

ORIGINAL PAPER

Open Access



Seiches and the slide/seiche dynamics; subcritical and supercritical subaqueous mass flows and their deposits. Examples from Swiss Lakes

Christoph Siegenthaler* 

Abstract

Four historically documented large and potentially dangerous lacustrine waves in Swiss lakes show that these waves have been seiches (standing waves) triggered by sublacustrine slides; a statement which is in accordance with the experience of seismologists who see earthquakes triggering seiches in lakes. Nevertheless, large historical waves in Switzerland have recently been modeled as progressive shallow water waves (tsunamis), probably because the slide/seiche dynamics are not known, and experiments with subaqueous slides fail to generate seiches in test-flumes. It appears that these tests exhibit a small shear–energy/slide–energy ratio ϵ , if compared with the situation in lakes. These facts incite a *shear–stress lemma* that states that ϵ is the constituent factor for the slide/seiche coupling. The structure of the subaqueous mass flow deposit (MFD) in lakes Lucerne and Geneva suggests the occurrence of subcritical and of supercritical slide flows. The former would generate a contortite, a MFD with contorted bedding, the latter a debrite (mudclast conglomerate). Potential slide energy considerations are used for an estimation of the amplitudes of large seiches produced by subaqueous slides, a proceeding that yields partly similar and partly very different results, as compared with numerical tsunami simulations.

Keywords: Historical reports, Homogenite, Contortite, Debrite, Internal hydraulic jump, Shear energy, Slide/seiche dynamics, Shear–stress lemma, Lake Geneva, Lake Lucerne, Lake Brienz

1 Seiches and progressive shallow water waves (Tsunamis) in lakes

Since almost 20 years after Siegenthaler et al. (1987) had found an earthquake/MFD coupling in Lake Lucerne, several studies on Swiss sublacustrine mass flow deposits (MFD) have been published, primary to reconstruct the local earthquake history (Kremer et al., 2015; Schnellmann, 2004; Schnellmann et al., 2002, 2006; Schwestermann, 2016; Strasser & Anselmetti, 2008; Strupler, 2017). Later, the coupling “subaqueous slide/wave” came into

the focus of interest because of the need to know more about the hazards of dangerous large waves in lakes. Siegenthaler et al. (1987) identified large and potentially dangerous waves in Lake Lucerne as seiches, triggered by subaqueous slides after an earthquake occurred. The seiche/earthquake coupling in lakes had been already been demonstrated by Mercanton (1946), Wilson (1953), Kvale (1955), Richter (1958) and McGarr and Vorhis (1968). Schnellmann (2004) called these waves “tsunami and/or seiches” and from that time on large waves in Swiss lakes have always been called tsunamis without any further discussion (Strasser & Anselmetti, 2011; Girardclos & Kremer, 2012; Kremer et al., 2012, 2015; Hilbe & Anselmetti, 2015; Strupler, 2017).

Editorial handling: Daniel Ariztegui.

*Correspondence: christoph.siegenthaler@bluewin.ch
Zürich, Switzerland



© The Author(s) 2021. **Open Access** This article is licensed under a Creative Commons Attribution 4.0 International License, which permits use, sharing, adaptation, distribution and reproduction in any medium or format, as long as you give appropriate credit to the original author(s) and the source, provide a link to the Creative Commons licence, and indicate if changes were made. The images or other third party material in this article are included in the article's Creative Commons licence, unless indicated otherwise in a credit line to the material. If material is not included in the article's Creative Commons licence and your intended use is not permitted by statutory regulation or exceeds the permitted use, you will need to obtain permission directly from the copyright holder. To view a copy of this licence, visit <http://creativecommons.org/licenses/by/4.0/>.

Usually, tsunami waves are understood to be surface gravitational waves exhibiting periods within the range $T \sim 10^2 - 10^4$ [s]. Tsunamis pertain to long waves, therefore not only the subsurface layer, but the entire thickness of water becomes involved in the motion. The propagation velocity c of long waves in a reservoir of depth D is determined by the formula $c = (gD)^{1/2}$, g is the free-fall acceleration of gravity (Lewin & Nosov, 2009). For tsunamis, which are shallow water waves, λD^{-1} is larger than ~ 10 (Katopodes, 2019) and the period p is $= \lambda c^{-1}$ with $p > 10 (D/g)^{1/2}$, λ is the wavelength. The potential and the kinetic energies of the tsunami are both $0.25 \cdot \rho g a^2$ per unit horizontal area, ρ is the water density, and a is the amplitude of the wave (Wiegel, 1955). The large horizontal kinetic energy of tsunamis leads to important wave set-ups when approaching a shore and strengthens the destructive forces of the waves. It turns out that for hydrostatic reasons the lead of a tsunami is a wave crest if the wave has been triggered by a submarine slide (Rabinovich et al., 2003): the displacement of parts of a delta towards the open sea provokes a depression of the sea level above the delta and a sea level elevation seawards.

Seiches, or standing waves, are rhythmic, rocking motions that water bodies undergo after they have been disturbed and then sway back-and-forth as gravity and friction gradually restore them to their original, undisturbed conditions (Korgen, 1995). The water level is constant at nodal lines and is a maximum and a minimum at antinodal lines. In long basins the antinodes are usually encountered at the front sides of elongated basins, associated with a wave set-down depending on the topography of the shore. The period T_n in rectangular basins is $2 \cdot l \cdot n^{-1} \cdot (gD)^{-1/2}$, n is the number of nodes, $n = 1, 2, 3, \dots$, l is the basin length and $2 \cdot l \cdot n^{-1}$ is the wave-length (Merian, 1828; Rabinovich, 2010). The period is hardly affected by small deviations from the vertical rectangularity of basins, e.g., with a trapezoidal lake bottom (Wilson, 1953). The horizontal water velocity is a maximum below a node with a back-and-forth motion $V = \pm 2 \cdot a \cdot (gD)^{1/2} \cdot D^{-1}$, a is the wave amplitude (Katopodes, 2019). This motion disappears below an antinode. The fundamental oscillation mode with $n = 1$ often prevails in narrow basins such as Lake Zurich and Lake Geneva (personal observations, Anonymous, 1954). A special seiche is the harbor wave with $n = 0.5$, the node being at the entrance of the harbor or bay and the antinode at the end of the bay. The energy of a seiche is half the energy of a tsunami if both waves have the same amplitude (Wiegel, 1964). Damages due to seiches are often limited to harbors, where fixed and floating installations, such as ships, are destroyed—a typical seiche attribute (Rabinovich, 2010). It is important to know that relevant aspects of seiches are not yet known,

especially the slide/seiche energy relation if the seiche is triggered by a slide.

