TSUNAMIS AND TSUNAMI WARNING SYSTEMS

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Contents

Summary

This article describes the source mechanism, generation, and transmission of seismic sea waves (tsunami) across the global ocean surface. The dispersion, refraction, and transformation by the continental shelf of these potentially disastrous “tidal” waves are described, as well as alarm systems to provide early warning for evasive action and evacuation strategies to be implemented in a timely manner. Prototype and model data are also discussed and theoretical relationships presented.

The article covers in detail the origins of tsunami from deep-seated seismic disturbances on the ocean floor, seen in historic perspective. The theory of tsunami generation, propagation across the global oceans, and terminal effects on shorelines around the world is presented. This includes source energy parameters, generation mechanics, energy redistribution at the continental shelves, and runup phenomena over coastal slopes. Because of the long periodicity and a wavelength several times the depth of the

ocean traversed, a tsunami is effectively a shallow-water wave, and its progression and terminal effects can be described by shallow-water wave theory.

The impact and threat of tsunami on coastal and inland populated areas have been severe in isolated cases in the past; nevertheless, the threat to circum-Pacific and other coastal localities is recognized, and tsunami warning system networks have been set up. Seismic observations, early warnings of tsunami generations, and estimated travel and arrival times are issued by the authorities involved. Numerical modeling analysis is carried out and confirmed by observations made during actual occurrences.

1. Overview

The course of human civilization was changed abruptly by a tsunami, or seismic sea wave when, in 1450 BC, the volcano Santorini in the Aegean Sea erupted explosively and, in conjunction with caldera collapse and related faulting, sent out a series of waves that devastated the northern coast of Crete. The Minoan society, then the highest culture in the Western world, never recovered. Other disastrous tsunamis have occurred in Calabria and Sicily, and elsewhere in Europe, also in the Pacific Ocean: Chili, Alaska, Japan, Philippines, Indonesia (Krakatoa 1883) mostly in conjunction with earthquakes, but also as a result of volcanic explosions.

The word *tsunami* is derived from Japanese, denoting port or harbor (*tsu*) and sea wave (*nami*) caused by seismic activity, which phenomenon along with earthquakes are well known to the people of Japan and Asia. This natural hazard is dreaded and respected whenever a major earthquake in the circum-Pacific volcanic belt is reported. With the earthquake source providing its energy, a tsunami propagates thousands of kilometers over the ocean to coastlines and shores, where it impacts with varying degrees of severity (see *Nature of Earthquakes*).

Much more frequent than in Europe are the tsunamis in the Pacific Ocean, usually due to undersea tectonic dislocations, such as in geological faults along the deep ocean trenches. These tsunamis may have vertical motions at their source of more than 10 m (much more in a few rare cases). Because wave amplification may occur, the resulting tsunamis may have runup on adjacent coastlines of 20 m to 30 m amplitude—and as much as 10 m to 20 m runup on distant shorelines (see *Plate Tectonics*).

As an introduction to the tsunami phenomenon and to tsunami-warning systems, first consider idealized cases of the generation of a tsunami, its propagation, and its runup onto a sloping beach. These cases are all so simple that theoretical analysis is possible, even though the runup problem is strongly disproportional. Concentration on elementary situations involves a few parameters and permits understanding of the relationships between the parameters. After grasping the fundamentals, more realistic conditions for models of the ocean-earth conditions are considered. These are treated by numerical methods—finite-difference or finite-element.

All of the foregoing is done for a cross-section of the ocean, from the undersea generating source to the runup on the beach. This is a two-dimensional process, although sometimes called one-dimensional because an integration process eliminates the second dimension, the vertical dependence in deep water (more than 200 m). When the third dimension—that is laterally along the shoreline—becomes important, the possible extent of the effects of the additional dimension may also be evaluated (see *Hydraulic Structures for Coastal Protection*).

Tsunami warning systems are much more complicated even than tsunamis themselves, because people and instruments are also involved. Six tsunami warning systems exist worldwide: French, Russian, Japanese, Hawaiian, Aleutian, and Pacific. These are also discussed below.

2. The Tsunami Phenomenon

Like ancient Gaul, the tsunami phenomenon can be said to be divided into three parts. The beginning is the generation of the tsunami; the middle is the tsunami propagation across one or more oceans; and the end is the termination and runup of the tsunami onto a coastline.

Certain features of the tsunami need to be known. These are called parameters, from which a predictive capability has to be developed. Some parameters can be measured directly, but others must be deduced from measurement of some of the different characteristics; so the interrelationships among these parameters are of continual concern in our study.

