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The Storegga Slide tsunami—comparing field observations with numerical simulations

Stein Bondevik[a,*], Finn Løvholt[b], Carl Harbitz[b], Jan Mangerud[c],
Alastair Dawson[d], John Inge Svendsen[c]

[a]*Department of Geology, University of Tromsø, N-9037 Tromsø, Norway*
[b]*International Centre for Geohazards, Norwegian Geotechnical Institute, P.O. Box 3930 Ullevaal Stadion, N-0806 Oslo, Norway*
[c]*Department of Earth Science and Bjerknes Centre for Climate Research, University of Bergen, Allégaten 41, N-5007 Bergen, Norway*
[d]*Centre for Quaternary Science, Coventry University, CV1 5FB Coventry, UK*

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Abstract

Deposits from the Storegga tsunami have been found in coastal areas around the Norwegian Sea and North Sea, from the northeast coast of England to beyond the Arctic Circle in northern Norway. The tsunami deposits reach onshore elevations of 10–12 m above sea level of their time in western Norway, 3–6 m in northeast Scotland and above 20 m on the Shetland Islands. These elevations are compared with surface (wave) elevations derived from a numerical simulation of the Storegga slide. A good agreement is obtained for a retrogressive slide that descends at 25–30 m/s, and that has short time lags of 15–20 s between each individual slide-block.

Keywords: Tsunami deposits; Storegga Slide; Tsunami modelling

1. Introduction

For more than a decade it has been assumed that the Storegga slide generated a large tsunami. Traces of this event were independently discovered in Scotland (Dawson et al., 1988; Long et al., 1989) and western Norway (Svendsen and Mangerud, 1990). A numerical simulation of the waves generated by the 'Storegga slides' predicted that most coastlines bordering the Norwegian Sea and North Sea could have been inundated by the tsunami (Harbitz, 1992). As a result of more systematic investigations in the subsequent years, deposits from the Storegga tsunami have now been identified along a considerable stretch of the Norwegian coastline (Bondevik et al., 1997a; Bondevik, 2003), The Faeroe Islands (Grauert et al., 2001), Shetland Islands (Bondevik et al., 2003) and Scotland (Dawson et al., 1988; Long et al., 1989; Dawson and Smith, 2000). From the elevations of these deposits we also know fairly well the run-up of the tsunami in the different regions. The highest deposits found so far are from Shetland, where sand has been traced to more than 20 m above sea level at that time. On the outer coast of western Norway, proximal to the back-wall of the slide, the waves inundated lakes up to 10–12 m above sea level, but failed to reach lakes 13 m high (Fig. 1).

In the present paper we compare these field observations with run-up heights deduced from new numerical simulations of the slide generated water waves. Such a comparison is important because the geographical pattern of run-up-heights provides a sensitive test to quantify some essential slide properties as initial acceleration, the maximum velocity, the volume of the slide and how the slide developed (Løvholt et al., 2005). Both geotechnical and morphological studies demonstrate that the slide retreated backwards (Kvalstad et al., 2005; Haflidason et al., 2005). The time lag between the individual blocks sliding

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* Corresponding author.
E-mail address: stein.bondevik@ig.uit.no (S. Bondevik).

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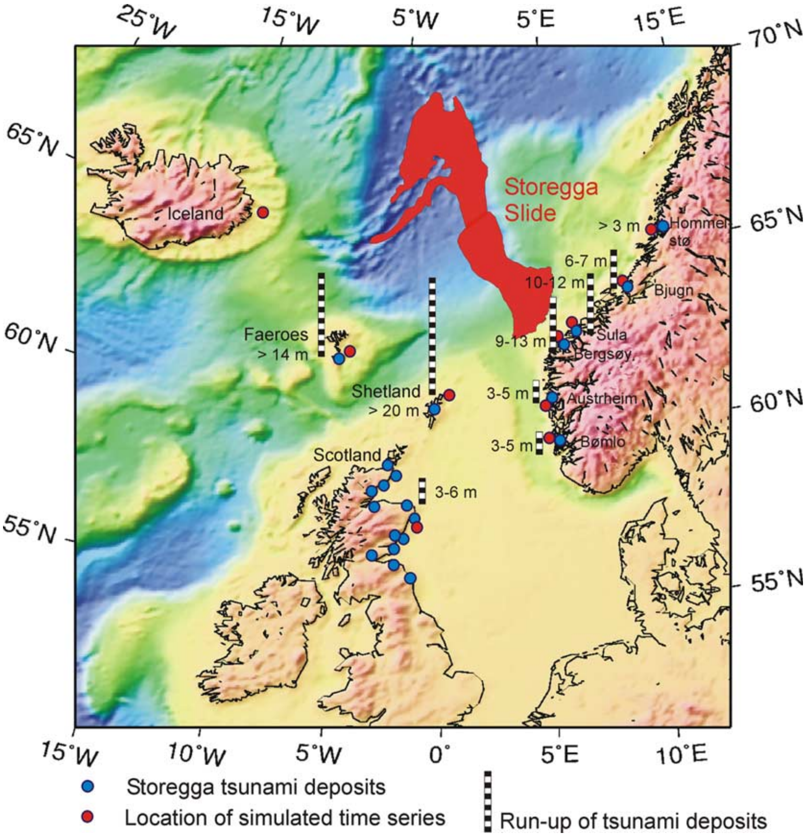


Fig. 1. Map of the Storegga Slide. Blue dots show where tsunami deposits have been studied and numbers show elevation of the deposits above the contemporary sea level. Red dots show approximate position of the time series plotted in Fig. 2, or discussed in Table 1.

off as the slide retreated backwards is considered to be a decisive factor on the magnitude and pattern of the resulting waves. The run-up heights can therefore be used to constrain the time development of the slide.

The shape and volume of the modelled slide used by Harbitz (1992) have been adjusted to fit the new and much more detailed reconstruction of the slide based on the comprehensive marine-geological investigations during the Ormen Lange project (Forsberg, 2002; Haflidason et al., 2004). In the revised slide model the maximum thickness (400 m) of the slide is near the upper headwall and it becomes gradually thinner towards the slide front in the offshore direction. The volume of the slide involved in the generation of the tsunami is estimated to be 2400 km^3.

