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Spatial impulse wave generation and propagation

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Abstract: Rapid landslides into water bodies may generate massive water waves posing a threat to riparian settlements and infrastructure. These waves are referred to as impulse waves and exhibit tsunami-like characteristics. The generation and in particular the spatial propagation of impulse waves was studied in a hydraulic laboratory wave basin. A videometric measurement system was applied to track the water surface displacement. Compared to fixed wave gauges typically applied in previous studies, this technique yields a quasi-continuous representation of the water surface allowing for a detailed analysis of spatial propagation patterns. In total 74 experiments with deformable mesh-packed slides were conducted thereby varying the slide impact velocity, the slide mass, the slide thickness, the slide width, the slide impact angle, and the stillwater depth. Empirically derived prediction equations are presented and discussed for key wave characteristics including wave amplitudes and celerities. In the context of a preliminary hazard assessment, these equations allow for the estimation of wave magnitudes at prototype-scale.

Author keywords: Impulse wave; Landslide; Physical modelling; Prediction method; Spatial wave propagation.

Introduction

If a landslide, an avalanche, or glacier calving interacts with a large body of water, massive waves may be generated. The wave generation mechanism involves a momentum transfer from the slide mass to the water column. Waves generated by extremely rapid gravity-driven subaerial mass movements are commonly referred to as impulse waves (Heller *et al.* 2009) and may be observed in coastal areas as well as in inland waters (Roberts *et al.* 2014). An impulse wave event involves three phases as shown in Fig. 1. During the wave generation phase, the subaerial slide mass transfers its momentum to the water column, thereby generating a wave train with several crests and troughs. The amplitudes and wave lengths of the wave train are transformed in the wave propagation stage. Depending on the bathymetry of the water body, these transformation effects include refraction, diffraction, and shoaling (Heller *et al.* 2009). In addition, the waves are subject to frequency and amplitude dispersion (Heller and Hager 2010). Wave runoff (e.g. Müller 1995, McFall and Fritz 2017), overland flow (e.g. Fuchs and Hager 2015), or wave overtopping (e.g. Müller 1995, Kobel *et al.* 2017) characterize the wave impact phase. The first two phases are in the scope of this study.

Fig. 1. Phases of landslide generated impulse wave event: (1) wave generation, (2) wave propagation, and (3) wave impact including wave runoff, overland flow, and dam overtopping (Evers 2017, with permission)

A multitude of impulse wave events have been reported in the past. One of the most prominent cases is the impulse wave event in Lituya Bay, USA, which was triggered by an earthquake in 1958 and caused runoff heights of more than 500 m (Miller 1960). Bornhold *et al.* (2007) describe a historical example in the sixteenth century, when impulse waves generated by a rockslide at Knight Inlet, Canada, presumably destroyed an indigenous settlement. Impulse wave events of the 21st century involving subaerial landslides in coastal areas include Paatuut, Greenland,

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in 2000 (Dahl-Jensen *et al.* 2004), Aysén Fjord, Chile, in 2007 (Sepúlveda *et al.* 2010), Taan Fjord, USA, in 2015 (George *et al.* 2017, Higman *et al.* 2018), and Karrat Fjord, Greenland, in 2017 (Poli 2017). A well-documented event in inland waters occurred in 2007 when a three million cubic meters landslide impacted Chehalis Lake, Canada, and caused runup heights of 38 m at the opposite shore (Roberts *et al.* 2013, Wang *et al.* 2015). In the case of a water body impounded behind an artificial or natural dam structure, impulse wave overtopping may have a devastating impact on downstream areas. The wave overtopping event at Vajont Dam, Italy, in 1963 claimed nearly 2000 fatalities (Genevois and Ghirotti 2005). Risley *et al.* (2006) conducted a hazard analysis of potential impulse wave overtopping at the Usoi landslide dam, Tajikistan. A global overview with 254 events covering both inland and coastal waters was compiled by Roberts *et al.* (2014).

Based on the slide properties and the bathymetry, a prediction of the generated wave magnitude may be conducted. Heller *et al.* (2009) describe five different prediction methods within the context of hazard assessment: (1) generally applicable equations developed from model tests, (2) prototype-specific model tests, (3) numerical simulations, (4) empirical equations derived from field data, and (5) analytical investigations. Heller *et al.* (2009) and Evers *et al.* (2018) discuss the capabilities and limitations of these methods. Item (1) yields estimated wave magnitudes at low cost and time requirements. Therefore, this method is advantageous when an event is imminent or as a first assessment to determine whether additional more accurate investigations are needed.

