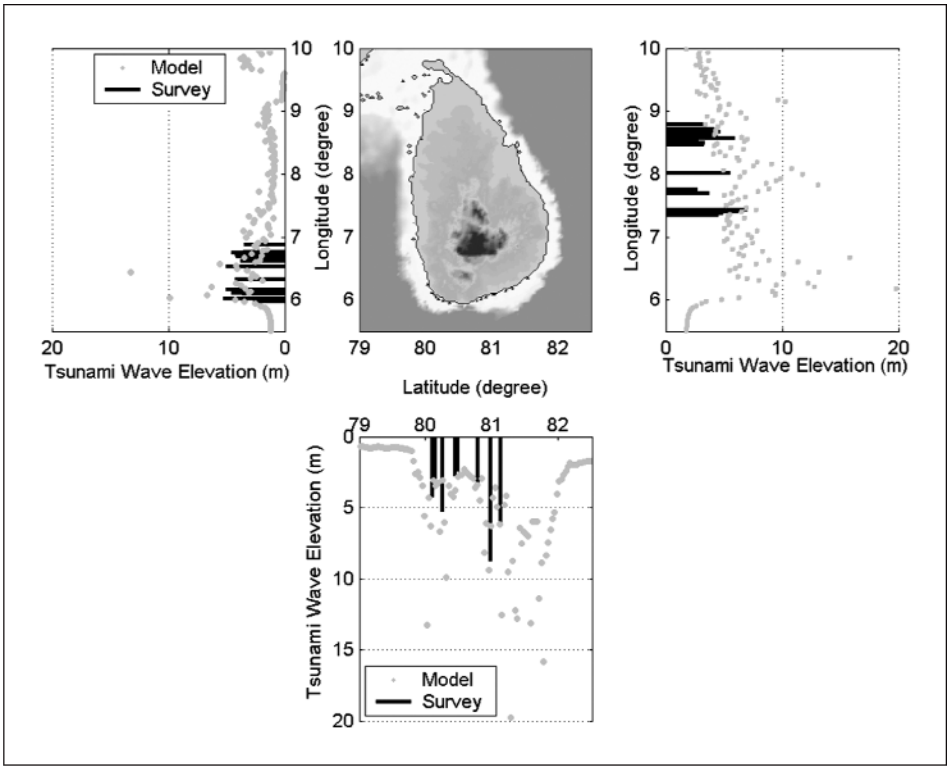

FIGURE 2 Surveyed (bars) and calculated (dots) tsunami wave heights along the coast of Sri Lanka.

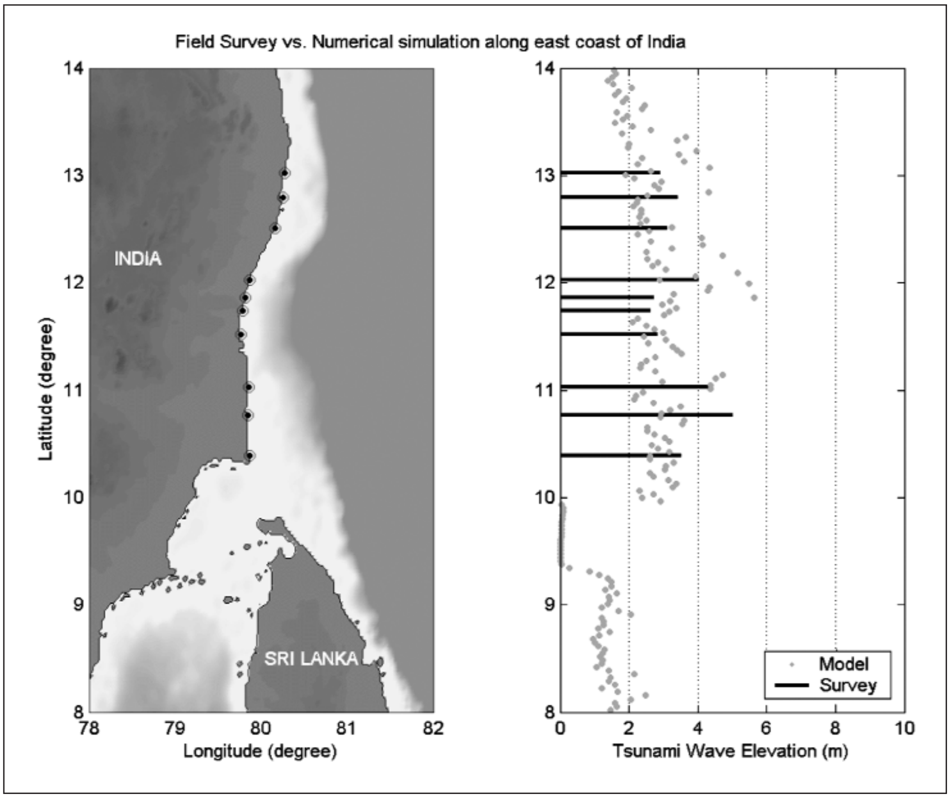

FIGURE 3 Surveyed (bars) and calculated (dots) tsunami wave heights along the east coast of India.

Numerical Simulations of Tsunami Propagation

Numerical simulations of tsunami propagation have been greatly improved in the last 30 years. Several computational models are being used in the National Tsunami Hazard Mitigation Program, sponsored by the National Oceanic and Atmospheric Administration (NOAA), to produce tsunami inundation and evacuation maps for Alaska, California, Hawaii, Oregon, and Washington. These models will also be used to

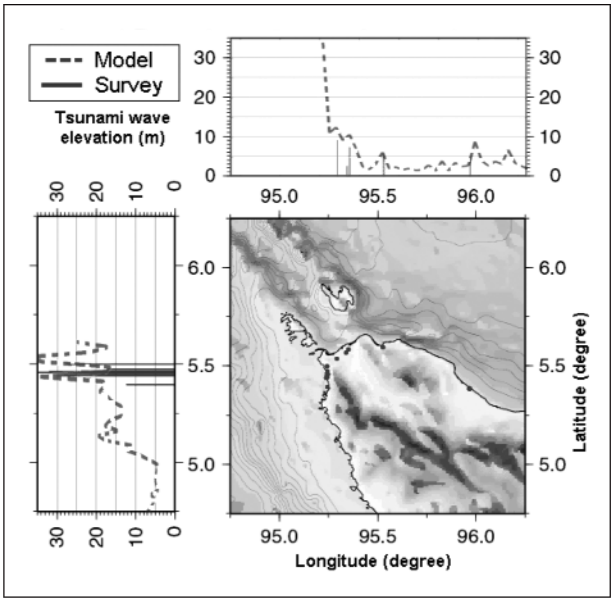

FIGURE 4 Surveyed (bars) and calculated (dots) tsunami wave heights along the north coast of Aceh, Indonesia. Source: EERI, 2005.

FIGURE 5 A damaged building near Kalmunai in Sri Lanka.

design and operate early warning systems. The computational models include MOST (method of splitting tsunami), developed originally by researchers at the University of Southern California (Titov and Synolakis, 1998); COMCOT (Cornell multi-grid coupled tsunami model), developed at Cornell University (Liu et al., 1994); and TSUNAMI2, developed at Tohoko University in Japan (Imamura, 1996). All of these models require further validation by large-scale laboratory experiments and field data.

A series of numerical simulations of tsunami propagation were performed for the December 26, 2004, earthquake using different fault-plane mechanisms to test their validity. Numerical results were compared with data from field surveys and available tidal-gauge records. In this paper, I describe numerical results based on two fault mechanisms, one provided by USGS (Ji, 2005) and one provided by NOAA (Dr. Vasily Titov, University of Washington, Joint Institute for Study of the Atmosphere and Ocean, personal communication). The USGS fault-plane parameters (Table 1) were calculated using the Harvard University CMT solution. The estimated length of the fault plane was 500 km; the estimated width was 150 km. Because the strike angle was 320°, which denotes the angle from the north to the fault line in a clockwise direction, the fault line pointed northwest. For the seismic moment 3.57×10^{29} dyne-cm, the rigidity of Earth's crust can be estimated as $\mu = 4.3 \times 10^{10} N/m^2$.

The NOAA fault-plane parameters (Table 2) are based on suggestions by Stein and Okal (2005) that fault slips occurred over the northern part of the rupture zone. Three subfault planes are oriented along the northern Sunda Trench. The total length of the fault zone is 1,170 km; the width of the fault plane is kept as a constant at 150 km. Using $\mu = 4.3 \times 10^{10} N/m^2$ for rigidity of Earth's crust, the total seismic moment is estimated as 1.13×10^{30} dyne-cm, which is significantly bigger than the estimate with the USGS fault-plane mechanism.

The seafloor displacements for both fault-plane mechanisms were calculated using the linear elastic-dislocation theory with a rectangular uniform fault plane (e.g., Mansinha and Smylie, 1971). Because the water is incompressible and the rupture is assumed to occur instantaneously, the water-surface deformation mimics

TABLE 1 Fault Parameters from USGS

Fault Parameters	Fault Plane
Fault depth	10 km
Length of fault plane	500 km
Width of fault plane	150 km
(Strike, Dip, Slip)	(320°, 11°, 110°)
Dislocation	11 m

TABLE 2 Source Parameters

Source Parameters	Fault Plane 1	Fault Plane 2	Fault Plane 3
Fault depth	5 km	5 km	5 km
Length of fault plane	200 km	670 km	300 km
Width of fault plane	150 km	150 km	150 km
(Strike, Dip, Slip)	(300°, 13°, 90°)	(345°, 13°, 90°)	(365°, 13°, 90°)
Dislocation	15 m	15 m	15 m

the seafloor deformation. Figures 7 and 8, generated by the USGS and NOAA fault-plane mechanisms, respectively, show the contours of the initial free-surface elevations. The free-surface profiles exhibit N-wave characteristics, with an elevated waveform on the western side and a depression waveform on the eastern side of the fault plane. The maximum positive amplitude of initial free surface based on the NOAA fault-plane mechanism is about 7 m; the maximum based on the USGS fault-plane mechanism is about 4 m.

FIGURE 6 Typical damage from scouring at the foundation of a building on the east coast of Sri Lanka.

The numerical model COMCOT was used to simulate tsunami propagation. COMCOT adopts a modified leapfrog finite-difference scheme to solve (both linear and nonlinear) shallow-water equations (Liu et al., 1994). (Only the linear shallow-water equations in spherical coordinates are shown here). In the model, the coastline is placed at a water depth equal to or less than 5 m; the model did not take into account the nearshore bathymetry or inland topography, which might change the direction of wave propagation and the overland flow pattern.

The simulated domain covers almost the entire Indian Ocean, ranging from 30°E to 110°E longitude and –25°S to 23°N latitude, with a grid size of 2 minutes (ETOPO2). The dimension of grids is 2,401 by 1,441. The simulations were done on a desktop computer (1.5GB RAM and Athlon XP 2600+ CPU).

Numerical Results

According to the initial free-surface profiles calculated, the NOAA fault-plane mechanism is more energetic and would generate a much larger tsunami. Furthermore, because the NOAA fault plane stretched farther north, the generated tsunami would have much more severe impacts on the coast of Sri Lanka and the east coast of India. The calculated maximum tsunami wave amplitudes along shorelines of Sri Lanka, India, and Aceh, Indonesia, based on the NOAA fault-plane mechanism, are shown in Figures 2, 3, and 4, respectively. The overall agreement between the observation data and the numerical results is reasonable, considering that the present model does not resolve the nearshore bathymetry and topography. The numerical results based on the USGS fault-plane mechanism (not presented here) significantly underestimated wave heights everywhere.

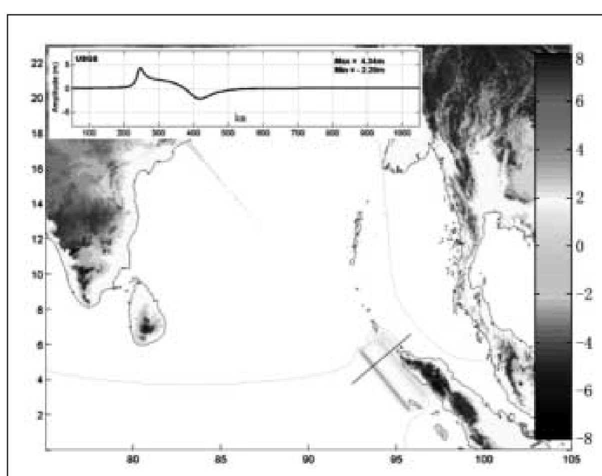

FIGURE 7 Initial surface profile from USGS fault-plane parameters.

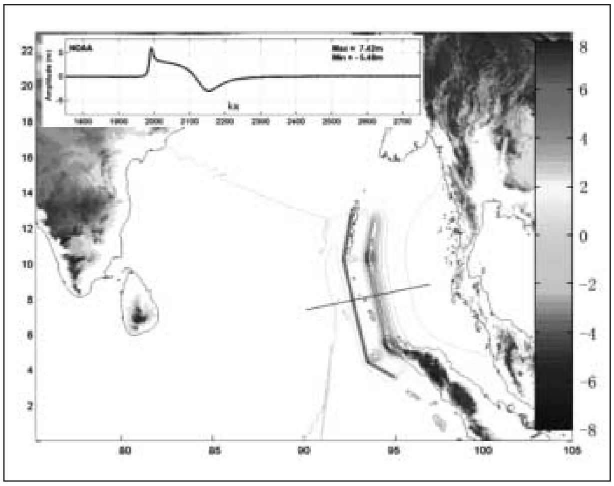

FIGURE 8 Initial surface profile calculated based on NOAA fault-plane parameters.

The numerical simulations showed that a large portion of wave energy was reflected from Maldives and propagated back towards the south and west coasts of Sri Lanka. This was confirmed by eyewitness accounts near Colombo, Sri Lanka.

The University of Hawaii Sea Level Center (supported by NOAA) maintains a network of sea-level stations in the Indian Ocean that report real-time sea-level data on Global Sea Level Observing System (GLOSS) sites. The numerical results of the NOAA model were compared with the available tide-gauge data (with tidal fluctuations removed) at Colombo, Sri Lanka; Gan, Maldives; and Male, Maldives (Figure 9). Figure 9 shows typical results from these comparisons. The numerical results show the correct phase of leading waves, but the amplitudes are lower than the measured data. Moreover, the arrival time of leading waves is about 10 to 20 minutes earlier in the model. However, considering the low grid resolution (2 minutes) and uncertainty in the estimation of fault-plane parameters, the numerical results match the tide-gauge records fairly well.

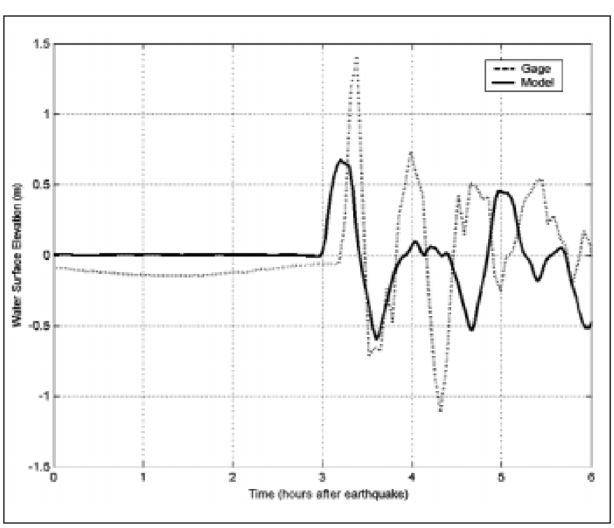

FIGURE 9 Comparison of numerical results (solid line) and tide gauge data (dotted line) at Male, Maldives.

