

Mechanisms of tsunami generation by submarine landslides: a short review

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The characteristics of a tsunami generated by a submarine landslide are mainly determined by the volume, the initial acceleration, the maximum velocity, and the possible retrogressive behaviour of the landslide. The influence of these features as well as water depth and distance from shore are discussed. Submarine landslides are often clearly sub-critical (Froude number $\ll 1$), and it is explained that the maximum tsunami elevation generally correlates with the product of the landslide volume and acceleration divided by the wave speed squared. Only a limited part of the potential energy released by the landslide is transferred to wave energy. Examples of numerical simulations with fractions of 0.1-15 % are presented. Frequency dispersion is of little importance for waves generated by large and sub-critical submarine landslides. Retrogressive landslide behaviour normally reduces associated tsunami heights, but retrogression might increase the height of the landward propagating wave for unfavourable time lags between release of individual elements of the total landslide mass. Tsunamis generated by submarine landslides often have very large run-up heights close to the source area, but have more limited far-field effects than earthquake tsunamis. It is further shown that the combination of landslides and earthquakes may be necessary to explain observed tsunami behaviour. The various aspects mentioned above are exemplified by simulations of the Holocene Storegga Slide, the 1998 Papua New Guinea, and the 2004 Indian Ocean tsunamis. Comparisons are also made to tsunamis generated by rock slides. Rock slides are most often super-critical and the resulting tsunamis are determined by the frontal area of the rock slide, the impact velocity of the rock slide on the water body, the permeability of the rock slide, and the bathymetry.

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Introduction

Wave formation and propagation due to submarine landslides are complex phenomena that may be divided into four parts: Landslide dynamics, energy transfer from landslide motion to water motion, wave propagation in open water, and wave run-up along the shores. This paper focuses on the energy transfer from landslide motion to water motion, i.e. the generation of tsunamis by submarine landslides.

Tsunamis are surface waves due to an impulsive perturbation of the sea, having features intermediate between tidal waves and swell waves in the spectrum of gravity water waves. Submarine landslides, in addition to submarine earthquakes, are the principal cause of large tsunamis. Earthquakes can play an indirect role as the landslide triggering mechanism. The distinctive characteristics of landslide and earthquake generated tsunamis are discussed, as is the special case of landslides (rock slides) which initiate from subaerial slopes before entering a lake or the sea.

In agreement with Hampton et al. (1996) and Masson

et al. (2006), the term 'submarine landslides' is here used as a general term for submarine high density flows (slides, slumps, debris flows, mud flows, granular flows), driven primarily by gravity.

The first part of the present paper describes how various submarine landslide parameters influence wave characteristics, with emphasis on the importance of sub- or super-critical landslide velocities. Brief sections on the importance of two-way landslide/wave coupling, frequency dispersion, and retrogression are also included. Subsequently landslide tsunamis are compared to tsunamis generated by earthquakes and rock slides. Herein is also included a discussion on effects of combined earthquake/submarine landslide sources.

Although large-scale submarine landslides are rare, tsunamis of various origins are relatively frequent in a global perspective. With the dramatic consequences in mind, tsunamis must be considered a high-risk geohazard. Risk assessment of tsunamis generated by submarine landslides includes both geotechnical and geological considerations for the probability and the tsunami-genic power of the landslide, as well as tsunami evalua-

tions for determination of the consequences in terms of spatial distribution and run-up heights of the waves. Because submarine landslides are rare on a human timescale, unpredictable, and almost impossible to observe and instrument, numerical modelling is seen as one of the key ways forward, both for understanding the submarine landslides themselves and for the prediction of landslide tsunamis. Aspects of tsunami risk assessment and challenges related to numerical modelling of tsunami generation by submarine landslides are discussed by Masson et al. (2006).

Tsunamis generated by submarine landslides

Tsunamis generated by submarine landslides can most often be classified as long waves as most of the energy transferred from the landslide to the water motion is distributed on waves with typical wavelengths much larger than the characteristic water depth. From this assumption it follows that the pressure is approximately hydrostatic and that the vertical variation of the horizontal velocity is small. The particle motion is then approximately uniform over the entire water column and effects of frequency dispersion (see below) can be neglected.

The characteristics of tsunamis generated by submarine landslides depend primarily upon the volume and the

dynamics of the sliding masses, as well as the water depth. The initial acceleration (Lovholt et al. 2005; Haugen et al. 2005; Grilli and Watts 2005) and the maximum velocity (Ward 2001; Tinti et al. 2001) of the submarine landslides are particularly important. Also the friction on the landslide/water interface might be important (see, e.g. Harbitz 1992).

In the following we label the linear long-wave speed at a water depth h as $c_0 = (gh)^{1/2}$, g being the acceleration of gravity. A Froude number Fr is then defined as $Fr = u/c_0$, where u is the landslide speed. Sub-critical, critical, and super-critical landslide motion are then defined as $Fr < 1$, $Fr = 1$, and $Fr > 1$, respectively. Moreover, the surface elevations and landslide thicknesses are defined relative to the water depth, that is $\eta_r = \eta/h$ and $d_r = d/h$, respectively.

Effects of submarine landslide parameters for clearly sub-critical motion

Submarine landslides are often clearly sub-critical, i.e., the Froude number is much less than one. This implies that the tsunami will run away from the wave-generating landslide, limiting the build-up of the wave.