3. Generation Mechanics

The typical tsunami is formed by an earthquake—a tectonic earthquake, which means that the crust of the earth, deep down, is deformed permanently or temporarily during the earthquake. The vertical component of the deformation, up or down, will lift or lower any overlying part of the ocean. If there is no ocean, there will be no tsunami. The earthquake represents the relatively sudden conversion of potential energy, in the form of crustal rocks strained on each side of a fault, into kinetic energy, which works, first, by moving the rock, including the emission of seismic waves; second, by lifting the overlying ocean; and third, by heating the fault interface, which is not of present interest.

Lifting of the ocean occurs slowly, on the order of tens or hundreds of seconds, so the water does not fly off into space but simply temporarily forms a raised mound of water atop the vertically deformed crust. This mound of water has potential energy, because it is at a higher potential in the gravity field of the Earth than it was before being uplifted. And being in an unstable condition, this potential energy is immediately converted into kinetic energy. The water elevated in the mound, however, does not flow off the mound, as might be expected, but bears down on the water underneath, which then has to move sideways because it cannot pass into the underlying rock. Energy thereupon spreads out in the form of a water-wave system, as the mounded water area begins to oscillate up and down.

Consider the generation situation schematically shown in Figure 1. The total potential energy of the mound of water is the density, times the area, times the mean rise (where

ρ is the density, S is the area, and η is the mean rise, equal to one half the rise, η_{total}). The density may be approximated as unity, and the less significant kinetic energy that the earthquake directly puts into the water may for simplification be ignored.

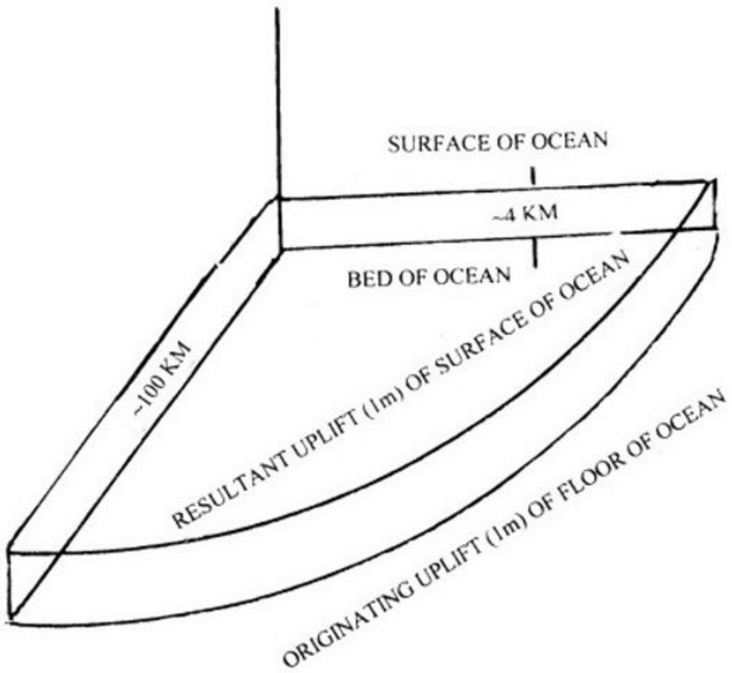

Figure 1. Cross-section of an ocean showing the generation process of a tsunami: the uplifted portion of the ocean floor raises the overlying ocean to form a mound of water having potential energy

4. Parameters of the Source of a Tsunami

Assume the source area is circular in plan and that the uplift is uniform over the source area. The area of uplift in a large earthquake—such as would generate a tsunami hazardous to humankind—has radial dimensions of hundreds of kilometers, as indicated by the distribution of aftershocks and other water evidence. This radial length determines the dominant wavelength of the radiated gravity-type water waves or tsunamis, and, most important, is more than an order of magnitude greater than the average depth of the ocean, which we take to be about 4 km.

Water wave theory indicates that this is a special extreme case, called the *shallow-water* or *long-wave* approximation. This simplification is permissible, even though the ocean is not thought of as being "shallow." The propagation velocity, V, for such long wavelengths, long compared to the depth, is independent of wavelength and depends only on the value of gravitational acceleration, g, and the depth of water, H: thus $V = \sqrt{(gH)}$. The relationship of tsunamis to other types of waves such as ocean swell and tides is described in detail elsewhere.