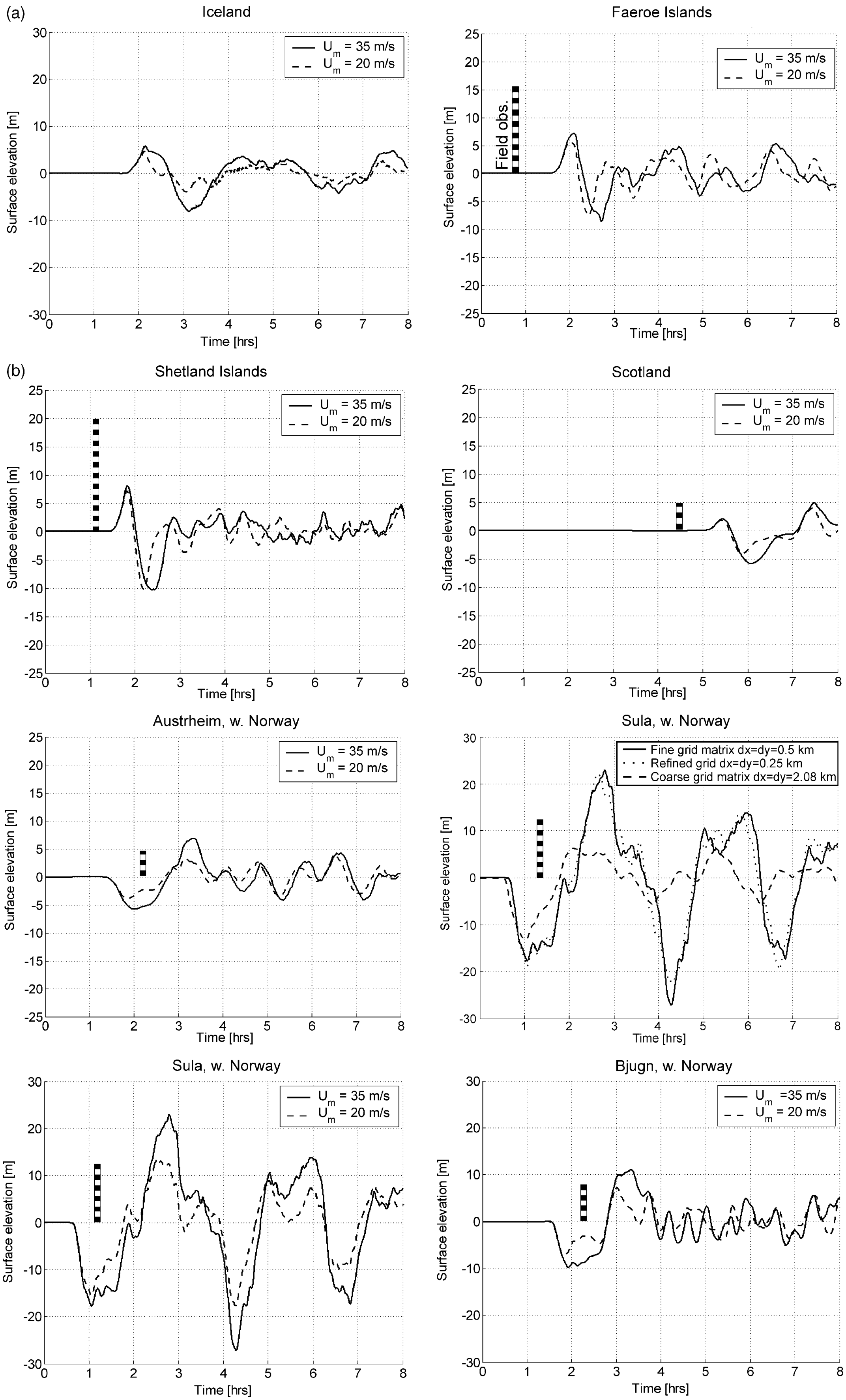
In this paper we present time series of sea surface elevations (Fig. 2) derived from the numerical simulations at locations very close to the field sites where run-up has been inferred from tsunami deposits. The best fit is obtained for a retrogressive slide having a maximum velocity below 35 m/s, probably around 25–30 m/s. The time lag between the individual slide blocks was not more than 15–20 s.

2. Methods—field observations

2.1. Identification of Storegga tsunami deposits

The best preserved Storegga tsunami deposits are found in near-shore coastal lake basins. Cores from such basins show that the accumulation of fine-grained organic mud were suddenly interrupted by the flooding of the tsunami (Figs. 3 and 4B) that eroded and ripped up the lake floor and transported marine sand and gravel into the lakes. Deposits from the Storegga tsunami have now been

Fig. 2. Time series of sea surface elevations. U_m is maximum velocity reached by the slide. The ruler indicates the field observations. Time series from the Faeroe Islands and Shetland Islands are obtained from the coarse grid simulation at offshore locations in open water (Fig. 1), whereas the field observations are from within the fjords. The discrepancy between the field observations and the simulated surface elevations from these areas are caused by the amplification and focusing of the wave in the fjords. The time series from western Norway are simulated using the fine grid matrix of 0.5×0.5 km. For comparison, the first time series from Sula shows simulations using the 0.25, 0.5 and 2.08 km grids with a maximum slide velocity of 35 m/s. For information about the other time series, see Table 1.


(a)
Iceland
Faeroe Islands
Field obs.
(b)
Shetland Islands
Scotland
Austrheim, w. Norway
Sula, w. Norway
Fine grid matrix dx=dy=0.5 km
Refined grid dx=dy=0.25 km
Coarse grid matrix dx=dy=2.08 km
Sula, w. Norway
Bjugn, w. Norway
U_m = 35 m/s
U_m = 20 m/s
Surface elevation [m]
Time [hrs]