Conclusion

Although a very coarse grid size was adopted for the numerical simulations, numerical results, based on the NOAA fault-plane mechanism, match the field survey data fairly well along the coastlines of Sri Lanka, India, and Indonesia. However, there are still discrepancies for both arrival time and wave amplitude between numerical results and tide-gauge data. The discrepancies could be caused by the large grid size used and uncertainties in the fault-plane mechanism. Keep in mind also that the effects of slow rupture propagation have not been considered in the present results.

An examination of the data obtained by satellite radar altimeters, including the TOPEX/Poseidon satellite that passed across the Indian Ocean from southwest to northeast about two hours after the earthquake (TOPEX/Poseidon passed the equator at 03:01:57UTC on December 26, 2004) and the Jason-1 satellite that passed by 1:56 hours after the earthquake (Jason-1 passed the equator at 02:55:24UTC on December 26, 2004), can further our understanding of the characteristics of Indian Ocean tsunamis and the fault-plane mechanism. The accuracy of these sea surface elevation data is better than 5 cm (JPL, 2005). These data could be used to improve the parameterization of fault-plane mechanism.

Finally, evaluating the impacts of tsunamis in affected coastal regions will require higher resolution bathymetry/topographic data. Nonlinear effects, including wave breaking, must also be clarified and included in the simulation model.

Acknowledgment

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NOAA has been using technology to detect and warn of tsunamis for more than three decades.

Tsunami Warning Systems

Vice Admiral Conrad C. Lautenbacher Jr., U.S. Navy (Ret.), is undersecretary of commerce for oceans and atmosphere and NOAA administrator.

Conrad C. Lautenbacher Jr.

When our planet flexes its natural muscles, it often creates hazards for the humans who live on its surface. The tsunami that struck Southeast Asia and parts of Africa in December was a shocking reminder of Earth's power. Although we may not be able to control when Earth flexes her muscles, we can and should be able to provide people with the necessary resources and warnings to minimize losses of life and property from natural disasters.

Human curiosity leads us to try to make some sense of the world in which we live. But our understanding sometimes stalls in the face of the complexities of our planet. Undaunted, however, we continue the pursuit, knowing that the questions we ask today may not be answered until long after we are gone and that processes we put in place now may benefit future generations if not our own. In the meantime, we can use the information gained along the way in beneficial ways. Our reactions to tsunamis over the past half-century have followed this model.

In a television special about the December 26, 2004, tsunami, an individual interviewed said, "Before December 25, very few people knew what a tsunami was. After December 26, almost everyone does." Even before this tragedy, however, much was known about tsunamis. We know what they are and what causes them, and when we detect one, we can make reasonable predictions of where and when it might strike.

Although infrequent, tsunamis are a significant natural hazard that can cause great destruction and loss of life within minutes on shores near their source. Approximately 85 percent of tsunamis occur in the Pacific region, but they are known to happen in every ocean and sea, except the Arctic. Some tsunamis can cause destruction within hours across an entire ocean basin, as was tragically demonstrated last December 26.

A tsunami wave can pass under a ship without those aboard the vessel noticing.

Tsunamis are series of very long waves generated by rapid, large-scale disturbances of the sea—the sudden displacement of a large volume of water, generally from the raising or lowering of the seafloor caused by undersea earthquakes; landslides above ground or under water; or even volcanic eruptions. Once a tsunami has been generated, its energy is distributed throughout the water column, regardless of the water depth, and the waves travel outward on the surface of the ocean in all directions away from the source, much like ripples caused by throwing a rock into a pond. The wavelength of the tsunami waves and their period depend on the generating mechanism and the dimensions of the source event.

In the deep ocean, the height of a tsunami from trough to crest can range from a few centimeters to a meter or more depending on the generating source. Tsunami waves in the deep ocean can travel at high speeds for long periods of time over distances of thousands of kilometers and lose very little energy in the process. The deeper the water, the greater the speed of tsunami waves. A tsunami wave can travel more than 800 kilometers per hour (km/h) in the deep ocean, but slows to 30 to 60 km/h in shallow water near land. At these high speeds, a tsunami generated in the Aleutian Islands in Alaska could reach Hawaii in less than four and a half hours, but, amazingly, pass under a ship in the ocean with those aboard the vessel hardly noticing.

Tsunamis arrive at a coastline as a series of successive crests (high water levels) and troughs (low water levels) usually 10 to 45 minutes apart. As they enter the shallow waters of coastlines, bays, or harbors, their speed decreases. For example, in 15 meters of water, the speed of a tsunami wave may be only 45 km/h. However, 100 or more kilometers away, another tsunami wave traveling in deep water toward the same shore is moving at a much greater speed, and behind it another wave is traveling at even greater speed. As the tsunami waves become compressed near the coast, their wavelengths are shortened, and the wave energy is directed upward—thus considerably increasing the height and force of the waves.

Tsunami waves may smash into the shore like a wall of water or move ashore as a fast moving flood or tide—carrying along everything in their path. The historic record shows that many tsunamis have struck with devastating force, sometimes reaching heights of 30 to 50 meters. It should be remembered that a tsunami run-up of more than 1 meter is dangerous and, because flooding by individual waves typically lasts from 10 to 30 minutes, the danger can last for hours.

Americans were introduced to the power of tsunamis on March 28, 1964, when the largest earthquake (magnitude 8.4) of the twentieth century in the Northern Hemisphere caused massive devastation in Alaska; some areas were raised as much as 15 meters and others subsided. The resulting Pacific-wide tsunami killed 120 people, destroyed Alaska's port facilities, and affected the entire California coastline. Five of Alaska's seven largest communities were devastated by the combination of earthquake and tsunami damage.

As a direct result of the 1964 earthquake, the West Coast Tsunami Warning Center was built in Palmer, Alaska, in 1967. This center was subsequently combined with a similar center built in 1949 in Hawaii to protect everyone living along the U.S. Pacific coast. With knowledge comes power, and these two centers have combined observations and monitoring with research into the mechanics of tsunamis to offer some warning when a tsunami might strike. The center in Hawaii has since become a partner of the U.N. Intergovernmental Oceanographic Commission International Coordination Group to provide timely tsunami warnings to other Pacific nations.

These warning centers are connected to seismic monitors around the globe and sea-level monitors in the deep ocean and in harbors around the Pacific Ocean. When an earthquake occurs, scientists are alerted, triggering a rapid earthquake analysis. If the earthquake exceeds a magnitude of 7.5 *and* is near a coastline, a tsunami warning is issued immediately for the area surrounding the earthquake. The warning center then monitors sea-level instruments to determine if a tsunami has actually been generated. If the sea-level instruments do not detect a tsunami or if they detect a small tsunami, the warning is cancelled. If the instruments detect a large tsunami, the warning is expanded to all coastlines of the Pacific.

FIGURE 1 A network of DART buoys in the Pacific Ocean that monitors conditions in real time can detect tsunamis with an amplitude of only one centimeter in 6,000 meters of water.

The Deep-Ocean Assessment and Reporting of Tsunamis (DART) System

Although much of the world has focused on tsunamis relatively recently, the National Oceanic and Atmospheric Administration (NOAA) has been conducting research on the causes and consequences of tsunamis and using technology to help detect and warn of their presence for more than three decades. The first deep-ocean assessment and reporting of tsunamis (DART) buoy, or "tsunameter," was created in the engineering laboratory of NOAA's Pacific Marine Environmental Laboratory (PMEL) in Seattle, Washington. DART systems use bottom-pressure recorders (BPRs) capable of detecting and measuring a tsunami with an amplitude as small as 1 centimeter in 6,000 meters of water. Data are then relayed by acoustic modem to a surface buoy (Figure 1), which transmits the information to a ground station via satellite. The data are displayed in real time at *http://www.ndbc.noaa.gov/dart.shtml.*

PMEL began development of the DART system in 1987, and a prototype system was deployed for two months off the Washington-Oregon coast in the summer of 1995. The surface buoy performed well, but data losses of approximately 5 percent were noted. In March 1997, a redesigned system was deployed in deep water off Oahu, Hawaii. This newer system was designed to reduce data loss by quantifying the acoustic-beam pattern, signal-to-noise levels, acoustic-modem baffle performance, and mooring and hardware design parameters. The deep-water test was successful, and two demonstration systems were subsequently fabricated and tested.

The standard DART surface buoy has a current design life of one year, and the seafloor BPR package has a life of two years. The system has proven to be robust and reliable with a cumulative data return of 96 percent since 1998. The DART, or tsunameter, which costs about $250,000 for each station, has demonstrated its value many times over for the state of Hawaii.

DART is one of NOAA's many research-to-operations success stories. The transition period for the newest system began in 2001 and ended in October 2003. On November 17, 2003, DART detected a small tsunami generated by an earthquake near Adak, Alaska, but based on data collected from DART buoys, no warning was issued for this event, which saved Hawaii an estimated $68 million. This event showed that sometimes the greatest benefit of a warning system is knowing when not to evacuate (Figure 2). This becomes clear when we look back to an event of similar magnitude in 1986 in the same region that resulted in the evacuation of Hawaii's coastal areas. At the time, predictions of the amplitude of tsunamis were difficult to make, and the tsunami that eventually struck the coastline was less than a foot in height. Thankfully, it caused no damage, but the Hawaii Department of Business, Economic Development and Tourism estimated that the evacuation cost the state $40 million in lost productivity and business.

FIGURE 2 A team of NOAA scientists deploys a DART buoy in the Pacific Ocean. In the future, both the Atlantic and Pacific oceans will be covered by 38 buoys that will provide nearly 100 percent coverage for the coastal United States.

The Next-Generation Systems

NOAA is working on the next generation of tsunameters, learning from the lessons of the first generation of buoys, and using new technology to increase their usefulness. NOAA has also incorporated numerical modeling technology to forecast tsunamis in real time. Tsunameter data, sent from the DART system in real time, is assimilated into a set of nested numerical models that produce a forecast for a specific coastal town or city. The new generation of tsunameters will be the sentinels in the sea for the expanded tsunami network. The first generation of tsunami forecast models will convert data from these sentinels into tsunami forecasts in time for coastal populations to take evasive action, if necessary.

The tsunami forecast models were first used to create inundation maps for tsunami-susceptible areas. These models simulated tsunami events and indicated areas of possible flooding. In Hawaii, similar inundation maps are printed in the front of telephone directories so residents will know where to seek shelter.

On January 14, 2005, the United States announced plans to expand its U.S. tsunami detection and warning capabilities and committed $37.5 million over two years to do so. That investment will enable NOAA to deploy 32 new buoys, thus expanding existing coverage to all countries on the Atlantic and Pacific oceans, including almost 100 percent coverage in the United States, where half the population lives in coastal areas. The new tsunami-monitoring system is truly a multinational effort that will have multinational benefits, a good example of integrated observations that can make people safer.

The new tsunami-monitoring system is a multinational effort that will have multinational benefits.

Looking to the Future

Unfortunately, the capabilities of technology are limited. Despite the extensive technology and procedures in place to detect tsunamis in the Pacific, no similar systems are in place in the Indian Ocean, which greatly increased the devastation caused by the December tsunami. With no buoys or tide gauges in the Indian Ocean, it was impossible to determine if a tsunami was generated by the December 26, 2004, earthquake, and specific warnings could not be issued. As I noted in my remarks to the Earth Observation Summit this February in Brussels, "Tragic as the tsunami was, it also served to illustrate the power of a networked system. By linking our observational capabilities in a more comprehensive way, we will be able to keep the citizens of every nation more safely out of harm's way."

Although there are thousands of moored and free-floating data buoys and thousands of land-based environmental stations around the world and more than 50 environmental satellites orbiting the globe, all providing millions of data sets, most of these cannot yet "talk" to each other. Until they do—and until all of the individual technologies are integrated into a comprehensive system of systems—there will continue to be blind spots and scientific uncertainty. Linking observational capabilities is precisely the goal of an international effort now under way to develop what is being called the Global Earth Observation System of Systems (GEOSS for short). With benefits that will reach the entire planet, this U.S.-led initiative promises to make people and economies around the globe healthier, safer, and better equipped to manage basic daily needs.

The U.S. tsunami warning system will be an integral part of this larger Earth-observing system. Combined with efforts under way in the Indian Ocean, we will be casting a safety net across the world to prevent the kind of devastation we saw last December. The goal is to make twenty-first century technology as interrelated as the planet it observes and protects and to provide a scientific basis for making sound policy decisions. With an integrated system, we will truly be able to take the pulse of the planet.

Technology, however, is only as good as our ability to use the information it provides. An effective communication system for issuing warnings and all-clear messages, coupled with well marked evacuation routes and public education, must complete the picture. Children in Hawaii and many U.S. West-Coast communities, especially communities that have been designed TsunamiReady by NOAA's National Weather Service, conduct evacuation drills to ensure that citizens know what to do if an alarm is sounded.

In some parts of the country, the first week of April has been designated Tsunami Preparedness Week.

Bright blue and white "tsunami hazard zone" signs mark evacuation routes, although, sadly, some communities have reported that the signs have attracted souvenir hunters. In addition, a variety of items, including mugs, magnets, and bookmarks, carry instructions about how to get out of harm's way, and posters and other printed materials can be found on many websites.

The National Tsunami Hazard Mitigation Program, working with the International Tsunami Information Center, creates educational materials and provides information for all age levels and encourages their use. Even when technological means are not available, education alone can save lives. This was demonstrated after the 1998 Papua New Guinea tsunami, when more than 2,000 lives were lost along the north coast of the country's main island. Subsequently, an educational video created by the United Nations Education, Science, and Cultural Organization (UNESCO) was distributed to some tsunami-prone areas. One such area was a village on Pentecost Island, one of 83 islands in the southwest Pacific that compose the nation of Vanuatu. When a tsunami struck that village in 1999, only five of the 500 inhabitants (1 percent) died. The majority of villagers said they had learned from the video that they should move inland or flee to higher ground when they felt the ground shaking. Thus, it is important to educate everyone who lives near a coast about what to do when an earthquake hits and the ground begins to shake.

Conclusion

When fundamental research is transferred into operational technology, science gains real value for citizens of the world. When operational technology is combined with a coordinated educational campaign, it becomes fully integrated into the fabric of society and creates a legacy of understanding for generations to come. The recent tsunami was a tragedy of epic proportions, but just as tragic would be for us not to do everything in our power to give people the tools they need to protect themselves from these natural disasters in the future.

It is too soon to know if Indian Ocean populations are better prepared today than they were last December.