The wave pattern introduced by a sub-critical landslide spreads out within a certain sector as displayed in the simulations of the Storegga Slide by Bondevik et al. (2005), and appears as a characteristic, symmetric sickle-shaped surface elevation followed by a surface

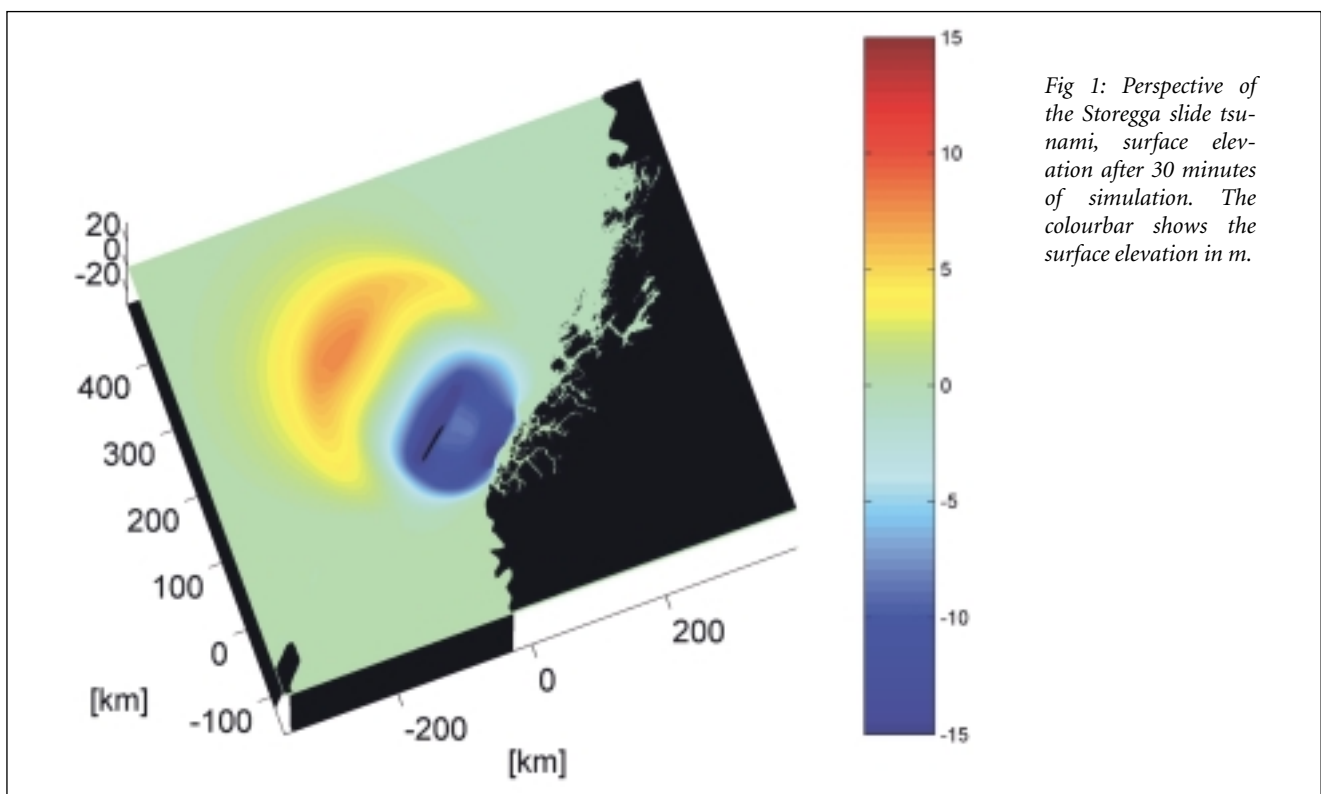


Fig 1: Perspective of the Storegga slide tsunami, surface elevation after 30 minutes of simulation. The colourbar shows the surface elevation in m.