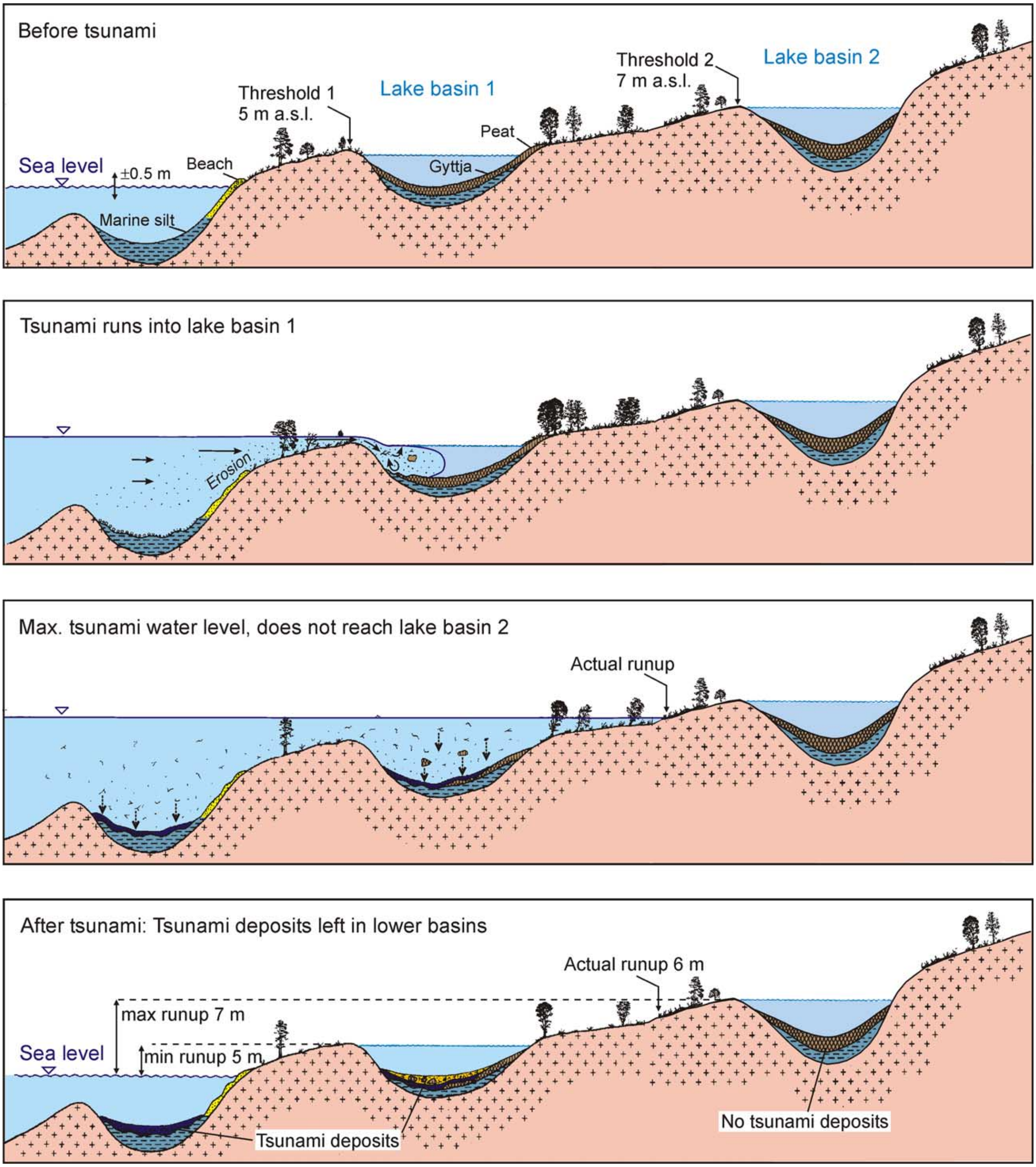


Fig. 3. Illustration to show how the Storegga tsunami inundates a coastal lake and how the thresholds of the lakes are used to estimate run-up heights. The tsunami runs across the threshold at 5 m a.s.l. but not into lake basin 2 at 7 m a.s.l. The reconstructed run-up would in this case be 5–7 m.

described from more than 20 lakes in western Norway (Bondevik et al., 1997a), four lakes on the Shetland Islands (Bondevik et al., 2003; Bondevik et al., in press) and one on the Fareoe Islands (Grauert et al., 2001). Tsunami sedimentary facies in lakes are described in detail by Bondevik et al. (1997b). Storegga tsunami deposits are also found as a sand layer that can be traced several hundred meters inland in raised estuarine mudflats in Scotland (Dawson et al., 1988; Long et al., 1989) and in peat outcrops in Shetland (Bondevik et al., 2003).

The deposits show some common features that distinguish them from the enclosing sediments. They rest on an erosional unconformity that typically shows more erosion towards the sea. A normal graded sand bed or a massive

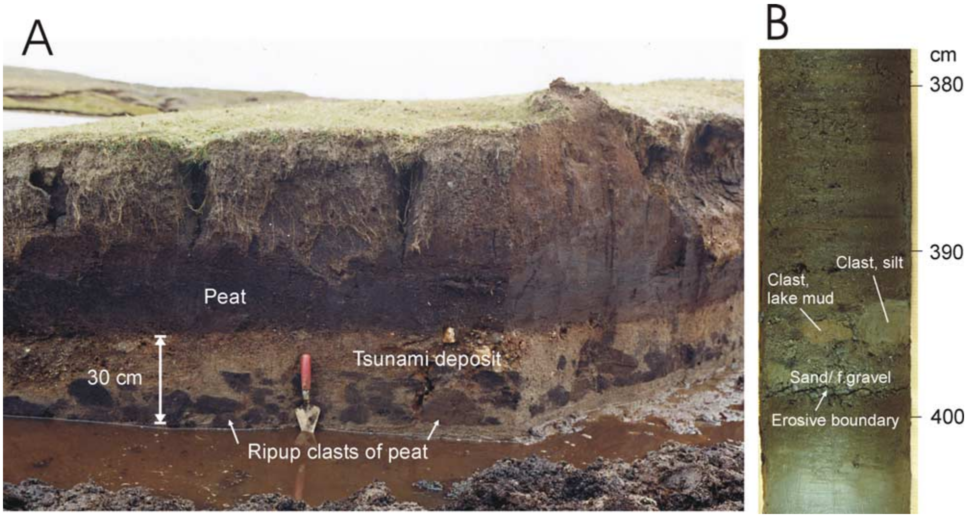


Fig. 4. (A) Storegga tsunami deposits in a peat outcrop in Sullom Voe, Shetland (Bondevik et al., 2003). Large rip-up clasts of peat and pieces of wood make up a bed within the sand, with a distinct lower boundary. We interpret this as a result of at least two waves inundating the land. The first wave eroded the peat surface and transported rip-up clasts of peat and sand. The backwash left the eroded clasts and other organic remains at the surface of the tsunami-laid sand. The following wave buried the clasts in sand. Storegga tsunami deposits inferred to show repeated waves are also known from coastal lakes in western Norway (Bondevik et al., 1997b) and peat in Scotland (Dawson and Shi, 2000). (B) Storegga tsunami deposits from a lake basin on Shetland (Bondevik et al., 2003). The Storegga tsunami deposit has a sharp, erosive lower boundary at 398.5 cm that rests on late glacial silt and early Holocene lake mud. Coarse sand and fine gravel are found on top of this boundary. The sand contains rip-up clasts of silt and lake mud. Up-core, to 311 cm, the tsunami deposit is a mixture of different re-deposited material.

sand bed overlies the erosive boundary. The sand bed gradually thins in the landward direction and decreases in grain size. Very often rip-up clasts of peat, gyttja (lake mud) or silt (Fig. 4) are found either on top of the sand layer or within the sand. The deposits frequently contain marine fossils, including shells and shell- fragments, foraminifera and diatoms.

The primary lines of evidence that these facies were deposited by a tsunami generated from the Storegga slide are: (1) The source of the deposit appears to be the ocean; there are marine fossils in the deposit, it shows landward fining, and the seaward side shows more signs of bed erosion. (2) Many of the characteristics of these deposits are reported from known modern tsunami deposits; extensive erosion, rip-up clasts, decrease in thickness and grain-size landwards, and massive or normal grading. (3) The elevation of the deposits far exceeds any storm surge amplitude; the deposits are found from 3 to 20 m above the contemporaneous high tide level. (4) The tsunami deposits and the slide have the same age. Radiocarbon dates of the deposits show ages between 7000 and 7300 ^{14}C yr BP in all the different areas. According to many AMS ^{14}C dates of plant fragments the most accurate age for the tsunami is 7250–7350 ^{14}C yr BP (Bondevik et al., 1997a). The slide itself has been dated to 7250 ± 250 ^{14}C yr BP (Haflidason et al., 2005). (5) The waves were largest in the regions adjacent to the Storegga slide. The height of tsunami deposits along the outer coast of Norway are gradually decreasing away from the slide area (Fig. 1) (Bondevik et al., 1997a).