Two types of impulse wave propagation patterns are commonly investigated in model tests: unidirectional and omnidirectional. While the former is investigated in wave flumes (2D), e.g. by Fritz *et al.* (2004), Zweifel *et al.* (2006), and Di Risio and Sammarco (2008), the latter is studied in wave basins (3D). Generally applicable equations developed from model tests accounting for omnidirectional impulse wave propagation were presented by Panizzo *et al.* (2005), Heller *et al.* (2009), Mohammed and Fritz (2012), Heller and Spinneken (2015), and McFall and Fritz (2016). Evers and Hager (2016a) applied the equations of the former four 3D studies to selected experiments of this study's data set to assess their applicability on an extended range of test parameters. They found limitations regarding slide model replication, i.e. rigid block vs. deformable granular slides, constant test parameters, e.g. a single slide impact angle or slide width, or a lack of experimental validation. In addition, all studies were based on wave gauge data from a limited number of measurement locations. Bregoli *et al.* (2017) demonstrated the advantages of a videometric measurement approach: First, this approach allows for a continuous representation of the water surface and therefore an adaptive tracking of specific wave conditions in the impact region. Second, in contrast to capacitance wave gauges, the measurement devices may not be damaged by the impacting slide mass. Note that the measurement approach by Bregoli *et al.* (2017) was limited to a single wave propagation direction along the slide axis, although their experiments were conducted in a wave basin.

The main objective of this study is to advance the understanding of spatial propagation of landslide generated impulse waves by applying a videometric measurement technique to track arbitrary water surfaces in 3D. For designing protection measures against wave impact, engineers require quantitative information on expected wave magnitudes at a certain location depending on its position relative to the wave source. Therefore, generally applicable empirical prediction equations are derived from a broad set of slide parameters for key wave characteristics to improve the quality of hazard assessments.

Physical model

Experimental setup

The experiments were conducted in a 4.5 m by 8 m wave basin 0.75 m high (Fig. 2). The impulse waves were generated with a movable chute featuring an inclinable sliding plane, a release box, and lateral guidance walls. The sliding plane allowed for impact angles of 30°, 45°, 60°, and 90°. Mesh-packed slides were applied, allowing for a simplified handling similar to rigid slides while maintaining a granular matrix and deformability. Evers and Hager (2015a) showed that the impulse wave characteristics generated by this type of slide are predictable with empirical equations derived from experiments with free granular slides within a similar scatter range, e.g. $\pm 30\%$ for the wave height, provided that the slide centroid velocity is the reference velocity in both cases. The mesh-packed slides were composed of granular material loosely filled into bags made of sifting media (SEFAR, NYTAL PA-38GG-500, Sefar AG, Heiden, Switzerland) with a mesh opening of 500 μm and 47% porosity. The granular material was made of 87% BaSO₄ and 13% PP of grain (subscript g) diameter $d_g = 8$ mm, grain density $\rho_g = 2,420$

kg/m^3 , and a bulk slide density $\rho_s = 1,338 \text{ kg/m}^3$ (Heller 2008). The release box allowed for predefining the slide geometry including the slide width between 0.25 m and 1.00 m. The slides were accelerated by gravity from various drop heights after manual release from the box. During acceleration, the slide deformation was found negligible and the slide centroid velocity was consequently equal to the slide front velocity. The latter was measured with two Laser Light Barriers (OHDK 14, Baumer Electric AG, Frauenfeld, Switzerland) mounted perpendicular to the sliding plane. The sensors' short response time $< 0.5 \text{ ms}$ resulted in a measurement accuracy of approximately $\pm 5\%$ for the maximum measured slide impact velocity of 4.76 m/s over a measuring section of 0.1 m. A porous filter foam was placed in the basin acting as wave damper to reduce the waiting time between experimental runs.

Fig. 2. Experimental setup of 3D wave basin (adapted from Evers 2017)

