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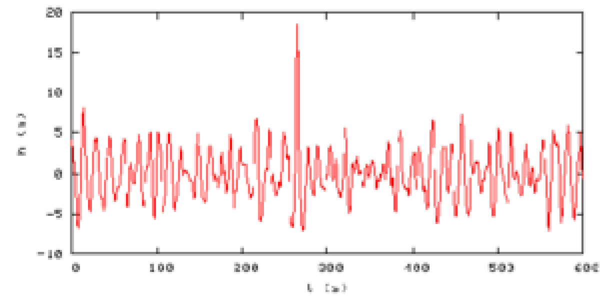
Rogue wave

Rogue waves (also known as **freak waves**, **monster waves**, **episodic waves**, **killer waves**, **extreme waves**, and **abnormal waves**) are large, unexpected and suddenly appearing surface waves that can be extremely dangerous, even to large ships such as ocean liners.[2]



The Draupner wave, a single giant wave measured on New Year's Day 1995, finally confirmed the existence of freak waves, which had previously been considered near-mythical.[1]

Rogue waves present considerable danger for several reasons: they are rare, unpredictable, may appear suddenly or without warning, and can impact with tremendous force. A 12-metre (39 ft) wave in the usual "linear" wave model would have a breaking pressure of 6 metric tons per square metre [t/m^2] (8.5 psi). Although modern ships are designed to tolerate a breaking wave of 15 t/m^2 (21 psi), a rogue wave can dwarf both of these figures with a breaking pressure of 100 t/m^2 (140 psi).[3]

A 1943 photograph of a large wave breaking over the islet of Rockall, in the North Atlantic Ocean. Rockall's peak is about 56 feet (17 m) above sea-level, and the height of the spray has been estimated at about 170 feet (52 m).

In oceanography, rogue waves are more precisely defined as waves whose height is more than twice the significant wave height (H_s or SWH), which is itself defined as the mean of the largest third of waves in a wave record. Therefore, rogue waves are not necessarily the biggest waves found on the water; they are, rather, unusually large waves for a given sea state. Rogue waves seem not to have a single distinct cause, but occur where physical factors such as high winds and strong currents cause waves to merge to create a single exceptionally large wave.[2]

Rogue waves can occur in media other than water. They appear to be ubiquitous in nature and have also been reported in liquid helium, in nonlinear optics and in microwave cavities. Recent research has focused on optical rogue waves which facilitate the study of the phenomenon in the laboratory. A 2015 paper studied the wave behavior around a rogue wave, including optical, and the Draupner wave, and concluded that "rogue events do not necessarily appear without a warning, but are often preceded by a short phase of relative order".[4]. The physical origin of a rogue wave can be defined by the rogue wave theorem.

Contents

Background

Rogue waves are an open water phenomenon, in which winds, currents, non-linear phenomena such as solitons, and other circumstances cause a wave to briefly form that is far larger than the "average" large occurring wave (the significant wave height or 'SWH') of that time and place. The basic underlying physics that makes phenomena such as rogue waves possible is that different waves can travel at different speeds, and so they can "pile up" in certain circumstances – known as "constructive interference". (In deep ocean the speed of a gravity wave is proportional to the square root of its wavelength—the distance peak-to-peak.) However other situations can also give rise to rogue waves, particularly situations where non-linear effects or instability effects can cause energy to move between waves and be concentrated in one or very few extremely large waves before returning to "normal" conditions.

Once considered mythical and lacking hard evidence for their existence, rogue waves are now proven to exist and known to be a natural ocean phenomenon. Eyewitness accounts from mariners and damage inflicted on ships have long suggested they occurred. The first scientific evidence of the existence of rogue waves came with the recording of a rogue wave by the Gorm platform in the central North Sea in 1984. A stand-out wave was detected with a wave height of 11 metres (36 ft) in a relatively low sea state.[5] However, the wave that caught the attention of the scientific community was the digital measurement of the "Draupner wave", a rogue wave at the Draupner platform in the North Sea on January 1, 1995, with a maximum wave height of 25.6 metres (84 ft) (peak elevation of 18.5 metres [61 ft]) . During that event, minor damage was also inflicted on the platform, far above sea level, confirming that the reading was valid.[1]

Their existence has also since been confirmed by video and photographs, and satellite imagery and radar of the ocean surface,[6] by stereo wave imaging systems,[7] by pressure transducers on the sea-floor and notably by oceanographic research vessel.[8] In February 2000, a British oceanographic research vessel, the RRS *Discovery*, sailing in the Rockall Trough west of Scotland encountered the largest waves ever recorded by scientific instruments in the open ocean, with a SWH of 18.5 metres (61 ft) and individual waves up to 29.1 metres (95 ft).[9] "In 2004 scientists using three weeks of radar images from European Space Agency satellites found ten rogue waves, each 25 metres (82 ft) or higher."[10]