2.2. Reconstructing the run-up from tsunami deposits

The presence of tsunami deposit in a coastal lake means that the tsunami overflowed the outlet threshold of the lake. The elevation of the threshold relative to the sea level at tsunami time shows a minimum run-up (Fig. 3). Along the Norwegian coast the tsunami deposits were traced successively to lakes at higher elevations. The first lake basin with no traces of any inundation by the tsunami was taken as an indicator that the tsunami did not reach this level (Bondevik et al., 1997a). The upper limit of the flooding is thus somewhere between the highest basin with tsunami deposits and the lowermost basin without such traces (Fig. 3). The smaller the difference in altitude between these two lakes, the more precise estimate of the run-up can be obtained. Tsunami deposits in peat have been traced to their maximum elevations and levelled relative to the inferred high tide when the tsunami struck.

Run-up is measured relative to the contemporary sea level, which therefore has to be known. Along the Norwegian coast a number of well-documented sea-level curves have been constructed (Kaland, 1984; Anundsen, 1985; Kjemperud, 1986; Svendsen and Mangerud, 1987; Bondevik et al., 1998). Because of uplift due to glacial unloading of Fennoscandia the 7300 ^{14}C yr BP shorelines are tilted and found above the present sea level. This is also true for Scotland. However, in both Shetland and the Faeroe Islands the shorelines of that time are submerged 10–15 m below present sea level. Unfortunately, there are little data constraining sea level for these islands. The uncertainty of

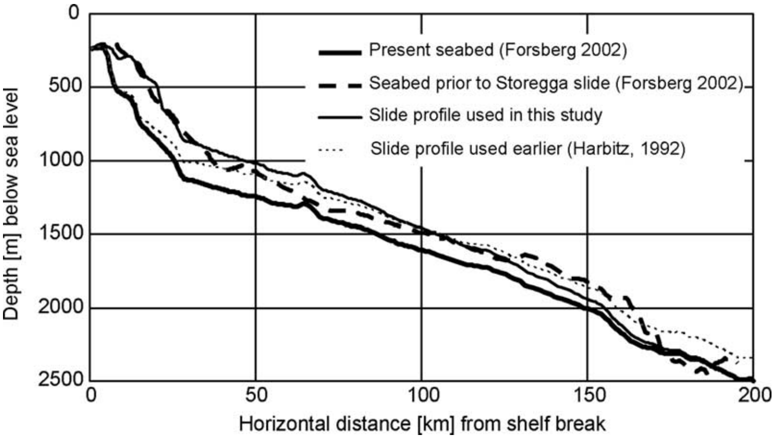


Fig. 5. Cross-section showing the present sea floor in the Storegga Slide scar area, the reconstructed pre-Storegga slide sea floor (Forsberg, 2002) and the modelled sea floor, as described by the new slide block used in the simulations. The new slide block is a close approximation to the reconstructed pre-Storegga slide sea-floor.

the run-up estimates is therefore much larger for these areas than for the western coast of Norway and Scotland.

Another uncertainty in the reconstructed run-up is that sediments possibly were not deposited up to the very highest level of inundation. This is well known from observations of modern tsunamis (Nishimura and Miyaji, 1995; Dawson and Shi, 2000), and tsunami deposits thus only give a minimum estimate of run-up. Absence of tsunami deposits within the flooding area is probably more likely on a slope than in a lake basin that acts as a sediment trap. Still, in some cases it may be difficult to detect tsunami deposits in lakes that were located just below the flooding limit.

The reconstructed sea levels are high tide elevations. If the tsunami struck the coast at low tide, the run-up would be 2–3 m higher than our estimates. Thus, the given heights should be regarded as minimum estimates of run-up because the sediments only give a minimum estimate and because they are measured from the high tide level.

3. Methods—numerical simulation

The numerical simulations consist of two different slide models. First we simulate the waves generated from a slide that is very similar to the reconstructed morphology of the Storegga Slide. This slide is released as one body that moves along the seabed using two different maximum slide velocities. Then we investigate the effects of a retrogressive slide motion by simulating a uniform slide in 2-D that is comparable in size to the Storegga Slide. This slide consists of 167 blocks that are released one at a time. By varying the time lag between the blocks we can study how the retrogressive slide motion affects the resulting tsunami waves.

3.1. Storegga slide released as one body

The slide is modelled as a box that is skewed and smoothed to reproduce the reconstructed morphology of the Storegga slide (Forsberg, 2002; Haflidason et al., 2005). This gives a thicker slide near the headwall with a shorter total length than the one used by Harbitz (1992) (Fig. 5). The width of the box is 100 km and the total length is 150 km. The maximum thickness is slightly above 400 m (Fig. 6).

The slide is released as one body that moves along the sea bed as a flexible blanket. In map view the slide moves along a straight line, with a prescribed velocity profile. We performed two simulations. In simulation 1 the slide reaches a maximum velocity $U_m = 35$ m/s, while in simulation 2 the slide reaches $U_m = 20$ m/s. Both simulations uses a run-out distance $R = 150$ km and an initial

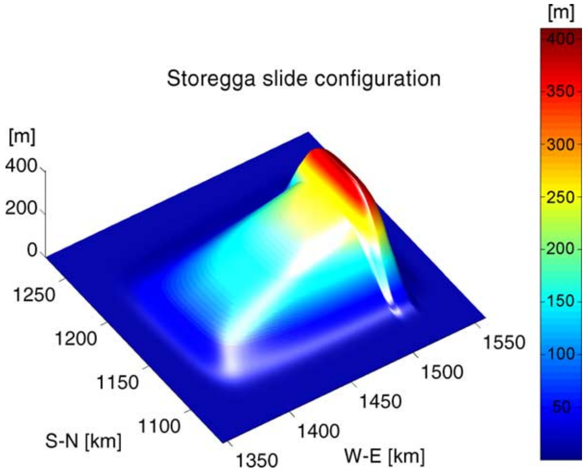


Fig. 6. A 3-D view of the slide block used in the simulations. Compared to older simulations (Harbitz, 1992) this slide is thicker near the headwall and has a shorter total length. The maximum thickness is slightly above 400 m.

acceleration $a_0=0.016$ m/s^2. For simulation 1 the acceleration distance (distance covered from rest to maximum velocity) $R_a=75$ km and in simulation 2 it is 24.5 km. For further details on the slide dynamics see Løvholt et al. (2005).

3.2. Retrogressive slide motion in 2 D

Although we model the slide as a whole block sliding downwards, the slide developed retrogressively, i e. the headwall retreated up-slope (Kvalstad et al., 2005; Haflidason et al., 2005). In this way the slide would start somewhere in the lower part of the slope sending off wedges and blocks down-slope as it retreated up-slope. In general this would reduce the height of the generated waves.

