Slide-induced impulse waves in mountainous regions

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ABSTRACT

Impulse waves occur as a natural hazard particularly in mountainous regions with lakes surrounded by a steep shoreline. Landslides, rockslides, glacier calvings or avalanches then transfer its momentum to the water body thereby generating large tsunamigenic waves.
At lakes, damages are expected for the shore vegetation or possible infrastructure. In presence of a reservoir, potential dam overtopping could lead to downstream damages due to (a) direct wave impact, (b) float impact, (c) deposited float and debris or even (d) complete dam failure.
Using physical model tests conducted within various PhD theses at the Laboratory of Hydraulics, Hydrology and Glaciology (VAW) of ETH Zurich, the impulse wave generation and the wave-shore interaction were intensively investigated. Based on a computation guideline published in 2009, the possible hazard potential may be assessed. The present contribution provides an overview on impulse waves and an evaluation of underwater slide propagation and deposition features. These data are useful for the calibration of numerical models or the above mentioned assessment approach.

KEYWORDS

Landslide; Impulse wave; Physical modelling; Wave height; Slide deposition

INTRODUCTION

Impulse waves are considered a severe danger in mountainous regions. They are generated in lakes or reservoirs following a landslide, rockslide, rockfall, avalanche, or glacier impact. The usually short propagation distance and the negligible wave attenuation due to the tsunamigenic long wave behavior lead to a massive damage potential. Damages at the opposite shore are generated due to (a) direct wave impact on buildings and structures, (b) driftwood and float, and (c) their deposits after water retreat. Possible dam overtopping may lead to structural damages or even (d) a total dam failure. The generated dam break wave may then propagate downstream endangering distant settlements due to widespread flooding.
The proglacial lake at the Lower Grindelwald Glacier in Switzerland was created due to a combination of glacier melt and glacier retreat. The lake level varies over the year with an increase starting in spring with rising temperature and thus, glacier melt, a maximum still water depth of ≈ 34 m and a decrease in autumn up to complete drainage at the end of a year (Hählen 2010). The steep and unstable rock flanks provoke frequent minor slide events.
A larger 100,000 m³ landslide entered the lake in May 2009 thereby generating impulse

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waves (Fig. 1). According to video records and photographs, the initial splash height was determined to ≈ 100 m and wave run-up to ≈ 10 m.

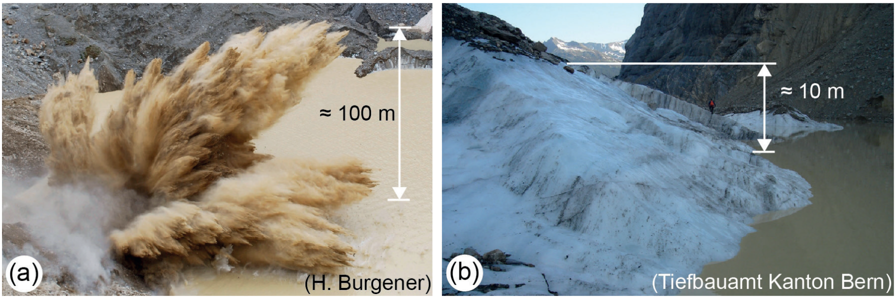

Figure 1. 2010 Grindelwald glacier lake event with (a) slide impact, (b) run-up traces

In 2010 a ≈ 300,000 m³ rock-ice avalanche impacted a glacier lake near Carhuaz, Peru. Despite a 20 m freeboard the wave overtopped the natural rock-dam with ≈ 1×10^6 m³ of water (Schneider et al. 2014). The generated flood wave transported an increasing amount of material with increasing propagation distance and finally caused significant damages to the village of Carhuaz, located 15 km downstream and 2000 m below the glacier lake (Fig. 2).
In the course of global warming, glacier retreat creates additional glacier lakes thereby increasing the hazard risk for mountainous regions.