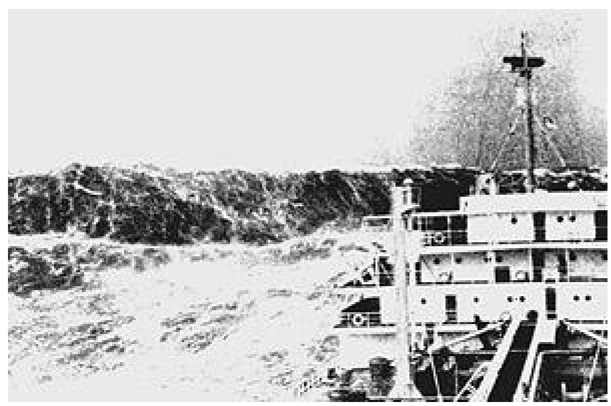
A rogue wave is a natural ocean phenomenon that is not caused by land movement, only lasts briefly, occurs in a limited location, and most often happens far out at sea.[2] Rogue waves are considered rare but potentially very dangerous, since they can involve the spontaneous formation of massive waves far beyond the usual expectations of ship designers, and can overwhelm the usual capabilities of ocean-going vessels which are not designed for such encounters. Rogue waves are therefore distinct from tsunamis.[2] Tsunamis are caused by massive displacement of water, often resulting from sudden movement of the ocean floor, after which they propagate at high speed over a wide area. They are nearly unnoticeable in deep water and only become dangerous as they approach the shoreline and the ocean floor becomes shallower;[11] therefore tsunamis do not present a threat to shipping at sea (the only ships lost in the 2004 Asian tsunami were in port). They are also distinct from megatsunamis, which are single massive waves caused by sudden impact, such as meteor impact or landslides within enclosed or limited bodies of water. They are also different from the waves described as "hundred-year waves", which is a purely statistical prediction of the highest wave likely to occur in a hundred-year period in a particular body of water.

Rogue waves have now been proven to be the cause of the sudden loss of some ocean-going vessels. Well documented instances include the freighter MS *München*, lost in 1978[12] and the MV Derbyshire lost in 1980, the largest British ship ever lost at sea.[13][14] A rogue wave has been implicated in the loss of other vessels including the Ocean Ranger which was a semi-submersible mobile offshore drilling unit that sank in Canadian waters on 15 February 1982.[15] In 2007 the US National Oceanic and Atmospheric Administration compiled a catalogue of more than 50 historical incidents probably associated with rogue waves.[16]

History of rogue wave knowledge

Mythical waves

In 1826, French scientist and naval officer Captain Jules Dumont d'Urville reported waves as high as 33 metres (108.3 ft) in the Indian Ocean with three colleagues as witnesses, yet he was publicly ridiculed by fellow scientist François Arago. In that era it was widely held that no wave could exceed 30 feet (9.1 m).[17][18] Author Susan Casey wrote that much of that disbelief came because there were very few people who had seen a rogue wave, and until the advent of steel double-hulled ships of the 20th century "people who encountered 100-foot rogue waves generally weren't coming back to tell people about it."[19]



Merchant ship labouring in heavy seas as a huge wave looms ahead, ca. 1940. Huge waves are common near the 100-fathom line in the Bay of Biscay.

For almost 100 years, oceanographers, meteorologists, engineers and ship designers have used a mathematical system commonly called the Gaussian function (or Gaussian Sea or standard linear model) to predict wave height.[20] This model assumes that waves vary in a regular way around the average (so-called 'significant') wave height. In a storm sea with a significant wave height of 12 metres (39.4 ft), the model suggests there will hardly ever be a wave higher than 15 metres (49.2 ft). One of 30 metres (98.4 ft) could indeed happen – but only once in ten thousand years (of wave height of 12 metres [39.4 ft]). This basic assumption was well accepted (and acknowledged to be an approximation). The use of a Gaussian form to model waves has been the sole basis of virtually every text on that topic for the past 100 years.[20][21]

The first known scientific article on "Freak waves" was written by Professor Laurence Draper in 1964. In that paper which has been described as a 'seminal article' he documented the efforts of the National Institute of Oceanography in the early 1960s to record wave height and the highest wave recorded at that time which was about 67 feet (20.4 m). Draper also described *freak wave holes*.[22][23][24][25]

> “ It is of interest that far from ridiculing the old sailors' stories about enormous waves, modern research has confirmed that such monsters can occur, and that wave heights can exceed by an appreciable amount the maximum values which have been accepted in responsible circles. ”
>
> Professor Lawrence Draper (1971)[25]

Draupner Wave

In 1995, strong scientific evidence for the existence of rogue waves came with the recording of what has become known as the Draupner wave. The Draupner E is one structure in a gas pipeline support complex operated by Statoil about 160 kilometres (100 mi)58°11′19.30″N 2°28′0.00″E offshore and west by southwest from the southern tip of Norway.[26][27][28] The Draupner E platform is the first major oil platform of the jacket-type attached to the seabed with a bucket foundation instead of pilings and a suction anchoring system.[28] As a precaution, the operator (Statoil) fitted the platform with an extensive array of instrumentation. The instruments continuously check the platform's movements in particular any movement of the foundations during storm events. The state-of-the-art instrumentation fitted to the platform was able to continuously measure seven key parameters:[28]

- wave height,
- wave slope,
- wave hold,
- pressure of the bucket foundations,
- tension in the platform pillars, and
- acceleration on deck and foundations.