The uplift occurs in about one minute over the entire source region: there are some other interesting features dependent upon this rate of uplift and the properties of the fracturing material, but these are not relevant here. For larger earthquakes, greater than about Richter magnitude 7, the source area will be elongated along the strike of the fault, which usually lies parallel to the adjacent coastline. This, too, leads to important variations in the radiation pattern, which are not further discussed here. To keep the model simple, the uplift is assumed to occur due to a source area situated in the deep ocean; the effect of a tsunami being created in a coastal area is considered later.

Because the driving cause of a tsunami is the potential energy due to uplift in a gravitational field, the tsunami is called a "gravity wave." As the energy of the tsunami spreads out from the source, there are two different velocities involved, and understanding the difference is important. The rate propagation, at which the front of the wave spreads outward, is known as the wave velocity, or celerity, of the tsunami.

For a water depth of 4 km and a gravitational acceleration field of 9.8 m/s^2, this celerity is about 200 m/s—equal to about 720 km/h. This is the velocity of the energy propagation, *not* the velocity of the water itself. The particles of water move and interact in such a manner as to transfer the energy radially outward along the travel path of the tsunami. Both theory and observations indicate that this *particle velocity* is much lower, being only about 2 cm/s (72 m/h). This is the reason the passage of tsunamis in the deep ocean is not noticed by observers on ships at sea. The orbit of the particle of water during the passage of a tsunami is shown in Figure 2.

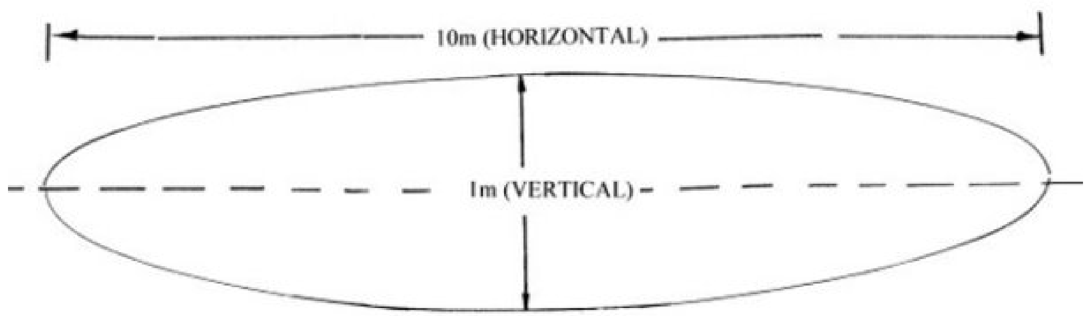

Figure 2. Cross section showing the particle motion at the ocean surface: the particle velocity has both vertical and horizontal components with the horizontal component being dominant—about 10 times the vertical component

The shape of a simulated tsunami, moving outward from an impulsive source across an ocean of constant depth, was determined theoretically, and is shown in Figures 3(a) and 3(b). The vertical axis denotes the amplitude and the horizontal axis the distance. This is the theoretical prediction of what a tsunami would look like if the entire ocean were suddenly frozen and a vertical slice taken out along the path of the tsunami. We cannot do this, but we can look at Mare Orientalis on the Moon, which is partly visible through binoculars or telescope (Cherrington) and seen edge-on from the Earth on the last quarter limb of the waning Moon. This impressive feature is seen (on images from space) to be surrounded by concentric circular ridges and troughs, as is shown on the enclosed image taken from a Moon-orbiting spacecraft, Figure 3(c). This might be evidence of a “frozen” tsunami.