The Megatsunami of December 26, 2004

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From 1992 to 2002, tsunamis in the wake of large, but not gigantic, earthquakes, caused significant damage to coastal areas about once a year. These tsunamis resulted in more than 3,000 fatalities, 2,100 in 1998 alone from the catastrophic tsunami in Papua New Guinea. But these events were dwarfed by the December 26, 2004, megatsunami, with a final death toll that may exceed 230,000. By some accounts, the death toll is higher than for all other tsunamis in the past 300 years combined.

Tsunami hazard mitigation involves detection, forecasting, and emergency preparedness. Direct tsunami detection is now possible through tsunameters. Real-time forecasting requires not only validated numerical models, but also a reliable database of inundation parameters against which models can be tested through simulations of tsunami generation, propagation, and interaction with the shoreline. Emergency preparedness requires an understanding of the crucial characteristics of flooding, namely run-up, inundation, and overland flow depth. Mitigation measures must also be based on past experience, which can help identify flow phenomena and locales with complexities that are often impossible to anticipate.

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The National Science Foundation (NSF) has contributed significantly to the development of comprehensive 2+1-dimensional inundation numerical models and large-scale laboratory experiments. NSF has also funded workshops for comparing the results of numerical models with both laboratory models and field data for validation (Liu et al., 1991; Synolakis, 2004). With current technologies, real-time tsunami forecasting can be done through a combination of tsunami detection buoys (tsunameters) operated by National Oceanic and Atmospheric Administration (NOAA)-Pacific Marine Environmental Laboratory (PMEL) and the MOST (method of splitting tsunami) numerical model (Titov and Synolakis, 1998). In this paper, we highlight the most important results of past surveys, particularly how they have contributed to our understanding of the factors that determine the destructive impact of waves on coastal communities. We also discuss briefly how field results have contributed to the development of numerical models and how lessons learned from earlier catastrophes might have saved lives in December 2004.

Field Surveys

In the past decade, systematic post-tsunami field surveys have been undertaken by international teams of scientists (ITSTs), generally within a few weeks of the disaster. Figure 1 shows the locations of these surveys. The objective of a tsunami field survey is to quantify the inundation pattern and determine the run-up height and inundation-depth distribution along the stricken coastline. Combined with validated numerical codes, these data sets can help us predict inundation in nearby areas, if the same seismic zone ruptures at a comparable location in the future. Through hydrodynamic inversion, we may be able to determine if this is the worst-possible event expected in the area and whether there may be a transoceanic tsunami in a future rupture.

Comparisons of field data and model predictions may also help explain why an event may initially appear anomalous (e.g., when tsunami damage seems incommensurate with the size of the parent earthquake). Field observations sometimes lead to the identification of new offshore hazards, which can improve inundation maps, such as those that have been developed for Hawaii, Japan, and most parts of California, Oregon, Washington, and Alaska. Figure 2 shows still images from animations of landslide-triggered tsunamis attacking southern California (Figure 2a) and the tsunami that attacked Papua New Guinea in 1998 (Figure 2b); these animations led to further studies on the hazards of landslide tsunamis. Inundation maps help local authorities prepare for emergencies and decide where to locate schools, hospitals, fire stations, and other critical facilities.

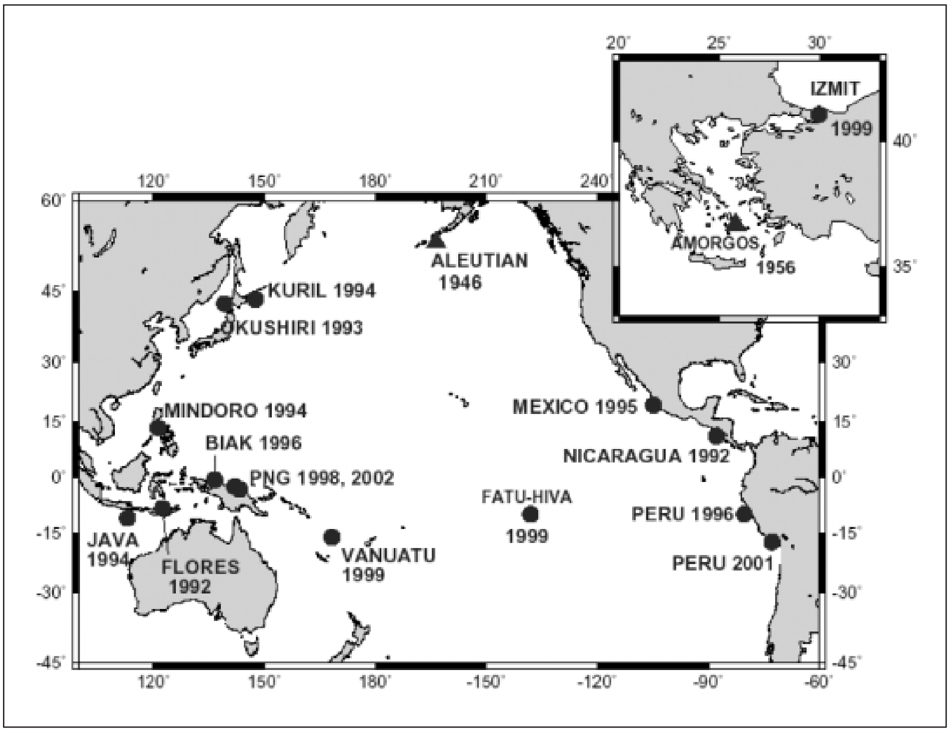

FIGURE 1 Location of field surveys of tsunamis in 1992–2002.

Although the scientific rationale behind tsunami surveys is evident, ITSTs must strike a delicate balance between the necessity of acting promptly to recover ephemeral field data and the obvious priority of search-and-rescue operations in the immediate aftermath of a disaster. In this context, we note that most tsunami watermarks are short-lived and may be lost after a single large storm. In addition, earth-moving equipment may destroy vegetation that holds clues to

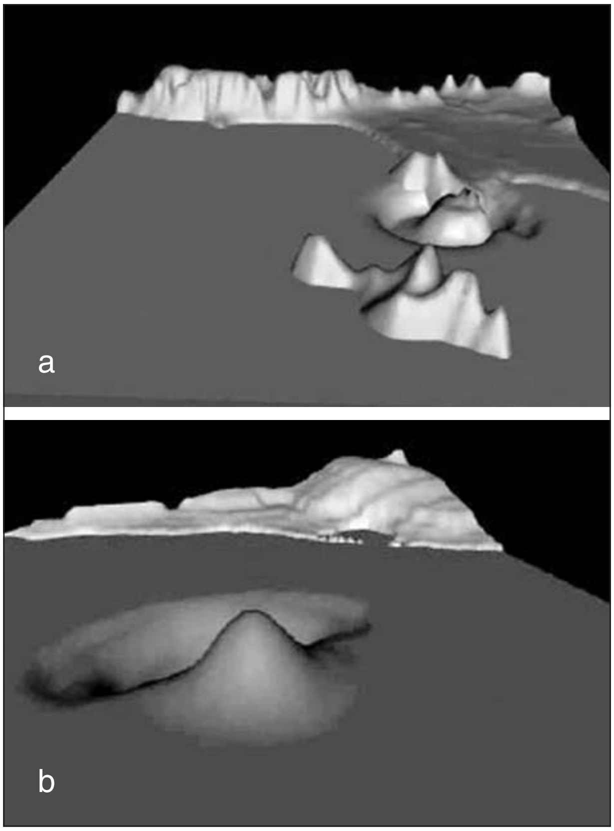

FIGURE 2 Still images of landslide waves attacking Southern California (a) and a similar landslide wave attacking Papua New Guinea (b) in 1998.

the direction and intensity of tsunami currents, and eyewitnesses usually move to safer areas or are relocated. To complicate matters further, once an official version of events circulates, all eyewitnesses tend to report identical information, as people tend to trust what they hear or read in the press more than what they have seen with their own eyes.

Based on past experience, therefore, surveys are most useful within two to three weeks of the event, allowing sufficient time for search-and-rescue efforts but still giving the ITST access to the scene. The work of ITSTs is generally unobtrusive, and teams have always been met with enthusiastic support by local people, who are not only hopeful that surveys will lead to benefits for their communities, but who also ask many interesting and difficult questions that contribute to the surveys.

The essential elements of the database of post-tsunami surveys include measurements of *run-up, inundation,* and *flow depth.* Run-up is the maximum vertical elevation of a point located on initially dry land that is inundated by the waves. Inundation is the maximum horizontal penetration of waves in the direction normal to the beach during the flooding. The data point characterizing water penetration can be based either on a watermark, such as a line of debris deposited either on land or in vegetation, or on eyewitness reports. The local flow depth is inferred from watermarks on walls or from debris left dangling from trees or posts. Figure 3 shows an example from Sri Lanka after the recent tsunami. In most cases, a record is kept of the precise time of measurements so they can be correlated with tide-gauge measurements of the still waterline at the time of the event.

Post-tsunami surveys also include geotechnical documentation of tsunami flows based on quantifications of the amount and direction of sedimentation or erosion and the nature of granular deposits. These data can be used for quantitative reconstructions of the currents involved in the inundation (Gelfenbaum and Jaffe, 2003).

Through interviews with eyewitnesses, we record the experiences of survivors, both to document the physical properties of the waves (e.g., their number, intervals in time, and the occurrence of down-draws, which leave no watermarks). Some eyewitnesses have volunteered

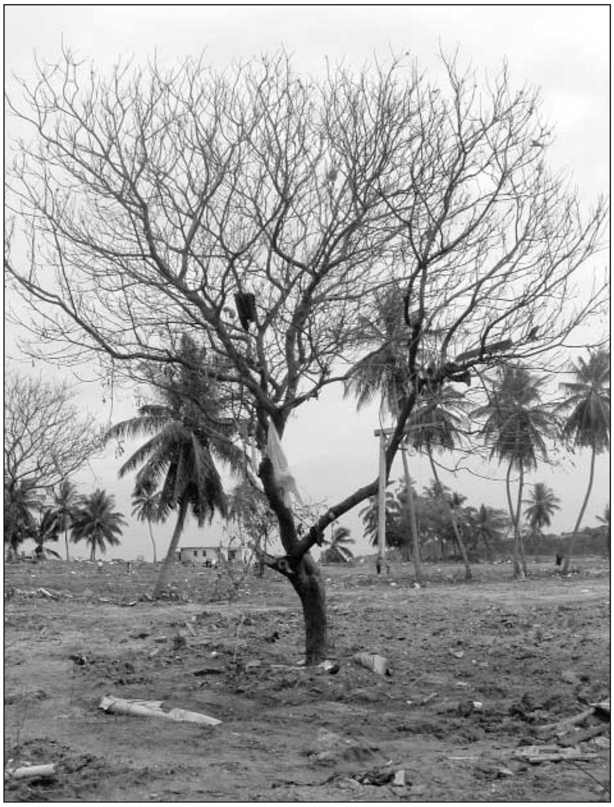

FIGURE 3 Debris dangling from trees is used as watermarks to infer flow depths. Hambandote, Sri Lanka, 2004.

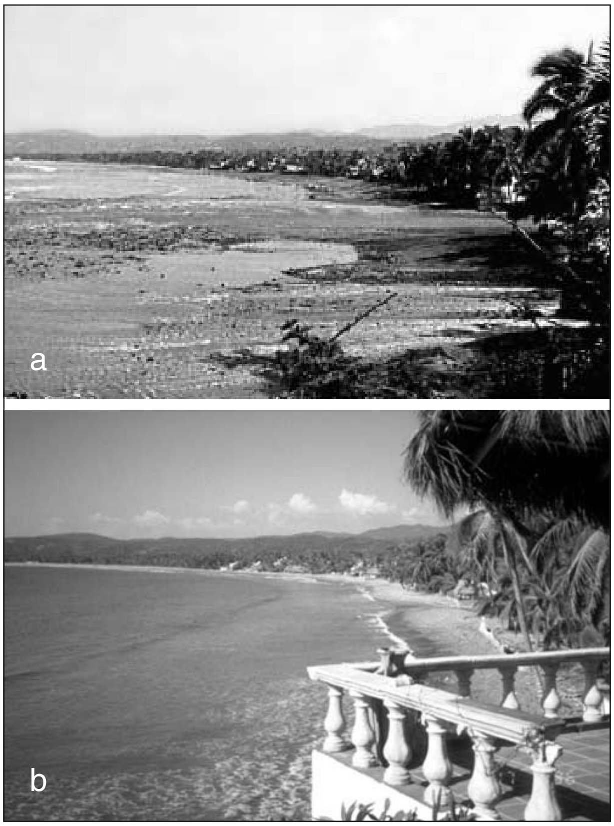

FIGURE 4 Photographs of the leading depression wave (shoreline recession) in Manzanillo, Mexico, in 1995, during (a) and after (b) the event.

dramatic photographs. Figure 4, for example, shows the shoreline recession following the 1995 Manzanillo tsunami. These photographs resolved the question of whether leading-depression N-waves were hydrodynamically stable (Tadepalli and Synolakis, 1996). Interviews also help document human responses (e.g., whether the tsunami was recognized and whether the area was evacuated before or upon arrival of the waves). Whenever possible, interviews with eyewitnesses are videotaped and permanently archived, after informed consent.

An important aspect of the work of ITSTs is outreach to local communities. Working closely with community leaders, local teachers, nongovernmental organizations, or United Nations authorities, we hold meetings in town halls, churches, schools, and hospitals, and we make presentations to local populations. Figure 5 shows a meeting in Vanuatu during the 1999 survey. During recent field surveys, meetings were held in Indonesia, Sri Lanka, Maldives, Kenya, Somalia, and possibly elsewhere. In a more casual way, ITSTs talk continuously with groups of residents who simply congregate around the scientists.

Not surprisingly, we have found considerable differences in sensitivity to tsunami hazards among populations of various regions. In the most earthquake-prone areas, such as the coast of Peru, local residents feel many earthquakes every year, and most of them have been or will be exposed to a perceptible tsunami in their lifetimes. As a result, the concept of tsunami hazard is passed along by ancestral tradition, and people are well educated in this respect; self-evacuation upon noticing anomalous behavior of the sea is a well developed reflex. Evacuation contributed significantly to the relatively low death toll from the 1999 and 2001 Peru tsunamis (Okal et al., 2002).

