1. WALLS OF WATER

Tsunamis

> I got outside my hotel, and saw that the ocean was now level with our island. To my horror, a wall of water—boiling, frothing, angry as hell—was bearing straight down at us, and a strange mist that looked like thick fog blocked out the sun. I stopped breathing . . . .
>
> —*Dave Lowe, eyewitness to the 26 December 2004 tsunami on the South Ari Atoll in the Maldives*

We relate Christmas to happiness, but no holiday can shield us from grief. On the night of 25 December 2004, some breaking news shook North America. A catastrophe had killed thousands of people in Southeast Asia, many foreign tourists among the dead. The number of reported victims was growing by the hour.

The rim of the Indian Ocean had been hit by a *tsunami*—also known as a *tidal wave*—a tremendous shift of water that acts like a deluge. Waves of such force are triggered by marine earthquakes, landslides, and volcanic eruptions, or by large meteoritic impacts. While in deep waters, tsunamis might pass undetected because of their long and gentle shape. But once the seabed shallows, they swell and invade the shore with a force that may flatten the ground.

I will never forget the images shown on television: the incoming wave, the water rushing through the windows of a restaurant, the old man swept away from the terrace of his hotel, the woman trying to cling to the branch of a palm tree, the father and the child running for their lives, the scream of the desperate mother, the indigenous boy rescuing a blond girl from the flood . . . .

There were many stories, most of which I have forgotten—stories of loss, grief, hope, or happy reunion. But one of them, which I heard months later, stayed with me. It was the tale of a survivor, a story told with inner peace and resignation during a *Larry King Live* show on CNN. This is what I learned from it.

The Model and the Photographer

Petra Nemcova and Simon Atlee spent their Christmas holiday in Khao Lak, a lavish beach resort in southern Thailand. Petra was a Czech supermodel, and Simon a British photographer. They had fallen in love while he was shooting pictures of her for a fashion magazine. But because they traveled on different assignments, they hadn't seen much of each other during the past few months.

This vacation had been Petra's idea. She found Thailand amazing—a country with wonderful people, soothing climate, and breathtaking landscapes. The trip was meant to be a surprise for Simon, so she told him about it only shortly before their departure.

Christmas Day went by peacefully. They tanned on the beach and talked about marriage and children. The wedding date was something they had still to set. After dinner they went to their room to watch *White Christmas*, the 1950s' musical comedy with Bing Crosby, Danny Kay, Rosemary Clooney, and Vera Ellen. Petra had not seen the movie before, and Simon thought she would like it.

The next morning they woke up early. Their stay at this orchid resort had come to an end, and they wanted to get ready for departure. But first they had breakfast and took a walk along the beach. On returning, Petra started packing. Simon went for a shower. Then tragedy hit with almost no warning.

Through the balcony window Petra saw people running away from the beach. They were screaming in panic as if a noisy marine monster were following them.

"What's happening?!" Simon shouted from the bathroom.

"I don't know! An earthquake or something!"

Seconds later the glass window broke. In no time, the tsunami blew up their bungalow and swept them away.

"Petra!! Petra!!" Simon cried.

"Catch the roof!" Petra called out before she was pulled under a swirl of dirty water.

Debris hit her, tore off her clothes, and she felt a strong pain in her pelvis. When she resurfaced, Simon was nowhere to be seen. Then the wave covered her again.

She thought she would die. Hope revived when she came close to a palm tree, but her attempts to cling to it failed. Luckily another tree appeared in her way, and with great effort she grabbed one of its branches. Although debris hit her repeatedly, assailing her naked, battered body, she clung to the trunk. Desperate voices could be heard from neighboring trees.

As the first shock receded, Petra thought of Simon. He was a good swimmer, so she hoped that he had made it to a safe spot. She prayed for him, and she prayed that the tree holding her would stand the force of the stream.

Time passed. Petra often had the illusion that this was just a nightmare from which she would awake soon, but the pain brought her back to reality. Although she felt very tired and her arms had grown numb, she knew that she had to stay put. Between ocean and sky, her life hung in the balance.

Eight hours later, two courageous Thai men rescued her. They had to handle her carefully because every move made her cry. She would go through a lot of pain in the days to come. Fortunately the immediate danger had passed. She spent several weeks in a Thai hospital with internal injuries and a shattered pelvis, and she needed several months to recover completely.