Large seiches in lakes can be disastrous: on June 26, 1954, eight fishermen were swept away from the pier when a ~ 3 m seiche hit the Chicago waterfront on Lake Michigan. A seiche in Lake Erie on October 18, 1844, demolished buildings and claimed 39 lives. In Lake Lucerne 9 lives were claimed on September 16, 1601 (Cysat, 1601; Katopodes, 2019).

The symbols and notions most frequently used are as follows. a : wave amplitude [m]; c : wave velocity [ms^{-1}]; g : gravitational acceleration [ms^{-2}]; g' : densimetric gravitational acceleration $g \cdot (\rho_{\text{sed}} - \rho_w) \cdot \rho_{\text{sed}}^{-1}$, ρ is the density [kg m^{-3}]; h : slide thickness; D : water depth; E : energy; ε : energy ratio; L : the slide length; V : velocity; mass flow deposit, MFD: the slide mass plus the lake bottom sediments eroded by the slide [m^3]; contortite: MFD with contorted bedding; mudclast–conglomerate or debrite: a MFD, matrix and conglomerate are both fine grained and differ generally only in color; homogenite: a fine-grained deposit of a suspension cloud; hydraulic jump, a forced internal supercritical flow impinging on an obstacle. The subscripts w, sl, sh and sed refer to water, slide, shear, and sediment. The Reynolds number Re for shear is $VL\nu^{-1}$ and the Froude number Fr of the slide is $V(g' h)^{-0.5}$, V is the slide velocity; $\nu \cdot (10^{-6} \text{ m}^2 \text{ s}^{-1})$ is the kinematic viscosity of water.

2 Historical large waves in Swiss Lakes

On February 23, 1549, the surface of Lake Constance rose and fell at Constance with an amplitude of ~ 0.3 m, the Rhine flowed backwards and forwards near the town and there was no wind. This happened five times in about 1 h until after noon, but decreased with time. No damages were noticed (Hollan et al., 1980). A subaqueous MFD in 70 m depth is known, with a volume of $70,000 \text{ m}^3$ and dated 1581 ± 93 (Schwestermann, 2016). On March 11, 1584, after an earthquake, a rocking of Lake Geneva occurred, the Rhone flowed backwards at Geneva. The riverbed dried out for an estimated quarter of an hour and people looked for fish and iron in the riverbed. This happened three or four times, the difference between low and high water was 1.5 m, obviously enlarged by the funnel-shaped Little Geneva Lake. The description of the activities of the riparians in Geneva during low water suggests a wave period of around one hour. The water was impetuous in the harbors and was quiet nearby and “at many other places”. A wave height of three spears (~ 6 m) is mentioned with no further particulars about the location but only minor damages were reported (Egli, 1901; Fritsche et al., 2012; Schwarz–Zanetti, 2008). The volume of the MFD is difficult to figure, a simultaneous subaqueous slide south of Lausanne

amounts to 1 Mm^3 , another slide is presumed in the Rhone delta (Kremer et al., 2015). The total slide volume is possibly not more than 1.5 Mm^3 . On September 16, 1601, large waves occurred in Lake Lucerne after an earthquake, a rock-fall and more than 10 sublacustrine slides. At that time the lake level was $\sim 1\text{--}2 \text{ m}$ lower than today (Siegenthaler et al., 1987). According to the eyewitness Cysat (Cysat, 1601) the water went up and down in Lucerne with a period of $\sim 10 \text{ min}$ and the bed of the river Reuss dried out periodically. After around eight hours the movements faded out. In the funnel-shaped basin of Küssnacht the wave was as high as $\sim 4 \text{ m}$. Nine persons drowned at Buochs and Beckenried, two locations in the vicinity of the largest slide with a volume of $\sim 50 \text{ Mm}^3$, when an estimated 4 m surge flooded the alluvial plane of Buochs 800 m further inland. Ships were destroyed at several places; other damages were not reported. The volumes of all the 1601 MFDs amount to around 80 Mm^3 (Schnellmann, 2004; Siegenthaler et al., 1987). At ten in the night of September 23, 1687, the waters of Lake Uri went up and down during one or two hours “like a marine tide”, as well as in Lucerne with an amplitude of 0.7 m . Severe damages occurred in Brunnen and in Treib, on the other side of the lake, where the water rose more than 2 m ; at Brunnen displacements of large rocks and destructions of harbor walls were reported. It was night and most people were at home and sheltered. More than 10 Mm^3 of the Muota delta at Brunnen had slumped down into the basin of Uri (Siegenthaler & Sturm, 1991).

Excuse 1. Many large prehistoric MFDs are documented in Lake Lucerne (Schnellmann, 2004). In the seventeenth century the contemporaries of Lucerne and Uri called large destructive waves “Wasserbidem”. The expression is unknown today, as well as the verb “bidmen”, which describes a rocking motion (Bachmann & Gröger 1898), a description identical with Korgen’s definition of seiches (Korgen, 1995). The expression “Wasserbidem”, which was used until at least 1687 by the riparians of Lake Lucerne, is seen as an indication that the occurrence of large seiches was always present in language as a collective memory (Halbwachs, 1967).