Water surface tracking and test repeatability

The application of a videometric measurement system required an opaque fluid allowing for the projection of a grid pattern on the free surface. Therefore, deionized water was mixed with 4 kg/m^3 titanium dioxide (TiO_2) pigments (KRONOS 1002, KRONOS Worldwide, Inc., Dallas, USA) as demonstrated by Przadka *et al.* (2012) and Evers and Hager (2015b). The addition of TiO_2 had negligible effects on the water viscosity and surface tension (Przadka *et al.* 2012). A regular grid pattern with 79×79 intersections was projected onto the water surface with a projector (Götschmann G 67 P, Gecko-Cam GmbH, Putzbrunn, Germany), thereby defining the measurement zone. As the general wave propagation pattern is considered symmetrical, the measurement zone covered only half of the full wave pattern (Fig. 2). For a slide width of 1 m, the chute allows for a completely symmetrical setup. For slide widths of 0.25 m and 0.5 m the sliding plane extends towards $-x$ (Fig. 2). However, the influence of this limited shore extension is assumed to be negligible for wave propagation towards x . The commercially available ProSurf-system (AICON 3D Systems GmbH, Braunschweig, Germany) was applied to track the spatial positions of the grid intersections. It comprised four cameras positioned around the wave basin (Fig. 2), synchronized by a control box to an acquisition rate of 24 Hz. The cameras' spatial positions and orientations were calibrated, enabling the tracking of the grid intersection by triangulation (Evers 2017).

Fig. 3. Water surface profiles $[h + \eta](r)$ of five experimental runs with similar governing parameters for wave propagation angle $\gamma = 0^\circ$

Fig. 3 shows the water surface profiles of five experimental runs repeated with identical preset parameters at $t = 0.5$ s, 1.5 s, and 2.5 s. Within the vicinity of the slide impact location at $r = 0$ m, the measured profiles feature larger deviations, while wave crests and troughs are captured sufficiently consistent and detailed for larger propagation distances. However, the deviations are not necessarily related to inaccuracies of the measurement system but are also caused by the repeatability of the experiments; e.g. the slide impact velocities range within the measurement accuracy of the laser light barriers between 4.35 m/s and 4.55 m/s. The measurement accuracy of the videometric system was discussed by Frank and Hager (2014). They found absolute deviations of <2 mm to point gauge measurements of solid surfaces. Evers and Hager (2015b) compared the videometrically tracked water level displacements with those measured with capacitance wave gauges and found good overall agreement. Based on the given findings, the measurement accuracy for water surface tracking was estimated to ± 1 mm.

Process description

Governing parameters

Both, the governing wave generation parameters as well as the targeted wave characteristics are shown in Fig. 4. The wave generation parameters include the slide impact velocity V_s , the slide mass m_s , the slide thickness s , the slide width b , the slide impact angle α , and stillwater depth h . The wave characteristics included into the analysis are first wave crest amplitude a_{c1} , the first wave trough amplitude a_{t1} , the first wave height H_1 , the first wave period T_1 , the second wave crest amplitude a_{c2} , as well as the celerities of the first and the second wave crests c_{c1} and c_{c2} . The positions of the respective wave features were defined within a polar coordinate system with the pole representing the slide impact location and the angular and radial coordinates equaling the wave propagation angle γ and distance r , respectively.

Fig. 4. Definition plot for spatial impulse wave propagation with governing parameters and wave characteristics with (a) side view, (b) plan view (adapted from Evers 2017)

The dimensionless quantities derived from the governing wave generation parameters include the slide Froude number F , the relative slide mass M , the relative slide thickness S , and the relative slide width B , defined as

$$F = V_s / (gh)^{0.5} \quad (1)$$

$$M = m_s / (\rho_w b h^2) \quad (2)$$

$$S = s / h \quad (3)$$

$$B = b / h. \quad (4)$$

Most existing empirical equations for the prediction of wave characteristics include these parameters (Di Risio *et al.* 2011, Evers and Hager 2016a). The first three parameters F , M , and S were included by Heller and Hager (2010) into the impulse product parameter P , describing impulse wave propagation in 2D wave channels, defined as

$$P = F S^{0.5} M^{0.25} \{\cos([6/7]\alpha)\}^{0.5}. \quad (5)$$

Table 1 gives an overview of the experimental parameter ranges. The complete dataset including the experimental parameters is provided by Evers (2018). A total of 74 experiments were conducted and analyzed. The test numbers given in this article refer to these according to Evers (2018).

Table 1. Overview of experimental quantities

Parameter	Test range
V_s [m/s]	0.72 – 4.76
m_s [kg]	10 – 40
s [m]	0.06 – 0.12
b [m]	0.25 – 1.00
α [°]	30 – 90
h [m]	0.2 – 0.4
F	0.40 – 3.40
M	0.25 – 1.00
S	0.15 – 0.6
B	0.83 – 5.00
P	0.13 – 2.08

The propagation distance of an outgoing impulse wave train within the basin was limited by the vertical side walls. Wave reflection was accounted for by extrapolating the position of the first initial uplifting of the stillwater level closest to one of the basin walls both in space and time. The extrapolation involved the propagation celerity of the first initial uplifting before reflection as well as the residence time at the wall (Chen *et al.* 2015). Wave features affected by reflection from the side walls were excluded from the analysis. To avoid significant scale effects, the tests were conducted with stillwater depths $h \geq 0.20$ m (Heller *et al.* 2008).