The rig was built to withstand a calculated 1 in 10,000 years wave with a predicted height of 64 feet (19.5 m) and was also fitted with state-of-the-art laser wave recorder on the platform’s underside. At 3 p.m. on 1 January 1995 it recorded an 85 feet (25.9 m) rogue wave (i.e. 21 feet [6.4 m] taller than the predicted 10,000 year wave) that hit the rig at 45 miles per hour (72.4 km/h). This was the first confirmed measurement of a freak wave, more than twice as tall and steep as its neighbors with characteristics that fell outside any known wave model. The wave was recorded by all of the sensors fitted to the platform[28] and it caused enormous interest in the scientific community.[26][28]

Modern knowledge

Statoil researchers presented a paper in 2000 which collated evidence that freak waves were not the rare realizations of a typical or slightly non-gaussian sea surface population (*Classical* extreme waves) but rather they were the typical realizations of a rare and strongly non-gaussian sea surface population of waves (*Freak* extreme waves).[29] A workshop of leading researchers in the world attended the first Rogue Waves 2000 workshop held in Brest in November 2000.[30]

In 2000 the British oceanographic vessel RRS *Discovery* recorded a 29-metre (95 ft) wave off the coast of Scotland near Rockall. This was a scientific research vessel and was fitted with high quality instruments. The subsequent analysis determined that under severe gale force conditions with wind speeds averaging 21 metres per second (68.9 ft/s) a ship-borne wave recorder measured individual waves up to 29.1 metres (95.5 ft) from crest to trough, and a maximum significant wave height of 18.5 metres (60.7 ft). These were some of the largest waves recorded by scientific instruments up to that time. The authors noted that modern wave prediction models are "known" to significantly under-predict extreme sea states for waves with a 'significant' height (H_s) above 12 metres (39.4 ft). The analysis of this event took a number of years, and noted that "none of the state-of-the-art weather forecasts and wave models—the information upon which all ships, oil rigs, fisheries, and passenger boats rely—had predicted these behemoths." Put simply, a scientific model (and also ship design method) to describe the waves encountered did not exist. This finding was widely reported in the press which reported that "according to all of the theoretical models at the time under this particular set of weather conditions waves of this size should not have existed".[2][9][26][31][32]

Most popular texts on oceanography up until the mid 1990s such as that by Pirie made no mention of rogue or freak waves.[33] The popular text on Oceanography by Gross (1996) only gave rogue waves a mention and stated that "Under extraordinary circumstances unusually large waves called rogue waves can form" without providing any further detail.[34] From about 1997 most leading authors acknowledged the existence of rogue waves with the caveat that wave models had been unable to replicate rogue waves.[17] The first scientific research which comprehensively proved that waves exist that are clearly outside the range of Gaussian waves was published in 1997.[35] Some research confirms that observed wave height distribution in general follows well the Rayleigh distribution, but in shallow waters during high energy events, extremely high waves are more rare than this particular model predicts.[10]

It is now proven via satellite radar studies that waves with crest to trough heights of 20 metres (65.6 ft) to 30 metres (98.4 ft), occur far more frequently than previously thought.[36] It is now known that rogue waves occur in all of the world's oceans many times each day. In 2004 the ESA MaxWave project identified more than ten individual giant waves above 25 metres (82 ft) in height during a short survey period of three weeks in a limited area of the South Atlantic. The ESA's ERS satellites have helped to establish the widespread existence of these 'rogue' waves.[37][38]

Thus acknowledgement of the existence of rogue waves (despite the fact that they cannot plausibly be explained by even state-of-the-art wave statistics) is a very modern scientific paradigm.[39] It is now well accepted that rogue waves are a common phenomenon. Professor Akhmediev of the Australian National University, one of the world's leading researchers in this field, has stated that there are about 10 rogue waves in the world's oceans at any moment.[40] Some researchers have speculated that approximately three of every 10,000 waves on the oceans achieve rogue status, yet in certain spots—like coastal inlets and river mouths—these extreme waves can make up three out of every 1,000 waves because wave energy can be focused.[41]

Rogue waves may also occur in lakes. A phenomenon known as the "Three Sisters" is said to occur in Lake Superior when a series of three large waves forms. The second wave hits the ship's deck before the first wave clears. The third incoming wave adds to the two accumulated backwashes and suddenly overloads the ship deck with tons of water. The phenomenon is one of various theories as to the cause of the sinking of the SS Edmund Fitzgerald on Lake Superior in November 1975.[42]

In reference to extreme events, rogue waves and soliton theory

“ These are considered to be the most important discoveries in the twentieth and twenty first centuries mathematical and experimental physics. ”

Optical sciences group, Australian National University[43]

Serious studies of the phenomenon of rogue waves only started about 20–30 years ago and have intensified since about 2005. One of the remarkable features of the rogue waves is that they always appear from nowhere and quickly disappear without a trace. Recent research has suggested that there could also be 'super-rogue waves' which are up to five times the average sea-state. Rogue waves has now become a near universal term given by scientists to describe isolated large amplitude waves, that occur more frequently than expected for normal, Gaussian distributed, statistical events. Rogue waves appear to be ubiquitous in nature and are not limited to the oceans. They appear in other contexts and have recently been reported in liquid helium, in nonlinear optics and in microwave cavities. It is now universally accepted by marine researchers that these waves belong to a specific kind of sea wave, not taken into account by conventional models for sea wind waves.[44][45][46][47]

Researchers at the Australian National University have also recently (2012) proven the existence of *rogue wave holes*, an inverted profile of a rogue wave. In maritime folk-lore, stories of rogue holes are as common as stories of rogue waves. They follow from theoretical analysis but had never been proven experimentally. In 2012 the ANU published research confirming the existence of rogue wave holes on the water surface observed in a water wave tank.[48]