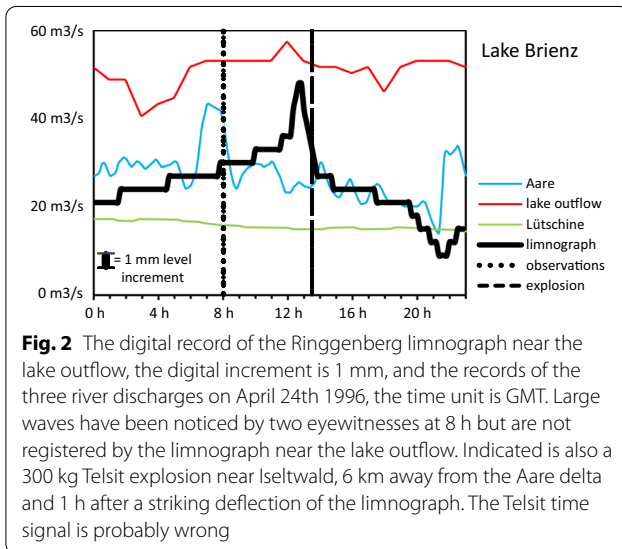
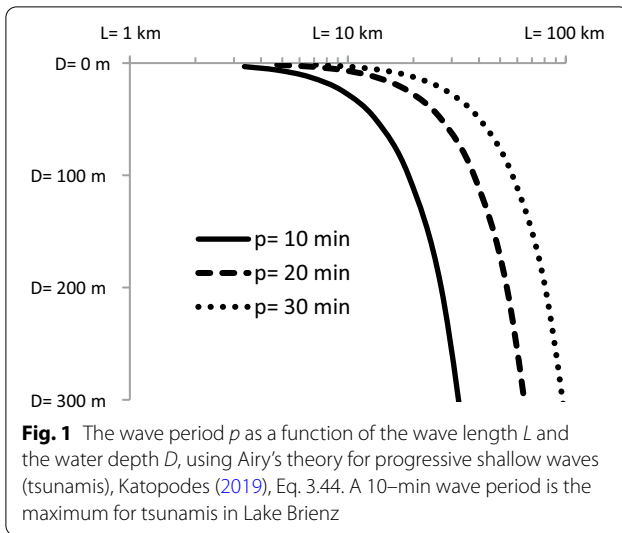
According to all these accounts the water level went quietly up and down, causing damages mainly to the fastened ships in harbors, phenomena typical for large seiches (Rabinovich, 2010). Hazardous events, especially 1601 and 1687 in Lake Lucerne and probably 1584 in Lake Geneva, occurred near the slides. Such waves are considered to be large local surges and have been erroneously interpreted as tsunamis, e.g. by Siegenthaler and Sturm (1991).

The April 24th, 1996, events in Lake Brienz were examined by Girardclos et al. (2007). A floating 50-ton

dredging bagger was tightly anchored with five wire cables, two of them onshore and three anchored offshore in the Aare delta. At about 8:00 GMT two wire cables, one onshore and one offshore broke at once. After this incident, upon reaching the harbor, the team reported that the boat was then half a meter lower on the quay than normal. Sometime later, the workers noted that the boat was then half a meter higher than its former position and deduced that the lake level was greatly fluctuating without generating any noticeable surface waves. The period between the highest and the lowest lake level was $15\text{--}20 \text{ min}$. The wave phenomenon is regarded, without further substantiation, as a tsunami or tsunami-like wave by Girardclos et al. (2007).

Lake Brienz is a NE–SW orientated basin, whose length, mean width, and maximum depth are 14 km , 2 km and 260 m , respectively. The lake basin is distally connected by a 5 km long channel to the 17 km long and 3 km broad Lake Thun. On April 24th, a collapse of the Aare delta generated a turbidity current and a 2.7 Mm^3 turbidite. The digital limnograph near the lake outflow measures the lake level every second and lists the mean during periods of $d = 10 \text{ min}$, i.e., 600 measurements per period. Such a limnograph program would ignore sinusoidal water-level motions with periods $p = d/n$, $n = 1, 2, 3, \dots$, since at the end of the period p the record of the water level returns to the position at the start of that period. The fundamental seiche period ($n = 1$) in Lake Brienz is $\sim 10 \text{ min}$. The period is $\sim 20 \text{ min}$ ($n = 0.5$) and is possible if Lake Brienz is regarded as an appendix of Lake Thun. Such a seiche is called harbor wave.

The slow vertical motion of the water-table at the shore, observed by the eyewitnesses, is a strong indication against a tsunami, a wave which may not occur in lake Brienz if the wave period is $\geq 10 \text{ min}$ (Fig. 1). Decisive are the limnograph data of the station Ringgenberg near the western end of the lake. These data do not give the slightest indication of a wave around 8:00, April 24th (Fig. 2), a tsunami is therefore definitely excluded. The opposite opinion of Girardclos et al. (2007) is not comprehensible, since they knew, but do not report, the limnograph data of that day. The following interpretation of the April 24 event is proposed. (i) The observed wave is a seiche. (ii) The eyewitnesses mistook an observed wave–period of $15\text{--}20 \text{ min}$ for a half wave period, communicated ten years after the event. (iii) The seiche was a harbor wave with a 20 min period, a wave with this period a limnograph near the node at the lake outflow cannot register. (iv) The limnograph data indicate another event the same day, thirty minutes past noon.



Possibly a second sub-lacustrine slide occurred, triggered by a nearby explosion, provided the given times are not correct (Fig. 2).