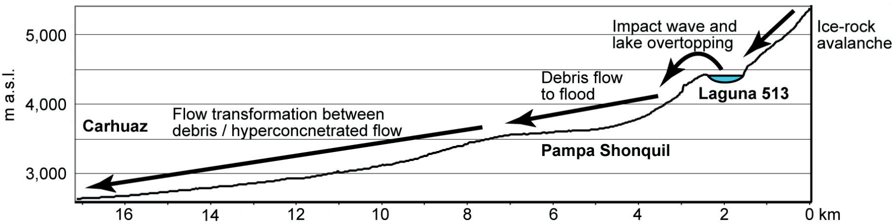

Figure 2. Process scheme of 2010 Carhuaz impulse wave flood event (adapted from Schneider et al. 2014)

During the planning phase of a reservoir, potential impulse wave events may be physically modelled in a laboratory. This procedure requires certain cost and duration and thus is not suitable for a quick hazard assessment in case of observed rock or slope instabilities at existing reservoirs or lakes. The VAW assessment guideline (Heller et al. 2009) summarizing the past impulse wave research at VAW and accounting for a literature review, allows for a quick and adequate assessment of slide-induced impulse waves in reservoirs.
The present contribution provides a general overview on impulse waves and details a recent evaluation of underwater slide propagation and deposition features. These data are particularly useful for the calibration of numerical models or the above mentioned assessment approach using generally applicable equations.

RESULTS OF PAST VAW IMPULSE WAVE RESEARCH

Impulse wave events may be modelled either as solid body slides, for which the slide characteristics are easily controlled and measured (e.g. Russell 1837, Wiegel 1955, or Kamphuis and Bowering 1972) or using granular material, thereby significantly complicating the modelling procedure (e.g. Huber 1980, Fritz 2002; Zweifel 2004; Heller 2007; Mohammed 2010; Bregoli et al. 2013; or Evers and Hager 2015). The simplified use of solid bodies has to be carefully selected depending on the prototype slide granulometry. Given a granular slide impacts the water with a small slide velocity, a 3-phase flow may be generated, incorporating the slide material, the water and air, thereby leading to significant energy dissipation. Investigations may either involve a simple 2D test-setup corresponding to a wave channel, or a more advanced three-dimensional (3D) setup accounting for complex wave propagation features, e.g. reflection, refraction or diffraction. Given such a wave basin (3D setup) the slide protrudes radially below the water surface and waves propagate radially from the slide impact location. With the wave energy being distributed over an increasing area, the resulting wave attenuation is larger as compared with the 2D case. The waves observed in laboratory were mainly of Stokes-type, cnoidal-like or solitary-like types. A more detailed review of the impulse wave generation process is provided by Heller et al. (2009).

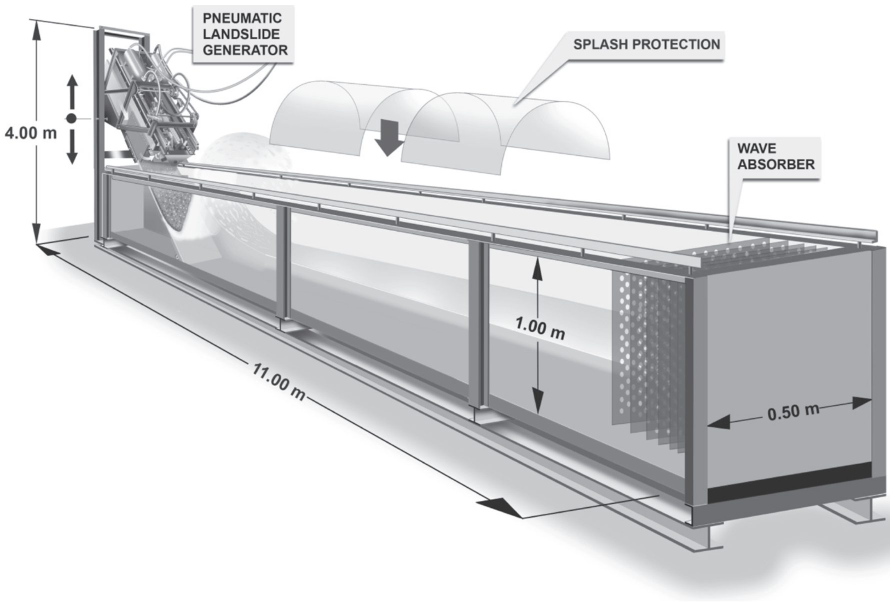

Figure 3. VAW impulse wave channel (Fritz 2002)

Starting in 1998, the PhD research cycle on impulse waves at VAW involved a wave channel equipped with a pneumatic landslide generator (Fig. 3). This unique setup allowed for the independent variation of all basic parameters, e.g. the still water depth ***h***, slide thickness ***s***, slide impact velocity V_s, bulk slide volume $\forall_s$, bulk slide density ρ_s, and slide impact angle α (Fig. 4a). The resulting wave height H was then determined for various propagation distances x.