But Petra never saw Simon again. Some human remains found in March 2005 were identified as his. He met the fate of the more than 200,000 people who happened to be in the path of destruction on that godforsaken day. The saddest part of the story is that most of those lives could have been saved.

How It Happened

On 26 December at 6:58 AM local time, an earthquake shook the Indian Ocean, off the Indonesian coast of northern Sumatra, 250 kilometers southeast of Banda Aceh. Initial estimates put its magnitude at 9.0. The shock was felt as far as the Bay of Bengal. The earthquake occurred between the India and Burma plates as the former

Figure 1.1. The shores affected by the Indian Ocean tsunami on 26 December 2004

shifted beneath the latter, raising the ocean's bottom by 10 meters in some places. This event triggered a tsunami, which hit the beaches bordering the Indian Ocean in Indonesia, Sri Lanka, India, Thailand, Somalia, Myanmar, the Maldives, Mauritius, Malaysia, Tanzania, Seychelles, Kenya, and Bangladesh (fig. 1.1.). No tsunami ever has claimed so many lives.

Some scientists flew to Indonesia to learn more about the cause of the disaster. Others began to analyze the data. Richard Gross, a geophysicist with NASA's Jet Propulsion Laboratory, reported that a shift of mass toward Earth's center caused the planet to move one millionth of a second faster and tilted its axis at the poles by an inch. Seismologists Seth Stein and Emile Okal of Northwestern University claimed later that the earthquake had been much larger than initially thought, namely, 9.3 on the *moment-magnitude scale*, for which a one-point increase corresponds to about a thirtyfold effect.

Such reevaluations are not unusual. The rupture zone had been bigger than reported, the initial estimates ignoring the slower shifts along the fault. To extract these data, Stein and Okal relied on theoretical results they had developed three decades earlier with Robert Geller, now a professor at the University of Tokyo.

Shortly after the earthquake, Sumatra's coast was hit by a wall of water higher than the coconut palms lining its beaches; the tsunami, however, traveled almost two hours before reaching Thailand, India, and Sri Lanka. A warning procedure, like the ones used in North America and Japan, might have reduced the casualties to a minimum. Alas, such a system was nonexistent in the affected zones.

The ideal scenario would have been to forecast the tsunami and take suitable measures days or hours in advance. But are such predictions possible?

Solitary Waves

To forecast events, we must know how they form and develop and what laws govern them. Tsunamis occur rarely and look like big wind-generated waves, but instead of breaking at the shore, they go inland. Progress toward understanding them has been slow. The nature of tsunamis remained unclear until the end of the nineteenth century. All their possible causes became apparent only several decades ago.

Research on solitary waves began in August 1834 when a young engineer named John Scott Russell conducted some experiments on the Union Canal near Edinburgh in Scotland. The railroad competition threatened the horse-drawn boat business, and Russell had to assess the efficiency of the conversion from horsepower to steam. In his report, he described the following occurrence.

As a rope got entangled in the device used for measurements, the boat suddenly stopped and the water "accumulated round the prow of the vessel in a state of violent agitation, then rolled forward with great velocity, assuming the form of a large solitary elevation—a rounded, smooth and well defined heap of water—which continued its course along the channel without change of form or diminution of speed."

This *wave of translation*—as he called it—intrigued him, so he "followed it on horseback, and overtook it still rolling on at a rate of eight or nine miles an hour, preserving its original figure some thirty feet long and a foot to a foot and a half in height," until he lost it in the meanders of the channel. This event was the start of a struggle to understand an unusual phenomenon and—what would be an even more difficult task—to prove the existence of water waves that could travel forever.

In 1830 he invented a steam carriage, but his undertaking failed because the officials opposed its implementation. Russell had more success with the Union Canal Company, which hired him to study the connection between wave generation and resistance to motion. This opportunity had also been triggered by chance. When a horse dragging a boat on a Glasgow canal took fright and ran off, the vessel's prow rose and the boat sailed faster. Russell understood that the solitary wave caused the reduced resistance and the rise of the boat, so he focused his research on the wave.