ITST presentations stress three fundamental facts regarding tsunamis and their mitigation: (1) tsunamis are natural phenomena, part of Earth's normal geological processes, and they do and will recur; (2) any local earthquake felt strongly enough to disrupt people's activities could produce significant changes in sea level and should dictate the evacuation of low-lying areas; and (3) any withdrawal of the sea is a harbinger of the destructive return of an inundating wave and should trigger an immediate evacuation of the beaches. Based on local conditions, we suggest guidelines for choosing evacuation areas and emphasize the need for vigilance for several hours, because the overall duration of a tsunami cannot be safely predicted from the first arrivals. We also distribute pamphlets, if possible in local languages, summarizing tsunami hazards and simple mitigation guidelines. To local government and civil defense authorities, we stress the importance of sensible controls of development in low-lying areas and

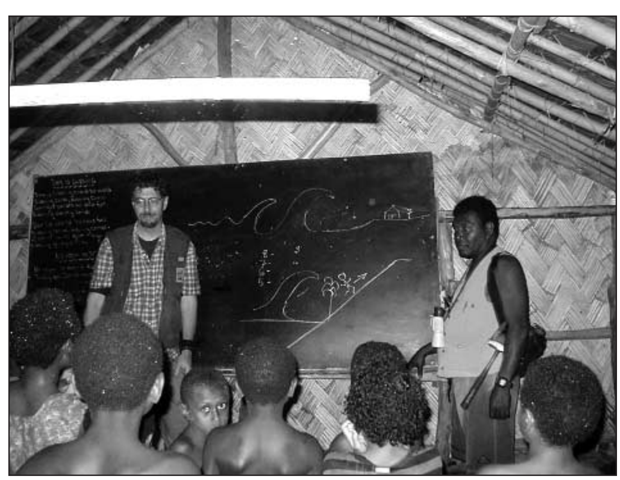

FIGURE 5 Photograph from Vanuatu showing eyewitness interviews and public outreach meeting.

of educating people about tsunami hazards through various exercises, such as yearly drills like the ones conducted in Japan and Peru.

On a more formal level, ITSTs have enthusiastically invited the participation of scientists from the affected countries not only to provide them with *in situ* training during and after the survey, but also to establish a basis for closer international cooperation. Local scientists also contribute regularly to data analyses and are joint authors of most publications resulting from field surveys.

Progress to Date

Based on pre-Sumatran events, significant advances were made in numerical codes for predicting tsunami evolution, and, indeed, most inundation maps in the United States are based on codes that have been validated by large-scale laboratory experiments and field data. Thus, NOAA-PMEL is now able to forecast tsunamis in real time and predict inundations with tested numerical codes. Leading depression N-waves have replaced solitary waves as the prevailing paradigm for theoretical analyses of tsunamis. Based on large-scale experiments of moving blocks, direct numerical simulations (DNSs) have been done using the Navier-Stokes equations of landslide generation and run-up, at least for laboratory-scale models (Liu et al., 2005b). However, using hydrodynamic inversion to infer seafloor motion from run-up or inundation remains largely unexplored.

Based on differences between the run-up distribution in the long-shore direction of the Papua New Guinea tsunamis in 2002 and 1998 (Figure 6), Okal and Synolakis (2004) inferred that data sets of run-up amplitudes in the near field can be used to identify the source (dislocation or landslide) of a tsunami. They proposed that two dimensionless quantities ($I_1 = b/\otimes\upsilon$ and $I_2 = b/a$) behave as invariants, characteristic of the class of tsunami source (dislocation or landslide) but largely independent of the exact parameters describing these sources. They argued that one measure of the maximum run-up, *b*, should be principally controlled by the slip on the fault, $\otimes\upsilon$; the long-shore extent, *a*, of the inundation should reflect the lateral extent of the source. Noting the fundamentally different distribution fields of underwater deformation for dislocations and landslides, and particularly that the strain release in an earthquake is limited by the strength of crustal rocks, Okal and Synolakis (2004) showed that I_2 (as well as I_1 when $\otimes\upsilon$ is sufficiently well known) can be used as a discriminator

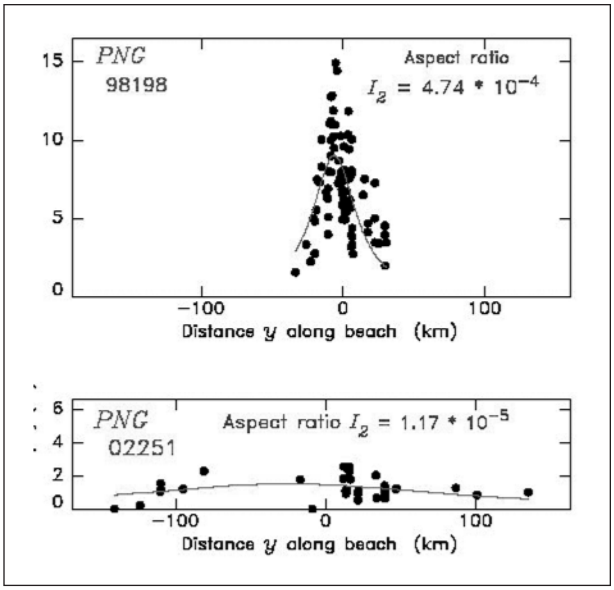

FIGURE 6 Comparison of run-up distribution in the long-shore direction for the 1998 Papua New Guinea landslide tsunami and the 2002 Papua New Guinea tectonic tsunami.

of the nature of a tsunami source. A simple rule of thumb is that dislocation sources cannot have aspect ratios, I_2, greater than 10^{-4}. The analysis confirms the widely known but unpublished Plafker rule, which suggests that the run-up is never more than twice the slip, except in areas where extreme coastal steepness contributes to tsunami evolution (Plafker, 1997).

The methodology outlined above has been extended to study older events with triggers and unusually large tsunamis that have remained vexing mysteries, notably the Unimak, Aleutian Islands, tsunami of April 1, 1946 ($M_0 = 9 \times 10^{28}$ dyne-cm), and the Amorgos, Greece, tsunami of July 9, 1956 ($M_0 = 5 \times 10^{27}$ dyne-cm) (Okal et al., 2002).

Sumatra, Indonesia, December 26, 2004

The Sumatran earthquake and tsunami, which are feared to have caused more than 230,000 deaths, struck on December 26, 2004. The moment estimate ($M_0 = 1.3 \times 10^{30}$ dyne-cm), based on the measurement of split modes of free oscillations of Earth, is about three times larger than the 4×10^{29} dyne-cm measured from traditional long-period surface waves. Thus, the Sumatran earthquake was the second largest ever instrumentally reported, larger than the 1964 Alaskan event ($M_0 = 8.2 \times 10^{29}$ dyne-cm), but smaller than the 1960 Chilean earthquake ($M_0 > 2 \times 10^{30}$ dyne-cm), assuming their reported moments reflect their true size (Stein and Okal, 2005).

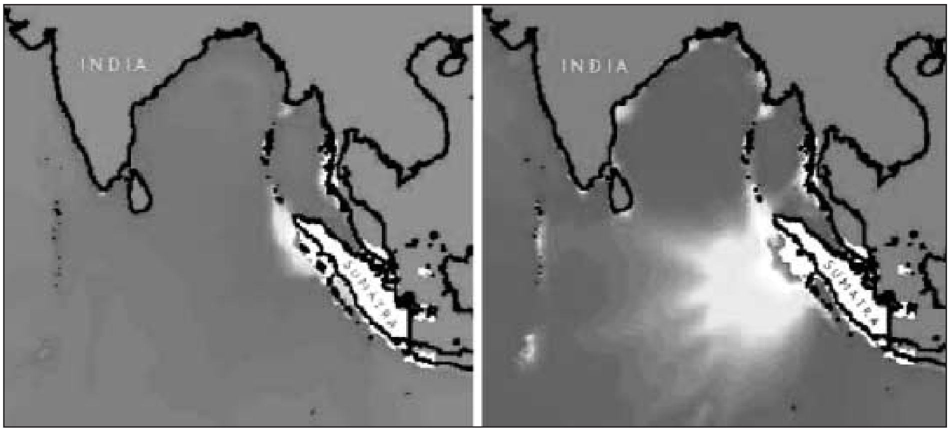

FIGURE 7 Maps of maximum wave heights during the March 28, 2005, event, showing the effect of the islands on Nias and Simeulue off Sumatra. Without the islands, the simulations suggest the tsunami would have been much larger, underscoring the need for direct tsunami detection.

In the Sumatran earthquake, the location of the slow slip is still uncertain, but a likely explanation is that it occurred over the entire 1,200-kilometer length of the rupture zone, as suggested by aftershocks. The southern third was probably a region of faster slip, and the rupture moved slower as it moved northward. The tsunami run-up in the near field on Sumatra is 25 to 30 meters, which implies a slip of 12 to 15 meters, by the rule of thumb that run-up does not usually exceed twice the fault slip.

An interesting question is whether the slow slip contributed to the tsunami excitation. This possibility is suggested by the successful simulations of the amplitude of the tsunami on the high seas, as detected by the JASON satellite, using the MOST code (Titov and Synolakis, 1998) and a source that includes the northern segment (V. Titov and D. Arcas, research scientists, NOAA-PMEL, personal communication).

Stein and Okal (2005) argued that, if the entire aftershock zone has already slipped significantly, there is no immediate danger of a large tsunami being generated by slip on this segment of the plate boundary; however, the danger of a great earthquake to the south remains. Their conjecture was borne out during the March 28, 2005, event, which indeed ruptured to the south but caused no significant tsunami in the far field, possibly because of the presence of two islands off Sumatra (Figure 7) that limited tsunamigenesis, as reported by Arcas and Synolakis (Kerr, 2005).

With satellite imagery, we can now make unprecedented comparisons of an area before and after an inundation. Using geographic information systems (GIS) layers with existing topographic maps and satellite images of Banda Aceh, Borrero (2005) was able to locate precisely the inundation and infer flow directions and inundation heights (Figure 8).

Lessons Learned and Not Learned

In the aftermath of the horrific tsunami of December 2004, many attempts will be made to place blame or quickly "fix" problems (Synolakis, 2004). We will not attempt such a deconstructionism here, nor comment on what, if anything, the four warning centers in the Pacific might have done differently, other than to note that they had no operational responsibility in the Indian Ocean. Clearly, the evacuation warnings following the March 28, 2005, event (just three months later) showed that nations in the Indian Ocean are more prepared now, at least to issue evacuation warnings. But this is only a start. The evolving ad hoc Indian Ocean tsunami warning system must avoid recommending unnecessary evacuations or risk losing the confidence of coastal populations.

The images from Sri Lanka, India, and Thailand that have filled our television screens—and the descriptions by survivors—are all too familiar, at least to those of us who have conducted tsunami field surveys. They reminded us of Nicaragua and Flores in 1992, East Java in 1994, Irian Jaya in 1996, Biak in 1996, Papua New Guinea in 1998, and Vanuatu in 1999, countries with similar landscapes and coastal construction.

The responses of some local residents and tourists in the great Sumatran tsunami, however, were not familiar. In one report, swimmers approaching the beach felt the current associated with the leading depression wave but hesitated to get out of the water because of the "noise" and the fear that if there was an earthquake they would be safer away from buildings. They had to be told by tourists from Japan—where an understanding of tsunamis is now almost hard-wired into the genes—to run to high ground. In Phuket, many pictures show tourists casually watching the onslaught of the tsunami within 100 meters or less of the coastline, and in Sri Lanka tourists and locals rushed to explore the exposed seafloor after the leading depression wave receded. Undoubtedly most of them perished. Obviously, neither tsunami folklore, nor pictures of the tsunami in Manzanillo had reached the public worldwide.

In another report, vacationers spending the day on Phi Phi Island in Thailand were taken back to Phuket one hour after the event began. As we learned from the 1960 Chilean and 1993 Okushiri tsunamis, waves can persist for several hours. Thus, transporting tourists back to the hazard zone was nothing less than grossly irresponsible.

Contrast these reactions with those of the inhabitants of Vanuatu in 1999. In Baie Martelle, a rather pristine enclave with no electricity or running water, the locals watch television once a week when a pick-up truck with a satellite dish, a VCR, and a TV stops by their village. Only months earlier, the residents had watched a UNESCO video of a tsunami. Thus, when they felt the ground shake during the earthquake, they ran to a nearby hill. The tsunami swept through, at night, razing the village to the ground, but only 1 percent (5 people) of the 500 inhabitants died.

Consider what was learned from the 1992 Nicaraguan tsunami, where the damage was extensive in El Transito but less so in adjacent Playa Hermosa because of an opening in the reef fronting most of the central coast of Nicaragua. In El Transito, the opening was about 20 meters wide, allowing for easy navigation to the beach; hence the rapid development of El Transito as a fishing village. When the tsunami hit, the wave funneled through and inundated the region fronting the opening, which, sadly, was where most of the human activity was concentrated.

At Aonae, Japan, during the 1993 tsunami, a man-made sand dune and about 50 concrete dolos (wave protectors) channeled the tsunami into the populated portions of the town and protected the unpopulated areas. As Liu et al. (2005a) report, in Sri Lanka, the "Sumudra Devi," a passenger train out of Colombo, was derailed and overturned by the tsunami almost halfway between Galle and Colombo killing more than 1,000 people. In the immediate fronting area, there had been significant coral mining related to tourism development, and the reef that might have protected that area was reported to have suffered large losses. Tsunami run-up in the area was nearly 8 meters; compare this to 10 meters in El Transito, where about 100 people died.

Consider, too, the consequences of poor land use. The Papua New Guinea tsunami in 1998 is perhaps best known among scientists because of its landslide source (Synolakis et al., 2002). In numerous documentaries produced since then, Sissano Lagoon has become infamous for its death toll and its serene but deadly topography. Villagers lived on a narrow sand spit sandwiched between the Bismark Sea on the north and Sissano Lagoon on the south. Once the tsunami hit, there were no escape routes. The wave overran the sand spit resembling a classic open-channel flow over a sill. Similar conclusions had been drawn from Pancer in Java during the 1994 East Javan tsunami. Although scientists had repeatedly warned that such locations in tsunami-prone areas were death traps, thousands of people were killed in December in south Sri Lanka where many locations resemble Sissano. For example, in Hambandote, hundreds of buses, many allegedly carrying passengers, were reportedly swept into the lagoon behind the town. Some were still visible there when the ITST arrived (Figure 9).

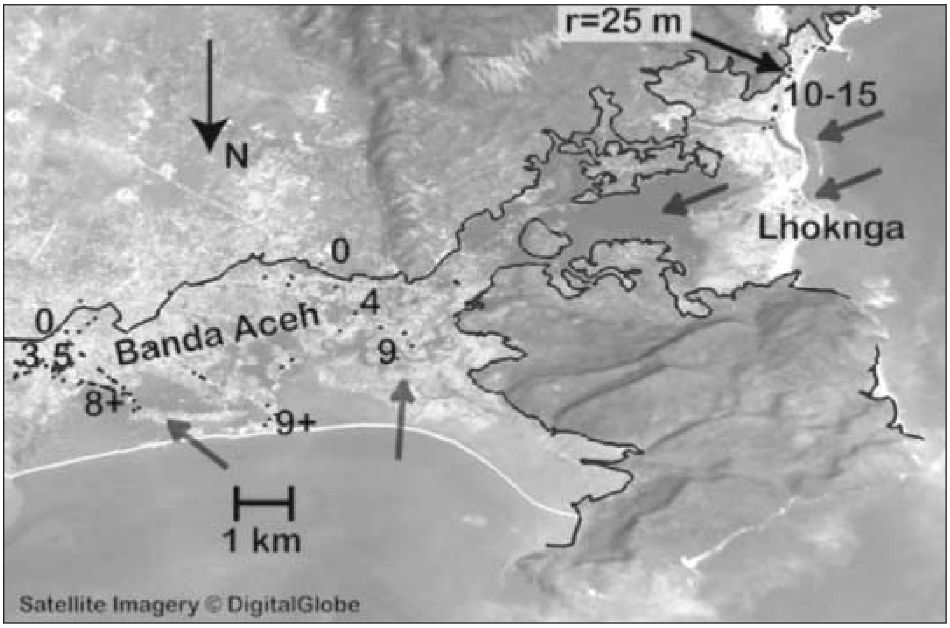

FIGURE 8 Satellite images superposed on inundation measurements show the direction of the tsunami attack in Banda Aceh.