No eyewitness report is known about the great wave disaster in Lake Geneva, 563 CE, with many casualties, and generated by a sublacustrine slide with an estimated volume of 250 Mm³ (Kremer et al., 2015). A large slide scar is still visible on the 1:25'000 map, a deep depression in the western part of the Rhone delta, adjacent to the steep north-dipping flank of the lake basin (Office Fédéral de Topographie 2018, map #1264). The 563 CE event

is mentioned in two chronicles, a short text from bishop Marius who was 573 CE sent to Avenche, the diocese of Lausanne, and a longer chronicle from the bishop of Tours, 500 km W of Geneva and written 20 years after the event (Schoeneich et al., 2015). The former chronicler mentions that there were victims and severe damages in the city of Geneva. Conversely, no casualties were reported in Lausanne, the biggest city and namesake of the lake at that time, Lacus Lausonnus, Lacus Losanete (Bergier, 2009). The bishop of Tours on the other hand tried to elaborate a logical sequence of events which did lead to the catastrophic 563 CE wave. He assumes a huge landslide that dammed the river in the upper Rhone valley and generated a lake behind this barrier. There is evidence neither for a landslide nor for a lake at that place (Schoeneich et al., 2015) and hence it must have been an invention of the bishop's chronicler.

Excuse 2. The chronicler of Tours did use the suppositious lake in the upper Rhone valley to explain the enormous water wave in Lake Geneva after a suppositious breakdown of the dam. It is extremely strange that he used the expression *aqua retrorsum petiit*, the water flowed backwards, just for to say that a lake is growing behind the suppositious landslide. Writing a text on such a strange event 20 years earlier, any chronicler must obviously evaluate a multitude of often-contradictory messages, letters, rumors, eyewitness reports of such a disaster never heard of before. A chronicler could omit what is not credible or he could try to find an explanation for the unbelievable if he thinks to have rather trustworthy reports. It seems that the chronicler of Tours tried to attempt the latter. He could of course not believe an information about a backward flow of the Rhone at Geneva, concomitant with the flooding of the town. So, he transferred such reports eastward to the supposed dammed and growing lake in the upper Rhone valley and thus attested credibility to corresponding informants. His text suggests that the chronicler invented a dammed lake in the upper Rhone valley to explain the wave disaster in Lake Geneva, but also to move to the upper Rhone valley reports of a *Rhodanus retrorsum petiit* at Geneva.

A tsunami, 563 CE, would be excluded if a backward flow of the Rhone at Geneva had been observed by contemporaries: after the arrival of a tsunami crest, there would have been no witness to watch the Rhone's behavior during the subsequent wave trough. A wave crest/trough sequence is expected if the tsunami is generated by an underwater slide (Rabinovich, 2010).

3 The shear–stress lemma

In the nineties the author ran, together with K. Kelts, a series of tests with sliding subaqueous bodies in the 6 m long and tiltable flume of the Geological Institute of the ETH Zürich. Standing waves did never occur. In laboratory conditions seiches result if a wind shear stress is applied on the water surface, as shown by Tickner (1961). This fact would suggest that a shear stress at the other boundary of a water basin, the lake bottom, exerted by a sublacustrine slide, does produce seiches. Such a proposition, called *shear–stress lemma*, is plausible if it can be shown that the shear–energy/slide–energy ratio, $E_{sh}/E_{sl} = \varepsilon$, is less in flumes than in lakes. The following approximation operates with mean values of the shear force W and mean values of the free fall velocity V ,

$$W = \rho_w V^2 b L c_w \cdot \cos(\beta) \left[\text{kg m s}^{-2} \right], \quad (1)$$

if the subaqueous slide is considered to be a rigid plate (Blasius 1908; Schlichting, 2006, Eq. 2.10); L and b are the slide length and width, ρ_w is the water density, c_w [–] is the drag and β is the slope angle of the slide. The kinetic energy of a slide with thickness h is

$$E_{sl} = \rho_{sl} V^2 b L h \left[\text{kg m}^2 \text{s}^{-2} \right] \quad (2)$$

and the shear/slide energy ratio is

$$\varepsilon = E_{sh}/E_{sl} = c_w \cdot \rho_w / \rho_{sl} \cdot L/h \cdot \cos(\beta) \quad (3)$$

ε is an expression of the kinetic slide energy percentage transferred as shear energy to the water body. $E_{sh} = WL$ is the shear energy transferred to the water. The drag c_w of a plate is a function of the Reynolds number,

$$k^{-1} \ln(0.5 \cdot c_w \cdot \text{Re}) - 5 = 0 \quad (4a)$$

if $\text{Re} > \sim 10^4$ (Schlichting, 2006, Eq. 18.98), k is the Karman constant, $k = 0.4$; or

$$c_w = 1,328 \text{ Re}^{-0.5}, \quad (4b)$$

if $\text{Re} < \sim 10^4$, according to Blasius (1908) (Schlichting 2006, Eq. 2.10). The addend -5 in equation 4a presupposes a rough slide/water interface; the result is insignificantly affected if the interface is interpreted as smooth. The function

$$\varepsilon = f(\text{Re}) \quad (5)$$

is plotted in Fig. 3, which shows that the energy ratio ε is less in flumes with $\text{Re} \sim 10^5$, if compared with lakes. The shear–stress lemma can explain the absence of seiches generated by slides in flumes and would predict seiches in miniature models with $\text{Re} < 10^4$.