He built a water tank, generated waves of translation by releasing a column of water through a sliding panel, and performed hundreds of experiments, recording the details he observed. Although the wave's fast speed was remarkable, Russell was more impressed by its persistence. He had expected the wave to shrink after traveling long enough, but the tests proved him wrong. The solitary wave looked more stable than anything he had seen before.

The wave of translation appeared only if the boat reached a critical speed. Below it, the vessel met water resistance; above it, the wave became self-sustained, allowing the boat to move easier. After repeated experiments, Russell concluded that the wave's velocity depends both on the depth of the water and on the wave's height.

His result explains why tsunamis move at high speed in midocean but slow down close to the shore, and why boats overcome water resistance in shallow canals as they reach the critical speed. In deep seas, however, ships are slow, moving well below the critical speed, so by trying to move faster they encounter more resistance. Russell solved this problem by designing hollow-lined prows, which part the water without ruffling its surface. He noted that pirates, to whom speed was essential, had built similar prows in the past.

Russell also studied the interaction between waves. Intuition suggests that, at impact, waves traveling in opposite directions break. But this never happens. They meet, merge for an instant, and pass through each other unchanged. This phenomenon shows why the idea to kill a tsunami through a collision with an artificially generated wave doesn't work.

Apart from conducting some 20,000 experiments with toy models and ships ranging from a few hundred grams to 1,300 tons, Russell spent years analyzing the shape and motion of the translation wave. Among other things, he learned that, unlike wind-generated waves, which involve vertical motion, the solitary wave is a horizontal shift of mass with a shape about six times longer than tall. So instead of moving up and down, as ordinary waves do, a tsunami pushes ahead like a shelf of water.

Russell also had an original idea about tides, which he viewed as very large solitary waves. He divided his tidal theory in two parts, one founded on celestial mechanics, to explain water elevation in seas and oceans, and the other based on hydrodynamics, to account for the swell of small basins, rivers, and canals.

Russell presented his research in several articles, which he submitted to different meetings attended by mathematicians, physicists, engineers, and astronomers interested in fluid dynamics. Among them was George Biddell Airy, who opposed Russell's results. Airy had a theory of his own, and he deemed the solitary wave impossible.

Meeting Resistance

No fancy idea permeates the scientific world with ease, particularly when a personality opposes it. Airy was no ordinary scientist. He held the Lucasian Professorship at Cambridge, a position Isaac Newton had occupied in the seventeenth century, and had the most envied astronomical job in Britain, that of astronomer royal. He would later preside over the Royal Society and accept a knighthood, but only after declining it three times because he could not afford the fees.

Airy made important contributions to science, from improving the orbital theory of Venus and the Moon to a mathematical study of the rainbow. He preferred applications to theory and was often at odds with his colleagues about the research direction in which important mathematics prizes should go.

Outside his professional work, Airy showed broad interests. He read history and poetry and was keen about architecture, geology, engineering, and religion. He even tried to identify the location of Julius Caesar's landing in Britain and the place from where the

Roman consul departed. But later in life he spent most of his time in administration.

When Russell announced his results, Airy was still very active in research. The astronomer royal had constructed his own theory of waves, which he had initially based on the work of the French mathematician Pierre Simon Laplace. But because Laplace's equations applied only to shallow waves, Airy came up with some improvements. His goal was to predict the height of tides. Alas, he failed in this endeavor as much as his French predecessor did; their calculations didn't come even close to reality.

Airy, however, considered his theory suitable for understanding waves. In an article published in 1845, he praised Russell's experiments because his own theory explained them. But he warned against Russell's analysis. The equations Airy developed could not account for large shifts of mass, so an everlasting wave made no sense to him.

Although this authoritative judgment failed to shake Russell's belief in the value of his discovery, the Scottish engineer received another blow soon. In 1846 the new leader of British hydrodynamics, Cambridge mathematician George Gabriel Stokes, published a paper about the state of the field. Stokes's point was clear: permanent translation waves could not exist.

Further Opposition

Age twenty-seven at that time, Stokes was eleven years younger than Russell, and his paper confirmed his leading role in the field. In 1846, when this report appeared, he could not accept the idea of a sea wave that travels thousands of miles undisturbed. In his opinion, waves of translation had to shrink, and the stability Russell proclaimed was illusory because he had drawn his conclusions from experiments performed in short tanks.