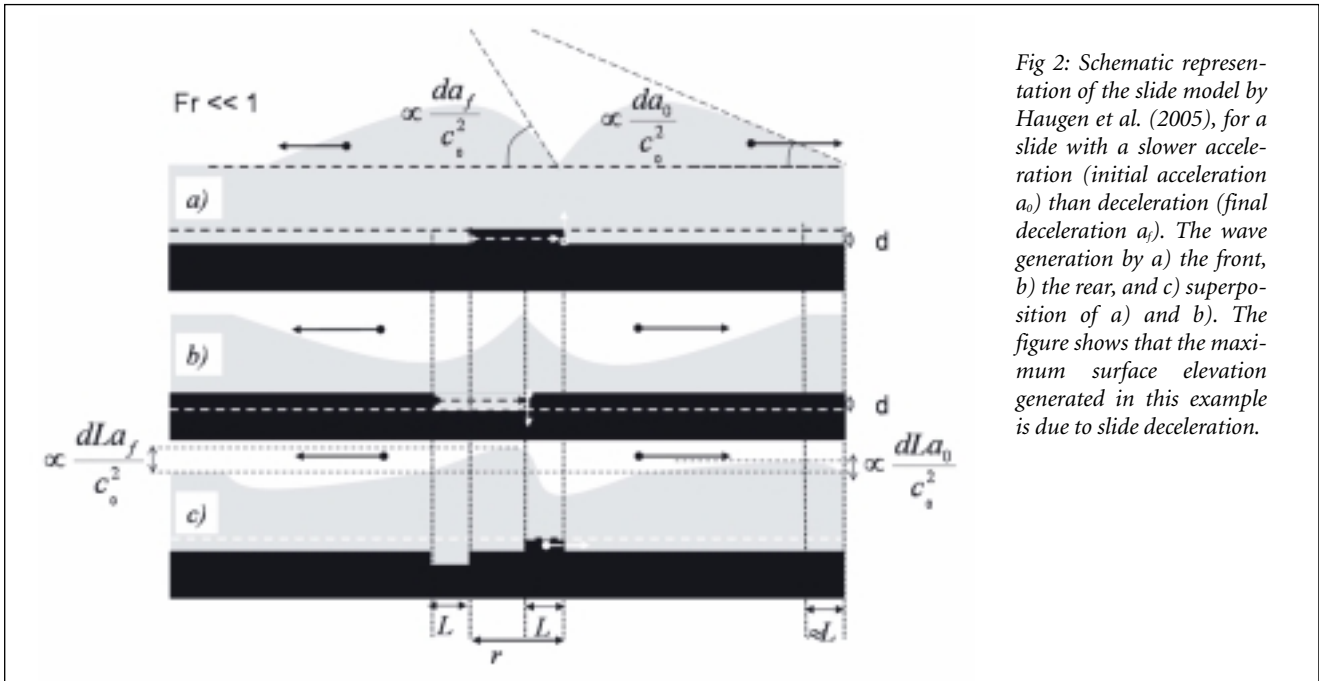


Fig 2: Schematic representation of the slide model by Haugen et al. (2005), for a slide with a slower acceleration (initial acceleration a_0) than deceleration (final deceleration a_f). The wave generation by a) the front, b) the rear, and c) superposition of a) and b). The figure shows that the maximum surface elevation generated in this example is due to slide deceleration.

depression, Figure 1. The effects of dispersion are negligible for such large landslides, see below.

For strongly sub-critical landslide motion ($Fr \ll 1$), the maximum surface elevation generally correlates with the product of landslide volume and acceleration divided by the wave speed squared, whilst the elevated water volume correlates with the product of the landslide volume and the Froude number (Lovholt et al. 2005).

The reasons behind this scaling behaviour, i.e. the effects of landslide dimensions and dynamics, were demonstrated by Haugen et al. (2005), by considering a block with uniform thickness moving on a horizontal seabed with constant velocity. Ignoring dispersion, the length of the block affects only the wavelength, while the surface elevation is determined by the thickness of the block, the landslide velocity, and the wave speed (which again depends on the water depth). Secondly, a more complex velocity distribution was introduced, where the landslide accelerated from rest, demonstrating how the landslide length now influences both the wavelength and the surface elevation. They also showed how a higher acceleration implies that the frontal wave reaches a larger elevation. Similarly, an abrupt deceleration might also contribute to larger surface elevations, see Figure 2. In contrast, an elongated run-out as a result of less abrupt deceleration implies reduced wave heights. Since the first positive wave propagating in the opposite direction of the submarine landslide (normally landward) is generated in this deceleration phase, this wave will also be generated further offshore and in deeper water as a result of elongated run-out. This can cause either lower surface elevations along the coast as a result of more room for

radial damping, or higher surface elevations as a result of shoaling from deeper to shallower waters. More precisely, the surface elevation for a non-dispersive wave spreading radially over a distance r is proportional to $h^{1/4}r^{1/2}$. Finally, an elongated landslide velocity profile delays the appearance of the first positive landward propagating wave and hence reduces the chances of constructive interference along the coast.

Grilli & Watts (2005) found that assuming a realistic maximum displacement for a slump, everything else being equal, the slump generates smaller tsunami surface elevations and wave lengths than a corresponding slide, particularly in the far-field. With identical initial acceleration, tsunami characteristics of similar slides and slumps are initially similar, but differences arise since the acceleration phase lasts longer and the displacement is larger for a slide. Grilli & Watts (2005) also found that landslide deformation may enhance tsunami generation (particularly in the far-field), see also section on retrogression below.

Extension to critical and super-critical submarine landslide motion

Submarine landslide motion in shallow waters is often characterised by a higher Froude number, since the speed of wave propagation is lower here. This implies higher waves. Moreover, shallower water normally means less distance to the coast and a shorter distance available for radial damping.

In Ward (2001) wave generation for sub-critical, critical, and super-critical submarine landslides was investi-

gated with a frequency domain method for linear full potential flow. An example with constant water depths and constant landslide speeds omitting effects of acceleration and deceleration is reviewed here. Landslide geometries were limited to solid blocks of finite widths, lengths, and thicknesses. The maximum relative surface elevation generated by the landslide, here labelled $\eta_{r,max}$, was then investigated as a function of the Froude number. Not surprisingly, as shown in Figure 3, Ward (2001) found increasing values of $\eta_{r,max}$ for sub-critical landslide motion, reaching its maximum at $Fr \approx 1$, while for super-critical landslide motion, $\eta_{r,max}$ slowly decreases to unity for large Fr . For $Fr \ll 1$, a linear relation similar to Lovholt et al. (2005) was found. Figure 3 also shows that $\eta_{r,max}$ increases for large widths and lengths, and that $\eta_{r,max}$ increases with decreasing depth. The wave patterns found by Ward (2001) for critical landslide motion revealed a large surface elevation located at the landslide front that totally dominated the solution. For $Fr \approx 0.5$ this effect is much less pronounced, but still the surface elevation close to the landslide front is clearly larger than the surface elevation close to the landslide rear due to the Doppler shift. Similar Doppler shift effects were also found by Haugen et al. (2005).

Tinti et al. (2001) studied sub- and super-critical submarine landslide motion for constant landslide speeds using the shallow water approximation neglecting dispersion. The waveforms are in agreement with both Ward (2001)

and Haugen et al. (2005). Waveforms were computed for a rigid (non-deformable) landslide for both variable and constant depth. For the constant depth the mean value of the variable depth was taken. The comparison of the waveforms for variable and constant depth at different times of the simulation gave only minor discrepancies for both sub- and super-critical landslide motion (see Tinti et al. 2001; their figures 6-8). This also supports the observation that the initial stages are most important for the wave generation, as discussed above.