Water surface evolution

The application of the videometric measurement system yields a quasi-continuous contour representation of the water surface. Fig. 5 shows oblique views of the grid projection of Test 043 (Evers 2018). At $t = 0.179$ s, the splash screen of the impact crater has attained its highest elevation level. The impact crater then collapses up to 0.750 s. While the first wave crest is then hardly visible, the first wave trough has clearly formed at $t = 1.125$ s. The water surface close to the slide impact location is irregularly distorted at this stage. At $t = 1.500$ s, the second wave crest forms. Note the spilling second wave crest for small wave propagation angles γ . The second wave crest has further propagated at $t = 1.875$ s along with reduced wave spilling.

Fig. 5. Oblique view of Test 043 (Evers 2018) with $V_s = 2.38$ m/s, $m_s = 20$ kg, $s = 0.06$ m, $b = 0.50$ m, $\alpha = 60^\circ$, $h = 0.40$ m, and $P = 0.26$ (adapted from Evers 2017)

Fig. 6 shows the contour plots of Test 043 as in Fig. 5. These plots were produced by interpolating between the projected grid intersections tracked by the videometric measurement system. Note that Fig. 6 starts at $t = 0.375$ s, while Fig. 5 includes $t = 0.179$ s as the first time step. The slide impacts the water surface at $t = 0$ s at the origin of the y -axis. At $t = 0.375$ s, the first wave crest has just emerged; it has a large amplitude for $\gamma = 0^\circ$ (y -axis), decreasing toward $\gamma = 90^\circ$ (x -axis). The blank area close to the impact location arises from the simultaneous collapse of the impact crater. The continuous tracking of the water surface is limited by the strong deformation of the water surface. At $t = 0.750$ s, the first wave crest propagated to $r \approx 1.1$ m and is subjected to amplitude decay. The first trough of the wave train emerges at the same time. At $t = 1.125$ s, the first wave trough is fully captured by the videometric measurement system. The water surface around the impact location is strongly distorted and consequently the blank area increases. The second wave crest is fully developed at $t = 1.500$ s and has further propagated at $t = 1.875$ s, while the first wave crest has partially left the measurement area. A second wave trough has formed at $t = 2.250$ s. A qualitative visual comparison with the first wave shown at full extent at $t = 1.125$ s reveals that the wave length of the second wave is substantially shorter, which was also observed by Mohammed and Fritz (2012) as well as McFall and Fritz (2016). However, note that the water surface for propagation distances

$r > 1.5$ m at $t=2.250$ s is potentially affected by reflections from the basin sidewalls; the second wave trough amplitude was not included in the quantitative analysis, therefore.

Fig. 6. Contour plots $z(x, y)$ of Test 043 (Evers 2018)

Fig. 7. Contour plots $z(x, y)$ of Tests 072, 004, and 059 (Evers 2018) with $[V_s; m_s; s; b; \alpha; h, P]$ (a) $[3.03 \text{ m/s}; 10 \text{ kg}; 0.06 \text{ m}; 0.25 \text{ m}; 60^\circ; 0.20 \text{ m}; 0.93]$, (b) $[2.70 \text{ m/s}; 20 \text{ kg}; 0.06 \text{ m}; 0.50 \text{ m}; 60^\circ; 0.20 \text{ m}; 0.83]$, and (c) $[2.78 \text{ m/s}; 40 \text{ kg}; 0.06 \text{ m}; 1.00 \text{ m}; 60^\circ; 0.20 \text{ m}; 0.86]$

The effect of slide width b on spatial impulse wave propagation is shown in Fig. 7. All plots refer to the identical instant at $t = 1.500$ s for three different experimental runs. While their impulse product parameters P were similar, the slide widths were $b = 0.25$ m, 0.50 m, and 1.00 m, respectively. The first wave crest amplitudes a_{c1} ($y \approx 2$ m) increase significantly with increasing slide width for spatial, i.e. 3D, wave propagation. In contrast, P was derived from experiments in a wave flume. In this 2D type of setup, a doubling of the flume width along with slide width b and the slide mass m_s has no effect on the generated wave magnitudes (Evers and Hager 2016b). Fig. 7 demonstrates that the effect of b has to be accounted for in 3D water bodies to allow for the prediction of spatial impulse wave propagation.