Stokes's interest in waves faded soon, but he returned to them time and again. In October 1879 he wrote to William Thomson, better known as Lord Kelvin: "I have in mind when I have occasion to go to London to take a run down to Brighton if a rough sea should be telegraphed, that I may study the forms of waves about to break. I have a sort of imperfect memory that swells breaking on a sandy beach became at one phase very approximately wedge-shapes." When Kelvin invited him "to see and *feel* the waves" on his yacht, Stokes answered in September 1880: "You ask if I have done anything more about the greatest possible wave. I cannot say that I have, at least anything to mention mathematically. For it is not a very mathematical process taking off my shoes and stockings, tucking up my trousers as high as I could, and wading out into the sea to get in line with the crest of some small waves that were breaking on a sandy beach."

Stokes's change of mind about the value of practical observations stemmed from his new conviction that Russell had been right. Three weeks later he wrote to his friend again: "Contrary to an opinion expressed in my report [of 1846], I am now disposed to think there is such a thing as a solitary wave that can be theoretically propagated without degradation." Kelvin disagreed. His opposition resided in some technicalities related to the mathematical model, which was not transparent to the subtleties of solitary waves.

Russell never learned about this exchange or of Stokes's approval of his work. At that time, he had lost his ambitions. In the 1860s he had suffered several blows: his attempts to build an iron vessel called *Great Eastern* failed, he got involved in a financial dispute about an armament contract, and he was expelled from the Council of the Institute of Civil Engineers. These setbacks made him withdraw on the Isle of Wight, in southern England, where he died on 8 June 1882, at age seventy-four.

At the time of these developments, unknown to Russell, Kelvin, and Stokes, a young French mathematician named Joseph Boussinesq was also studying solitary waves.

The French Connection

Two mathematical giants—a Frenchman, Jean Le Rond d'Alembert, and a Swiss, Leonhard Euler—had initiated the study of waves more than a century earlier. In 1747 d'Alembert won the prize of the Prussian Academy for his pioneering work on partial differential equations, which model many physical phenomena, including waves. In spite of its sound mathematics, however, the paper's physics left much to be desired. For instance, d'Alembert erroneously stated that tides, not heat, generate winds.

Nevertheless, Euler saw the value of d'Alembert's methods, developed them further, and found their true physical meaning. But the Swiss mathematician gave d'Alembert little credit, a fact that triggered animosity between them. In spite of this rivalry, both d'Alembert and Euler followed each other's papers to lay the foundations of wave theory. Their ideas were further developed by two other mathematical geniuses: Joseph Louis Lagrange and Pierre Simon Laplace.

In 1776 Laplace published his celebrated theory of tides, which was based on a model for the propagation of small waves in shallow water. Lagrange extended Laplace's ideas to deep-water waves, but many of his assertions were speculative. The two mathematicians showed more interest in the shape of the surface than in how the fluid moved. Consequently neither of them could guess the existence of the solitary wave.

A step forward was made in 1813, when the Academy of Sciences established a prestigious prize. Laplace drafted the question: "An infinitely deep fluid mass, initially at rest, is set into motion by a given force. It is asked to determine the form of the external surface of the fluid and the velocity of every molecule on the surface after a given time." The mathematician who came close to solving the problem was Siméon Denis Poisson, the most brilliant disciple of Laplace. In his midthirties at that time, Poisson was already established as a professor at École Polytechnique and astronomer at the Bureau des Longitudes in Paris. But since he was also a member of the jury, Poisson could not compete for the prize.

The award went in 1816 to the twenty-seven-year-old Augustin Louis Cauchy, best known today for putting calculus on a rigorous foundation. Notable is the significant overlap between the results of Poisson and Cauchy, though they worked independently. Both men used a theory their countryman Jean Joseph Fourier had developed a decade earlier, but unlike Poisson, Cauchy re-created most of its tools from scratch.

A problem Cauchy analyzed was the disturbance created by the sudden immersion of a solid body into a fluid. This issue was close to the study of a boat's motion on water. Cauchy, however, didn't go far enough to see any connection with the solitary wave. His failure comes as no surprise: nobody before Russell, and very few of Russell's peers, thought that this phenomenon existed. Among those who did was the French mathematician Joseph Boussinesq, who succeeded in going beyond Russell's practical experiments, laying the foundations of a solid theoretical framework.