Critical landslide motion at water depths larger than $h = 1000$ m requires landslide speeds around 100 m/s, which are considered unlikely. As an example, De Blasio et al. (2005) performed numerical simulations for the Storegga Slide that occurred on the continental slope off western Norway around 8200 years ago and is one of the largest and best-studied submarine landslides on Earth (Bugge et al. 1987; Bugge et al. 1988; Haflidason et al. 2003; Haflidason et al. 2004; Haflidason et al. 2005; Bryn et al. 2005; Kvalstad et al. 2005). They found a maximum velocity of $u_{max} = 60$ m/s for $h = 1500$ m (corresponding to $Fr \approx 0.5$). The maximum velocity was obtained assuming low seabed friction due to hydroplaning introduced to reproduce the observed run-out lengths. Although the maximum speed found for the Storegga Slide was large, tsunami generation was still clearly sub-critical. However, critical and super-critical effects cannot be excluded for submarine landslides in shallower water, especially for steep slopes causing high landslide velocities. For rock slides, critical effects will always be of large importance, as rock slide speeds are often large, and water depths at impact are generally small (see below).

Two-way landslide/water interaction

Only a limited part of the potential energy released by the landslide is transferred to wave energy. According to Ruff (2003), energy conversion can range from essentially zero to about 50 % as a practical upper boundary for reasonable geological and hydrodynamic parameters. Calculations of the wave energy for the Storegga Slide tsunami as simulated by Bondevik et al. (2005), cf. Figure 1, reveal that the fraction here was about 0.1 %.

The transmission of landslide energy to wave energy causes a wave resistance to the landslide motion. If for example 10 % of the initial potential energy of the landslide is transmitted to wave energy while the landslide accelerates to its maximum velocity without other energy losses, simple calculations reveal that wave resistance causes a reduction in this maximum velocity of roughly 5 % relative to the maximum velocity obtained with no wave resistance. Including other energy losses due to bed resistance, etc., increases the relative reduction in maximum velocity due to wave resistance.

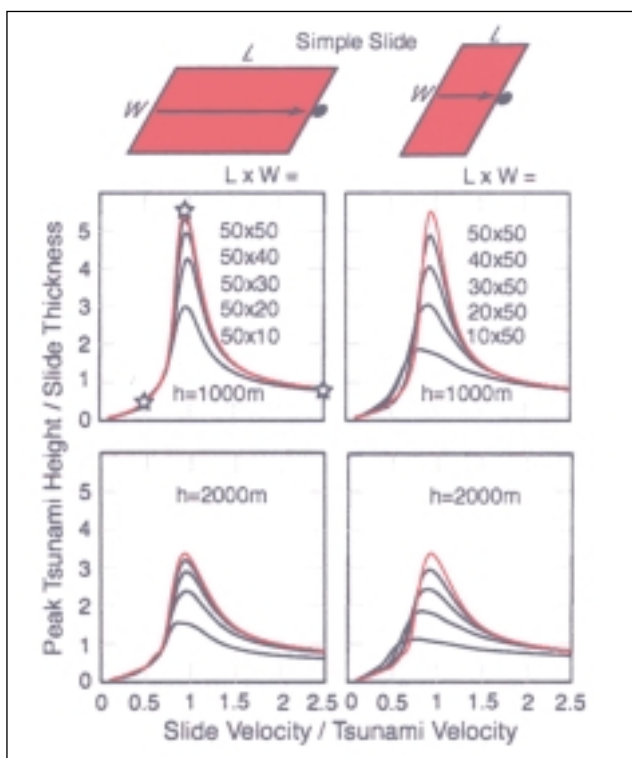


Fig 3: Scaled surface elevation η_r plotted versus Froude number (from Ward 2001). For critical slide velocities ($Fr = 1$), strong amplifications are observed for various slide scenarios.

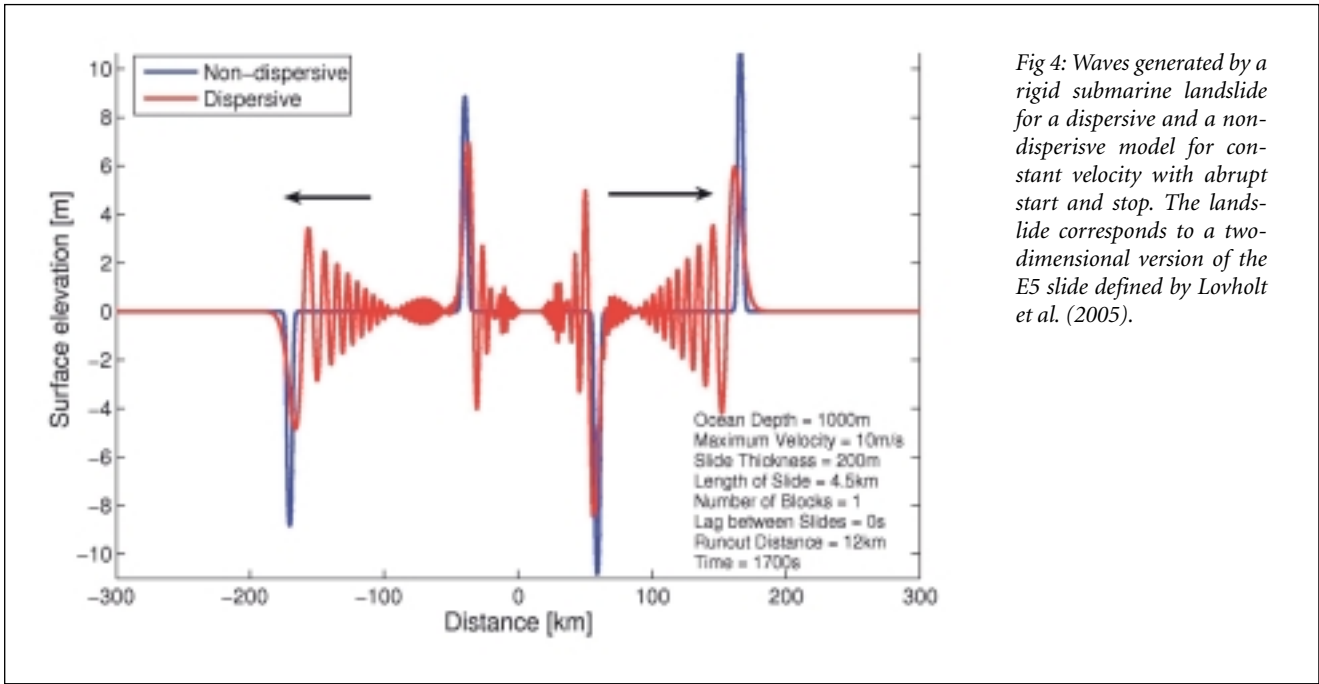


Fig 4: Waves generated by a rigid submarine landslide for a dispersive and a non-dispersive model for constant velocity with abrupt start and stop. The landslide corresponds to a two-dimensional version of the E5 slide defined by Lovholt et al. (2005).