The retrogressive slide is two dimensional. It consists of 167 rectangular blocks that are 240 m thick and 600 m long giving a thickness to block-length ratio of 240 m/600 m = 0.4, which is fairly typical for retrogressive slides (Kvalstad pers. comm. 2003). The slide is 167×600 m = 1000 km long. The blocks are released subsequently in a uniform water depth of 1000 m with an equal time lag (Δt) between the individual blocks. Time lags (Δt) vary from zero to 60 s. The maximum surface elevation of the waves ($\eta_{\max}$) from each time lag are then compared to the maximum surface elevation of the fixed shaped slide ($\Delta t=0$). All the blocks move with the same velocity profile, and the run-out distance is 150 km. The applied model is further described in Haugen et al. (2005); see Fig. 3 there for illustration).

3.3. Tsunami model and grid resolution

The numerical tsunami model is a linear, long wave model. For more details on the tsunami model, see Løvholt et al. (2005) and Harbitz (1992). We have used two different depth matrices for the bathymetry. For the western coast of Norway we applied a grid matrix with a resolution of 500×500 m which we here call the fine grid matrix. The grid covers an area of 765 km (west–east)×645 km (south–north) (Fig. 1 in Løvholt et al., 2005). The fine grid gives a bathymetry with sufficient resolution of the coastline with fjords, islands etc (Fig. 7a). To test the model for sensitivity to grid spacing we also ran one simulation (with $U_m=35$ m/s and $R=150$ km) on a 250×250 m grid, a grid that we produced by bilinear interpolation of the 500×500 m grid. The solutions using both the 250 and the 500 m grids converges reasonably well (Fig. 2—Sula), hence the fine grid resolves the coastline sufficiently.

The waves penetrate into fjords and sound by a fairly uniform increase in surface elevation with only minor variation in the transverse direction across the fjords (Fig. 7b). Due to the large wave length of about 600–800 km for the Storegga tsunami, and the relatively steep slopes along the Norwegian coast, the waves will be rather insensitive to local run-up effects (Pedersen et al., 1995). Based on the above arguments the 500×500 m grid should give reliable results of runup from the Storegga tsunami in complex fjords and straits along the Norwegian coast.

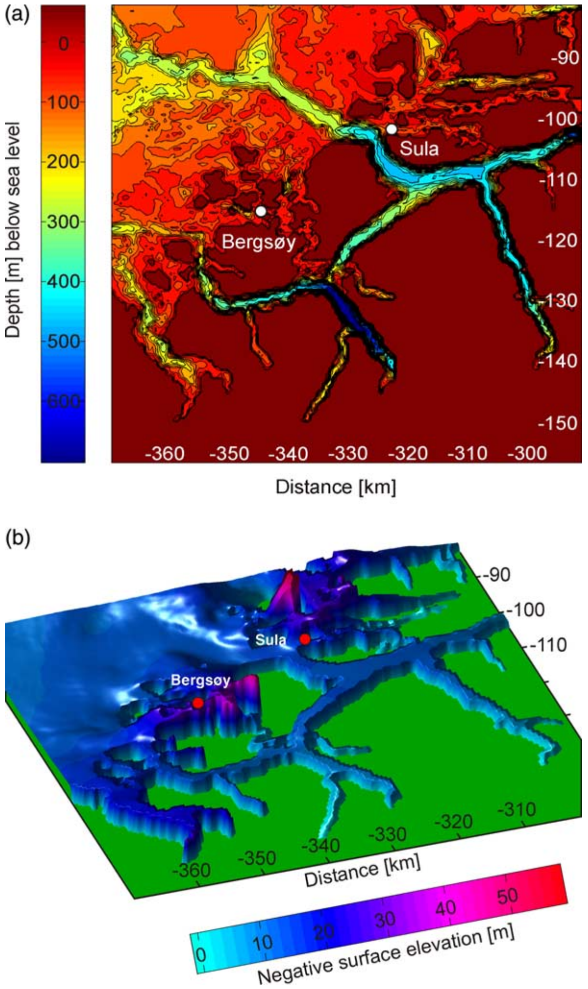


Fig. 7. (a) The 500×500 m grid from western Norway pictures a rather realistic coastline with sounds, straits, islands and fjords. Here is a segment of the grid that covers Bergsøy and Sula (Fig. 1), two of our field sites where runup has been inferred from tsunami deposits. Most straits and sounds adjacent to the sites are resolved with at least three or more grid points in the transverse direction of the incoming waves (see Fig. 7b). (b) A snapshot of the surface elevation 1 h after the release of the Storegga slide ($U_m=35$ m/s) showing the same segment as in Fig. 7a. In order to illustrate the problem of variation in surface elevation across fjords we here show an inverted image of the first negative wave to hit Norway. Note how the wave penetrates into the fjords and sounds by a fairly uniform change in surface elevation. Across the fjords there is only minor variation in surface elevation.

However, for areas outside western Norway we only had the coarse grid matrix that was used by Harbitz (1992) with a resolution of 12.5×12.5 km. We refined the grid by bilinear interpolation to a resolution of 2.08 km×2.08 km. The grid covers 2387.5 km×2485.5 km; including the Norwegian coast, Iceland, Greenland and Scotland (Fig. 8). However, the coarse grid is far too coarse to resolve the complex geometry of the coastal areas with fjords and islands. Thus, simulations of run-up in narrow fjords

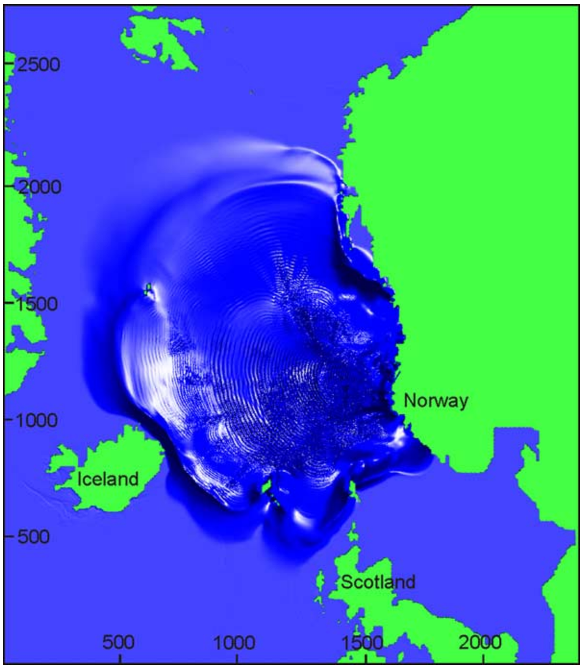


Fig. 8. Perspective view of sea-surface elevation 2 h after the release of the slide. The wave front, ca 3 m high has reached the Faeroe Islands and the Shetland Islands and approaches Greenland, Iceland and Scotland. The small ripples behind the wave front are caused by numerical noise. This noise does not affect the maximum surface elevations.

at the coast using this grid are likely to be underestimated (Fig. 2).