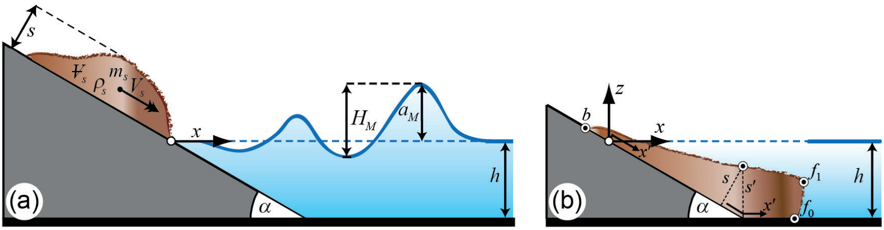

Figure 4. Parameter definition scheme for (a) slide induced impulse wave generation, (b) underwater slide characteristics

As a result of more than 400 tests, Heller (2007) identified the impulse product parameter P involving the slide Froude number $\mathsf{F} = V_s/(gh)^{½}$, the relative slide thickness $S = s/h$, and the relative slide mass $M = m_s/(\rho_w Bh^2)$ as the governing parameters for impulse wave generation

$$\mathsf{P} = \mathsf{F} S^{1/2} M^{1/4} \left[\cos(6/7 \cdot \alpha)\right]^{1/2} \tag{1}$$

with ρ_w as the water density and B as the slide width. The maximum wave height HM representing the vertical distance between the wave through and the wave crest in the near field is independent of the propagation direction and results as

$$H_M = (5/9)\mathsf{P}^{1/4} h \tag{2}$$

The subsequent wave-shore interaction can be treated either as run-up on a vertical wall for arch and gravity dams, wave run-up on linearly inclined embankment dams or shore slopes (e.g. Hall and Watts 1953; Synolaki 1987; Teng et al. 2000; Goseberg 2011; Baldock et al. 2012) or overland flow on a connected horizontal plane (Zelt and Raichlen 1991; Schüttrumpf and Oumeraci 2005; Sælevik et al. 2013; or Fuchs and Hager 2015). According to the latter, the maximum solitary wave run-up r on a linearly inclined shore in terms of the vertical distance between still water level and the maximum onshore water surface elevation is

$$r = 3(\tan\beta)^{-0.05} H \tag{3}$$

The maximum wave run-up height therefore mainly depends on the wave type, the wave height H in front of the shore, and the shore slope β. Due to scale limitations in physical models additional effects e.g. surface roughness in terms of shore vegetation or shore permeability are hard to address.

OBJECTIVE AND METHODOLOGY OF CURRENT STUDY

The underwater motion of subaerial granular slides has hardly received any attention in the past although the slide deposition might be important for infrastructure and dam safety elements, e.g. a reservoir bottom outlet. In addition, valuable information following a back-analysis of past slide events is useful to calibrate the calculation procedure or possible numerical models. Testing in the VAW impulse wave channel mostly involved video recordings for documentation purposes. Videos of 41 tests selected so that the range of initial basic parameters is covered best were analyzed regarding the underwater slide dynamics and their final deposition patterns. Video still images were corrected for distortion and the coordinates of distinctive slide points, namely the slide front position along bottom f_0, the maximum slide front position f_1, the maximum slide thickness s and s', respectively, and the rear slide position b (Fig. 4b) were evaluated over the test duration. The coordinate accuracy of ±30 mm for the largest underwater slide velocities of $V_s \approx 7.5$ m/s was mainly determined by the camera exposure time and thus blurry still images (Fig. 5a). For smaller slide velocities the accuracy was ±5 mm.

RESULTS ON UNDERWATER SLIDE PROPAGATION

Three distinctive tests were selected to demonstrate the variety of underwater slide motion of impulse wave events (Fig. 5). Test A corresponds to a slide impact angle of $\alpha = 45°$ and therefore represents a high velocity slide at a typical steep mountain shore. Whereas Test B corresponds to a vertical slide impact occurring e.g. for rock-fall scenarios, Test C represents a moderate $\alpha = 30°$ angle in combination with a small slide velocity, i.e. a slide that is initially located only slightly above the still water surface. The main slide parameters at water surface contact are listed in Tab. 1.