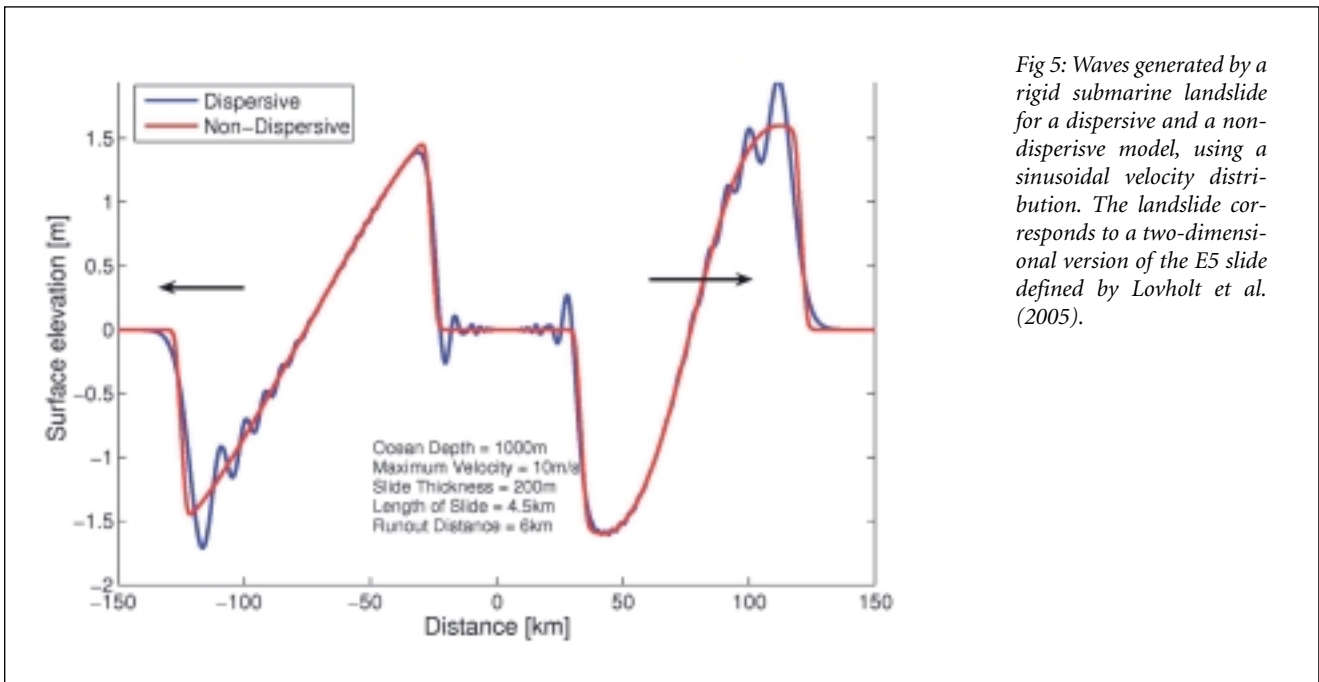


Fig 5: Waves generated by a rigid submarine landslide for a dispersive and a non-dispersive model, using a sinusoidal velocity distribution. The landslide corresponds to a two-dimensional version of the E5 slide defined by Lovholt et al. (2005).

Jiang & LeBlond (1992) discuss the two-way coupling of a submarine landslide (treated as the laminar flow of an incompressible viscous fluid) and the surface waves which it generates, i.e., how the submarine landslide generates the waves and at the same time how the pressure field established by the waves influences the dynamics of the landslide. They find that such a two-way coupling is of importance only for small flow-to-water density ratios and only for large flow-to-water depth ratios. The two-way coupling has most influence upon the thickness of the landslide. As an example, a flow-to-water density ratio of 1.2 and depth ratio of 0.4 imply

5-15 % reduction of flow thickness compared to a one-way coupling. Moreover, the effects are small on the maximum velocity of the flow, but the front velocity is reduced by 20 %. The water particle velocities are smaller than the flow particle velocities and are thus less influenced by two-way coupling. The ratio of wave energy to loss in landslide potential energy is more strongly influenced; a maximum value of 15 % is reported for a flow-to-water density ratio of 1.2. Altogether two-way coupling is important if the frontal flow-to-water depth ratio exceeds 0.4 and the flow-to-water density ratio is less than 1.2. Typical values for

actual submarine landslides are flow-to-water depth ratio < 0.1 and flow-to-water density ratio > 2 . In other words, two-way coupling is of little importance in most practical applications of tsunamis generated by submarine landslides.

Dispersion

Frequency dispersion of waves implies that the wave speed depends also on the wave-length and must be considered when the wave-length is not much larger than the water depth. Effects of dispersion for tsunamis generated by submarine landslides are discussed by, e.g., Ward (2001), Lynett et al. (2003), and Haugen et al. (2005). The errors made by using a Green's function approach for linear non-dispersive waves compared to a linear fully dispersive analysis were demonstrated by Haugen et al. (2005). Figures 4 and 5 demonstrate how dispersion is important for landslides with rapid acceleration or deceleration producing a large content of short wave-length components, while dispersion is of less importance for landslides with a smooth (sinusoidal) velocity distribution where large wave length components dominate. As stated above, the total wave-length is determined by the length of the landslide. Hence, dispersion is of little importance for waves generated by large and sub-critical submarine landslides with moderate acceleration and deceleration producing waves much longer than the water depth. Deformation of the landslide will increase the wavelength and reduce dispersive effects (Grilli & Watts 2005).