On a smaller scale, kayakers call unpredictable 'exploding waves' caused by wave interaction "clapotis".[49]

Research efforts

There are a number of research programmes currently underway focussed on rogue waves including:

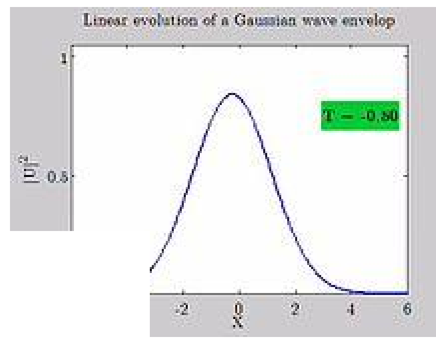
- In the course of Project MaxWave, researchers from the GKSS Research Centre, using data collected by ESA satellites, identified a large number of radar signatures that have been portrayed as evidence for rogue waves. Further research is under way to develop better methods of translating the radar echoes into sea surface elevation, but at present this technique is not proven.[37][50]
- The Australian National University, working in collaboration with Hamburg University of Technology and the University of Turin, have been conducting experiments in nonlinear dynamics to try to explain so-called rogue or killer waves. The "Lego Pirate" video has been widely used and quoted to describe what they call 'super rogue waves' which their research suggests can be up to five times bigger than the other waves around them.[51][52][53][53]
- European Space Agency continues to do research into rogue waves by radar satellite.[54]
- US Naval Research Laboratory, the science arm of the Navy and Marine Corps published results of their modelling work in 2015.[54][55][56]
- Massachusetts Institute of Technology. Research in this field is ongoing. Two researchers at the Massachusetts Institute of Technology partially supported by the Naval Engineering Education Consortium (NEEC) have considered the problem of short-term prediction of rare, extreme water waves and have developed and published their research on an effective predictive tool of about 25 wave periods. This tool can give ships and their crews a two-to-three minute warning of potentially catastrophic impact allowing crew some time to shut down essential operations on a ship (or offshore platform). The authors cite landing on an aircraft carrier as a prime example.[56][57][58]
- University of Colorado and the University of Stellenbosch.[54][59]
- Kyoto University.[60]
- Swinburne University of Technology in Australia recently published work on the probabilities of rogue waves.[61]
- University of Oxford. The Department of Engineering Science has recently (2014) published a comprehensive review of the science of rogue waves.[62][63]
- University of Western Australia.[62]
- Tallinn University of Technology in Estonia.[64]
- *Extreme Seas Project* funded by the EU.[64][65]
- Umeå University. A research group at the Umeå University in Sweden in August 2006 showed that normal stochastic wind driven waves can suddenly give rise to monster waves. The nonlinear evolution of the instabilities was investigated by means of direct simulations of the time-dependent system of nonlinear equations.[66]
- Great Lakes Environmental Research Laboratory. GLERL did research in 2002 which dispelled the long-held contentions that rogue waves were of rare occurrence.[8]
- University of Oslo. Has conducted research into: Crossing sea state and rogue wave probability during the Prestige accident; Nonlinear wind-waves, their modification by tidal currents, and application to Norwegian coastal waters; General Analysis of Realistic Ocean Waves (GROW); Modelling of currents and waves for sea structures and extreme wave events; Rapid computations of steep surface waves in three dimensions, and comparison with experiments; and Very large internal waves in the ocean.[67]
- National Oceanography Centre in the United Kingdom.[68]

- Scripps Institute of Oceanography in the United States.[69]
- Ritmare project in Italy.[70]

Causes

Because the phenomenon of rogue waves is still a matter of active research, it is premature to state clearly what the most common causes are or whether they vary from place to place. The areas of highest predictable risk appear to be where a strong current runs counter to the primary direction of travel of the waves; the area near Cape Agulhas off the southern tip of Africa is one such area; the warm Agulhas Current runs to the southwest, while the dominant winds are westerlies. However, since this thesis does not explain the existence of all waves that have been detected, several different mechanisms are likely, with localised variation. Suggested mechanisms for freak waves include the following:

Experimental demonstration of rogue wave generation through nonlinear processes (on a small scale) in a wave tank.



The linear part solution of the Nonlinear Schrödinger equation describing the evolution of a complex wave envelope in deep water.

Diffractive focusing

According to this hypothesis, coast shape or seabed shape directs several small waves to meet in phase. Their crest heights combine to create a freak wave.[71]

Focusing by currents

Waves from one current are driven into an opposing current. This results in shortening of wavelength, causing shoaling (i.e., increase in wave height), and oncoming wave trains to compress together into a rogue wave.[71] This happens off the South African coast, where the Agulhas Current is countered by westerlies.[63]

Nonlinear effects (modulational instability)

It seems possible to have a rogue wave occur by natural, nonlinear processes from a random background of smaller waves.[12] In such a case, it is hypothesised, an unusual, unstable wave type may form which 'sucks' energy from other waves, growing to a near-vertical monster itself, before becoming too unstable and collapsing shortly after. One simple model for this is a wave equation known as the nonlinear Schrödinger equation (NLS), in which a normal and perfectly accountable (by the standard linear model) wave begins to 'soak' energy from the waves immediately fore and aft, reducing them to minor ripples compared to other waves. The NLS can be used in deep water conditions. In shallow water, waves are described by the Korteweg–de Vries equation or the Boussinesq equation. These equations also have non-linear contributions and show solitary-wave solutions. A small-scale rogue wave consistent with the nonlinear Schrödinger equation (the Peregrine Solution) was produced in a laboratory water tank in 2011.[72] In particular, the study of solitons, and especially Peregrine solitons, have supported the idea that non-linear effects could arise in bodies of water.[63][73][74][75]