FIGURE 9 Photograph of Hambandote, Sri Lanka, showing an area sandwiched between the ocean and a lagoon. Note the bus, lower right.

Consider the response of the town of Seaside, Oregon, which has two sand spits sandwiched between the Pacific Ocean and the mainland. Based on inundation maps, which have been available for several years, and probabilistic inundation maps at 10-meter resolution, which are in the final stages of production, emergency preparedness measures have been undertaken to ensure that the people of Seaside and other Pacific towns are well informed and, hopefully, tsunami-ready.

In the 1994 East Java and 1996 Peru tsunamis, it had been observed that coastal dunes limited tsunami penetration, although no settlements were located in those specific locales. Kanoglu and Synolakis (1998) showed analytically that the last topographic slope encountered by long waves as they attack coastal topography has a noticeable effect on run-up. Yet, in Yala, Sri Lanka, a resort hotel had removed some of the dune seaward of the hotel to improve the view. In the December tsunami, the hotel was razed to the ground, and substantially higher water and greater damage were found on the hotel grounds than in neighboring areas located behind unaltered dunes. In essence, by removing some of the natural coastal protection in a localized area, a conduit was created through which the tsunami energy could flow.

As was observed during the 1992 Flores tsunami, low-lying coastlines are particularly vulnerable to tsunami attacks. When inundation maps were made in California, Eisner et al. (2001) observed that areas, such as Seal Beach, that were flooded during El Niño events also had the longest inundation distances in cyber-tsunamis. Areas where a tsunami can attack from two sides are prone to severe inundation, as was observed in 1994 in East Java and in 1996 in both Biak and Peru. Although the Great Sumatran earthquake was the fifth to hit Indonesia in 13 years, the population was unprepared and was decimated in the low-lying area between Banda Aceh and Longhka.

All over the Indian Ocean, observations of tsunami damage were similar. In numerous locations in Sri Lanka, churches and Buddhist temples were left standing. Closer to the beach in Aceh, mosques were the only structures standing in the devastated wasteland of coastal areas. In both locales, residents credited divine intervention; but places of worship are constructed "to a higher standard" than surrounding non-engineered buildings (Figure 10).

Few people knew that they should "evacuate vertically" to the second floor of these structures. In a tragic incident in Banda Aceh, a family fled its well designed, two-story villa, fearing that the building would collapse. However, the villa withstood the strong shaking unscathed. As the tsunami swept through minutes later, the father and one child died; the mother and the other child managed to climb to safety. Even in

FIGURE 10 Photograph of a mosque in Banda Aceh showing that well engineered buildings survived the devastation.

Vilufushi, the most severely impacted atoll in the Maldivian archipelago, the local school and city hall, both two-story structures, survived undamaged. People who took refuge in their own one-story houses perished. In these cases, vertical evacuation was the only choice. Sadly, the practice in Hawaii and Japan of vertical evacuation, which is often highlighted in TV documentaries, was not known to the victims.

The absence of official emergency responses had disastrous consequences. For example, neither India's storm-warning experience nor its sophisticated seismic networks led to warnings being issued on December 26, even after the tsunami had struck the Andaman and Nicobar Islands about two hours before hitting the Indian mainland and Sri Lanka (Synolakis, 2005). Allegedly, communications links had survived in Port Blair in the Andaman Islands, not to mention nearby air force and navy bases. Some have argued that as many as 40,000 people might have been saved if they had been warned.

The first tsunami forecast based on real-time computation was made in November 2003.

Contrast the lack of response to the real-time tsunami forecast by NOAA-PMEL during the tsunami on November 17, 2003. Based on a single reading off a NOAA tsunameter in the north Pacific, Titov et al. (2005) scaled their pre-computed scenario event that most closely matched the parent earthquake to evaluate the height of the leading wave off Hilo, Hawaii, and proceeded with a real-time computation that resulted in the first tsunami forecast.

There were some glimmers of hope last December. In the Maldives, after Malle had been hit, the Ministry of Atolls warned the outer islands of a "freak" wave approaching about 15 minutes before the tsunami arrived. As a result, some villagers were able to evacuate towards the centers of the small islands and were not exposed to the full fury of the advancing wave at the shoreline. In the yacht harbor in Langawi, Malaysia, once reports of a big wave hitting Aceh began arriving on short-wave radio, some mariners instinctively sailed their yachts to deeper water outside the marina. Anecdotal reports—too numerous to dismiss—suggest that some upscale hotels in Phuket evacuated guests to upper floors once the earthquake had been felt. In Sri Lanka, the ITST heard at least one report that a hotel in the south, warned by its sister hotel in Tricomalle in the east of a freak wave approaching, followed its standard evacuation plan for storm waves. Another hotel in the vicinity evacuated guests to the second floor after the first wave hit, again following pre-existing storm evacuation plans. Even though the second wave was catastrophic, some lives were spared. If one believes the hotel reports, no guests died in either hotel. Even in Aceh, some who ran from the beach when the first wave hit were spared, but we may never know how many who ran died. The very topography of Banda Aceh made it very difficult to escape the tsunami, which penetrated almost unhindered up to 3 kilometers inland.

Everyone now realizes the urgent need for a worldwide educational effort on tsunami hazards. By some accounts, about 1,000 Swedes died in Thailand, as well as many other tourists visiting from areas where tsunamis are unknown. Thus, educating local populations at risk will not be enough. In an era of global citizenship, people visit remote locales, often without reading up on the geological history of their destinations. It is important that everyone be able to identify the precursors of a tsunami and know they should head for high ground or inland as quickly as possible. If this is not possible, they should know to go to the upper floor of a well built structure that has survived the earthquake.

The Indian Ocean Today

Clearly, it is too soon to know if Indian Ocean populations are better prepared today than they were last December. Some signs are encouraging, but others are less so. The Pacific Tsunami Warning Center covers only the Pacific Ocean and has no tsunameters to verify tsunamigenesis in the Indian Ocean. NOAA plans to expand its network of tsunameters around the Pacific and to transfer NOAA-PMEL real-time capabilities for tsunami forecasting to the warning centers. In the United States and several other nations on the Pacific Rim, inundation maps have been developed for planning evacuations, standards and guidelines for tsunami-resilient communities have been established, and standards for the construction of structures are under development.

UNESCO's Intergovernmental Oceanographic Commission (IOC) has held several meetings, culminating in a meeting in Paris in March 2005, with the objective of setting up an Indian Ocean tsunami warning center (IOTWC). One welcome conclusion of the meeting was an acknowledgement of the need for global educational efforts, even before specific mitigation technologies are implemented and an IOTWC is in place.

The UNESCO meeting provided an opportunity to launch an IOTWC, and UNESCO worked hard to present existing warning and mitigation technologies. Surprisingly, however, countries with no experience in long-wave modeling or tsunami hazard mitigation announced that they intend to build expensive end-to-end systems from the ground up. The lack of experience with tsunamis even led some in the earth-science disciplines to present an unbalanced assessment of the value of their tools for tsunami hazards mitigation, leading one country to suggest it would "protect" communities of more than 10,000 people with broadband seismometers. The tidal-gauge community suggested that an expanded tide-gauge network could provide reliable warnings, even though tidal gauges are most often located in protected areas inside harbors and bays. Once a tsunami hits, tide gauges measure the response in the harbor or bay, but the amplitudes they record, although they confirm that a tsunami has been generated, provide little usable information for forecasting wave height in other locations.

The limitations of some of these approaches were evident during the March 28, 2005, event, the eighth largest earthquake ever reported. The earthquake was located and the magnitude determined within 15 minutes using the worldwide seismic network, and a nondestructive tsunami was detected by tide gauges. Based on those readings, most nations issued evacuation warnings, and emergency managers everywhere waited for several hours to be sure there was no tsunami before they issued the all-clear signal. Most experts agree that seismic observations and tidal gauges are not enough for predicting tsunamis. Reliable prediction will require a network of real-time accurate tsunami sensors in the deep ocean. Combined with public education, these are still our best tools for averting the next Indian Ocean tsunami disaster.

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NAE News and Notes

NAE Newsmakers

Jan D. Achenbach, departments of mechanical and civil and environmental engineering, Northwestern University, and **Robert M. Metcalfe**, general partner, Polaris Venture Partners, were each awarded a 2003 **National Medal of Technology** by President Bush at the White House on March 14, 2005. Dr. Achenbach was honored for "seminal contributions to engineering research and education and for pioneering ultrasonic methods for the detection of cracks and corrosion in aircraft, leading to improved safety for aircraft structures." Dr. Metcalfe was honored for "leadership in the invention, standardization, and commercialization of the Ethernet."

Rod C. Alferness, senior vice president, optical networking and photonics research, Bell Laboratories, Lucent Technologies, received the 2005 Institute of Electrical and Electronics Engineers (IEEE) **Photonics Award** at the Optical Fiber Conference. Dr. Alferness was honored for "seminal contributions to enabling photonics technologies and for visionary leadership in their application to networks and systems."

Vinton G. Cerf, senior vice president, architecture and technology, MCI, and **Robert E. Kahn**, president, Corporation for National Research Initiatives, have been named the winners of the 2004 **A.M. Turing Award**, considered the "Nobel Prize of computing," for pioneering work on the design and implementation of basic communications protocols of the Internet. The Turing Award carries a $100,000 prize and is funded by the Intel Corporation. The prize is presented by the Association of Computing Machinery.

Eddy W. Hartenstein, founding president and CEO of DIRECTV from 1990 to 1993 and vice chair of DIRECTV Group Inc. until his retirement in 2004, received the 2005 Institute of Sound and Communications Engineers (ISCe) Award on June 1. Dr. Hartenstein was honored for his significant achievements and outstanding contributions to the success of the satellite and communications industries.

Robert S. Langer, Kenneth J. Germeshausen Professor of Chemical and Biomedical Engineering, Massachusetts Institute of Technology, was the recipient of the 2005 **Washington Award** for his pioneering work in the field of tissue engineering. Dr. Langer was also cited for his extraordinary contributions to biomedical engineering and biomaterial design, including his pioneering work in the field of controlled drug-release delivery systems, specifically for the treatment of cancer. Dr. Langer received the Washington Award at the Chicagoland Engineering Awards Benefit on February 25, 2005.

Sanjit K. Mitra, professor of electrical and computer engineering, University of California, Santa Barbara, received the 2005 **SPIE Technical Achievement Award** of the International Society for Optical Engineering, and the **University Medal** of the Slovak University of Technology, Bratislava, Slovakia, in March 2005.

Gordon E. Moore, chairman emeritus, Intel Corporation, was the recipient of the Marconi Society 2005 **Lifetime Achievement Award**. Dr. Moore was honored for his innovative contributions to technologies that affect daily life, his entrepreneurial spirit, and his devotion to the collaborative genius that inspired the genesis and success of Intel. Dr. Moore is the third person to receive the Marconi Society Lifetime Achievement Award since the organization was founded 31 years ago.

Donald R. Paul, Ernest Cockrell Sr. Chair in Engineering and director, Texas Materials Institute, University of Texas at Austin, was awarded the **Alan S. Michaels Award for Innovation in Membrane Science and Technology** by the North American Membrane Society (NAMS) on June 14, 2005. Dr. Paul was honored for "40-plus years of significant contributions to the fundamental foundation and commercial development of this field by synergistically integrating academic research with industrial collaborations." Dr. Paul was also awarded the **NAMS Founders Award**, which includes lifetime membership in NAMS.

John M. Prausnitz, professor, Department of Chemical Engineering, University of California, Berkeley, was awarded the **National Medal of Science** by President Bush at the White House on March 14, 2005. Dr. Prausnitz was honored for "the development of engineering-oriented molecular thermodynamics, a powerful tool for design and operation of chemical plants to achieve improved efficiency, safety, energy conservation, and environmental protection."

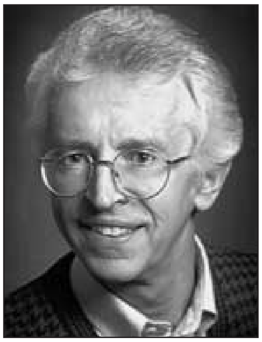
The Institute of Electrical and Electronics Engineers (IEEE) awarded medals to several NAE members in June. **James L. Flanagan**, retired vice president for research, Rutgers, the State University of New Jersey, was awarded the **IEEE Medal of Honor** "for sustained leadership and outstanding contributions in speech technology." **Jimmy K. Omura**, technology strategist, Gordon and Betty Moore Foundation, received the **Edison Medal** for "contributions to the theory of communication systems and the commercial applications of spread spectrum radios and public key cryptography." **H. Vincent Poor**, George Van Ness Lothrop Professor in Engineering, Princeton University, was awarded the **James H. Mulligan Jr. Education Medal** for "leadership in electrical engineering education through inspired teaching, a classic textbook, innovative curricular development and research." **Eugene Wong**, Professor Emeritus, University of California at Berkeley, was the recipient of the **Founders Medal** for "leadership in national and international engineering research and technology policy, for pioneering contributions in relational databases." **Neil J.A. Sloane**, technology leader, AT&T Laboratories Research, Florham Park, New Jersey, was awarded the **Richard W. Hamming Medal** for "contributions to coding theory and its applications to communications, computer science, mathematics and statistics." **Jerry M. Woodall**, C. Baldwin Sawyer Professor of Electrical Engineering, Yale University, was awarded the **Jun-ichi Nishizawa Medal** for "pioneering contributions to the liquid-phase epitaxy in the GaAs/AIGaAs systems, including applications to photonic and electronic devices." **Michael R. Stonebraker**, adjunct professor, Massachusetts Institute of Technology, was awarded the **John von Neumann Medal**, for "contributions to the design, implementation, and commercialization of relational and object-relational database systems." IEEE **Honorary Membership** was awarded to **Dean Kamen**, president, DEKA Research and Development Corporation.

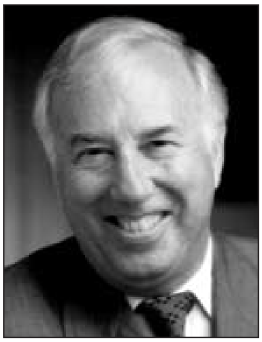
On May 3, 2005, four NAE members and one foreign associate were elected to the National Academy of Sciences: **Shu Chien**, director, Whitaker Institute of Biomedical Engineering, University Professor of Bioengineering and Medicine, and chair, Department of Bioengineering, University of California, San Diego, La Jolla (also a member of IOM); **Anthony G. Evans**, professor, Department of Materials, University of California, Santa Barbara; **Butler W. Lampson**, Distinguished Engineer, Microsoft Corporation, Cambridge, Massachusetts; **Margaret H. Wright**, professor and chair, Department of Computer Science, Courant Institute of Mathematical Sciences, New York University; and NAE foreign associate **Raghunath A. Mashelkar**, director general, Council of Scientific and Industrial Research, New Delhi, India.