Retrogression

Retrogressive submarine landslides differ from rigid block slides by gradual or stepwise release of the mass progressively upslope from the bottom end of the release zone. The total mass in motion is then a function of time. Haugen et al. (2005) modelled a retrogressive submarine landslide at constant depth, using a simplified approach. The landslide of total length L consists of a train of N fixed block slides released at different times t , but moving with identical velocity distributions. For simplicity, the blocks have the same thickness d and the same length L/N . Moreover, the time lag Δt between the release of two adjacent blocks is assumed to be equal.

For waves propagating in the same direction as the landslide, increasing Δt increases the distance between the surface elevations caused by the individual block modules. This decreases the overlap and results in a smaller amplitude and longer wave (See Masson et al. (2006), their figure 10). For small time lags, the wave remains smooth, but as Δt increases, the distances between the individual block modules become large and the discrete nature of the retrogressive landslide starts to show. Eventually, when Δt is sufficiently large, the waves generated by the block modules are completely separated.

Waves moving in the opposite direction of the block modules also move in the same direction of the retrogressive process. Thus, small time lags will decrease the distance between the surface elevations caused by the individual block modules. Consequently, the overlap increases, resulting in a larger amplitude but shorter wave. When the time lag equals the time it takes for the wave to traverse a block module, i.e., $\Delta t = L/(c_0 N)$, the individual surface elevations interfere in a perfectly constructive manner and the amplitude is at its maximum. As the time lags are increased further, the waves moving in the opposite direction of the block modules exhibit the same dependence on Δt as described above for the wave moving in the same direction as the landslide. A retrogressive landslide with short time lags may lead to both shorter wave components originating from individual blocks, and a longer total wave-length from superposition compared to rigid submarine landslides.

Provided that the time lag is relatively small (i.e., that the waves generated by individual blocks have not started to separate), the correlation for strongly sub-critical motion found by Lovholt et al. (2005) (discussed above) can be generalized such that the maximum surface elevation correlates with the rate of change in landslide momentum divided by the wave speed squared, whilst the elevated water volume still correlates with the landslide momentum divided by the wave speed.

Comparison to tsunamis generated by earthquakes

Tsunamis generated by submarine landslides often have very large run-up heights close to the landslide area, but have more limited far-field effects than earthquake tsunamis (Okal & Synolakis, 2004). This rapid damping of the tsunami is primarily the result of radial spreading from a local dipole source (for a small submarine landslide, effectively a point source). It contrasts with the lack of radial damping seen in some earthquake tsunamis because these tend to be linear features propagating perpendicular to the source fault, provided that the propagation distance is of the same order as the fault length or smaller. Farther afield radial damping will again play a role as it does for a local dipole source. One should be aware that dispersion can also contribute to the damping.

The energy available for the tsunami is proportional to the square of the uplift of the seabed. A submarine landslide moves less material, but might move it vertically up to 100 times as much as an earthquake resulting in a comparable amount of tsunami energy (Okal & Synolakis 2003). Hence, the energy of the tsunami might be of the same order. This confirms that large submarine landslides are potentially catastrophic tsunami generators. However, submarine landslides and earthquakes have fundamentally different time histo-