Normal part of the wave spectrum

Rogue waves are not freaks at all but are part of normal wave generation process, albeit a rare extremity.[71]

Constructive interference of elementary waves

Rogue waves can result from the constructive interference (dispersive and directional focusing) of elementary 3D waves enhanced by nonlinear effects.[7][76]

Wind wave interactions

> While it is unlikely that wind alone can generate a rogue wave, its effect combined with other mechanisms may provide a fuller explanation of freak wave phenomena. As wind blows over the ocean, energy is transferred to the sea surface. When strong winds from a storm happen to blow in the opposing direction of the ocean current the forces might be strong enough to randomly generate rogue waves. Theories of instability mechanisms for the generation and growth of wind waves—although not on the causes of rogue waves—are provided by Phillips[77] and Miles.[63][78]

Thermal expansion

> When a stable wave group in a warm water column moves into a cold water column the size of the waves must change because energy must be conserved in the system. So each wave in the wave group become smaller because cold water holds more wave energy based on density. The waves are now spaced farther apart and because of gravity they will propagate into more waves to fill up the space and become a stable wave group. If a stable wave group exists in cold water and moves into a warm water column the waves will get larger and the wavelength will be shorter. The waves will seek equilibrium by attempting to displace the waves amplitude because of gravity. However, by starting with a stable wave group the wave energy can displace toward the center of the group. If both the front and back of the wave group are displacing energy toward the center it can become a rogue wave. This would happen only if the wave group is very large.

The spatio-temporal focusing seen in the NLS equation can also occur when the nonlinearity is removed. In this case, focusing is primarily due to different waves coming into phase, rather than any energy transfer processes. Further analysis of rogue waves using a fully nonlinear model by R. H. Gibbs (2005) brings this mode into question, as it is shown that a typical wavegroup focuses in such a way as to produce a significant wall of water, at the cost of a reduced height.

A rogue wave, and the deep trough commonly seen before and after it, may last only for some minutes before either breaking, or reducing in size again. Apart from one single rogue wave, the rogue wave may be part of a wave packet consisting of a few rogue waves. Such rogue wave groups have been observed in nature.[79]

There are three categories of freak waves:

- "Walls of water" travelling up to 10 km (6 mi) through the ocean
- "Three Sisters", groups of three waves[80]
- Single, giant storm waves, building up to fourfold the storm's waves height and collapsing after some seconds[81]

Scientific applications

The possibility of the artificial stimulation of rogue wave phenomena has attracted research funding from DARPA, an agency of the United States Department of Defense. Bahram Jalali and other researchers at UCLA studied microstructured optical fibers near the threshold of soliton supercontinuum generation and observed rogue wave phenomena. After modelling the effect, the researchers announced that they had successfully characterized the proper initial conditions for generating rogue waves in any medium.[82] Additional works carried out in optics have pointed out the role played by a nonlinear structure called Peregrine soliton that may explain those waves that appear and disappear without leaving a trace.[83][84]

Reported encounters

It should be noted that many of these encounters are only reported in the media, and are not examples of open ocean rogue waves. Often, in popular culture, an endangering huge wave is loosely denoted as a *rogue wave*, while it has not been (and most often cannot be) established that the reported event is a rogue wave in the scientific sense — *i.e.* of a very different nature in characteristics as the surrounding waves in that sea state and with very low probability of occurrence (according to a Gaussian process description as valid for linear wave theory).

This section lists a limited selection of notable incidents.

19th century

- Eagle Island lighthouse (1861) – water broke the glass of the structure's east tower and flooded it, implying a wave that surmounted the 40 m (130 ft) cliff and overwhelmed the 26 m (85 ft) tower.[85]
- Flannan Isles Lighthouse (1900) – three lighthouse keepers vanished after a storm that resulted in wave-damaged equipment being found 34 metres (112 ft) above sea level.[86][87]