Fig. 8. Profile plots $[h + \eta](r)$ of Test 033 (Evers 2018) including impact radius r_0 and initial first wave crest amplitude $a_{0,c1}$ with $V_s = 4.55$ m/s, $m_s = 20$ kg, $s = 0.12$ m, $b = 0.50$ m, $\alpha = 60^\circ$, $h = 0.30$ m, and $P = 1.08$ at $\gamma = 0^\circ, 45^\circ, 90^\circ$

Fig. 8 shows the water surface profiles for $\gamma = 0^\circ, 45^\circ$, and 90° during the wave generation process. The water surface is undisturbed at $t = 0.000$ s. At $t = 0.292$ s, the impacting slide creates an impact crater and displaces the water surface. The crater collapses and the first wave crest starts to emerge from the slide impact zone at $t = 0.417$ s. The crest is fully developed at $t = 0.500$ s. The wave propagation distance r of the initial first wave crest amplitude $a_{0,c1}$ is defined as the impact radius r_0 . At $t = 1.000$ s and 1.292 s the respective water surface profiles show that also the initial first wave trough and second wave crest amplitudes are formed at the impact radius r_0 .

The wave generation and propagation process is divided into two zones: (I) slide impact zone and (II) wave propagation zone (Fig. 9). The impact radius r_0 separates these two zones. Zone I is affected by the generation of the impact crater and its collapse, involving strong turbulence and air entrainment. Distinct wave characteristics, e.g. wave amplitudes, become quantifiable first in Zone II by applying the videometric measurement system (Fig.

8). In addition to the wave propagation angle γ , the surrogate radial wave propagation distance $r^* = r - r_0$ describes the outgoing impulse wave train beyond r_0 within the polar coordinate system (Fig. 4b and Fig. 9).

Fig. 9. Definition plot of impact radius r_0 and the initial amplitude of the first wave crest $a_{0,c1}$

The first wave crest amplitudes a_{c1} , i.e. the shape of the first wave crest, is plotted versus the wave propagation angle γ in Fig. 10(a), for time steps between $t = 0.38$ s and 2.17 s. During propagation, a_{c1} decreases for all γ . However, the decay rate is higher for $\gamma = 0^\circ$ than for 90° (Fig. 10). While $a_{c1,90^\circ}$ accounts for 8% of $a_{c1,0^\circ}$ at $t = 0.38$ s, this ratio increases to 43% at $t = 2.17$ s (Fig. 10b). This indicates a lateral spreading effect on the wave crest normal to its propagation direction.

Fig. 10. First wave crest elevation profiles of Test 004 (Evers 2018) at $t = 0.38$ s, 0.83 s, 1.29 s, 1.75 s, and 2.17 s for (a) a_{c1} and (b) $a_{c1}/a_{c1,0^\circ}$ versus γ

Results

Slide impact zone

The definition plots (Fig. 4 and Fig. 9) show the impact radius r_0 . It represents the boundary between the slide impact zone and the wave propagation zone, defining the location at which impulse wave characteristics become first measurable. The relative impact radius is defined as $R_0 = r_0/h$, varying for spatial wave propagation with the wave propagation angle γ . It is governed by the impulse product parameter P , the relative slide width B , and the effective slide impact angle $\alpha_{\text{eff}} = (6/7)\alpha$. For $\gamma = 0^\circ$ and 90° the measured values R_0 are approximated by

$$R_{0,0^\circ} = r_{0,0^\circ}/h = 2.5(PB\cos\alpha_{\text{eff}})^{0.25} \quad (6)$$

$$R_{0,90^\circ} = r_{0,90^\circ}/h = (B/2) + 1.5(P\cos\alpha_{\text{eff}})^{0.25}. \quad (7)$$

The cosine of α_{eff} is included twice, since it is also part of P . As the center of the slide width represents the origin of $R_{0,90^\circ}$, its minimum value is $B/2$ (Fig. 4b); i.e. very wide slides create large $R_{0,90^\circ}$ regardless the magnitude of the other slide parameters. For γ between 0° and 90° , R_0 is approximated by an ellipse in polar form as

$$R_0(\gamma) = \sqrt{\frac{R_{0,0^\circ}^2 R_{0,90^\circ}^2}{R_{0,0^\circ}^2 \sin^2 \gamma + R_{0,90^\circ}^2 \cos^2 \gamma}}. \quad (8)$$

The measured impact radii $R_{0,\text{meas}}$ for all γ are plotted versus the predicted $R_{0,\text{pred}}$ in Fig. 11, including 65 of the total 74 experiments. For 9 experiments, the water surface close to slide impact location was not sufficiently captured by the videometric measurement system. Nonetheless, these experiments are still included in the results of the wave propagation zone. The coefficient of determination is $R^2 = 0.71$. For $R_0 > 3$, the predicted values tend to underestimate the measured values. However, most measured values scatter within a $\pm 30\%$ range.