In 1871, four years after obtaining his doctoral degree, Boussinesq became acquainted with Russell's work and the wave experiments of the French hydraulician Henri Bazin. Boussinesq had already rediscovered some known results. This exercise now led him to the solitary wave, whose existence he could prove. His solution was based on an ingenious method applied to Euler's equations. Although Lagrange had used the same idea a century earlier, he failed to push it through because he lacked the more refined mathematical techniques Boussinesq employed.

But Boussinesq was not the only one who rigorously proved the existence of the solitary wave. Five years later, independently of him, an English mathematician reached the same conclusion. His name was John William Strutt or Lord Rayleigh. Russell, Stokes, and Kelvin knew nothing of this feat.

The Tricks of History

John William Strutt was born the same year as Boussinesq, 1842, in Witham, Essex, as the son of the second Baron Rayleigh of Terling Place. Nobody in his family of landowners showed any interest in science, and John proved to be average in school. But his talent for mathematics sprouted in 1861 after he began to study at Cambridge. Stokes influenced his intellectual development, though he never encouraged Strutt to pursue research. After graduation Strutt was elected a fellow of Trinity College, and at the age of thirty he inherited his father's title.

In spite of traveling widely as a young man, Rayleigh dedicated much time to research. His theory of scattering, published in 1871, gave the first correct explanation of why the sky is blue. In 1879 he was appointed Cavendish Professor of Experimental Physics at Cambridge. This opportunity helped Rayleigh lay the foundations for his work on the density of gases and put him on the path of discovering the chemical element argon, contributions for which he was awarded the Nobel Prize for Physics in 1904.

While in his early thirties, Rayleigh became interested in wave theory and in Russell's work. He started like Boussinesq from Lagrange's principles but then distanced himself from the French school. Rayleigh had an idea that simplified his computations. Unlike Boussinesq, he looked at the wave as if riding on it, using a coordinate system bound to the wave, not fixed somewhere in space.

Some twenty years later, in 1895, the Dutch mathematician Diederik Johannes Korteweg and his doctoral student Gustav de Vries improved Rayleigh's method and extended it to the study of other types of waves, including the oscillatory ones and those of evolving shape. The equation they derived was a version of Boussinesq's.

Korteweg and de Vries also found the solution that corresponds to the wave of translation and duly mentioned the priority of Boussinesq and Rayleigh. But they showed no excitement about this rediscovery, seeing little merit in going where others had been. Like most mathematicians, they were more interested in obtaining original results and cared less about what applications those would have. Thus they emphasized "the new type of long stationary waves," called *cnoidal* today, which was their discovery.

The paper of the Dutch mathematicians made no immediate impression. Their peers considered the problem of the solitary wave completely solved and were seeking new (and more exotic) phenomena related to the motion of liquids. Later, when the experts understood the significance of this equation, they called it *Korteweg-de Vries.*

History played a trick on Boussinesq, who is only briefly mentioned in the field. For the two Dutch mathematicians, this was their most important achievement. Their merit cannot be denied, but they didn't excel in research as much as Boussinesq and Rayleigh did. Korteweg had become a professor at the University of Amsterdam in 1881, from where he retired in 1918 without publishing other important papers. De Vries achieved even less. He gave up research after writing two more articles about cyclones and made a living as a schoolteacher.

The Korteweg-de Vries equation, however, took on a life of its own. If, during the first decades of the twentieth century, it didn't stand out in any particular way, this was about to change. An apparently unrelated experiment would propel it to the limelight of mathematical research. The reason for this turn of events was the role played by an Italian physicist, also known as "the father of the atomic bomb."

A Numerical Experiment

Enrico Fermi, the key nuclear physicist of the Manhattan Project, also had a crucial contribution to the theory of waves. It all started a few years after the war, during one of Fermi's visits to Los Alamos. Among the friends the Italian scientist had made while working on the bomb was the Polish mathematician Stanislaw Ulam. Fermi had used his 1938 Nobel Prize award ceremony in Stockholm to flee fascist Italy and cross the Atlantic Ocean. Ulam had come to the United States a few months before Fermi as a Harvard junior fellow. When his contract expired, the Pole received a faculty position at the University of Wisconsin, where he engaged in mathematical research with military applications.