NAE Officers and Councillors Elected; Councillor Completes Service


William L. Friend


Elsa M. Garmire


Siegfried S. Hecker


C. Dan Mote Jr.


Charles M. Vest


Robert A. Pritzker

The spring 2005 election of NAE officers and councillors resulted in the reelection of the incumbent treasurer and three incumbent councillors and the election of one new councillor. All terms begin July 1, 2005.

NAE treasurer **William L. Friend** was reelected to a four-year term. Mr. Friend is chairman of the University of California President's Council on the National Laboratories, which manages the Los Alamos, Lawrence Livermore, and Lawrence Berkeley national laboratories for the U.S. Department of Energy. Mr. Friend retired as executive vice president and director of the Bechtel Group Inc. in 1998 after 41 years in the international engineering and construction industry.

Elsa M. Garmire, Sydney E. Junkins Professor of Engineering, Thayer School of Engineering, Dartmouth College, **Siegfried S. Hecker**, senior fellow, Los Alamos National Laboratory, and **C. Dan Mote Jr.**, president and Glenn Martin Institute Professor of Engineering, University of Maryland, were reelected to three-year terms as councillors. **Charles M. Vest**, president emeritus of the Massachusetts Institute of Technology, was elected for the first time to a three-year term as councillor.

On June 30, 2005, **Robert A. Pritzker**, president and CEO, Colson Associates Inc., completed six years of service as councillor, the maximum allowed under the NAE bylaws. Mr. Pritzker was recognized for his distinguished service to NAE during a luncheon in May attended by other NAE Council members and the NAE staff.

2005 Draper, Russ, and Gordon Prize Recipients Honored

NAE President **Wm. A. Wulf** hosted the NAE Annual Awards Dinner and Presentation Ceremony on February 21 to honor engineers whose ideas have transformed the world and improved lives. This year's ceremony honored the 2005 recipients of the **Charles Stark Draper Prize**, the **Fritz J. and Dolores H. Russ Prize**, and the **Bernard M. Gordon Prize**. More than 400 patrons attended the formal dinner in their honor at the historic Union Station in Washington, D.C.

(L to R) Craig Barrett, NAE Council chair; Vince Vitto, president and CEO, Charles Stark Draper Laboratory Inc.; Francis J. Madden, Minoru "Sam" Araki, Edward A. Miller, Don H. Schoessler, James W. Plummer (2005 Draper Prize recipients); and Wm. A. Wulf, NAE president.

Charles Stark Draper Prize

Minoru S. Araki, Francis J. Madden, Edward A. Miller, **James W. Plummer**, and Don H. Schoessler received the annual Charles Stark Draper Prize for the design, development, and operation of Corona, the first space-based Earth observation system. Starting from scratch, this innovative team built and flew the world's first top-secret photo-reconnaissance satellite system in just 16 months. Their remarkable achievement remained unknown, by necessity, for more than 35 years. The Corona Program revolutionized the collection of intelligence, developed technologies essential for civil and commercial space flight, and provided critical intelligence that contributed to the peaceful conclusion of the Cold War. For their heroic efforts, this dedicated team was honored in 1995 by the director of the Central Intelligence Agency.

Minoru S. Araki, an NAE member since 1990, was Lockheed system engineer for the Agena spacecraft—the upper stage for the Corona launch vehicle—and the three-axis stabilized spacecraft that carried the camera payload. Mr. Araki worked for Lockheed Missiles and Space Company and Lockheed Martin Missiles and Space Company for 38 years; he retired in 1997 as president of Lockheed Martin Missiles and Space Company. He is a fellow of the American Astronautical Society and a recipient of the 2004 von Braun Award for Excellence in Space Program Management from the American Institute of Aeronautics and Astronautics.

Francis J. Madden was responsible for designing, testing, and producing the original Corona cameras and their improved versions over the years. The panoramic Corona camera engineered by Mr. Madden moved film through a complex mechanism to produce high-quality imagery and, at the same time, met stringent weight limitations and withstood the harsh launch environment. He was chief engineer on Itek Corporation's Corona Camera Program until his retirement in 1975. During that time, he also collaborated with the Physical Research Laboratory of Boston University.

Edward A. Miller, project engineer and program manager at General Electric, was responsible for the design, construction, deployment, operation, and recovery of Corona's satellite recovery vehicle (SRV)—the first man-made object recovered from Earth orbit. He later became leader of Itek Corporation's Viking Lander Program, which sent back the first imagery ever transmitted from the surface of Mars in 1974. As assistant secretary of the Army in the mid-1970s, he directed a multi-faceted research and development program that yielded the Apache and Blackhawk helicopters, the Abrams M1 tank, and the Patriot high-altitude air defense system. Dr. Miller was awarded the Army Distinguished Civilian Service Decoration and was recognized as an Eminent Engineer by the National Engineering Honor Society (Tau

Beta Pi) in 1976. He was named a Pioneer of Space Technology in 1985.

James W. Plummer, an NAE member since 1978, was the Corona program manager at Lockheed Missiles and Space Company, and overall systems engineer for Corona. Mr. Plummer directed the establishment of an off-site facility where the satellite-borne camera and physical recovery system were built and launched in a period of nine months. Since then, Mr. Plummer has also been under secretary of the U.S. Air Force, director of the National Reconnaissance Office, vice president of Lockheed Corporation, and chairman of the Aerospace Corporation. He was designated a Space and Missile Pioneer by the U.S. Air Force in 1989 and is an honorary fellow of the American Institute of Aeronautics and Astronautics.

Don H. Schoessler, the primary interface engineer between the Corona Program and Eastman Kodak Company, was responsible for engineering, supplying, and processing the film used in the Corona system. Mr. Schoessler was instrumental in design changes in the photographic films used in the Corona camera, which included a new aerial film that could withstand the near-vacuum conditions of space; thinner films to increase the amount of film that could be carried on each mission; and finer grain, higher resolution films that improved the quality of intelligence and mapping imagery. At Eastman Kodak Company, Mr. Schoessler continued to support subsequent Corona, U-2, and National Reconnaissance Office projects for nearly 37 years. He retired in 1986.

Fritz J. and Dolores H. Russ Prize

Leland C. Clark Jr., an NAE member since 1995, was awarded the biennial Fritz J. and Dolores H. Russ Prize for the bioengineering of membrane-based sensors for medical, food, and environmental applications. The Clark oxygen electrode has revolutionized the field of medicine for the past 50 years, providing real-time monitoring of a patient's blood-oxygen level, which has made surgery safer for millions of people throughout the world. The remarkable versatility of the electrode has also triggered advances in cell culture, molecular genetics, aviation and space flight, soil chemistry, and even wine and beer production.

Dr. Clark attended Antioch College and the University of Rochester School of Medicine. In 1985, he received the American Physiological Society Hyrovsky Award in recognition of his invention of the membrane polarographic oxygen electrode. His more than 80 inventions have medical applications ranging from emergency care to molecular research. Dr. Clark has taught at Antioch College, the University of Cincinnati, and the University of Alabama and is a member of the National Association for Biomedical Research and the American Association for the Advancement of Science. Because Dr. Clark was unable to attend the event, Dr. William R. Heineman of the University of Cincinnati, a 20-year colleague, accepted the award on his behalf.

(L to R) William R. Heineman, nominator of Leland C. Clark Jr. (2005 Russ Prize recipient who was unable to attend); Dolores H. Russ, Fritz J. and Dolores Russ Prize benefactor; Roderick McDavis, president, Ohio University.

Bernard M. Gordon Prize

Edward J. Coyle, **Leah H. Jamieson**, and William C. Oakes were awarded the Bernard M. Gordon Prize for their innovations in engineering education. They developed and disseminated the Engineering Projects in Community Service (EPICS) Program, an engineering-design program to teach undergraduates critical skills by involving them in solving problems in their local communities. The EPICS Program, which focuses on long-term, team-based, multidisciplinary design projects in a community context, has been recognized by employers for teaching undergraduates "real-world" skills that are usually not learned until after graduation. Launched at

(L to R) Craig Barrett, NAE Council chair; Bernard M. Gordon, chairman, Neurologica Inc.; William C. Oakes, Leah H. Jamieson, Edward J. Coyle, 2005 Gordon Prize recipients; and Wm. A. Wulf, NAE president.

Purdue University with 45 students in the fall of 1995, EPICS programs are now offered at 15 universities nationwide. In 2003–2004, more than 1,350 students participated in EPICS programs.

Edward J. Coyle, a professor of electrical and computer engineering at Purdue University, is a co-founder of the EPICS Program at Purdue and of the National EPICS Program. He is currently director of the EPICS Entrepreneurship Initiative and co-director of Purdue's Center for Wireless Systems and Applications. Professor Coyle received his B.S. in electrical engineering from the University of Delaware and his M.S. and Ph.D. in electrical engineering and computer science from Princeton University. In 1982, he joined the faculty of the School of Electrical and Computer Engineering at Purdue, where he continues to teach today. In 1998, he was named a Distinguished Engineering Alumnus of the University of Delaware and elected a fellow of the Institute of Electrical and Electronics Engineers (IEEE) for his contributions to the theory of nonlinear signal processing. From 2000 to 2004, he was assistant vice president for research at Purdue. For his contributions to EPICS, he was a co-recipient of the Class of 1922 Award for Outstanding Innovation in Helping Students Learn and the American Society of Engineering Education 1997 Chester F. Carlson Award for Innovation in Engineering Education.

Leah H. Jamieson, who was elected to NAE this year, is co-founder and director of the Purdue EPICS Program and the National EPICS Program. Dr. Jamieson is associate dean of engineering for undergraduate education at Purdue University, Ransburg Professor of Electrical and Computer Engineering, and has a courtesy appointment in the Department of Engineering Education. Dr. Jamieson received her B.S. from the Massachusetts Institute of Technology and her Ph.D. from Princeton University; she has taught at Purdue since 1976. She was elected a fellow of IEEE and was president of the IEEE Signal Processing Society, vice president of the IEEE, and co-chair of the Computing Research Association Committee on the Status of Women in Computing Research. In 2000, she was awarded the IEEE Education Society Harriett B. Rigas Outstanding Woman Engineering Educator Award. In 2001, she was awarded the first National Science Foundation Director's Award for Distinguished Teaching Scholars, and in 2002, she was named Indiana Professor of the Year.

William C. Oakes joined Leah Jamieson and Edward Coyle in the EPICS Program at Purdue University in 1997, where he is now co-director of the program at Purdue and of the National EPICS Program. Professor Oakes received his B.S. and M.S. in mechanical engineering from Michigan State University and was awarded his Ph.D. in mechanical engineering from Purdue University, where he is currently an associate professor of engineering education. In addition, Professor Oakes is lead author of an introductory engineering textbook for first-year undergraduate and high-school students and an engineering service-learning textbook. He has conducted regional workshops across the country on engineering service-learning in collaboration with the U.S. Department of Housing and Urban Development and Campus Compact. Professor Oakes is the recipient of the Indiana Governor's Award for Outstanding Volunteerism for his work on EPICS, the Eaton Award for Electrical and Computer Engineering Design Education (2003), and the National Society of Professional Engineers Engineering Education Excellence Award (2004).

Draper Prize Acceptance Remarks

These remarks were delivered by James Plummer.

President Wulf, Council Chair Barrett, Mr. Vitto, NAE members, honored guests, ladies and gentlemen, we, of the Corona Project, want to thank you for the honor given us here tonight. Much of the credit must be given to the president's scientific advisors at the time for setting the parameters of the program. In response to his demands for overflight reconnaissance of the Soviet Union, they evaluated the country's assets, both the physical devices (such as booster and upper-stage rockets) and the technical capabilities of the aerospace community. The program they selected was to use a Thor ballistic missile, the Lockheed Agena upper-stage and orbiting vehicle, a payload section containing a camera by Itek, special film from Eastman Kodak, a physical recovery vehicle by General Electric to return the film from orbit, and finally an air-snatch recovery system by the U.S. Air Force.

In addition, they specified a management system that gave program direction jointly to the U.S. Air Force and the Central Intelligence Agency. With very small staffs, they issued contracts to our companies with very strict "need-to-know" security requirements. The work statement consisted of three pages calling for the first flight of the system in just nine months and production capability of one flight per month thereafter. A real challenge!

As a group, we have agreed that the one thing we wish to emphasize tonight is the teamwork of the project at all levels—government directors, contractors, and operators. Beyond those of us who were cleared to know the details of the project, other scientists, engineers, shop people, and operators were equally supportive and, in every sense, full members of the team. This led to a strong esprit de corps throughout. So on behalf of the entire team, let me again thank you for this honor.

Russ Prize Acceptance Statement

These remarks were delivered by William Heineman on behalf of Leland Clark, the Russ Prize recipient.

It is a great honor for me to accept the Russ Prize on behalf of Dr. Leland Clark. I met with Dr. Clark and three of his daughters last week to talk about the award, and this is the statement we prepared.

Unfortunately I am not able to be with you this evening, but I send my best wishes to everyone. I would like to express my gratitude to Fritz and Delores Russ, to Ohio University, to the award committee who selected me from what I am sure was a slate of stellar candidates, and to the respected colleagues who supported my nomination with their letters. I value their recognition more than I can say in a few words.

I cherish this award more than I would the Nobel Prize, because it comes from my peers and honors bioengineering, an area neglected by Nobel, even though he himself was an engineer. Needless to say, I value the contributions of, as well as the personal connections with, many, many co-workers. I will mention here only Rick Hoffman and Rob Spokane.

I especially want to acknowledge the contributions of my late wife, Eleanor, without whose emotional support and brilliant mind I cannot imagine having the career I did. My four daughters (Susan, Joan, Linda, and Becky) have contributed to my work and my life in countless ways, and they keep me laughing.

When I was a school child, one of my classmates was a "blue baby" who died before graduation. Another classmate was deaf. I felt bad because, compared to me, these kids did not get a fair shake. Giving everyone a fair deal gradually became an overriding principle in my life and in my work.

I think it is important to say, however, that, in my experience, invention and creativity have a special mother—not good intentions and not even necessity. At 86, I can now admit that I built the first heart-lung machine before I knew about the existence of defects in the heart (some of which produce blue babies) or saw any practical use for it.

In my life, invention has been like a bird in flight, one wing lifted by pure curiosity, the other by the simple joy of building things. Working out the applications—the humanitarian side—begins in earnest only when the bird touches down. The applications are, of course, the true goal of the work—to give everyone a fair deal. But to make this happen, we must honor the true nature of invention. I can remember the moment of each of my inventions, and each can be most honestly characterized as a playful flight. The need for allowing scientists these flights cannot be emphasized enough. And so, perhaps the mother of invention is a wise woman, an indulgent mother, who periodically makes sure that birds are freed from their cages so they can fly freely for a while.

I have loved my work.

Thank you. I am deeply honored.

Gordon Prize Acceptance Remarks

These remarks were delivered by Leah H. Jamieson.