Because of this we have adjusted the run-up heights analytically for sites located within fjords on the Faeroe Islands and Shetland. The amplification is estimated using Green's law, taking the incoming surface elevation derived from the numerical simulation, fjord narrowing and depth reduction into account. The amplification factor for the surface elevation from an offshore location to a fjord location is analytically given as $(w_o/w_f)^{1/2} \cdot (h_o/h_f)^{1/4}$. Here w and h are the fjord width and depth, respectively, and the subscripts' o′ and f′ indicates the offshore and fjord locations. Green's law does not consider boundary reflections. These estimates have a higher uncertainty than results from numerical simulations that uses a grid to resolve the local bathymetry. For details on Green's law, see for instance Mei (1989).

4. Results

The Storegga tsunami propagated outwards in all directions from the Storegga Slide (Fig. 8). On the Norwegian coast, the tsunami began as a withdrawal of the sea. Here time series (Fig. 2) show a sea level drop of 20 m around 30 min after the slide was released (Fig. 2). At the same time a positive wave with a maximum height of ca. 3 m in the open ocean propagated towards Iceland, Faeroe Islands, Shetland and Scotland. After 1.5 h the wave reached Shetland and the Faeroe Islands.

The time series (Fig. 2) also suggest that the coastlines would experience several subsequent waves. This is evident at many of the field sites. The Norwegian lakes close to the sea level at the time of the tsunami often show several sand layers alternating with organic layers. The sand layers were inferred to represent pulses of water (wave fronts) entering the basins while the organic layers represents the period between the waves when suspended material settled on the lake floor (Bondevik et al., 1997b). In Scotland the occurrence of several subunits within the larger sand body of the tsunami deposit are believed to reflect different waves running up the coast (Dawson and Shi, 2000). Fig. 4A shows evidence of at least two waves that hit Sullom Voe in Shetland (Bondevik et al., 2003).

The simulations based on the new slide configuration, with a finer grid of 500 m × 500 m, and more of the material placed in the upper slope, all return somewhat higher waves than the previous simulations carried out by Harbitz (1992). An interesting feature when applying the finer grid is that the sea level at the western coast of Norway (Sula) may have dropped to a level of −20 m in the period between the two first waves which imply that the total amplitude was nearly 40 m (Fig. 2).

4.1. Western Norway

The most accurate run-up estimates from field observations are from the Norwegian coast. Here the estimate at each site is based on several lake basins at different elevations (Table 1; Bondevik et al., 1997a). Furthermore, the contemporary high tide sea level is known with an uncertainty less than 1 m for all of the sites, except for Brønnøysund–Hommelstø.

Tsunami deposits are described from Bømlo in the south to Hommelstø in the north (Fig. 1). The highest estimate is from Sula on the northwest coast where the run-up is constrained to 10–12 m. From this area the run-up decreases to the north (Bjugn, 6–8 m) and south (Austrheim, 3–5 m) and this observation was used as an argument that the source for the tsunami was the Storegga Slide (Bondevik et al., 1997a)

Surface elevations have been calculated at Bergsøy, Sula, Bjugn and Brønnøysund (Fig. 1, Table 1) using both grid resolutions. The gauges on the coarse grid are slightly offshore compared to the corresponding locations on the fine grid (Table 1) because the finer grid extends farther into the coastal areas where the field sites are located. For the two sites proximal to the slide area, Bergsøy and Sula (Figs. 1 and 7a and b), the simulations using the fine grid give almost twice as high surface elevations as the coarse grid (Fig. 2; Table 1). The reason for this is local effects, which the coarse grid cannot resolve. A snapshot of the wave after reaching the outer coast illustrates that the wave penetrates into the fjords and sounds by a fairly uniform increase in

Table 1
Surface displacements derived from numerical simulations compared to field observations of maximum elevation of tsunami deposits

Locations					Numerical simulation of max. Surface elevation (m)				Field observations		Comments
Area	Site/position	Latitude	Longitude	Water depth (m)	($U_{max}=35$ m/s)		($U_{max}=20$ m/s)		Sites with tsunami deposits	Runup (m)	
					coarse grid	*fine grid*	*coarse grid*	*fine grid*			
N. Norway	Brønnøysund	65°26′ N[a] 65°27′ N	12°02′ E 12°02′ E	34 50	30.2	17.1	20.3	17.9			Modelled site on the outer coast, while field obs. from Hommelstø, located inland in fjord
N. Norway	Hommelstø	65°23′ N	12°35′ E						3 Lake basins	> 3	All studied basins below sea level at tsunami time, terrestrial plants and peat clasts within tsunami dep. indicate runup > 3 m
W. Norway	Bjugn	63°58′ N[a] 63°52′ N[b]	9°48′ E 9°49′ E	110 61	14.3	11.6	7.1	7.2			
W. Norway	Bjugn	63°50′ N	9°50′ E						3 Lake basins	6–8	Sea level 35–36 m a.s.l. Tsunami wave overflowed lake threshold at 42 m a.s.l. but not lake at 44 m a.s.l. (Bondevik et al., 1997a,b)
W. Norway	Sula	62°35′ N[a] 62°27′ N[b]	5°51′ E 6°05′ E	43 100	12.7	22.9	11.8	13.5			
W. Norway	Sula	62°26′ N	6°14′ E						6 Lake basins	10–12	Sea level 10–11 m a.s.l. Tsunami barely inundated lake at 21.5 m a.s.l. but not lake at 22 m a.s.l. (Bondevik et al., 1997a)
W. Norway	Bergsøy	62°24′ N[a] 62°18′ N[b]	5°35′ E 5°43′ E	33 50	13.4	20.2	9.5	17.4			
W. Norway	Bergsøy/ Leinøy	62°20′ N	5°39′ E						4 Lake basins	9–13	Lake 8–9 m above sea level at tsunami time show large erosion from tsunami. Two lakes 12–13 m above sea level at that time show no sign of tsunami deposits. (Bondevik et al., 1997a)
W. Norway	Austrheim	60°40′ N	4°42′ E	65	6.9		3.9				
W. Norway	Austrheim	60°47′ N	4°56′ E						5 Lake basins	3–5	Sea level 10–11 m a.s.l. Tsunami clearly inundated lake at 14 m a.s.l. but not lake at 15 m a.s.l. (Bondevik et al., 1997a)
W. Norway	Bømlo	59°5′ N	5°05′ E	36	6.6		3.4				
W. Norway	Bømlo	59°45′ N	5°20′ E						2 Lake basins	3–5	Sea level ca 12 m a.s.l. Tsunami deposits in lake at 15 m a.s.l. but not in bog at ca 16 m a.s.l. (Bondevik et al., 1997a)
Scotland	Scotland-E	57°57′ N	1°58′ W	76	5.9		4.2				

(*continued on next page*)

Table 1 (*continued*)