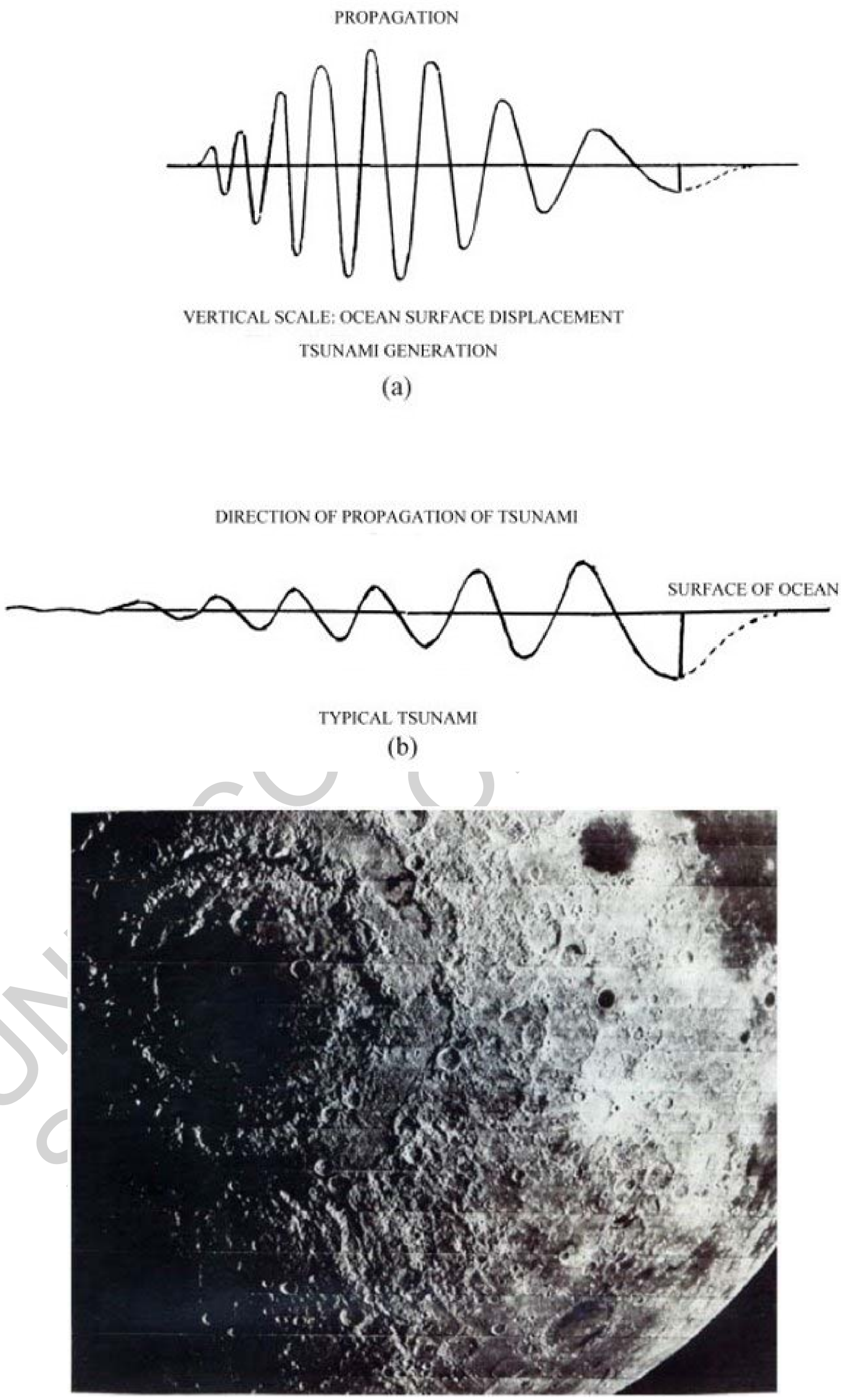

Figure 3. (a) and (b) Cross section of the surface of the ocean with a propagating tsunami (and no tide or swell); (c) *Mare Orientalis* on the Moon, as seen from space, in a NASA image, possibly a “frozen tsunami”

In Figure 3 (a) and (b), each oscillation has the appearance of a sinusoid. The horizontal axis is distance. The beginning of the tsunami is abrupt and the decay is gradual. The distance between the peaks is the wavelength, and the height of the peaks above the mean is the amplitude. For upward motion of the ocean floor at the source, the first wave formed will also be upward from the mean sea level, and for a downward sea floor motion at the source the first wave will also be downward. Some sources have both downward and upward areas of sea floor motion, e.g., vertical faulting in deep water leading to an infinite variety of possible complications. The energy lost propagating across the deep ocean is negligible; passage over an archipelago, such as the Hawaiian Islands, however, causes significant transformation of the tsunami wave form, reduction of the amplitude, and possibly frequency modifications.

5. Theory and Measurements

To check out the theory, it is necessary to know, first, the distance between the peaks (or troughs), and second, the amplitude of the peaks (or troughs). The problem is to derive such answers from what can be measured. Measurements of tsunamis in the ocean use the common tide recorder, which is located at a fixed distance from the source and records how the amplitude at that particular, single, radial distance varies with time as the tsunami passes the gauge; in other words, a time-record is obtained. A copy of such a recording of a tsunami is shown in Figure 4.