In the middle of the war, Ulam received an invitation to join a secret project in New Mexico. He was told little about it, so he felt no wish to go. But after learning the names of those who had recently vanished from campus, and suspecting a connection with the project, he agreed to go. This decision changed his life, propelling him into the circles of the world's mathematical elite. Part of his rise to fame was due to his collaboration with Fermi.

The postwar American scientific establishment was split about the newly invented electronic computers. Fermi took the side of those who welcomed them. In the early 1950s he began to think about finding some significant physics problem that would merit an investigation on one of the very first electronic computers, MANIAC I, which happened to be located at Los Alamos. He decided to study how crystals evolve toward thermal equilibrium.

Crystals are modeled as particles kept together by forces. The ensuing structure resembles the builder's scaffolding—the bars corresponding to the forces and the junctions to the particles. When not in equilibrium, crystals behave like structures whose bars bend and stretch. This three-dimensional model reflects reality quite well. A simpler, less realistic model is a two-dimensional one, which would look more like a chicken wire or a fishing net. A one-dimensional model would resemble a chain.

Apparently there is no overlap between waves and crystals, and Fermi never thought to connect them. But a bit of imagination reveals that a wave's surface looks like a bedsheet, which is nothing but a fishing net with tiny holes. Similarly, the spatial waves resemble "soft" scaffoldings with many joints and short bars. Therefore understanding the motion of crystals could shed light on the propagation of waves.

To keep computations easy, Fermi and Ulam decided to work on the one-dimensional case—the chain. However, in order to implement a suitable numerical technique, they needed an expert in computational methods. Thus a third Los Alamos expert joined the team. His name was John Pasta.

Fermi, Pasta, and Ulam drafted a research plan in 1952 and did their first numerical experiments the following summer. It was Fermi's idea that, instead of performing the standard calculus for a physical problem, one should take particular examples and test them with computer simulations. This approach would not only stimulate the development of wave theory but also prove crucial in the study of nonlinear phenomena—one of the main research directions in the mathematical sciences during the last three decades of the twentieth century.

The numerical experiments on the "chain crystal" revealed the existence of a solution that looked like the solitary wave, as if a snake curved its body into a bump that moved smoothly from head to tail. Fermi was not impressed, but he changed his mind soon. This revelation was probably his last. During the second half of 1954, the stomach cancer he was suffering from began to spread, and he died at the end of November, less than two months after turning fifty-four.

Solitons

In 1965 two engineers, Norman Zabusky of Bell Telephone Laboratories and Martin Kruskal of Princeton University, showed the Fermi-Pasta-Ulam experiment and the Korteweg-de Vries equation to be different sides of the same coin. They also brought numerical evidence that the solutions of the Korteweg-de Vries equation obeyed a property that Russell had observed in experiments more than a century earlier: translation waves pass through each other undisturbed.

It took a few years until the results of Zabusky and Kruskal were recognized, but starting with the early1970s, their paper had a strong impact on wave theorists, many of whom put their current research aside and jumped to the study of the Korteweg-de Vries equation, which had remained obscure for several decades. The experts felt there was something new to discover. They reopened a research direction that had made little advance during the first half of the twentieth century.

This was not the first time a mathematical field saw an unexpected revival. Chaos theory had a similar fate. At the end of the nineteenth century, the French mathematician Henri Poincaré pointed out the existence of deterministic phenomena whose high instability makes their long-term evolution difficult to predict. Very few people understood him, so this part of his research was neglected. The Fermi-Pasta-Ulam experiment influenced its resurrection.

Edward Lorenz, a meteorologist at the Massachusetts Institute of Technology, was one of the key players in the revival of chaos theory. In 1972 he addressed the American Association for the Advancement of Science with a talk entitled “Predictability: Does the Flap of a Butterfly’s Wings in Brazil Set Off a Tornado in Texas?” He explained why instability might amplify a small cause into a large effect. Thus the butterfly metaphor and the word *chaos* aroused the interest of many mathematicians.