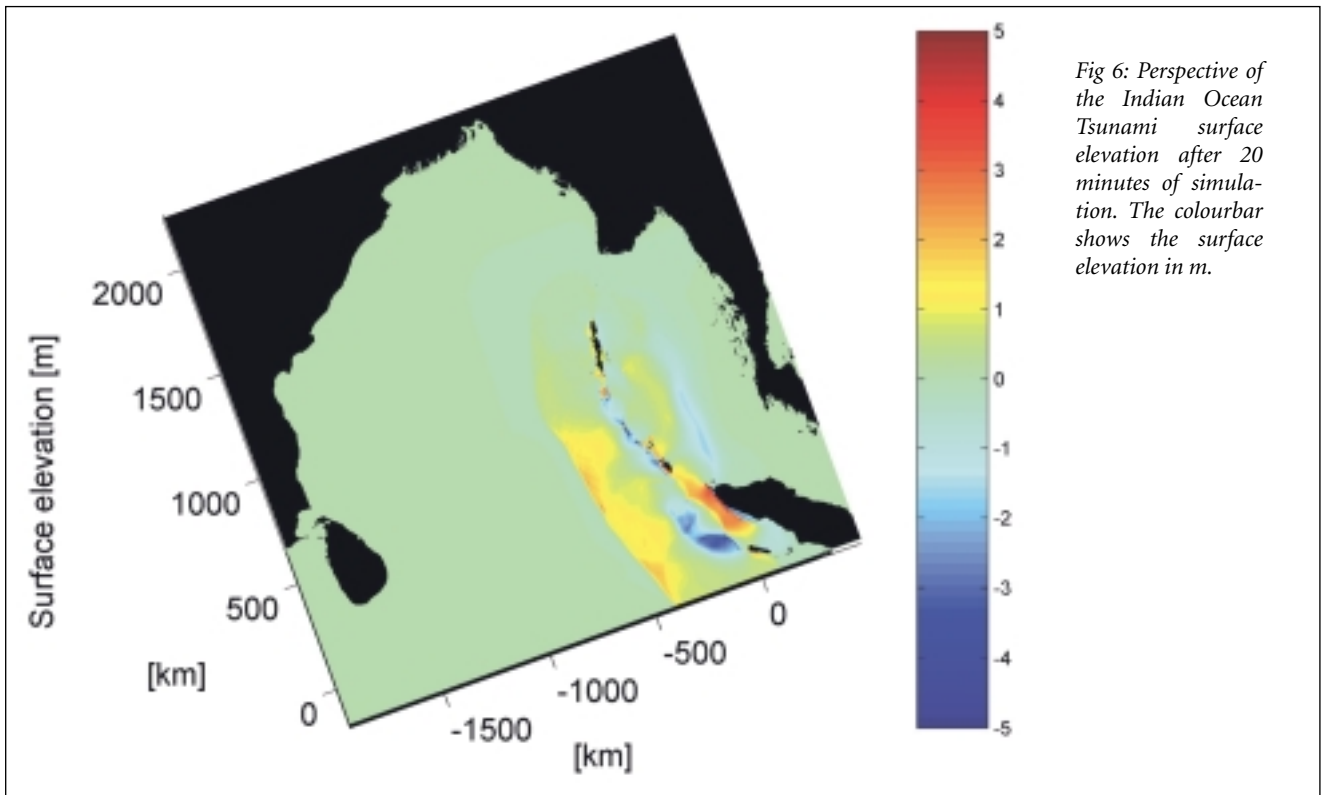


Fig 6: Perspective of the Indian Ocean Tsunami surface elevation after 20 minutes of simulation. The colourbar shows the surface elevation in m.

ries and the tsunami radiated by a moderate volume landslide also decays faster in the far-field because of its dipole nature. Satake & Tanioka (2003) summarise these observations by stating that the far-field tsunami surface elevations are proportional to the displaced water volume at the source, while the near-field tsunami surface elevations are determined by the potential energy of the displaced water.

The difference in tsunami generation from submarine landslides and earthquakes is illustrated by the Storegga Slide tsunami and the Indian Ocean tsunami. The Indian Ocean tsunami on the 26th December 2004 was generated by a magnitude 9.3 earthquake, causing a rupture more than 1200 km long extending from Sumatra to the Andaman Islands (Bilham et al. 2005; Kruger et al. 2005). Calculations reveal that the wave energy for the Storegga Slide tsunami as simulated by Bondevik et al. (2005), Figure 1, is about ten times higher than the wave energy of the Indian Ocean tsunami as simulated by Lovholt et al. (in review), Figure 6. The fraction of energy transferred from the source to the tsunami is of the order of 0.1 % for the Storegga Slide tsunami (Lovholt et al. in review), and 0.3% for the Indian Ocean tsunami (Lay et al. 2005). The tsunami generated by the Storegga Slide displays an initial dipole structure (Figure 1, time = 30 min), whilst the Indian Ocean Tsunami displays a source that is initially more similar to a line source (Figure 6, time = 20 min). Therefore, the propagation of the Storegga Slide tsunami is affected by radial spreading in all directions, while the Indian Ocean tsunami is only affected

by radial spreading in the north-south directions, again as long as the propagation distance is of the same order as the fault length or smaller. The lack of radial spreading in the east-west direction is also one reason for the devastating effects in the far-field of the Indian Ocean tsunami, for instance in Thailand, Sri Lanka and India (see, e.g., Glimsdal et al. 2006).

The depth at which submarine landslides and earthquakes occur also influences the wave generation differently. For a landslide occurring in shallow water, effects of critical landslide motion give large localized waves as illustrated by Ward (2001), resulting in more hazardous waves than if the same landslide should occur in deep water. In contrast, tsunamis generated by earthquakes are more hazardous when the seabed displacement occurs in deeper waters, as the initial wave (which in this case depends much less on the water depth) will become shorter and higher as a result of shoaling when propagating from deeper to shallower waters.

Tsunamis generated by a combination of earthquake and landslide: The 1998 Papua New Guinea tsunami

Submarine landslides frequently occur in the aftermath of an earthquake, causing tsunamis additional to and much more localized than those from the earthquake itself, but at the same time potentially very destructive

(Bardet et al. 2003; Okal & Synolakis 2003). Moreover, the wave-lengths may occasionally be much shorter than for tsunamis of seismic origin, which implies that often a dispersive model must be used (Lynett et al. 2003).

The fact that submarine landslide tsunamis often have large run-up heights close to the source area but appear to propagate much less efficiently than earthquake tsunamis was exemplified by the 1998 Papua New Guinea (PNG) tsunami, where run-up heights up to 15 m affected a 20 km segment of the coast, killing 2200 people (Dengler & Preuss 2003; McSaveney et al. 2000), while farther afield the tsunami was not a significant event (Okal & Synolakis 2004; Satake & Tanioka 2003).

Initially, the tsunami was believed to originate from an earthquake. However, attempts to model the tsunami using solely an earthquake source gave too small amplitudes and too late arrival times (e.g Geist 1998). It is now broadly accepted that the damaging part of the tsunami was due to a slump (Bardet et al. 2003; Tappin et al. 1999; Tappin et al. 2003; Sweet & Silver 2003), while the earthquake was responsible for the far-field tsunami and played an indirect role as the mass triggering mechanism.

Okal & Synolakis (2004) compared the 1998 PNG tsunami with the 2002 tsunami of Wewak, also located in Papua New Guinea. They found that although the 2002 earthquake was more destructive (in terms of structural damage) than the 1998 earthquake, the 2002 tsunami did not produce nearly as large a run-up as the 1998 tsunami, most likely because the 2002 earthquake did not produce a significant landslide. This is further supported by the fact that significant run-up for the 2002 tsunami was found over a larger geographical area than for the 1998 tsunami (Borrero 2003), showing that the earthquake generated tsunami is less affected by radial damping (Okal & Synolakis 2004).