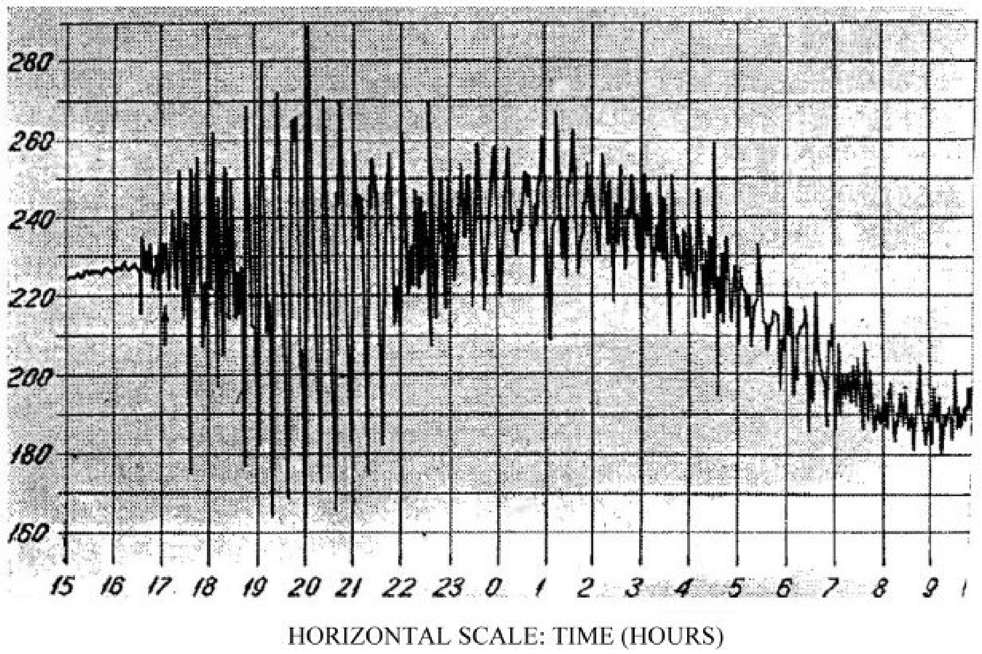

Figure 4. Typical recording, at one spot, of the passage of a tsunami.
The horizontal axis here is time; the time between consecutive peaks is the period;
the height of the peak above the mean is the amplitude.

From this recording, one can determine, first, the periodicity of the oscillations, usually of the order of about 1000 s, and, second, the amplitude of the oscillations, usually up to about 1 m in the deep ocean. If measurements are obtained at two different radial distances from the source (and in nearly equal water depths) for the same tsunami, then one can determine the wave propagation velocity or *celerity*, *V*. (Already knowing the period, *T*, with the wave celerity, *V*, thus known, one can determine the wavelength, *L*, from the relationship: $L = V \times T$.)

This is how one derives what one wants to know from what one can measure. The loss of energy during propagation or attenuation is negligible compared with the energy loss upon reflection of the tsunami from a coastline; and the dispersion or radial spreading (due to the dependence of the velocity of propagation upon the wavelength, or period) is also negligible in the deep ocean, at least within the first few wavelengths away from the source region.

There is one other complicating feature that needs to be understood. Propagation of a tsunami over the Earth's surface means the tsunami energy is spreading over the spherical Earth and not over an infinite flat plane. To simplify understanding, consider a planet uniformly covered with water: the amplitude (and energy density per unit area of surface) of a propagating tsunami will reduce as it spreads out to an angular displacement of 90° about its center (until it reaches an "equator" relative to its source).