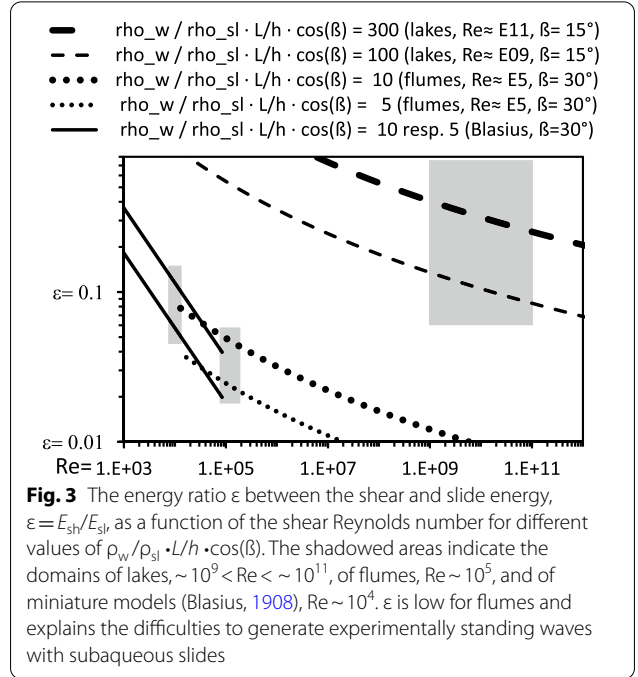
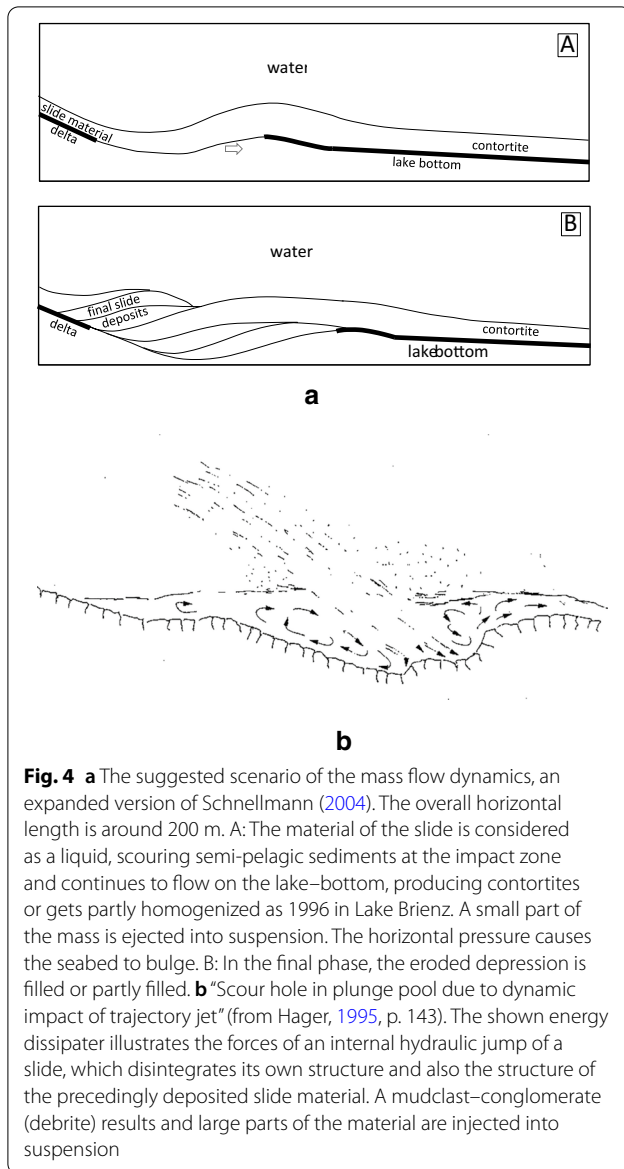


Fig. 3 The energy ratio ε between the shear and slide energy, $\varepsilon = E_{sh}/E_{sl}$, as a function of the shear Reynolds number for different values of $\rho_w/\rho_{sl} \cdot L/h \cdot \cos(\beta)$. The shadowed areas indicate the domains of lakes, $\sim 10^9 < \text{Re} < \sim 10^{11}$, of flumes, $\text{Re} \sim 10^5$, and of miniature models (Blasius, 1908), $\text{Re} \sim 10^4$. ε is low for flumes and explains the difficulties to generate experimentally standing waves with subaqueous slides

4 Mass flow deposits

Based on the detailed investigations of Schnellmann (2004), the sedimentary structures generated by the mass flow events in different basins of Lake Lucerne on September 16, 1601, suggest the following kinematics: A section of a slope or delta deposit becomes unstable and starts to move downward, hitting the lake bottom. The impact zone is seismically transparent and usually ~ 10 m deep and distally up to 200 m long, virtually identical with the impact zones of marine slides (Casalbore et al., 2016). The impact scours the lake bottom (Fig. 4a). The maximum velocity V of the slide is $(2 \cdot g' H)^{0.5}$ for free fall, H is the vertical distance of the slide mass center to the deposition plane. The Froude number for a subaqueous slide is $V \cdot (g' h)^{-0.5}$ and gets $\text{Fr} = (2H/h)^{0.5}$, h is the thickness of the slide; it is therefore expected that a slide flow can attain a supercritical state. The MFD distally of the impact zone was studied in Lake Lucerne by Schnellmann (2004) and Siegenthaler et al. (1987), and in Lake Geneva by Kremer et al. (2015). The deposit of these events comprises three different strata, which are from bottom to top:

- i. A sheet-like contortite, consisting of slope- or delta-sediments and of scoured lake-bottom layers, as shown in Fig. 4a. Its state during the flow is considered to be a fluid, as can be seen from the contortite of the 50 Mm³ slide in the Gersau basin where the even upper boundary of the contortite is not affected



by a 4 m high and 500 m wide bump of the underlying lake bottom (Siegenthaler et al., 1987). Contortites are the dominant MFDs in Lake Lucerne but are missing in the 563 CE in Lake Geneva, at least distally, proximal deposits are seismically not visible and out of reach for Kullenberg borings.