20th century

- SS Kronprinz Wilhelm, September 18, 1901 – The most modern German ocean liner of its time (winner of the Blue Riband) was damaged on its maiden voyage from Cherbourg to New York by a huge wave. The wave struck the ship head-on.[88]
- SS Waratah (1909) – Left Durban, South Africa with 211 passengers and crew but did not reach Cape Town, South Africa.[2]
- RMS Lusitania (1910) - On the night of 10 January 1910, a 75 feet (23 m) wave struck the ship over the bow, the forecastle deck was damaged and the bridge windows were smashed.[89]
- Voyage of the James Caird (1916) – Sir Ernest Shackleton encountered a wave he termed "gigantic" while piloting a lifeboat/whaler from Elephant Island to South Georgia Island.[90]
- USS Ramapo (AO-12) (1933) – Triangulated at 112 feet (34 m).[91]
- RMS *Queen Mary* (1942) – Broadsided by a 92-foot (28 m) wave and listed briefly about 52 degrees before slowly righting.[17]
- SS *Flying Enterprise* (1951) – Ripped apart amidships and eventually sank 40 miles (64 km) from Falmouth, England.
- *SS Michelangelo* (1966) – Hole torn in superstructure, heavy glass smashed 80 feet (24 m) above the waterline, and three deaths.[91]
- SS *Edmund Fitzgerald* (1975) – Lost on Lake Superior. A Coast Guard report blamed water entry to the hatches, which gradually filled the hold, or alternatively errors in navigation or charting causing damage from running onto shoals. However, another nearby ship, the SS *Arthur M. Anderson*, was hit at a similar time by two rogue waves and possibly a third, and this appeared to coincide with the sinking around ten minutes later.[42]
- MS *München* (1978) – Lost at sea leaving only "a few bits of wreckage" and signs of sudden damage including extreme forces 66 feet (20 m) above the water line. Although more than one wave was probably involved, this remains the most likely sinking due to a freak wave.[12]
- Esso Languedoc (1980) – A 25-to-30-metre (80 to 100 ft) wave washed across the deck from the stern of the French supertanker near Durban, South Africa, and was photographed by the first mate, Philippe Lijour.[92][93]
- Fastnet Lighthouse – Struck by 48 m (157 ft) wave in 1985 [94]
- MV *Derbyshire* (1980) – A 91,655 GRT bulk freighter – the largest British ship ever lost at sea – disappears without trace during Typhoon Orchid on 9 September 1980, with the loss of 44 lives. The wreck was located and extensively surveyed in 1994. One subsequent analysis (which won the 2001 Royal Institution of Naval Architects award for excellence) demonstrated that given the weather conditions pertaining, *Derbyshire* would almost certainly have encountered waves of at least 28 metres (92 ft), and that even a much smaller rogue wave would have easily destroyed one or more of *Derbyshire*'s cargo hatch covers, leading to the rapid loss of the ship.[95]
- Draupner wave (North Sea, 1995) – First rogue wave confirmed with scientific evidence, it had a maximum height of 25.6 metres (84 ft).[96]

- RMS *Queen Elizabeth 2* (1995) – Encountered a 29-metre (95 ft) wave in the North Atlantic, during Hurricane Luis: *The Master said it "came out of the darkness" and "looked like the White Cliffs of Dover."* [3] Newspaper reports at the time described the cruise liner as attempting to "surf" the near-vertical wave in order not to be sunk.

21st century

- MS *Bremen* and *Caledonian Star* (South Atlantic, 2001) encountered 30-metre (98 ft) freak waves. Bridge windows on both ships were smashed, and all power and instrumentation lost.[3]
- U.S. Naval Research Laboratory ocean-floor pressure sensors detected a freak wave caused by Hurricane Ivan in the Gulf of Mexico, 2004. The wave was around 27.7 metres (91 ft) high from peak to trough, and around 200 metres (660 ft) long.[97] Their computer models also indicated that waves may have exceeded 40 meters(130 ft) in the eyewall.[98]
- *Norwegian Dawn*, (Georgia [US], 2005) On April 16, 2005, after sailing into rough weather off the coast of Georgia, *Norwegian Dawn* encountered a series of three 70-foot (21 m) rogue waves. The third wave damaged several windows on the 9th and 10th decks and several decks were flooded. Damage, however, was not extensive and the ship was quickly repaired.[99] Four passengers were slightly injured in this incident.[100]
- *Aleutian Ballad*, (Bering Sea, 2005) footage of what is identified as a 60-foot (18 m) wave appears in an episode of *Deadliest Catch*. The wave strikes the ship at night and cripples the vessel, causing the boat to tip for a short period onto its side. This is one of the few video recordings of what might be a rogue wave.[101]
- In 2006, researchers from U.S. Naval Institute theorise rogue waves may be responsible for the unexplained loss of low-flying aircraft, such as U.S. Coast Guard helicopters during Search and Rescue missions.[102]
- On January 24, 2009 the Augusto González de Linares buoy, located 22 miles north of Santander, Spain reported a wave of 26.13 metres (85.7 ft), equivalent to 8 floors high, during a storm.[103]
- MS *Louis Majesty* (Mediterranean Sea, March 2010) was struck by three successive 8-metre (26 ft) waves while crossing the Gulf of Lion on a Mediterranean cruise between Cartagena and Marseille. Two passengers were killed by flying glass when a lounge window was shattered by the second and third waves. The waves, which struck without warning, were all abnormally high in respect to the sea swell at the time of the incident.[104][105]
- The Spanish Deepwater Buoys Network, in January 2014, measured a wave height of 27.81 metres (91.2 ft). The data was taken at the buoy Vilán-Sisargas (Cape Vilan) in Galicia (Spain) during the winter storms, which were particularly severe in Atlantic waters.[106]
- MS *Marco Polo* was struck by a rogue wave on the English Channel (February 2014). An 85-year-old man was killed and a woman in her 70s injured.[107]

Quantifying the impact of rogue waves on ships

The loss of the MS München in 1978 provided some of the first physical evidence of the existence of rogue waves. The MS München was a state-of-the-art cargo ship with multiple water-tight compartments, an expert crew and was considered unsinkable. She was lost with all crew and the wreck has never been found. The only evidence found was the starboard lifeboat which was recovered from floating wreckage some time later. The lifeboats hung from forward and aft blocks 20 metres (66 ft) above the waterline. The pins had been bent back from forward to aft, indicating the lifeboat hanging below it had been struck by a wave that had run from fore to aft of the ship which had torn the lifeboat from the ship. To exert such force the wave must have been considerably higher than 20 metres (66 ft). At the time of the inquiry, the existence of rogue waves was considered so statistically unlikely as to be near impossible. Consequently, the Maritime Court investigation concluded that the severe weather had somehow created an 'unusual event' that had led to the sinking of the München.[12][108]