The findings cited above illustrate that differences in source characteristics for the PNG tsunami are important for the spatial distribution of run-up heights. Suggested landslide sources produce (relatively) short-wave components, large offshore surface elevations, and evident dipole characteristics. The large offshore surface elevation is required to reproduce the devastating near-shore effects. However, the dipole shape and the short-wave components contribute to radial spreading (Okal & Synolakis 2004) and frequency dispersion (Lynett et al. 2003), respectively, which reduce the surface elevation in the far-field.

Tsunamis generated by rock slides

Rock slides plunging into fjords, lakes, or reservoirs are most often super-critical and can generate huge,

destructive waves. Tsunamis may cause large oscillations in basins or fjords, causing a series of incident waves. The first wave is not necessarily the largest. Wave activity may last for hours.

Such waves may especially endanger reservoirs due to the potential overtopping of the dam crest, causing floods in the down-stream valley. Examples of well documented rock slides in fjords are the 1934 Tafjord event in Norway (Harbitz et al. 1993) and the 1958 Lituya Bay event in Alaska (Miller 1960), causing maximum run-up heights of more than 60 m and 500 m, respectively. A well known example of a rock slide into a reservoir is the 1963 Vajont Dam event in Italy, where a 240 million m³ rock slide caused a wave that reached a height of more than 250 m around the dam and killed about 2000 people living in the villages downstream (Kiersch 1964; Müller 1964, 1968).

Tsunamis generated by rock slides are determined by the rock slide volume or the frontal area of the rock slide, the impact velocity of the rock slide when plunging into the water body, the permeability of the rock slide, and the bathymetry. When the rock slide penetrates down slope into the sea, the Froude number decreases because the rock slide velocity is reduced while the wave speed above the front of the rock slide increases when the water is deeper. The build-up of the wave persists as long as the Froude number is around unity. This is demonstrated by the experiments of Fritz et al. (2004) who investigated wave generation by granular slides at laboratory scale, mainly for investigating rock slide generated tsunamis. Depending on the granular slide characteristics, the investigated waves were strongly nonlinear in general, with features such as solitary or breaking waves. Fritz et al. (2004) also found that rock slides with large volumes or high speeds bring along an air cushion around the sliding masses increasing the effective volume of the rock slide. Based on the experiments, a power law for super-critical rock slide motion, $\eta_{r,max} = 0.25Fr^{1.4}d_r^{0.8}$, was found using multiple regression. For the data analysed, a rather good correlation coefficient of 0.93 was found for $1 < Fr < 10$. This result contrasts Ward's (2001) analysis for linear waves generated by a block slide in deep water, which predicts no influence of Fr when $Fr \gg 1$. The different behaviour for large Froude numbers is very likely due to nonlinear effects.

For rock slides, nonlinear effects may be important in the wave generation area, but often only in a restricted region and during a short period of time. The cumulative effect of non-linearity will probably not exceed the errors that originate from uncertainties in the configuration and dynamics of the rock slide. Outside the wave generation area, the characteristic maximum surface elevation of the waves is normally much less than the characteristic water depth.

Concluding remarks

The importance of submarine landslide volume, initial acceleration, maximum velocity, and possible retrogressive behaviour upon the characteristics of the resulting tsunami is discussed. The length of the landslide influences both the wave-length and the surface elevation, while the thickness and the acceleration or deceleration of the landslide as well as the wave speed (which again is determined by the water depth) determine the surface elevation. The maximum tsunami elevation generally correlates with the product of the landslide volume and acceleration divided by the wave speed squared, whilst the elevated water volume correlates with the product of the landslide volume and the Froude number.

Only a limited part of the potential energy released by the landslide is transferred to wave energy. While calculations based on the Storegga Slide reveal that only 0.1 % of the potential energy of the landslide is transferred to wave energy, other simulations with more favourable conditions for tsunami generation in terms of landslide-to-water depth and density ratios indicate that up to 15 % of the energy in a flow of a viscous fluid is transferred to wave energy. A high value of transferred energy indicates that two-way coupling between a submarine landslide and the surface waves that it generates can be important, but such a coupling can be neglected in most practical applications. The relative reduction of maximum landslide velocity is smaller than the relative amount of energy transferred from the landslide to the waves. Calculations also reveal that the wave energy for the Storegga Slide tsunami is about ten times higher than the wave energy of the December 2004 Indian Ocean tsunami, but the fraction of energy transferred from the source to the tsunami is about the same for both events.

Frequency dispersion is of little importance for waves generated by large and sub-critical submarine landslides with moderate acceleration and deceleration where large wave-length components dominate. Retrogressive landslide behaviour normally reduces associated tsunami heights, but retrogression might increase the height of the landward propagating wave for unfavourable time lags between releases of individual elements of the total released mass. A retrogressive submarine landslide with short time lags may lead to both shorter wave components originating from individual blocks, and a longer total wavelength from superposition compared to rigid slides.

Comparisons are made to tsunamis generated by earthquakes, illustrating the importance of three dimensional effects such as radial spreading of waves from a more local dipole source as opposed to lack of radial spreading of waves generated by a seismic fault that is

often more similar to a line source. Tsunamis generated by submarine landslides are most dangerous when generated in shallow waters, while on the other hand tsunamis generated by earthquakes are more dangerous when generated in deeper waters. Differences in tsunamis generated by submarine landslides and by earthquakes are further illustrated by the possible requirement for a combined source in numerical tsunami simulations. Sometimes observations of natural events can be reproduced only by using such a source.

Comparisons are also made to tsunamis generated by rock slides, which are strongly affected by nonlinear effects, at least in the initial stages. Rock slides are most often super-critical and the resulting tsunamis are determined by the frontal area of the rock slide, the impact velocity of the rock slide when plunging into the water body, the permeability of the rock slide, and the bathymetry. For rock slide tsunamis, the wave height depends on the Froude number.

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