- ii. A few dm thick mudclast-conglomerate occasionally overlays the contortites in Lake Lucerne, the slope angles of the slides are generally $\sim 20^\circ$ and the slide masses amount to a few Mm^3 . An up to 5 m thick mudclast-conglomerate, named debrite by Kremer et al. (2015), is distally the basal layer of the large 563 CE mass flow in Lake Geneva.

Excuse 3. In the late Eocene a ~ 10 m thick mudclast-conglomerate (called "Fleckenmergel", spotty marl-

stone, by hard-rock geologists) does ring in the impressive sequence of turbidites, the "Taveyannaz series", in the eastern Northhelvetic Flysch of Switzerland (Siegenthaler, 1974).

- iii. The final MFD is a homogenous silty mud with graded sand at its base but also occasionally intercalated within the deposit, as seen in the Gersau basin of Lake Lucerne. Kastens and Cita (1981) called such a deposit homogenite whereas Kremer et al. (2015) and Schnellmann (2004) regarded it as a turbidite. Strictly speaking, the homogenite corresponds to the last layer of the Bouma cycle and is the fall-out of a large suspension cloud. The mass-ratio, homogenite/(contortite plus debrite), is around 0.1 in the Lake Lucerne basins and around 0.5, in the 563 CE event in Lake Geneva.

Such a sequence does not occur in Lake Brienz. A probably important difference to the basins of Lake Lucerne concerns the densities of the sediments, which amount to $\sim 1.5 \text{ g/cm}^3$ in the former, and to $\sim 1.2 \text{ g/cm}^3$ in the latter lake (Girardclos et al., 2007; Schnellmann, 2004). g' , and the slide energy per unit mass, are therefore two times larger in Lake Brienz. In addition, it seems that two different slides occurred the same day in Lake Brienz.

Comparing the MFDs of the 563 CE event in Lake Geneva with the 1601 CE events in the basins of Lake Lucerne, the following facts can be noted:

- (i) A stratigraphic sequence "contortite — occasionally a thin debrite — homogenite" in Lake Lucerne, a "debrite — homogenite" sequence in Lake Geneva (contortites are missing distally),
- (ii) An always abrupt structural change at the "contortite — debrite" boundary in Lake Lucerne,
- (iii) A homogenite/slide mass ratio of ~ 0.1 in Lake Lucerne and of ~ 0.5 in Lake Geneva,
- (iv) Debrites associated with a large mass flow in Lake Geneva, and associated with steep slide planes in Lake Lucerne.

These observations suggest a possible change of the mass flow dynamics during the flow. If the slide attains a high velocity, the slide, considered as a liquid, may enter a supercritical state with $\text{Fr} > 1$. A forced internal shooting flow impinging on a soft rock is then established which is eroded and becomes fluidized, a situation comparable with an internal hydraulic jump (Hager, 1995). The sedimentary structures of the involved masses are completely destroyed by the impact and a debrite results; a large part is ejected into the water as a suspension cloud. Such a mass flow scenario is sketched in Fig. 4b.

Table 1 The seiche/slide energy ratio of two events in Lake Lucerne and in Lake Geneva have been used to estimate the seiche amplitudes, see Chapter 5; italics indicate input data

Lake Geneva: $f = 4.0$ slide density = 1400 [kg m ⁻³] $*0.19 = 0.75/f$	mean fall height of slides [m]	lake area [m ²]	slide volume [m ³]	E_{slide} : slide energy [J]	E_{seiche} : seiche energy [J]	energy ratio $E_{\text{seiche}}/E_{\text{slide}}$	seiche amplitude in the lake [m]	maximum amplitude at Geneva [m]
Lake Geneva 563 CE	150	$5.82 \cdot 10^8$	$2.5 \cdot 10^8$	$1.5\text{E} + 14$	$8.5\text{E} + 12$	5.7%	2.42	~ 10
Lake Geneva 1584 CE	150	$5.82 \cdot 10^8$	$1.5 \cdot 10^6$	$9.0\text{E} + 11$	$5.1\text{E} + 10$	5.7%	*0.19	0.75
Lake Lucerne 1601 CE	90	$1.10 \cdot 10^8$	$8.0 \cdot 10^7$	$2.9\text{E} + 13$	$9.7\text{E} + 11$	3.4%	1.88	
Lake Lucerne 1687 CE	100	$1.10 \cdot 10^8$	$1.0 \cdot 10^7$	$4.0\text{E} + 12$	$1.3\text{E} + 11$	3.4%	0.70	

The forecast seiche amplitude of the 1601 CE event, 1.88 m, is in the estimated range of 1–2 m (Schnellmann, 2004; Siegenthaler et al., 1987). The same procedure leads to an amplitude of 2.42 m, respectively 10 m at Geneva for the 563 CE event. f figures the increase of the seiche amplitude at Geneva shown on February 12, 1950, and on July 28, 1950, due to the funnel-shaped “Petit Lac”; it must be noted, that the values in the last column are independent on f . The much larger energy ratio in Lake Geneva as compared with Lake Lucerne is expected due to the complicated basin geometry of the latter. The 563 CE seiche–amplitude at Lausanne is estimated to be around 1 m for an expected one–node seiche and is much less compared than the 13 m tsunami simulation (Kremer et al., 2012). Such a large event would have been probably mentioned by the bishop of the diocese Lausanne