It is my privilege to represent the EPICS Program in expressing our thanks and a few thoughts on engineering education. Receiving the Bernard M. Gordon Prize is a breathtaking honor. We thank the National Academy of Engineering, Mr. and Mrs. Gordon, and the Gordon Foundation, not only for choosing EPICS, but also for creating this superb prize recognizing the importance of engineering education. We are deeply honored that EPICS has been selected to receive this award.

Community service organizations are facing a future in which they must take advantage of technology to improve, coordinate, account for, and deliver the services they provide. Engineering students are facing a future in which they will need much more than expertise in their disciplines in order to succeed. EPICS was born of a realization that these mutual needs created a unique opportunity. Integrating long-term, large-scale, team-based, multidisciplinary design projects into the undergraduate engineering curriculum and making community partnerships an integral part—in fact, the driving force—for those projects, has made EPICS an adventure every step of the way.

The Gordon Prize is about innovation and preparing future leaders. These are fitting themes for EPICS. EPICS is being recognized as an innovative program, but the innovation process is also at the heart of what students learn through their experiences in EPICS. This starts with identifying a community need that can be addressed by technology. The community partner and EPICS team play complementary roles in this step of the innovation process, which may be revisited often during the lifetime of the project. Innovation is evident as the project moves through the design, development, testing, and deployment phases. The project may also include the culminating stage of innovation, the entrepreneurial creation of a product or service. This concept of innovation encompasses not only the usual notion of "creativity," which is most pronounced in the design phase of a product, but also the innovation of bringing a new capability into being in a setting where it will have a significant impact.

The Gordon Prize also focuses on leadership. In EPICS, students gain explicit leadership skills through their project and team experiences. But they also gain a perspective that prepares them to be the true engineering leaders of the future—leaders who have a deep understanding of the role that their skills and their profession can have in the community and in the world. Engineering is not famous as one of the caring professions. But in the twenty-first century, engineering will be called upon to make the world a better place and will need leaders who understand that this is the true role and the true promise of engineering. EPICS is helping to create these leaders.

Finally, we are hopeful that this partnership between engineering and community will not only transform our students, but will also play a role in transforming the face of engineering. This is a Herculean goal—one might even say a goal of epic proportion—but one we believe is achievable, with the strong support that has brought EPICS to where it is today.

Purdue has been a rock-solid supporter of EPICS from the start. We especially thank Linda Katehi, dean of the College of Engineering; Dick Schwarz, former head of Electrical and Computer Engineering and former dean of engineering; and Kamyar Haghighi, head of the new Department of Engineering Education, who are here tonight.

Our community partners took a chance on this new endeavor when no one quite knew how it would work, or if it would work.

Our students are at the heart of everything EPICS has accomplished, and we are honored that four former students are here this evening, Aaron Ault, Annika Fischer, Jill Heinzen, and Sarah Nation.

Our colleagues—faculty team advisors and the wonderful EPICS staff—make EPICS work, both at Purdue and at the growing network of EPICS sites, which now number 15. Patrice Buzzanell, co-advisor of the EPICS Institute for Women and Technology team, is here this evening.

The U.S. Department of Education helped get EPICS started. The Corporation for National and Community Service and the National Science Foundation (NSF) have enabled the growth and dissemination of EPICS. We are honored that many representatives from NSF are here this evening.

Our corporate partners, often our most articulate spokespeople, are represented tonight by John Spencer of Microsoft, Wayne Johnson of Hewlett-Packard, and Ray Almgren of National Instruments. We thank you for all you do for EPICS.

And finally, our families—Trish Coyle, Kristin Oakes, and, from the bottom of my heart, my husband, George Adams, and our daughter, Caitlin Adams. Our families have been our touchstones as we traverse this uncharted territory.

And so we thank the growing family of friends of EPICS. We are honored by your recognition and proud that you will be with us as the adventure continues.

News and Terrorism Super Session

On April 20, a group of approximately 90 news directors and reporters attended a "super session" during the annual meeting of the Radio-Television News Directors Association in Las Vegas. The purpose of the super session was to explore how journalists can cover a terrorist attack responsibly and in a way that conveys accurate information to the public. The journalists were briefed on the nationwide workshop series, "News and Terrorism: Communicating in a Crisis," a project led by NAE in cooperation with the Radio-Television News Directors Foundation and the U.S. Department of Homeland Security. The super session was moderated by ABC News national security correspondent, John McWethy.

To give journalists an idea of the workshops, each of which features a two-hour tabletop scenario exercise, McWethy presented a hypothetical scenario attack to a panel of two TV news directors, an Associated Press wire service news director, an emergency manager, and a public health specialist. The scenario involved a quickly evolving situation and limited or confusing facts. Panelists were then asked to decide the best way to provide accurate information to the public.

The public health specialist, Dr. Jacqueline Cattani (director of the Center for Biological Defense, College of Public Health, University of South Florida) pointed out that, even though it is important that local news teams establish relationships with scientists and engineers, a flood of media enquiries following an event can be disruptive. She described the problems experienced at her laboratory when anthrax letters were discovered in Florida. Some members of the panel suggested that competing news teams "pool," or share, taped interviews or video coverage in the interest of the public good.

The panelists, all alumni of previous "News and Terrorism" workshops, agreed that the workshops had shown them how ill prepared they were, and several said they had subsequently developed strategies for allocating news resources and put together lists of scientists, engineers, and medical experts they could rely upon in a crisis.

Since August 2004, eight workshops have been held around the country, and two more are scheduled (Boston on July 7 and San Francisco on August 4). If you are interested in participating, please contact Randy Atkins at 202-334-1508 or <*atkins@nae.edu*>.

NAE provides fact sheets on different types of terrorist attacks that answer basic questions, dispel common misperceptions, and provide reputable sources of information. Fact sheets on biological, chemical, nuclear, and radiological attacks are available on the NAE website <*www.nae.edu*>.

Eighth German-American Frontiers of Engineering Symposium

On May 5–7, the eighth German-American Frontiers of Engineering (GAFOE) Symposium was held at the Hotel Sanssouci in Potsdam, Germany. Located in the center of Potsdam opposite the Potsdam Brandenburg Gate and near the Park Sanssouci with its splendid palaces, the setting provided a beautiful venue for the interaction and exchange of ideas that characterized the symposium.

Modeled on the U.S. Frontiers of Engineering Symposium, this bilateral meeting brought together approximately 60 engineers (ages 30 to 45) from German and U.S. companies, universities, and government agencies. The purpose of all Frontiers symposia is to provide a forum where emerging leaders in engineering can learn about leading-edge developments in a range of fields and to facilitate the interdisciplinary transfer of knowledge and methodology. Bilateral symposia have the added dimension of encouraging networking among younger engineers across national boundaries. NAE works with the Alexander von Humboldt Foundation to organize GAFOE symposia.

NAE member **Elsa Reichmanis**, director of the Materials Research Department at Bell Laboratories/ Lucent Technologies, and Theodor Doll, professor of microstructure physics and research director of the Institut für Mikrotechnik Mainz GmbH at the University of Mainz, co-chaired the organizing committee and the symposium. The four topics for this year were: air transportation; control and remediation technologies for energy by-products; visual communication; and microreactors in chemical synthesis/drug development. The presentations, by two Germans and two Americans on each topic, covered many specific subjects, including the integration of unmanned aerial vehicles into civil airspace, the impact of electricity generation and transmission on ecological systems, next-generation, active-matrix, flat-panel displays, and new approaches in drug discovery.

The participants engaged in spirited discussions during the formal sessions and during breaks, receptions, and dinners. Poster sessions on the first afternoon gave all participants an opportunity to talk about their research or technical work. The group had free time on Friday afternoon to see the sights in Potsdam. A dinner was held that evening at the historic Cecilienhof Palace, the venue for the Potsdam Conference held at the end of World War II.

Funding for the meeting was provided by the Alexander von Humboldt Foundation, NAE Fund, and the National Science Foundation. Plans for the ninth GAFOE meeting in 2006, to be hosted by Lucent Technologies at their facility in Murray Hill, New Jersey, are under way.

For more information, contact Janet Hunziker in the NAE Program Office at (202) 334-1571 or by e-mail at *jhunziker@nae.edu*.

Report of the Foreign Secretary

George Bugliarello

The Frontiers of Engineering Program is expanding. In addition to annual German-America and Japan-America symposia, the program will hold its first India-America Frontiers of Engineering Symposium in Agra, India, in March 2006. Frontiers symposia bring together accomplished engineers (ages 45 and younger) to establish connections among future leaders and to discuss advances in cutting-edge research topics. Topics for each symposium are selected by a bilateral committee.

The latest Japan-America Frontiers of Engineering (JAFOE) Symposium held in Kyoto, Japan, last November, was co-sponsored by the Engineering Academy of Japan, the Japan Science and Technology Agency, and NAE. The topics included biomedical instrumentation and devices, information technology for the elderly, optical communications, and hydrogen energy. The next JAFOE symposium will be held in the United States in November.

At the beginning of May, the eighth German-America Frontiers of Engineering (GAFOE) Symposium, co-sponsored by the Alexander von Humboldt Foundation and NAE, was held in Potsdam, Germany. **Lance Davis**, NAE executive director, welcomed the participants on behalf of NAE. He and President **Bill Wulf** (who arrived later) also participated in the meeting. The themes of the symposium were advances in air transportation, control and remediation technologies for energy by-products, visual communications, and microreactors in chemical synthesis and drug development. The next GAFOE symposium will be held in the United States next spring.

The 16th annual international Council of Academies of Engineering and Technological Sciences (CAETS) convocation will take place in Cairns, Australia, from July 10–14, 2005. A symposium on "Oceans and the World's Future" will be held in conjunction with the convocation. NAE is one of the founders of CAETS, and President Bill Wulf is a past president.

Our interactions with FUMEC, the Mexican Foundation for Science and Engineering, and the Mexican Academy of Engineering are currently focused on the issue of automotive electronics, at the request of our Mexican colleagues. NAE member **Jerry Rivard** is actively engaged in this program.

NAE is also involved in a number of international activities of the National Academies, including a program to expand the capacity of science academies in Africa, with a particular focus on health care (a U.N. Millennium Goal); the program is funded by the William and Melinda Gates Foundation. We are also engaged in a continuing dialogue with the Iranian Academy of Sciences; the next meeting is expected to take place in 2006. Six previous meetings have addressed a variety of topics in science and engineering.

The National Academies-Russian Academy of Sciences Joint Committee on Counterterrorism Challenges for Russia and the United States held its latest meeting in Washington, D.C., this winter. NAE foreign associate **Konstantin Frolov** and I were cochairs for this exploration of urban security. The Russian delegation was headed by Academician Nikolay Platé, vice president of the Russian Academy of Sciences; and the American delegation was headed by NAE Council member **Sig Hecker** of the Los Alamos National Laboratory. The Russian participants included Valentin Sobolev, deputy chairman of the National Security Council of the Russian Federation, and a number of prominent members of the Russian Academy of Sciences, as well as leaders of antiterrorism efforts in the city of Moscow. Academician Platé and President Wulf (on behalf of the National Academies), co-signed an agreement of collaboration between the U.S. and Russian academies. The meeting was followed by a two-day visit to New York City.

The Foreign Associates elected last February will be inducted at the NAE Annual Meeting next October. The importance of Foreign Associates to the establishment of ties with engineering leaders in other countries cannot be overstated, and the need for new associates from underrepresented countries is particularly important. Promising candidates for 2006 are being considered by NAE peer committees.

Finally, NAE is often visited by leaders of engineering academies from abroad and invited to visit them in return. NAE international programs are helping to create a community of interest among U.S. engineers and engineers from other countries. The success of these programs may be limited only by the resources NAE can devote to them.

George Bugliarello
Foreign Secretary

Engineering Studies at Tribal Colleges

Workshop attendees (from left to right) Richard Schwartz, chair of the ad hoc study committee; Henri Mann, study committee member; and James Tutt, president, Crownpoint Institute of Technology.

In January, NAE launched a consensus study headed by Richard Schwartz, dean of engineering at Salish Kootenai College in Pablo, Montana. The purpose of the study, which is funded by the National Security Agency, is to provide expert, independent advice to a partnership of 12 tribal colleges working toward establishing engineering programs on one or more of their campuses. The overall goal of the partnership is to permit qualified Native American students to remain in the tribal college system from pre-curriculum preparation through an ABET-accredited B.S. degree in engineering.

Committee members include: Richard Schwartz (chair), co-director, Birck Nanotechnology Center, and former dean of engineering, Purdue University; Ashok Agrawal (vice chair), ASEE Two-Year College Division and professor of engineering and technology, St. Louis Community College; Sandra Begay-Campbell, senior member of the Technical Staff, Sandia National Laboratories, and former executive director, American Indian Science and Engineering Society; Legand Burge, dean, College of Engineering, Tuskegee University; Larry Hall, president/general manager, S&K Electronics; Helen Klassen, professor, American Multicultural Studies Department, Minnesota State University, Moorhead; and Henri Mann, special assistant to the president, Montana State University-Bozeman.

The committee will address the following issues: unique qualities of Native Americans relevant to the practice of engineering; the most effective ways to attract Native American students to engineering studies and motivate them to pursue advanced degrees; what tribal colleges can do for their Native American constituencies that mainstream institutions cannot; the most appropriate model for initiating, developing, implementing, and sustaining engineering studies at tribal colleges; financial strategies for sustaining engineering programs in the long term; methodologies for teaching engineering at tribal colleges; and a road map for initiating, developing, implementing, and sustaining courses, course sequences, and pre-engineering and engineering degree curricula.

On March 15–16, 2005, NAE sponsored a workshop for representatives of the American Indian Higher Education Consortium, CIA Native American Affinity Group, National Science Foundation Tribal Colleges and Universities Program, White House Initiative on Tribal Colleges and Universities, American Indian Science and Engineering Society, Office of Congressional and Intergovernmental Affairs Indian Affairs Program, American Association of Community Colleges, Accreditation Board for Engineering and Technology Inc., National Security Agency, U.S. Department of Energy, IBM, National Aeronautics and Space Administration, Science and Engineering Alliance, and MESA. Two presidents of tribal colleges also attended the workshop—Renee Gurneau of Red Lake Nation College and James Tutt of Crownpoint Institute of Technology.

Engineering Stories on the Airwaves

For the past year-and-a-half, NAE media relations has produced a weekly radio piece on WTOP, Washington, D.C.'s all-news station. Recent stories have focused on how ultrasound might be used to open the blood-brain barrier, how ocean waves might be harnessed to produce energy, and how a new technology could be used to erect durable shelters quickly in world trouble spots. "Innovative Engineering" can be heard on the NAE website <*www.nae.edu*> or the WTOP Radio website <*www.wtopnews.com*>. If you have an idea for a future story, please e-mail Randy Atkins at <*atkins@nae.edu*>.

"Messages" for Engineering

In 2002, NAE published *Raising Public Awareness of Engineering* (funded by the S.D. Bechtel, Jr. Foundation), which described how hundreds of millions of dollars have been spent to improve public understanding of engineering with little apparent success. To address this problem, NAE brought together a small group of senior-level advertising professionals in April to explore ways to communicate more effectively with various audiences about the importance of engineering. The session (also funded by the S.D. Bechtel, Jr. Foundation) was part of NAE's Public Understanding of Engineering Program. NAE plans to develop proposals for follow-on activities, such as refining and testing the effectiveness of different messages via focus groups and telephone surveys.