Table 1. Initial parameters of Tests A, B, and C

	α [°]	h [m]	V_s [m/s]	s [m]	m_s [kg]
Test A	45	0.30	6.7	0.162	110
Test B	90	0.45	4.4	0.139	57
Test C	30	0.30	2.1	0.065	55

Due to the high impact velocity, the slide of Test A is compacted when reaching the water surface, thereby generating a large splash (Fig. 5 a-b). Subsequently the slide transfers its momentum to the water body, thereby creating the impulse wave. Note the vertical water column for Tests A (Fig. 5b) and B (Fig. 5f). The generated water crater collapses in outward direction (Fig. 5c-d) and the granular slide protrudes underwater and comes to rest at its final deposition pattern characterized by the maximum deposition length and thickness (Fig. 5d). With the reduced impact velocity of Test B, the splash at water contact is much reduced (Fig. 5e) as compared to Test A. Before reaching the channel bottom, the slide is deflected in

the channel direction (Fig. 5f) and the water crater collapses in inward direction (Fig. 5g-h), thereby pushing the slide backwards and thus affecting the deposition shape.
Due to the small impact velocity of Test C, the slide front is not compacted and almost no splash is generated (Fig. 5i). The fluid does not separate from the slide so that no impact crater is formed but fluid enters the slide pores leading to a disintegrated slide (Fig. 5j-k). The slide back does not reach the water but deposits on the slide ramp (Fig. 5l).

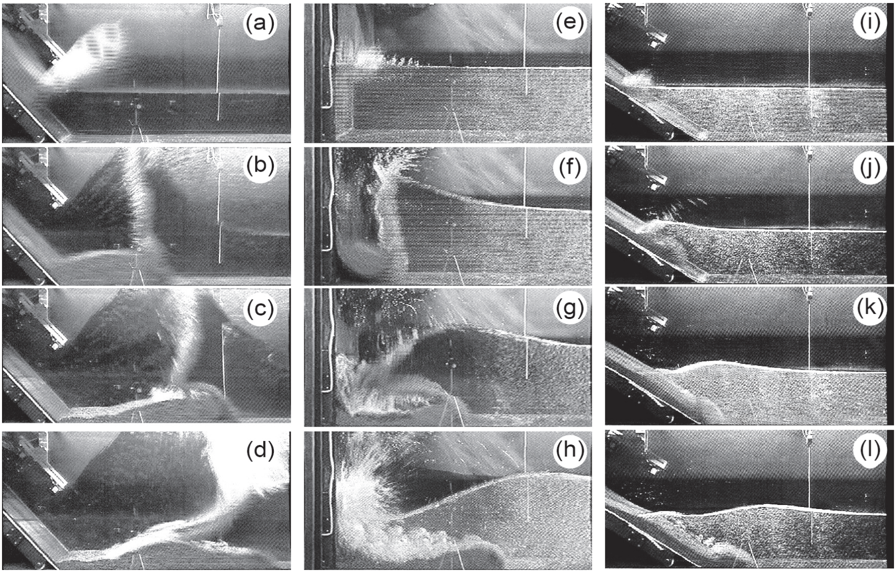

Figure 5. Still Image sequences for (a-d) Test A, (e-h) Test B, (i-l) Test C; time increment between images is $\Delta t \approx 6/25$ s

The underwater slide motion therefore shows large differences depending on the slide impact characteristics. However, given the slide front motion is normalized using values of the final deposition pattern, i.e. xf0, end as the maximum front position and tend as the time when the slide comes to rest and the final deposition is reached, the underwater slide trajectory follows in good agreement by (Fig. 6)

$$F_0 = x'_{f0} / x'_{f0,\mathrm{end}} = 1.03 \tanh(2T) \qquad (4)$$

where $T = t/t_{end}$

In addition to the underwater slide kinematics, characteristic values for the final deposition pattern were evaluated. Figure 7 shows the normalized slide front position $x'_{f0,end}/h$, the duration to reach the final position T_{end}, and the final deposition thickness s'_{end}/h. A good correlation was found to the impact angle-corrected impulse product parameter

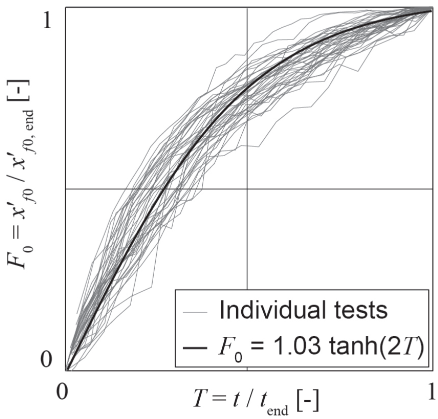

Figure 6. Normalized underwater slide propagation

$\mathsf{P}_s = \mathsf{P} \cdot \boldsymbol{sin[(6/7)\alpha]}$ (Fig. 7a,c,e) which almost corresponds to the governing parameter combination for the impulse wave generation (Heller et al. 2009). However, a similarly good correlation was found for the impact angle-corrected slide mass $\boldsymbol{M_s = M\ sin[(6/7)\alpha]}$ (Fig. 7b,d,f) without including a kinematic parameter in the impact characteristics. The corresponding equations read