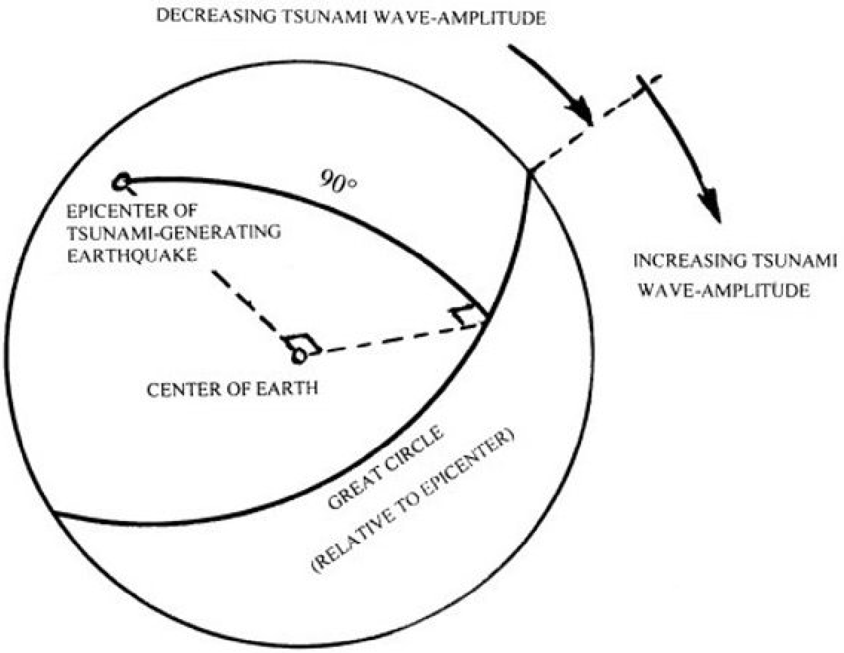

Figure 5. Propagation of a tsunami across a global ocean, such as the Pacific Ocean

Because the same energy up to this point is being spread out over a greater perimeter, as shown in Figure 5, one can say that the energy is diverging and therefore being diluted. Then comes the complication: beyond 90° angular displacement from the source, because the tsunami is spreading out farther over a sphere, convergence of the energy resumes, and the amplitude gradually becomes larger again with increasing radial distance! Ignoring this (and tsunami history) was disastrous for Japan in May 1960

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Biographical Sketches

William Mansfield Adams, Sr., is a retired professor of geophysics and ocean engineering, University of Hawaii, and former director of tsunami research, Hawaiian Institute of Geophysics, Honolulu, Hawaii, USA. He is a seismologist and has earned the degrees of B.A. (University of Chicago), B.S. (University of California at Berkeley), M.B.A. (Santa Clara University), and M.S. and Ph.D. (St. Louis University). He has written two books, edited two more books (one on tsunamis in the Pacific Ocean), and is author of more than 100 scientific articles. He received a Gulf fellowship (at St. Louis University) and a Fullbright grant (to Italy) and holds four US patents related to environmental issues.
His experience includes duties performed in Ottawa, Canada (scientific officer), Naples Italy (Fullbright grantee), Moscow (Lomonosov University), Tokyo (UNESCO seismology expert), and in USA: Laramie, Wyoming (chief seismologist), Livermore, California (test director), Honolulu, Hawaii (professor at the University of Hawaii and director of the Tsunami Research Group, Hawaii Institute of Geophysics), and at Indiana University, University of Colorado, and Western Washington University (exchange professor on sabbatical leave). He is at present a consultant and has traveled extensively in Europe, Africa, Asia (including New Zealand and Australia), and Alaska.

Jan Malan Jordaan Jr. is a retired civil engineer with experience in hydraulics, principally physical modeling of water-wave phenomena, but also design and modeling of hydraulic structures and investigation of fluvial hydraulic problems. He has earned the degrees of B.Sc. Eng. (Witwatersrand), M.S. (Wisconsin), C.E. and Sc.D. in civil engineering hydraulics (MIT). His professional career includes 28 years with the Department of Water Affairs and Forestry, RSA, and in Namibia, 4 years with the Council of Scientific and Industrial Research, Pretoria, and 4 years in total as associate professor in civil and oceanographic engineering, first at the University of Hawaii and then at the University of Delaware.
Prior to that, he helped to create a test facility, and as a research engineer, performed experiments on impulsive waves at the US Naval Civil Engineering Laboratory, Port Hueneme, California. He was responsible for extending the Look Oceanographic Engineering Laboratory of the University of Hawaii, Honolulu, Hawaii, USA, under a National Science Foundation grant, and for establishing hydraulic laboratories at Pretoria, South Africa, and at Windhoek, Namibia, for the Department of Water (and Environment) Affairs and Forestry of South Africa. For the 10 years up to and including 1998, he has been part-time professor of hydraulics at the University of Pretoria, South Africa, and was involved for a total period of one year with assessment of water projects in Bolivia and France. He also visited on official duty other water projects and attended international conferences in Europe, China and South America. He served as a member on advisory committees for the South African Water Research Commission and the South African Institution of Civil Engineers (retired Fellow); and was on the fluid mechanics journal editorial review board of the International Association for Hydraulic Engineering and Research (IAHR), of which he was a member for over forty years.