Presidential Classroom at the Academies

About 350 high-school juniors and seniors from 45 states and 14 countries, participants in the nonpartisan Presidential Classroom Program, visited the National Academies in early February as part of a week-long exploration of science and technology policy in the nation's capital. NAE program officer Greg Pearson, who heads projects focused on technological literacy, gave the keynote address. The purpose of his talk was to expand the students' concept of technology and highlight interactions between science/technology and public policy.

Calendar of Meetings and Events

May 17	NAE Regional Meeting Cambridge, Massachusetts
May 19	NAE Regional Meeting Albuquerque, New Mexico
June 2	NAE Regional Meeting Cleveland, Ohio
June 12	NAE Finance and Budget Committee Conference Call
June 16	India-America Frontiers of Engineering Committee Meeting
	NAE Audit Committee Meeting
	NRC Executive Committee Meeting
June 27	NAE Membership Policy Committee Meeting Tucson, Arizona
July 22	NAE Congressional Lunch
July 26	NRC Executive Committee Meeting
August 3–4	NAE Council Meeting Woods Hole, Massachusetts
August 5–6	NRC Governing Board Meeting Woods Hole, Massachusetts
September 13	NRC Executive Committee Meeting
September 13–15	NAE Noise Technology Workshop
September 22–24	U.S. Frontiers of Engineering Symposium Niskayuna, New York
October 7	Finance and Budget Committee Meeting
October 8	NAE Council Meeting
	NAE Peer Committee Meeting
October 9–10	NAE Annual Meeting
October 11	NRC Executive Committee Meeting
October 21	NAE Congressional Lunch
October 18–19	CASEE Annual Meeting
	Dane and Mary Louise Miller Symposium Indianapolis, Indiana

All meetings are held in the National Academies Building, Washington, D.C., unless otherwise noted. For information about regional meetings, please contact Sonja Atkinson at *satkinso@nae.edu* or (202) 334-3677.

In Memoriam

HOWARD K. BIRNBAUM, 72, Director Emeritus, Materials Research Laboratory, University of Illinois, died on January 23, 2005. Dr. Birnbaum was elected to NAE in 1988 for his work on the effects of hydrogen and hydrogen embrittlement on properties of metals.

DONALD C. BURNHAM, 90, retired chairman, Westinghouse Electric Corporation, died on April 17, 2005. Mr. Burnham was elected to NAE in 1968 for leadership in manufacturing engineering and research and contributions to solving social-technological problems.

HOWARD S. JONES, 83, retired engineer/scientist and chief of microwave research, Harry Diamond Laboratories, U.S. Department of the Army, and independent consultant in microwave electronics-university relations, died on February 26, 2005. Dr. Jones was elected to NAE in 1999 for the invention and development of antennas and microwave components for missiles and spacecraft.

LUDWIG F. LISCHER, 89, retired vice president of engineering, Commonwealth Edison Company, died on February 21, 2005. Mr. Lischer was elected to NAE in 1978 for contributions to the understanding of electric utility systems for the development of government and industry energy policy.

WILLIAM W. MOORE, 90, retired cofounder, Dames & Moore, died on October 23, 2002. Mr. Moore was elected to NAE for pioneering work in geotechnical engineering and contributions to earth sciences.

ROBERTA J. NICHOLS, 73, retired manager, Alternative Fueled Vehicle Development, Ford Motor Company, died on April 3, 2005. Dr. Nichols was elected to NAE in 1997 for contributions to the development of alternative fuels and flexible-fuel vehicles.

HERMAN P. SCHWAN, 89, Alfred Fitler Moore Professor Emeritus, University of Pennsylvania, died on March 17, 2005. Dr. Schwan was elected to NAE in 1975 for contributions to biomedical engineering research and education.

Publications of Interest

The following reports have been published recently by the National Academy of Engineering or the National Research Council. Unless otherwise noted, all publications are for sale (prepaid) from the National Academy Press (NAP), 500 Fifth Street, N.W., Lockbox 285, Washington, DC 20055. For more information or to place an order, contact NAP online at <*http://www.nap.edu*> or by phone at (888) 624-8373. *(Note: Prices quoted by NAP are subject to change without notice. Online orders receive a 20 percent discount. Please add $4.50 for shipping and handling for the first book and $0.95 for each additional book. Add applicable sales tax or GST if you live in CA, DC, FL, MD, MO, TX, or Canada.)*

Frontiers of Engineering: Reports on Leading-Edge Engineering from the 2004 Symposium on Frontiers of Engineering. This volume includes 14 papers from the National Academy of Engineering 10th annual U.S. Frontiers of Engineering Symposium held in September 2004. The U.S. Frontiers meetings bring together 100 outstanding engineers (ages 30 to 45) to discuss leading-edge technologies in a range of fields. The 2004 symposium covered four areas: engineering for extreme environments; designer materials; multiscale modeling; and engineering and entertainment.

Paper topics include scalable mobile robots for deployment in polar climates, the challenges of landing on Mars, thin-film active materials, vascular-tissue engineering, small-scale processes and large-scale simulations of the climate system, physically accurate illumination in computer graphics, and socially intelligent robots. Appendixes include information about contributors, the symposium program, and a list of meeting participants. This is the tenth volume in the U.S. Frontiers of Engineering series.

NAE member **Pablo G. Debenedetti**, Class of 1950 Professor in Engineering and Applied Science, Princeton University, chaired the organizing committee. Paper, $35.50.

Assessment of Options for Extending the Life of the Hubble Space Telescope: Final Report. The Hubble Space Telescope (HST) has been operating continuously since 1990. During that time, four space shuttle-based service missions (SMs) were launched, three of which added major observational capabilities to Hubble. A fifth, SM-4, was planned to replace key telescope systems and install two new instruments. After the loss of the space shuttle Columbia, however, NASA decided not to pursue SM-4, which would result in Hubble coming to the end of its useful life in 2007–2008. In response to an unprecedented outcry from scientists and the public, NASA began to explore and develop a robotic SM, and Congress directed NASA to request a study by the National Research Council (NRC) of robotic and shuttle-servicing options for extending the life of Hubble.

This report includes an overview of the contributions made by Hubble so far, describes the contributions that would follow an SM, and presents a comparative analysis of the potential risks of the two options for servicing Hubble. The study concludes that the space-shuttle option would be the most effective way of prolonging Hubble's productive life.

NAE member **Louis J. Lanzerotti**, consultant, Bell Laboratories, Lucent Technologies, chaired the committee. Other NAE members on the study committee were **Rodney A. Brooks**, director, Computer Science and Artificial Intelligence Laboratory, Massachusetts Institute of Technology; **B. John Garrick**, independent consultant, Laguna Beach, California; and Vice Admiral **Richard H. Truly**, retired director, National Renewable Energy Laboratory. Paper, $32.50.

Contaminants in the Subsurface: Source Zone Assessment and Remediation. At hundreds of thousands of commercial, industrial, and military sites across the country, subsurface materials, including groundwater, are contaminated with chemical waste. In the last decade, interest has been growing in aggressive source-remediation technologies to remove contaminants from the subsurface, although our understanding of their effectiveness and the overall effects of mass removal on groundwater quality is limited.

This report reviews the technologies available for source remediation and assesses how well they would meet cleanup goals, from regulatory standards for groundwater to cost reductions. The report suggests a protocol that should enable project managers to make decisions about source remediation at their sites.

NAE members on the study committee were **Linda M. Abriola**, dean of engineering, Tufts University, and **Gary A. Pope**, Texaco Centennial Chair in Petroleum Engineering, University of Texas at Austin. Hardcover, $57.00.

Facilitating Interdisciplinary Research. Advances in science and engineering increasingly address complex problems that cut across traditional disciplines, and new technologies may even transform existing disciplines and generate new ones. Thus, collaboration among scholars in different disciplines is becoming a necessity. At the same time, however, interdisciplinary research has been hampered by policies on hiring, promotion, tenure, proposal review, and resource allocation that favor traditional disciplines.

This report identifies steps that researchers, teachers, students, institutions, funding organizations, and disciplinary societies can take to facilitate interdisciplinary research. Throughout the report, key concepts are illustrated with case studies and survey results of individual researchers and university provosts.

NAE members on the study committee were **Robert Conn**, managing director of Enterprise Partners Venture Capital; **Mildred Dresselhaus**, Institute Professor of Electrical Engineering and Physics, Massachusetts Institute of Technology; and **Robert M. White**, University Professor and director of the Data Storage Systems Center, Carnegie Mellon University. Paper, $42.00.

Getting Up to Speed: The Future of Supercomputing. Supercomputers are becoming increasingly important for addressing many important science and technology problems. In recent years, however, progress in supercomputing in the United States has slowed. With the development of the Earth Simulator supercomputer by Japan, the United States stands to lose its competitive advantage and, more important, the national competence to achieve national goals.

The U.S. Department of Energy (DOE) asked the National Research Council (NRC) to assess the state of U.S. supercomputing capabilities and relevant research and development. Subsequently, the Senate directed DOE to ask the NRC to evaluate the Advanced Simulation and Computing program of the National Nuclear Security Administration at DOE in light of the development of the Earth Simulator (S.R. 107-220). This assessment of the status of supercomputing in the United States includes a review of current demand and technology, infrastructure and institutions, and international activities.

NAE member **Susan L. Graham**, Pehong Chen Distinguished Professor, University of California, Berkeley, cochaired the study committee. Other NAE members on the committee were **James W. Demmel**, professor, Computer Science Division, University of California, Berkeley; **Jack J. Dongarra**, Distinguished Professor, University of Tennessee, Knoxville; **Mary Jane Irwin**, A. Robert Noll Chair in Engineering, Pennsylvania State University; **Butler W. Lampson**, Distinguished Engineer, Microsoft Corporation; and **Steven J. Wallach**, vice president, technology, Chiaro Networks. Paper, $35.00.

Improving the Characterization and Treatment of Radioactive Wastes for the Department of Energy's Accelerated Site Cleanup Program. The U.S. Department of Energy (DOE) Office of Environmental Management (EM) directs the massive cleanup of more than 100 sites that were involved in the production of nuclear weapons materials during the Manhattan Project and the Cold War. This report offers suggestions for improving the characterization and treatment of "orphan" and special-case wastes.

The report identifies technical improvements that could save time and money without compromising health and safety, such as making more effective use of existing facilities and capabilities for waste characterization, treatment, and disposal; eliminating self-imposed requirements that have no clear technical or safety basis; and investing in new technologies to improve existing treatment and characterization capabilities. For example, the report suggests that EM work with DOE classification officers to declassify (wherever possible) materials classified as wastes. The report also suggests a new approach for treating waste that will be left in place.

NAE member **Milton Levenson**, retired vice president, Bechtel International, chaired the study committee, and NAE member **Lloyd A. Duscha**, retired deputy director of engineering and construction, U.S. Army Corps of Engineers, served on the committee. Paper, $18.00.

Interim Design Assessment for the Pueblo Chemical Agent Destruction Pilot Plant. In 1996, Congress directed the U.S. Department of Defense to assess and demonstrate technology alternatives to incineration for the destruction of chemical weapons stored at Pueblo Chemical and Blue Grass Army Depots. Since then, the National Research Council (NRC) has been evaluating candidate technologies and reviewing engineering design studies and demonstration testing. This report is an evaluation of designs for pilot plants at Pueblo and Blue Grass that would use chemical neutralization to destroy the chemical agent and energetics in the munitions stockpiles of these two depots.

The report also provides an interim assessment of the Pueblo Chemical Agent Destruction Pilot Plant (PCAPP) to help the Army respond to significant problems as they arise. The report also includes an analysis of controversial issues about the current PCAPP design and provides findings and recommendations for addressing public concerns and involving the public in the decision process.

NAE members on the study committee were **Harold K. Forsen**, retired senior vice president, Bechtel Corporation, and **Kenneth A. Smith**, Edwin R. Gilliland Professor of Chemical Engineering, Massachusetts Institute of Technology. Paper, $18.00.

The Owner's Role in Project Risk Management. Effective risk management is essential for large projects built and operated by the U.S. Department of Energy (DOE), particularly for one-of-a-kind projects. To improve its risk management, DOE asked the National Research Council to prepare a summary of the most effective practices used by leading owner organizations. The primary objective of the study was to provide DOE project managers with a basic understanding of (1) the project owner's risk-management role and (2) effective oversight of risk-management activities delegated to contractors.

NAE member **Kenneth F. Reinschmidt**, J.L. Frank/Marathon Ashland Petroleum LLC Professor of Engineering Project Management at Texas A&M University, chaired the committee. Other NAE members on the study committee were **Donald A. Brand**, retired senior vice president and general manager, Pacific Gas and Electric Company; **Lloyd A. Duscha**, retired deputy director of engineering and construction, U.S. Army Corps of Engineers; and **Theodore C. Kennedy**, founder of BE&K Inc. Paper. $18.00.

Regional Cooperation for Water Quality Improvement in Southwestern Pennsylvania. The city of Pittsburgh and the surrounding area of southwestern Pennsylvania face complex water-quality problems, due in large part to aging wastewater facilities that cannot handle sewer overflows and storm-water runoff. Other problems, such as acid mine drainage, are historical legacies of the region's coal mining, heavy industry, and manufacturing economy. Currently, water planning and management in southwestern Pennsylvania involves the federal and state governments, 11 counties, hundreds of municipalities, and other entities. Coordination and cooperation among these groups are at a minimum.

The report finds that the area needs a comprehensive, watershed-based approach to meet water-quality standards throughout the region in the most cost-effective way. Technical and institutional alternatives are outlined for the development and implementation of such an approach.

NAE member **Jerome B. Gilbert**, consulting engineer, Orinda, California, chaired the study committee. NAE member **Perry L. McCarty**, Silas H. Palmer Professor Emeritus, Stanford University, also served on the committee. Paper, $47.00.

Risk and Decisions About Disposition of Transuranic and High-Level Radioactive Waste. The U.S. Department of Energy (DOE) manages dozens of sites that focus on research, design, and production of nuclear weapons and nuclear reactors for national defense. Radioactive wastes at these sites pose a national challenge, and DOE is considering the most effective ways to clean them up. The processing and disposal of transuranic and high-level radioactive waste pose some of the highest projected risks, cleanup costs, and technical challenges.

This report addresses how DOE should incorporate risk into its decisions about using deep geologic disposal or alternative methods for some of these wastes. The report recommends that DOE use an exemption process and proposes criteria for risk assessment and key elements of a risk-informed approach. The report also describes the types of wastes that are candidates for alternative disposition, potential alternatives to deep geologic disposal for low-hazard wastes, and assessments of the compatibility of these alternatives with current regulations.

NAE member **David E. Daniel**, dean, College of Engineering, University of Illinois at Urbana-Champaign, chaired the study committee. NAE member **Theofanis G. Theofanous**, professor and director, Center for Risk Studies and Safety, University of California, Santa Barbara, was also on the committee. Paper, $37.00.

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