Locations					Numerical simulation of max. Surface elevation (m)				Field observations		Comments
Area	Site/position	Latitude	Longitude	Water depth (m)	($U_{max}=35$ m/s)		($U_{max}=20$ m/s)		Sites with tsunami deposits	Runup (m)	
					coarse grid	*fine grid*	*coarse grid*	*fine grid*			
Scotland	Scotland-mainland coastline	55°40′ N - 58°40′ N	1°40′ W - 4°30′ W						Numerous sites	3–6	All sites occur within estuarine sequences where tsunami deposits are enclosed with a) pre-existing estuarine silts and clays and b) within peat. At each site the tsunami deposit can be traced landward where it becomes thinner and increases in elevation. The range of runup estimates are between 3 and 6 m, but it is possible that individual sites may have experienced runup in excess of this range (Dawson, 1999; Dawson and Smith, 2000)
Shetland	Shetland-NE	60°47′ N	0°48′ W	43	8.0	–	7.1	–			
Shetland	NE-coast	60°16′ N	1°09′ W						4 Lake basins	> 12	Lakes located 0.5–3 m above present high tide level. Sea level probably 10–15 m below present sea level. (Bondevik et al., submitted)
Shetland	Sullom Voe	60°28′ N	1°20′ W						Outcrop in peat	> 20	Sand layer in peat traced to 9.2 m above high tide. Sea level probably 10–15 m below present sea level. (Bondevik et al., 2003)
Faeroe Islands	Suderøy-E	61°28′ N	6°33′ W	122	7.2	–	5.7	–			Modelled site is in open water E of field obs
Faeroe Islands	Suderøy, Vagur	61°20′ N	6°15′ W						1 Lake basin	> 15–20	Field obs. at the head of 5 km long fjord 4 m a.s.l. Sea level probably 10 m below present sea level. (Grauert et al., 2001)
Iceland	Iceland-E	65°12′ N	12°54′ W	157	6.3	–	4.7	–			No field observations from Iceland

Sites using the coarser grid are in open water outside field site.
Sites using the finer grid are closer to the field sites.

[a] Site coordinates refer to coarse grid.

[b] Site coordinates refer to fine grid.

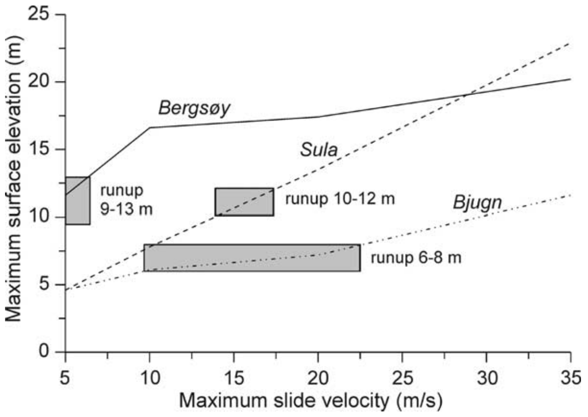


Fig. 9. Maximum surface elevation for sites in western Norway as a function of maximum slide velocity, calculated using the fine grid bathymetry. The field observations (horizontal bars) indicate a slide velocity less than 20 m/s. Note that all field observations are measured relative to high tide. If the tsunami occurred at low tide, the wave elevation would increase with about 2–3 m.

surface elevation, with only minor surface variation across the fjords (Fig. 7b). Hence the simulations using the fine grid is regarded to give the representative surface elevations comparable to the field observations. This result is important because the sites in Scotland, Shetland, and the Faeroe Islands are only computed using the coarse grid.

Surface elevations computed using a maximum slide velocity of 20 m/s fit the field observation data reasonably well (Table 1, Fig. 9), while the results with a maximum slide velocity of 35 m/s returns surface elevations that are up to two times times higher than the field observations for many of the locations in western Norway.

4.2. The Faeroe Islands

Storegga tsunami deposits have so far only been described from one lake basin situated 4 m a s.l. (meters above sea level) at the Faeroe Islands (Grauert et al., 2001). This lake is situated on the southernmost island, Suderøy, at the head of a 5 km long fjord that opens towards the east. The tsunami scoured the lake floor down to bedrock and then deposited sand containing marine fossils and rip-up clasts of lake mud. The large erosion suggests very strong currents through the basin and indicates that the waves extended to a much greater height than 4 m a.s.l., probably at least 10 m a.s.l. Also, based on the tsunami deposits, Grauert et al. (2001) concluded that at least two large waves inundated the basin.

Sea level has been below present day sea level on the Faroe Islands during the last 10,000 years. Grauert et al. (2001) estimated that sea level when the tsunami happened was at least 10 m below present day sea level. This gives a minimum runup of 14 m. Considering that the wave was probably reaching many meters above the above mentioned lake, we think the runup in this area may have been as high as 20 m.

The numerical simulation of the wave in open water just to the east of Suderøy Island (Fig. 2, Table 1) show maximum surface elevations of between 5.7 and 7.2 m, well below the field observations. The field observation site is located at the head of a fjord. The fine grid simulations from western Norway show that the bathymetry near the coast is of importance for the surface elevation. We have thus calculated the wave propagation into the fjord using Greens law. This calculation shows that the wave height increases to 19 m using simulation 2 and 22 m using simulation 1 at a water depth of 45 m in the fjord, 6–7 km from the field site. However, the uncertainties in these analytical estimates are higher than for the results from the numerical model.

4.3. The Shetland Islands

Storegga tsunami deposits are present both in lakes and in peat outcrops (Bondevik et al., 2003). The sites are located in the northern and eastern part of Shetland. In a fjord/inlet called Sullom Voe, the Storegga sand layer could be traced in peat up to 9.2 m above present high tide. The thresholds of the studied lakes are all found a couple of meters above the present sea level.

Sea level at the time of the Storegga tsunami was much lower than today. Dated submerged peat (Hoppe, 1965) and a modelled sea level curve (Lambeck, 1993) suggest the sea level to be more than 10–15 m lower than today at this time. This suggests a vertical run-up of at least 20–25 m for the Sullum Voe area. For the lakes that were located a couple of meters above sea level on the eastern and northern coast the run-up may have been less than the 20–25 m found for the Sullom Voe area, but still larger than 12–15 m (Bondevik et al., in press)

The surface elevations generated by the Storegga tsunami have been calculated just to the north of Shetland giving values of 7.1–8.0 m (Fig. 1, Table 1). The time series is used as a basis for estimating the maximum surface elevation near the field site Sullom Voe. Using the analytical method as for the Faeroe Islands we obtained surface elevations of 19–21 m at a present water depth of 48 m, about 3 km north of the field location.

4.4. Scotland

On mainland Scotland the tsunami deposit occur as a sand layer found within estuarine clay and silt and continue into terrestrial peat. At each site the sand layer can be traced landward where it becomes thinner and increases in elevation. The range of run-up estimates is between 3 and 6 m above the high water mark (Dawson, 1999; Dawson and Smith, 2000). The sites in Scotland are similar to the Shetland sites in that the deposits are found within peat, but differ from them in that here they can be traced seawards into former estuarine sediments and that the latter can be used to define the position of the high tide when the tsunami struck.