5 An attempt to estimate the 563 CE wave in Geneva using a seiche energy approach

The 563 CE wave was a catastrophe for the city of Geneva, the riparians of the Petit Lac and those near the collapsing delta where a large local surge is expected. If the event is considered as a tsunami its digital simulation leads to amplitudes of 8 m in Geneva and to 13 m in Lausanne (Frei & Marongiu, 2019). An energy comparison is used for a rough estimation of the amplitudes of a seiche generated by a subaqueous slide, with the following assumptions: (i) The seiche/slide energy ratio of a specific basin is independent of the slide mass magnitude. This assumption is tested in Lake Lucerne with two mass flow events, 1687 CE and 1601 CE, and slide volumes of 10 Mm^3 and 80 Mm^3 , respectively. (ii) The wave–amplitude increase in the funnel-shaped “Petit Lac” is similar to the amplitude increase of wind driven seiches measured during a limnograph campaign 1950–1952 in Lake Geneva (Anonymous, 1954). (iii) The wave set-down of large seiches at shores is neglected. The result is shown in Table 1. The calculated seiche amplitude of 10 m in Lake Geneva is similar to the modeled tsunami amplitude (Girardclos & Kremer, 2012) but the seiche energy is only half of the tsunami energy, the destructive forces of a seiche are therefore significantly lower. The estimated seiche/slide energy ratio e in Lake Geneva is 5.7%, the shear/slide energy ratio ε is $\sim 20\%$ according to the shear stress lemma (Fig. 3, $\text{Re} \sim 10^{11}$). It follows that $\sim 1/3$ of the shear energy is converted to seiche energy.

6 Conclusions

Archive studies show that historically documented large and potentially dangerous waves in Swiss lakes were seiches with periods of ~ 10 up to probably 70 min, accompanied by periodic river outflow interruptions, destructions of ships in harbors and large surges in the

vicinity of the sublacustrine slides. These waves had been triggered by subaqueous slides caused by earthquakes. Since the middle of the last century, seismologists claimed that earthquakes do indeed generate lake–seiches, documented by dozens of events. Assuming tsunamis in lakes is obviously just a construction to allow digital modeling and leads to an exaggerated wave risk. Distally from the impact zone of a slide, the MFD occasionally exhibits a sedimentary structure, called a debrite, that suggest the occurrence of a supercritical slide flow regime which ejects a large mass into suspension, generating a thick homogenite. Important aspects of standing waves, especially the energetic slide/seiche coupling, are difficult to investigate. Such a coupling is weak in usual models such as flumes, as postulated by shear–stress lemma which states that it is the shear force at the slide/water boundary that leads to a seiche. This lemma can explain why slide/seiche couplings may occur in lakes and in miniature lake models but not in flumes.

Received: 24 September 2020 Accepted: 2 August 2021
Published online: 04 October 2021

References

- Anonymous (1954). Les Dénivellations du Lac Léman. Département Fédéral des Postes et des Chemins de Fer. Communications du Service Fédéral des Eaux, 40, 103 p., annexes.
- Bachmann, A. & Gröger, O. (1898). Idiotikon. Schweizerisches Wörterbuch der schweizerdeutschen Sprache. Bd. IV. Antiquarische Gesellschaft Zürich.
- Bergier, J.F. (2009). Léman (lac). Dictionnaire historique de la Suisse. Attinger, Hauterive.
- Blasius, H. (1908). Grenzsichten in Flüssigkeiten mit kleiner Reibung. *Z. Math. Physik*, 56, 1–37.
- Casalbore, D., Bosman, A., Chiocci, F.L., Ingrassia, M., Macelloni, L., Sposato, A., & Martorelli, E. (2016). New insights on failure and post-failure dynamics of submarine landslides on the intra-slope Palmarola ridge (Central Tyrrhenian Sea). In: G. Lamarche, et al. (Eds.) *Submarine movements and their consequences*. (vol. 41, pp. 93–110). Springer