In their paper Zabusky and Kruskal coined a magical word too, the *soliton*—short for the “solitary-wave solution” of the Korteweg-de Vries equation. As happened to chaos theory, the combination of an inspired word (soliton) and a surprising property (wave crossing) triggered a research boom in the study of waves. Zabusky and Kruskal were the tipping point in the development of the field.

But once this new branch of wave theory sprouted, the mathematicians focused on understanding the abstract world of the Korteweg-de Vries and other related equations, neglecting the solitary wave. Those who didn't lose the original track were the engineers. They followed the latest mathematical results and applied them to tsunamis.

From Theory to Practice

Russell and his immediate followers never saw a real tsunami. Neither is there any indication that they heard about the formation of translation waves in the world's oceans. Those who witnessed such events were unaware of the scientists' efforts, so the bridge between theory and practice was a slow one to build. Moreover, tsunamis are more complicated than solitons, which resemble them only in a first approximation. But the contributions mentioned earlier laid the foundation for understanding these waves.

A first difficulty engineers encountered was the nonlinearity of the Korteweg-de Vries equation. Although Poincaré had initiated the study of nonlinear phenomena at the end of the nineteenth century, the field boomed only in the 1960s, triggered by contributions such as those of Lorenz, Fermi, Pasta, and Ulam. Thus the first attempts to grasp the generation and propagation of tsunamis were restricted to linear models, which approximated Korteweg-de-Vries-type equations.

Work started in the 1950s in Japan, a country often hit by tsunamis. (In fact the word "tsunami" is Japanese for "harbor wave" and was used by the fishermen who returned home to devastated harbors.) The early studies determined the general wave pattern near the source region for a variety of bed motions in simplified situations. These attempts continued in the 1960s for more realistic models, which allowed good estimates for the size of tsunamis relative to how much the seabed changes during an earthquake.

The transition from linear to nonlinear models took place gradually. Various authors employed linear equations with some nonlinear perturbation terms. Their results did not add much knowledge about tsunamis but led to a refining of the mathematical techniques used until then. These achievements, together with the independent development of nonlinear analysis in the early 1970s, allowed experts to study the formation and propagation of tsunamis in the more general and realistic framework of nonlinear theory—the research direction followed today.

Physics also plays an important role in understanding tsunamis. For instance, the recent analysis done by Jack Hills and Patrick Goda of the Los Alamos National Laboratory in New Mexico showed that the marine impact of a 500-meter meteorite could produce a 1- or 2-kilometer-high tsunami, which might penetrate hundreds of kilometers inland. Critics, however, are skeptical that their model matches reality and think that waves this high are impossible on Earth. Independently of height, the probability of such events is small, but—as chapter 6 will show—far from zero.

Other directions of research have identified dangerous geographic zones. When such places are populated or economically important, the communities can prevent potential disasters by building antitsunami walls, as was done in Japan, or by planting forests on the shore to dissipate the wave's destructive energy.

During the past few decades, experts have also learned about the circumstances triggering tsunamis. If the cause is an earthquake, for example, its magnitude must be significant to create a deadly wave. But when the earthquake provokes landslides that generate tsunamis, then even lower magnitudes are sufficient to produce large waves.

None of these scientific efforts, however, can tell precisely when a tsunami will strike. The reason for this drawback stays with the triggering event, which precedes the tsunami. Later chapters will discuss two of the generating factors—earthquakes and meteorite impacts—and describe the state of the art of their prediction.

The theoretical studies described here allow scientists to compute the size of a wave relative to the geography of the location, such that housing developments can be planned sufficiently high above the sea level. Combined with observations and experiments, these achievements have led to the discovery of the signs that warn about an incoming tsunami at least a few minutes in advance. Moreover, North

America and Japan implemented warning systems, which allow the quick evacuation of the potentially affected zones whenever a triggering event happens. Practice shows that if there is enough time left, the evacuation can be effective.

Educating people about the signals indicating the approach of tsunamis can save lives. We don't have to look too far to understand the advantage of recognizing the danger and acting decisively. The recent Indian Ocean disaster offers a stunning example.

The English Girl

On the morning of 26 December 2004, Tilly Smith was with her parents and younger sister on the Mai Khao beach in Phuket, not far from where Petra Nemcova and Simon Atlee were getting ready for departure. Ten years old, blond hair falling on her shoulders, Tilly looked jolly and fresh as she smiled in the sun. She had good reasons to be happy, thinking of the damp, cold England she had left behind.