The numerical simulation from the east coast of Scotland (Fig. 1) shows maximum surface elevations of 4.2–5.9 m. The field observations along the Scottish coast are located in sheltered estuaries rather than deep fjords and thus the simulated surface elevations near Scotland are probably not amplified to the same extent as close to the field sites at the Faeroe Islands and Shetland.

4.5. Simulation of retrogressive slides

According to both morphological and geotechnical studies the Storegga slide developed retrogressively. This means that the slide started somewhere in the lower part of the slope releasing blocks and wedges as it retreated up-slope. Obviously this effect had some impact on the surface elevations. Fig. 10 shows that the effect of the time lag on the generated maximum surface elevation varies for different maximum slide velocities for a slide similar in size to the Storegga slide (see Section 3 for further details). The simulations also show that the effect is directional, i.e. that the maximum surface elevation is reduced more as a function of the time lag at front of the slide than at the rear. Even small time lags reduce the maximum surface elevation in the front, while the maximum surface elevation at the rear is increased for time lags less than 10–12 s. For the waves propagating sideways, one should expect a mean value of the front and rear correction to the maximum surface elevation generated by a fixed shaped slide.

5. Discussion

Deposits from the Storegga tsunami are found from Northern England to Northern Norway. Sites in Shetland and on the Faeroe Islands show a large run-up, more than 15–20 m at the head of small fjords. The run-up estimates from deposits along the outer coast of Norway show run-up of 9–13 m near the slide area, decreasing away from the slide. These large waves extending over such a vast area indicate that most of the volume of the slide was involved in the generation of the tsunami.

According to both morphological and geotechnical studies the Storegga slide developed retrogressively. This means that the slide started somewhere in the lower part of the slope releasing blocks and wedges as it retreated up-slope. If the slide developed with very short time lags between the blocks it can be regarded as one block sliding downwards as we have done in our model. A slide velocity below 20 m/s gives the best fit to the field observations in western Norway. Both Bjugn and Sula show a good fit for a maximum velocity around 15 m/s, while Bergsøy indicate a maximum velocity below 10 m/s (Fig. 9). The more distal sites Scotland, Shetland and the Faroe Islands also fit to a maximum velocity of 20 m/s (Fig. 2, Table 1).

For larger maximum velocities the model does not match the field observations (Fig. 9) without involving a retrogressive motion of the slide that significantly reduces the wave heights. A maximum velocity of 35 m/s without a retrogressive slide motion agrees well to the sites in Shetland and the Faeroe Islands (Fig. 2, Table 1), when

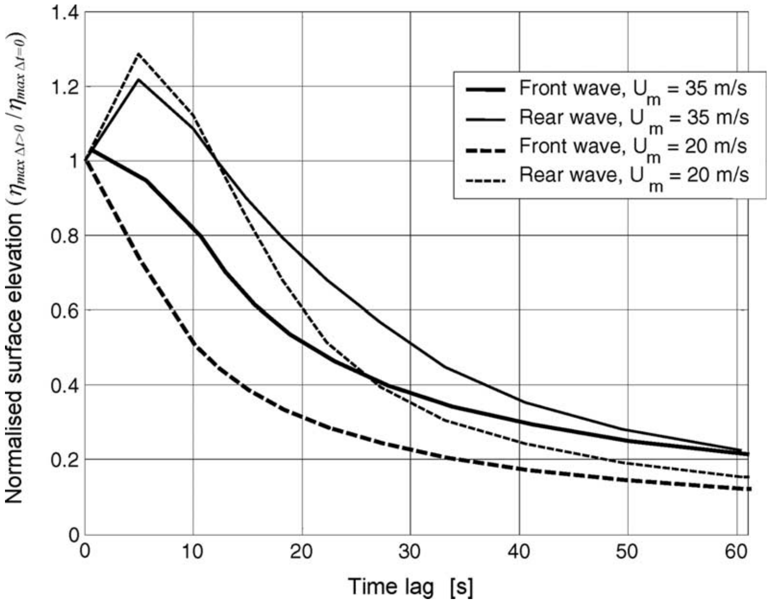


Fig. 10. Maximum surface elevation ($\eta_{\max}$) as a function of time lag (Δt) between rectangular sliding blocks in a 2-D slide model. The 2-D model is comparable in size to the Storegga slide. It consists of 167 blocks, each being 240 m thick and 600 m wide, that are released with an equal time lag (Δt) between the individual blocks in a basin with a uniform water depth of 1000 m (see Haugen et al. (2005) for more details on the model). The values on the *y*-axis are the maximum surface elevation $\eta_{\max}$ for $\Delta t \geq 0$ divided by the maximum surface elevation $\eta_{\max}$ for a fixed shaped slide ($\Delta t = 0$). This illustrates the change in maximum surface elevation due to the retrogressive nature of the slide. A time lag of 15–20 s between the individual blocks would reduce the surface elevation with a factor of 0.75.

fjord amplification is taken into account, but does not fit any of the sites in western Norway (Fig. 2, Table 1). Largest deviation is seen for Bergsøy and Sula where the simulated waves reach heights of 20 and 23 m which is twice the elevations from the field observations.

A maximum velocity between 25 and 30 m/s with a retrogressive reduction of the surface elevation with a factor of 0.75 would make the best match to the field observations (Fig. 10; Table 1). According to our retrogressive slide model such a reduction is obtained with a very little time lag, about 15–20 s between the sliding blocks. Velocities of 25–30 m/s are also supported by De Blasio et al. (2005), who finds mean (centre of mass) slide velocities of 25–35 m/s in their run-out studies of the Storegga slide. To make the 35 m/s-velocity simulations fit the field observations in western Norway a time lag of about 30 s must be applied. However, such a large reduction does not match the field observations in the coastal areas to the west of the Storegga slide.

6. Conclusions

(1) The Storegga slide generated exceptionally large waves that inundated most coastlines around the North Sea/Norwegian Sea. Deposits are found from northern England to northern Norway. In fjords in Shetland and the Faeroe Islands deposits show that the waves reached elevations to at least 20 m above the contemporary sea level. These large waves, which extended over such a large area, show that most of the volume of the slide was involved in the generation of the tsunami.

(2) The numerical simulation is based on a slide model that fits the new reconstructions of the Storegga slide. In this model a larger portion of the slide occurs in the upper part of the slope where it is 400 m thick. Because of this, the simulations of tsunami run-up at the Norwegian coast are much more sensitive to changes in the parameters describing the slide than areas to the west of the slide.

(3) The time series derived from the numerical simulations are compared to field observations of tsunami run-up from western Norway, Scotland, Shetland and the Faeroe Islands. (a) If the slide developed as one block sliding downwards, or with very short time lags (less than 5 s) between the individual blocks, a slide with a maximum velocity of 20 m/s fits the field observations best. (b) However, if the slide developed with a larger time lag between the blocks a maximum velocity in the range of 25–30 m/s with a time lag of 15–20 s gives the best agreement with the field observations. (c) A time lag >30–40 s between the individual blocks will generate waves that are too small to match the field observations.

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