Fig. 11. (a) measured impact radii $R_{0,\text{meas}}$ versus predicted $R_{0,\text{pred}}$ (Eq. 8) and (b) measured initial first wave crest amplitudes $A_{c1,\text{meas}}(R_0)$ versus predicted $A_{c1,\text{pred}}(R_0)$ (Eq. 10)

The relative initial first wave crest amplitude $A_{0,c1}$ represents the maximum wave crest elevation at R_0 for $\gamma = 0^\circ$. It is governed by the impulse product parameter P , the relative slide width B , and the effective slide impact angle α_{eff} and is approximated with

$$A_{0,c1} = a_{0,c1}/h = 0.2P^{0.5}B^{0.75}(\cos\alpha_{\text{eff}})^{0.25}. \quad (9)$$

For γ between 0° and 90° , the relative first wave crest amplitude A_{c1} at R_0 follows

$$A_{c1}(R_0) = A_{0,c1} \left[\text{sech} \left(3.2 \frac{\gamma}{90^\circ} \right) \right]^{\cos \alpha_{\text{eff}}}. \quad (10)$$

The hyperbolic secant function describes the initial wave crest shape over γ . This function features an inflection point, which may also be observed in the measurements as shown in Fig. 10(a). The effect of α on the initial wave crest shape is accounted for by the exponent. While the ratio of $A_{c1}(R_{0,0^\circ})$ to $A_{c1}(R_{0,90^\circ})$ is $\cong 1.75$ for the vertical impact ($\alpha = 90^\circ$), it increases to approximately 9.6 for $\alpha = 30^\circ$. The measured initial first wave amplitudes $A_{c1,\text{meas}}$ at R_0 for all γ of the 65 experiments are plotted versus the predicted $A_{c1,\text{pred}}$ in Fig. 11 ($R^2 = 0.91$).

Wave propagation zone

The following wave characteristics were tracked and analyzed in the wave propagation zone: first wave crest amplitude a_{c1} , first wave trough amplitude a_{t1} , second wave crest amplitude a_{c2} , first wave height H_1 , first wave period T_1 , as well as the first and the second wave celerities c_{c1} and c_{c2} (Fig. 4). These wave characteristics allow for assessing the magnitude and consequently the impact of the outgoing wave train front at a specific location relative to the wave source.

The definition plots (Fig. 4 and Fig. 9) show the surrogate radial wave propagation distance r^* . It extends the impact radius r_0 and is the radial coordinate for describing the wave characteristics in the wave propagation zone, i.e. outside the slide impact zone. The relative wave propagation distance r/h is defined as the sum of the relative impact radius R_0 and the relative surrogate radial wave propagation distance R^*

$$r/h = r_0/h + r^*/h = R_0 + R^*. \quad (11)$$

The crest elevation above the stillwater surface of the first outgoing wave is defined as the first wave crest amplitude a_{c1} (Fig. 4). The measured relative first wave crest amplitudes $A_{c1} = a_{c1}/h$ for all γ are approximated by

$$A_{c1}(R^*, \gamma) = A_{0,c1} \exp\left(-0.4 A_{0,c1}^{-0.3} \sqrt{R^*}\right) \left[\operatorname{sech}\left(3.2 \frac{\gamma}{90^\circ}\right) \right]^{\cos \alpha_{\text{eff}} \exp(-0.15 \sqrt{R^*})}. \quad (12)$$

Eq. (12) extends Eq. (10) by including R^* to describe the wave decay effect. The first exp-function accounts for the amplitude decay in the propagation direction $\gamma = 0^\circ$. The second exp-function in the exponent of the hyperbolic secant function includes the effect of lateral wave crest spreading, i.e. the decreasing ratio of the amplitudes at $\gamma = 0^\circ$ to 90° during wave propagation as shown in Fig. 10. Fig. 12 shows a histogram with the distribution of the measured wave amplitudes versus those predicted. In total, $n = 208,685$ data points were extracted in 1° steps between $\gamma = 0^\circ$ and 90° from the interpolated water surface measurements and included into the analysis. The horizontal axis shows the relative deviation of the measured values from the predicted as

$$\Delta_{\text{meas}}(\text{variable}) = 1 - \left(\frac{\text{measured value}}{\text{predicted value}} \right). \quad (13)$$

Therefore, $A_{c1,\text{meas}}/A_{c1,\text{pred}} = 1$ represents 0% deviation. In the box plot of Fig. 12, the first and the third quartiles are represented by the box. The band inside the box is the median. The whiskers depict the 5th and the 95th percentiles, i.e. 90% of the measured data scatter within a range of -45% and +25% around Eq. (12). The coefficient of determination is $R^2 = 0.89$.