The 1980 loss of the MV *Derbyshire* during Typhoon Orchid south of Japan with the loss of all crew marked a turning point for ship design. The *Derbyshire* was an ore-bulk-oil combination carrier built in 1976. At 91,655 gross register tons, she was—and remains—the largest British ship ever to have been lost at sea. The wreck was found in June 1994. The survey team deployed a remotely operated vehicle to photograph the wreck. A private report was published in 1998 which prompted the British government to reopen a formal investigation into the sinking. The British government investigation included a comprehensive survey by the Woods Hole Oceanographic Institution which took 135,774 pictures of the wreck during two surveys. The formal forensic investigation concluded that the ship sank because of structural failure and absolved the crew of any responsibility. Most notably, the report determined the detailed sequence of events that led to the structural failure of the vessel. A third comprehensive analysis was subsequently done by Douglas Faulkner, professor of marine architecture and ocean engineering at the University of Glasgow. His highly analytical and scientific report published in 2001 examined and linked the loss of the MV *Derbyshire* with what he called the emerging body of scientific evidence regarding the mechanics of freak waves. Professor Faulkner concluded that it was almost certain that *Derbyshire* would have encountered a wave of sufficient size to destroy her. Faulkner's conclusions have not been refuted in the more than 15 years since they were first presented (as of 2016). Indeed, subsequent analysis by others has corroborated his findings. Faulkner's finding that the *Derbyshire* was lost because of a rogue wave has had widespread implications on ship design.[13] Faulkner has subsequently proposed the need for a paradigm shift in thinking for the design of ships and offshore installations to include what he calls a Survival Design approach additional to current design requirements. There is however no evidence that his recommendations have yet been adopted (as of 2016).[14][109] [110][111]

In 2004 an extreme wave was recorded impacting the Admiralty Breakwater, Alderney in the Channel Islands. This breakwater is exposed to the Atlantic Ocean. The peak pressure recorded by a shore-mounted transducer was 745 kPa which corresponds to a pressure of 74.5 tonnes/m2 or 74.5 Mt/m^2 (metric tonnes per square metre). This pressure far exceeds almost any design criteria for modern ships and this wave would have destroyed almost any merchant vessel.[5]

More recent work by Smith in 2007 confirmed prior forensic work by Faulkner in 1998 and determined that the MV *Derbyshire* was exposed to a hydrostatic pressure of a *static head* of water of about 20 metres (66 ft) with a resultant static pressure of 201 kN/m^2.[nb 1] This is in effect 20 metres of green water (possibly a *super rogue wave*)[nb 2] flowing over the vessel. The deck cargo hatches on the *Derbyshire* were determined to be the key point of failure when the rogue wave washed over the ship. The design of the hatches only allowed for a static pressure of less than two metres of water or 17.1 kN/m^2,[nb 3] in other words the typhoon load on the hatches was more than ten (10) times the design load. The forensic structural analysis of the wreck of the *Derbyshire* is now widely regarded as irrefutable.[36]

In addition fast moving waves are now known to *also* exert extremely high dynamic pressure. It is known that plunging or breaking waves can cause short-lived impulse pressure spikes called Gifle peaks. These can reach pressures of 200 kN/m^2 (or more) for milliseconds which is sufficient pressure to lead to brittle fracture of mild steel. Evidence of failure by this mechanism was also found on the *Derbyshire*.[13] Smith has documented scenarios where hydrodynamic pressure of up to 5,650 kN/m^2 or over 500 metric tonnes per square metre could occur.[nb 4][36]

Ship failure mechanism

Very few ship-wrecks have ever been fully investigated. The most recent bulk-carrier loss on the open seas to have been subjected to thorough investigation (as at March 2011) was the UK-owned M.V. *Derbyshire*, which sank in 1980. Its entire crew of forty-four, all British citizens, perished. It took 14 years of pressure from the British public and a privately funded expedition to locate the wreck before a formal remote-camera search and investigation was done by the British government. At least a couple of hundred bulk carriers have been lost since 1980 and none have been properly investigated. A survey of 125 bulk carriers that sank between 1963 and 1996 found that seventy-six *probably* flooded, another four because of hatch-cover failure, the rest from *unidentified* causes. Nine other vessels broke completely in two. Causes of the remaining forty losses are unknown.[112] Montgomery-Swan has outlined the generic mechanism of ship failure when encountering a rogue wave:

> The scenario is very simple: the weight of the ship accelerates her down the back slope of the previous wave, the bow sticks into the lower part of the front of the giant incoming wave, and thousands of tons of green water fall onto the fore part of the ship. What happens next depends on the structure of the vessel.[23]

Professor Faulkner who did the forensic independent analysis of the loss of the M.V. *Derbyshire* explains why this is such a problem for bulk carriers. He states that "It is quite possible that some of the many unexplained heavy weather losses (of bulk carriers) may have been caused by hatch cover or coaming failures because fore end plunging due to flooding of large holds can be rapid." He noted in his report that "because of their high inertias and natural pitch periods, these large ships do not rise to the waves, as appropriately experienced masters have confirmed. They tend to bury into them." Faulkner concluded that "beyond any reasonable doubt, the direct cause of the loss of the M.V. *Derbyshire* was the quite inadequate strength of her cargo hatch covers to withstand the forces of Typhoon Orchid." He also noted that "It is not possible to say which of the eighteen covers failed first, or from which direction the waves came; but evidence and other arguments suggest that the no. 1 hatch covers were probably the first to yield, probably from waves over the bow with the ship hove-to."[13]