As mother and daughter went down to the water, Tilly noticed that the sea looked bubbly and frothy like on the top of a beer. This image triggered some recent memories in her mind. Two weeks earlier, during her geography class at Danes Hill School in Oxshott, Surrey, Tilly saw a movie about the Hawaii tsunami of 1946. She recognized the same warning signs: just minutes before the deadly wave hit, the water had begun to form bubbles and turn foamy, so very much as it did now.

"A tsunami is coming!" Tilly shouted. "We must run away!"

Her mother, Penny, had noticed that strange phenomenon too, but thought it was due to a bad day at sea, so she didn't take Tilly seriously.

"Mummy, we must get off the beach *now*!" Tilly insisted.

Penny began to worry about her daughter, who started shouting madly at her, frustrated that her mother was blind to the danger. But in spite of Tilly's anxiety and irritation, she didn't give up. She had to convince her mother somehow.

"If you're not coming," she screamed, "I'm going to leave you here!"

Penny remembered Tilly's recent geography class about tsunamis, so she gave in, and they both ran to Colin, Tilly's father. After he heard the story, Colin alerted a lifeguard, who evacuated the tourists from the beach. It was a wise decision. Minutes later the killer wave showed up.

In September 2005, back in England, Tilly received the Thomas Gray Award of the Marine Society in recognition of her timely and decisive actions, which saved human lives. But she most cherished the inner satisfaction that she and her family, as well as the about one hundred other people who had been on the Mai Khao beach, were alive because she alone had recognized the danger.

Warning Signs

Nothing happens without warning; it's just that the signs are often obscure or opaque. Heart attacks, for instance, take many by surprise because they do not recognize the symptoms. The same problem occurs with most natural disasters. But the difficulty to acknowledge the message and act on the spot can be eliminated through training.

Most tsunamis give notice tens of minutes before they reach the shore. One or several of the following signs may be seen, heard, or felt:

- an earthquake occurs
- the sea recedes to a considerable distance
- the sea bubbles
- the water stings the skin
- the sea smells of rotten eggs or oil
- a flash of red light sparks on the sea near the horizon
- a boom is followed by a whistle, or by a jet-plane- or helicopter-like noise

Each phenomenon depends on circumstances, and their explanations vary. The sea's recession compensates for the soon-to-arrive wave. The bubbling and the stinging of the skin, which resemble the effects of sparkling water, are consequences of the air or gases the wave pushes ahead of it. An earthquake or a volcano eruption may release chemical components with funny smells or lead to reactions that produce electrical discharges. Finally, the noises can be consequences of those reactions or may occur because of the friction between the large wave and the shallow seabed.

Some early warnings, which often occur before any of the physical signs are apparent, may come from nearby animals. The first documented animal reaction to a tsunami appears for the underwater earthquake of 1755, whose epicenter was some 350 kilometers southwest of Lisbon. The combined disaster killed between 60,000 and 100,000 people in Portugal, Spain, and North Africa, with the tsunami playing a lesser role in those deaths.

The earthquake struck on the morning of 1 November, causing wide fissures in Lisbon's center. Those who rushed to the docks for safety watched as the receding water revealed a seafloor littered by shipwrecks and cargo. More than an hour after the earthquake, a 20-meter-high tsunami, followed by two more waves, engulfed Lisbon's harbor and downtown area. The animals are said to have run away from the shore long before the wave showed up.

The reason why animals feel the approach of tsunamis is yet unknown. Some scientists speculate that animals can detect certain earthquake waves, which propagate through Earth's crust, as I will explain in the next chapter.

Nevertheless, warning signs exist for tsunamis. But we need to learn how to read them. This is not always easy because we may see danger when there is none. Aesop's tale about a shepherd boy who cried wolf to make fun of his fellow villagers shows how false alarms could do more harm than no warning at all. Nevertheless, Tilly Smith's example proves that instruction and vigilance can save lives.

So are there ways to forecast the events that may trigger tsunamis? After all, a big earthquake or a large meteoritic impact might be worse than a solitary wave. Their effect may range from killing half a million people to wiping out most life on Earth. The prediction of these phenomena is therefore worth pursuing.