Fig. 12. (a) Scatter plot of measured relative first wave crest amplitudes $A_{c1,\text{meas}}$ versus predicted $A_{c1,\text{pred}}$ (Eq. 12), (b) histogram, and box plot with whiskers at 5th and 95th percentiles of $\Delta_{\text{meas}}(A_{c1})$

In Fig. 13 the box plots are subdivided according to the relative wave propagation distance r/h and the wave propagation angle γ , respectively. Again, 0% represents perfect agreement between predicted and measured values. The scatter is largest for r/h between 1.5 and 9. However, note that most of the measured data are in that parameter range. The amplitudes for $\gamma > 60^\circ$ are slightly more overestimated by Eq. (12), while the scatter is increasing.

Fig. 13. Box plots with whiskers at 5th and 95th percentiles for $\Delta_{\text{meas}}(A_{c1})$ versus (a) relative propagation distance r/h and (b) wave propagation angle γ

The depression below the stillwater surface following a_{c1} is defined as the first wave trough amplitude a_{t1} (Fig. 4). Its relative value $A_{0,t1}$ at R_0 and $\gamma = 0^\circ$ follows

$$A_{0,t1} = a_{0,t1}/h = 0.35(PB\cos\alpha_{\text{eff}})^{0.5}. \quad (14)$$

The measured relative first wave trough amplitude $A_{t1} = a_{t1}/h$ are approximated by

$$A_{t1}(R^*, \gamma) = A_{0,t1} \exp\left(-0.4 A_{0,t1}^{-0.3} \sqrt{R^*}\right) \left[\text{sech}\left(3.6 \frac{\gamma}{90^\circ}\right)\right]^{\cos\alpha_{\text{eff}} \exp(-0.15\sqrt{R^*})}. \quad (15)$$

A total of 90% of the measured data in Fig. 14 scatter between -20% and $+40\%$. The coefficient of determination is $R^2 = 0.91$. As shown in Fig. 15, the underestimation is highest close to the impact location and slightly increases for $r/h > 7$. Furthermore, the measured values are slightly underestimated for γ between 20° and 80° .

Fig. 14. (a) Scatter plot of measured relative first wave trough amplitudes $A_{t1,\text{meas}}$ versus predicted $A_{t1,\text{pred}}$ (Eq. 15), (b) histogram, and box plot with whiskers at 5th and 95th percentiles of $\Delta_{\text{meas}}(A_{t1})$

Fig. 15. Box plots with whiskers at 5th and 95th percentiles for $\Delta_{\text{meas}}(A_{r1})$ versus (a) relative propagation distance r/h and (b) wave propagation angle γ

The second wave crest amplitude a_{c2} is defined as the crest elevation above the water surface of the second outgoing wave (Fig. 4). The relative initial second wave crest amplitude $A_{0,c2}$ at R_0 and $\gamma = 0^\circ$ is approximated by

$$A_{0,c2} = a_{0,c2}/h = 0.14(PB\cos\alpha_{\text{eff}})^{0.25}. \quad (16)$$

The measured relative second wave crest amplitudes $A_{c2} = a_{c2}/h$ for all γ are approximated by

$$A_{c2}(R^*, \gamma) = A_{0,c2} \exp\left(-0.1A_{0,c2}^{-0.3}\sqrt{R^*}\right) \left[\text{sech}\left(3\frac{\gamma}{90^\circ}\right)\right]^{\cos\alpha_{\text{eff}} \exp(-0.15\sqrt{R^*})}. \quad (17)$$

Fig. 16 shows measured values for A_{c2} . Compared to A_{c1} (Eq. 12), the scatter is substantially larger with 90% of the data points within -60% and $+50\%$ ($R^2 = 0.69$). The largest scatter occurs for $r/h < 5$, i.e. close to the slide impact location (Fig. 16).