Design standards

In November 1997 the International Maritime Organization (IMO) adopted new rules covering survivability and structural requirements for bulk carriers of 150 metres (492.1 ft) and upwards. The bulkhead and double bottom must be strong enough to allow the ship to survive flooding in hold one unless loading is restricted.[113]

It is now widely held that rogue waves present considerable danger for several reasons: they are rare, unpredictable, may appear suddenly or without warning, and can impact with tremendous force. A 12-metre (39 ft) wave in the usual "linear" model would have a breaking force of 6 metric tons per square metre [t/m^2] (8.5 psi). Although modern ships are designed to (typically) tolerate a breaking wave of 15 MT/m^2, a rogue wave can dwarf both of these figures with a breaking force far exceeding 100 MT/m^2.[3][nb 5] Smith has presented calculations using the International Association of Classification Societies (IACS) Common Structural Rules (CSR) for a typical bulk carrier which are consistent.[nb 6][36]

Peter Challenor, a leading scientists in this field from the National Oceanography Centre in the United Kingdom was quoted in Casey's book in 2010 that "We don't have that random messy theory for nonlinear waves. At all", he says. "People have been working actively on this for the past 50 years at least. We don't even have the start of a theory".[26][31]

In 2006 Smith proposed that the International Association of Classification Societies (IACS) recommendation 34 pertaining to standard wave data be modified so that the minimum design wave height be increased to 65 feet (19.8 m). He presented analysis that there was sufficient evidence to conclude that 66 feet (20.1 m) high waves can be experienced in the 25-year lifetime of oceangoing vessels, and that 98 feet (29.9 m) high waves are less likely, but not out of the question. Therefore, a design criterion based on 36 feet (11.0 m) high waves seems inadequate when the risk of losing crew and cargo is considered. Smith has also proposed that the dynamic force of wave impacts should be included in the structural analysis.[114]

It is notable that the Norwegian offshore standards now take into account extreme severe wave conditions and require that a 10,000-year wave does not endanger the ships integrity.[115] Rosenthal notes that as at 2005 rogue waves were not explicitly accounted for in Classification Societies' Rules for ships' design.[115] As an example, DNV GL, one of the world's largest international certification body and classification society with main expertise in technical assessment, advisory, and risk management publishes their Structure Design Load Principles which remain largely based on the 'Significant Wave height' and as at January 2016 still has not included any allowance for rogue waves.[116]

The U.S. Navy historically took the design position that the largest wave likely to be encountered was 21.4 m (70 ft). Smith observed in 2007 that the navy now believes that larger waves can occur and the possibility of extreme waves that are steeper (i.e. do not have longer wavelengths) is now recognized. The navy has not had to make any fundamental changes in ship design as a consequence of new knowledge of waves greater than 21.4 m (70 ft) because they build to higher standards.[36]

A characteristic of the shipping industry is that there are no uniform codes or international standards. There are more than 50 classification societies worldwide, each has different rules. Ship design has historically largely been led by the ship insurers who inspected, classified and insured vessels. Hence the widespread adoption of new rules to allow for the existence of rogue waves is likely to take many years.[36]

See also

Oceanography, currents and regions

- Antarctic Circumpolar Current
- Agulhas Current
- Bermuda Triangle
- Gulf Stream
- Kuroshio Current
- Ocean current
- Ocean surface wave
- Wave–current interaction

Waves

- Extreme value theory
- Clapotis
- Sneaker wave
- Soliton (and especially, Peregrine soliton)
- White squall
- Resonance

Footnotes

1. A failure load pressure of 201 kN/m^2 is the same as 20,500 kgf/m^2 or 20.5 Mt/m^2 (metric tonnes per square metre).
2. Note that the term *super rogue wave* had not yet been coined by ANU researchers at that time.
3. A design load pressure (of the hatches) of 17.1 kN/m^2 is the same as 1,744 kgf/m^2 or 1.7 Mt/m^2 (metric tonnes per square metre).
4. A hydrostatic pressure of 5,650 kN/m^2 is the same as 576,100 kgf/m^2 or 576.1 Mt/m^2 (metric tonnes per square metre).
5. Note that MT/m refers to metric tonnes per square metre.
6. Smith has presented calculations for a hypothetical bulk carrier with a length of 275m and a displacement of 161,000 metric tonnes, the design Hydrostatic pressure, 8.75 m below waterline is 88 kN/m^2 or 88 kPa or 8.9 MT/m^2 (metric tonnes per square metre). For the same carrier the design Hydrodynamic pressure is 122 kN/m^2 or 122 kPa or 12,440 kgf/m^2 (kilograms of force per square metre) or 12.44 Mt/m^2 (metric tonnes per square metre).

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External links

Extreme seas project

- Design for Ship Safety in Extreme Seas (http://www.mar.ist.utl.pt/extremeseas/)

MaxWave report and WaveAtlas

- Freak waves spotted from space (http://news.bbc.co.uk/2/hi/science/nature/3917539.stm), BBC News Online
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