- Cysat, R. (1601). *Collectanea Chronica und denkwürdige Sachen pro Chronica Lucernensi et Helvetiae*. In: Quellen und Forschungen zur Kulturschichte von Luzern und der Innerschweiz (Ed J. Schmid) (vol. 1, pp. 882–888). Diebold Schilling Verlag, Luzern.
- Egli, E. (1901). Das Erdbeben im Waadtland. *Zwingliana. Mitteilungen zur Geschichte Zwinglis und der Reformation*. Zürich, 1, 240–245.
- Frei, P.Y., & Marongiu, S. (2019). Un Tsunami sur la Léman. *Tauredunum* 563. PPUR Lausanne, 187 p.
- Fritsche, S., Fäh, D., & Schwarz-Zanetti, G. (2012). Historical intensity VIII earthquakes along the Rhone valley (Valais, Switzerland): Primary and secondary effects. *Swiss Journal of Geosciences*, 105, 1–18.
- Girardclos, S., & Kremer, K. (2012). Giant Lake Geneva tsunami in AD 563. *Nature Geoscience*, 5, 756–757.
- Girardclos, S., Schmidt, O. T., Sturm, M., Ariztegui, D., Pugin, A., & Anselmetti, F. S. (2007). The 1969 AD delta collapse and large turbidite in Lake Brienz. *Marine Geology*, 241, 137–154.
- Hager, W. H. (1995). Trajectory basins. In D. L. Vischer & W. H. Hager (Eds.), *Energy dissipators* (pp. 111–150). Rotterdam Balkema.
- Halbwachs, M. (1967). *Das kollektive Gedächtnis*. Stuttgart 1967.
- Hilbe, M., & Anselmetti, F. S. (2015). Mass-movement induced by tsunami hazard on perialpine Lake Luzern (Switzerland): Scenarios and numerical experiments. *Pure and Applied Geophysics*, 172, 545–568.
- Hollan, E., Rao, D. B., & Bäuerle, E. (1980). Free surface oscillations in Lake Constance with an interpretation of the “Wonder of the rising water” at Konstanz in 1549. *Geophysik Und Bioklimatologie*, 1980, 315–317.
- Kastens, K. A., & Cita, M. B. (1981). Tsunami induced sediment transport in the abyssal Mediterranean Sea. *Geological Society of America Bulletin*, 92, 845–857.
- Katopodes, N.D. (2019). Free-surface flow. Shallow-water dynamics. Elsevier, Butterworth-Heinemann, 821 p.
- Korgen, B. J. (1995). Seiches. *American Scientists*, 83, 330–341.
- Kremer, K., Simpson, G., & Girardclos, S. (2012). Giant Lake Geneva tsunami in AD 563. *Nature Geoscience*, 5(11), 756–757.
- Kremer, K., Hilbe, M., Simpson, G., Decrouy, L., Wildi, W., & Girardclos, S. (2015). Reconstructing 4000 years of mass movement and tsunami history in a deep peri-alpine lake (Lake Geneva, France–Switzerland). *Sedimentology*, 62, 1305–1327.
- Kvale, A. (1955). Seismic seiches in Norway and England during the Assam earthquake of August 151950. *Seismological Society of America Bulletin*, 704, 847–854.
- Lewin, B.W., & Nosov, M.A. (2009). *Physics of tsunamis*. Springer, 327 p.
- McGarr, A., & Vorhis, R.C. (1968). Seismic seiches from the March 1964 earth quake. *Geological Survey Professional Paper* 544-E, 43 p.
- Mercanton, P. L. (1946). Le sisme du 25 janvier 1946—son effet sur les lacs suisses. *Society of Vaudoise Science Nature Bulletin*, 63(267), 321–323.
- Merian, J. R. (1828). Über die Bewegung tropfbarer Flüssigkeiten in Gefässen. PhD Basel. Reproduced by K. VonderMühl 1886. *Mathematische Annalen*, 27, 575–600.
- Rabinovich, A. B. (2010). Seiches and harbor oscillations. In Y. C. Kim (Ed.), *Handbook of coastal and ocean engineering* (pp. 193–236). World Scientific Publishing.
- Rabinovich, A. B., Thomson, R. E., Bornhold, B. D., et al. (2003). Numerical modeling of tsunamis generated by hypothetical landslides in the Strait of Georgia, British Columbia. *Pure and Applied Geophysics*, 160(7), 1273–1313.
- Richter, C.F. (1958). *Elementary seismology*. E. H. Freeman, 768 p.
- Schlichting, H., & Gersten, K. (2006). *Grenzschicht-Theorie* (10th ed., p. 799). Springer.
- Schnellmann, M. (2004). Late quaternary mass movements in a perialpine lake (Lake Luzern, Switzerland). Diss. ETH, 130 p.
- Schnellmann, M., Anselmetti, F. S., Giardini, D., McKenzie, J. A., & Ward, S. N. (2002). Prehistoric earth quake history revealed by lacustrine slump deposits. *Geology*, 30, 1131–1134.
- Schnellmann, M., Anselmetti, F. S., Giardini, D., & McKenzie, J. A. (2006). 15'000 years of mass-movement history in Lake Luzern: Implications of seismic and tsunami hazards. *Eclogae Geologicae Helvetiae*, 99, 409–428.
- Schoeneich, P., Weidmann, M., & Blomjous, C. (2015). L'énigme du Tauredunum enfin résolue? In: Reynard, E., Evéquo–Dayen, M., & Borel, G., Le Rhone, entre Nature et Société, Cahiers de Valesia, 29, 153–174.
- Schwarz-Zanetti, G. (2008). Erdbebenserie mit Flutwelle und Bergsturz vom 11. bis 14. März 1584 im Genferseegebiet. In: Gisler, M., Fäh, D., Giardini, D. (2008). *Nachbeben. Eine Geschichte der Erdbeben in der Schweiz*. Haupt Bern: 53–60.
- Schweizerisches Idiotikon (1881). Wörterbuch der schweizerdeutschen Sprache. Eds. A Bachmann, O Gröger.
- Schwestermann, T. (2016). Mass movement event stratigraphy in Lake Constance. Master Thesis, Manuscript, Department of Earth Science, ETH Zürich.
- Siegenthaler, C. (1974). Die nordhelvetische Flysch-Gruppe im Sernftal (Kt. Glarus). PhD Phi. Fak. Uni. Zürich, 87 p.
- Siegenthaler, C., & Sturm, M. (1991). Slump induced surges and sediment transport in Lake Uri, Switzerland. *Internationale Vereinigung Für Theoretische Und Angewandte Limnologie: Verhandlungen*, 24, 955–958.
- Siegenthaler, C., Finger, W., Kelts, K., & Wang, S. (1987). Earthquake and Seiche deposits in Lake Lucerne, Switzerland. *Eclogae Geologicae Helvetiae*, 80(1), 241–260.
- Strasser, M., & Anselmetti, F. S. (2008). Mass-movement event stratigraphy in Lake Zurich; a record of varying seismic and environmental impacts. *Beiträge Zur Geologie Der Schweiz*, 95, 23–41.
- Strasser, M., Hilbe, M., & Anselmetti, F. S. (2011). Mapping basin-wide sub-aquatic slope failure susceptibility as a tool to assess regional seismic and tsunami hazards. *Marine Geophysical Research*, 32(1–2), 331–347.
- Strupler, M.M. (2017). Basin-wide assessment of the earthquake-triggered landslide- and tsunami hazard: A conceptual approach and its application, tested in perialpine Lake Zurich (Switzerland). Diss. ETH No. 24407, 134 p. & Appendix.
- Tickner, E.G. (1961). Transient wind tides in shallow water. Technical Memorandum No. 123, Beach Erosion Board, 3+48 p., Appendix i–v.
- Wiegel, R. L. (1955). Laboratory studies of gravity waves generated by the movement of a submerged body. *Transactions American Geophysical Union*, 36, 759–774.
- Wiegel, R.L. (1964). *Oceanographical engineering*. Prentice Hall/Englewood, 532 p.
- Wilson, B.W. (1953). Coastal seiches, of Oscillations of the sea and the phenomenon of range. The Dock and Harbour Authority London, June, pp. 41–45.

Publisher's Note

Springer Nature remains neutral with regard to jurisdictional claims in published maps and institutional affiliations.