(R^2 = 0.71) (5)

$$x'_{f0,end}/h = 1.87\mathsf{P}_s + 2.4$$ (R^2 = 0.66) (6)

$$x'_{f0,end}/h = 1.88M_s + 2.7$$ (R^2 = 0.26) (7)

$$T_{end} = -0.57\mathsf{P}_s + 3.6$$ (R^2 = 0.31) (8)

$$T_{end} = -0.64M_s + 3.6$$ (R^2 = 0.59) (9)

$$s'_{end}/h = -0.17\mathsf{P}_s + 0.8$$ (R^2 = 0.71) (10)

$$s'_{end}/h = -0.2M_s + 0.79$$

From these observations follows that the larger the slide impact, the larger is the underwater slide protrusion, the smaller is the deposition thickness, and the shorter is the duration until the final deposition pattern is reached. A more detailed analysis of underwater slide features is presented by Fuchs et al. (2013).

CONCLUSIONS

Impulse waves may constitute a severe danger to the safety of dams or infrastructure in the surroundings of mountainous lakes. Based on the long and systematic expertise of the Laboratory of Hydraulics, Hydrology and Glaciology (VAW) including physical model testing and a literature review, an assessment guideline for landslide generated impulse waves in reservoirs was published in 2009 (Heller et al. 2009). Recently, video recordings of selected physical model tests were analyzed to investigate both the underwater slide kinematics and the resulting deposition characteristics. Based on estimates for specific slide deposit features, e.g. their length and thickness, it is demonstrated that final deposition patterns can be

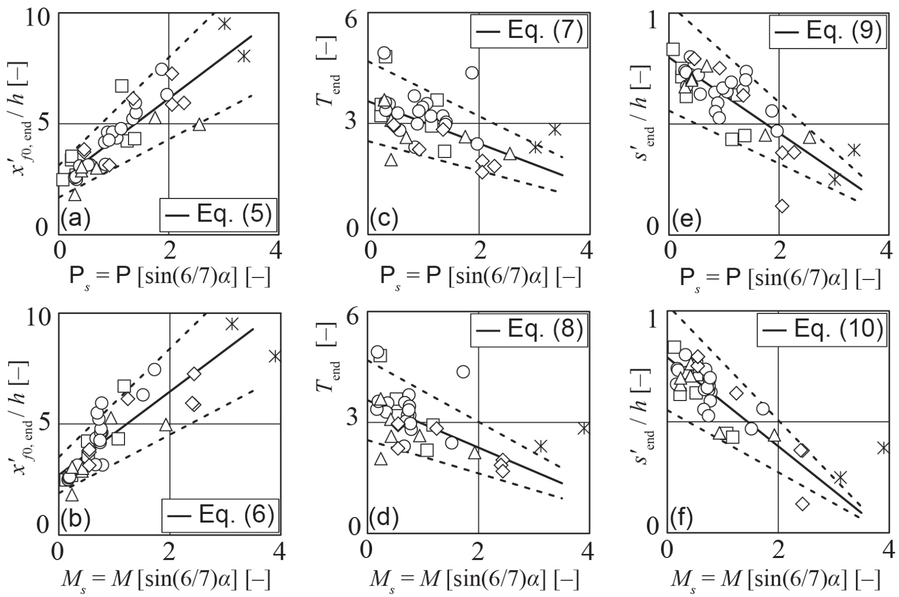

Figure 7. Normalized deposition characteristics of (a+b) slide front position, (c+d) propagation duration, and (e+f) deposition thickness versus P_s and $\boldsymbol{M_s}$, respectively (*) tests with h ≤ 0.2 m potentially affected by scale effects; (- -) = ±30%

described using only static input parameters but neglecting the slide kinematics. These results apply to calibrate a calculation procedure or to validate numerical models. This work thus contributes to the estimation of the risk assessment and to safety aspects relating to wave-shore interaction mainly in the Alpine environment.

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