Fig. 16. (a) Scatter plot of measured relative second wave crest amplitudes $A_{c2,\text{meas}}$ versus predicted $A_{c2,\text{pred}}$ (Eq. 17), (b) histogram, and box plot with whiskers at 5th and 95th percentiles of $\Delta_{\text{meas}}(A_{c2})$

Fig. 17. Box plots with whiskers at 5th and 95th percentiles of $\Delta_{\text{meas}}(A_{c2})$ versus (a) relative propagation distance r/h and (b) wave propagation angle γ

The first wave height H_1 is defined as the distance between the water surface elevation of the first wave crest and trough amplitudes at the same location (Fig. 4). The measured relative values $Y_1 = H_1/h$ are therefore given as

$$Y_1(R^*, \gamma) = A_{c1} + A_{t1}. \quad (18)$$

90% of the data in Fig. 18 scatter evenly between -30% and $+25\%$ with the median close to zero ($R^2 = 0.93$).

The first wave period T_1 is defined as the time difference between the initial uplifting of the first wave crest and the stillwater level intersection following the first wave trough at the same location (Fig. 4). The initial uplifting was tracked at the location where the water level exceeded an absolute threshold equal to the estimated measurement accuracy of 1 mm above the stillwater level. The measured relative first wave periods $T_1(g/h)^{0.5}$ are approximated by

$$T_1(R^*, \gamma)(g/h)^{0.5} = 10(Y_1)^{0.2} + (R^*/2). \quad (19)$$

The data in Fig. 19 has a narrow scatter range with 90% between -10% and $+15\%$ ($R^2 = 0.86$). $T_1(g/h)^{0.5}$ only depends on the relative wave height Y_1 and the relative surrogate radial wave propagation distance R^* .

Fig. 18. (a) Scatter plot of measured relative first wave heights $Y_{1,\text{meas}}$ versus predicted $Y_{1,\text{pred}}$ (Eq. 18), (b) histogram and box plot with whiskers at 5th and 95th percentiles of $\Delta_{\text{meas}}(Y_1)$

Fig. 19. (a) Scatter plot of measured relative first wave period $T_{1,\text{meas}}(g/h)^{0.5}$ versus predicted $T_{1,\text{pred}}(g/h)^{0.5}$ (Eq. 19), (b) histogram and box plot with whiskers at 5th and 95th percentiles of $\Delta_{\text{meas}}(T_1(g/h)^{0.5})$

The first and the second wave celerities c_{c1} and c_{c2} are defined as the propagation celerities of the first and second wave crests, respectively. The measured relative first wave celerities $c_{c1}/(gh)^{0.5}$ are approximated by

$$c_{c1}/(gh)^{0.5} = 0.95 (1 + A_{c1})^{0.5}. \quad (20)$$

The data scatter with 90% between -15% and $+10\%$ ($R^2 = -0.06$, Fig. 20). The measured relative second wave celerities $c_{c2}/(gh)^{0.5}$ are approximated by

$$c_{c2}/(gh)^{0.5} = 0.7 (1 + A_{c2})^{0.5}. \quad (21)$$

The data scatter with 90% between -25% and $+15\%$ ($R^2 = -0.03$, Fig. 21). The negative values of R^2 arise from the missing intercept in Eqs. (20) and (21). The measured values deviate acceptably from these predicted.

Fig. 20. (a) Scatter plot of measured relative first wave crest celerity $c_{c1,\text{meas}}/(gh)^{0.5}$ versus predicted $c_{c1,\text{pred}}/(gh)^{0.5}$ (Eq. 20), (b) histogram and box plot with whiskers at 5th and 95th percentiles of $\Delta_{\text{meas}}(c_{c1}/(gh)^{0.5})$

Fig. 21. (a) Scatter plot of measured relative second wave crest celerity $c_{c2, meas}/(gh)^{0.5}$ versus predicted $c_{c2, pred}/(gh)^{0.5}$ (Eq. 21), (b) histogram and box plot with whiskers at 5th and 95th percentiles of $\Delta_{meas}(c_{c2}/(gh)^{0.5})$

Discussion

The governing parameters given in Table 1 represent the limitations of the empirical equations proposed in the preceding section. The slide impact velocities V_s cover a range both below and above the shallow water wave celerity $(gh)^{0.5}$, i.e. $F < 1$ and $F > 1$. Although the slide mass m_s was varied in the experiments, the bulk slide density $\rho_s = 1,338 \text{ kg/m}^3$ remained constant. However, all equations include the impulse product parameter P , representing the momentum transfer per unit slide width, derived from 2D experiments with ρ_s between 590 kg/m^3 and 1720 kg/m^3 (Heller and Hager 2010). Therefore, the application range of the equations presented may be potentially extended to bulk slide densities lower than the water density although these were not covered in the present experiments. The limitations of the wave propagation angle γ have to be assessed based on the geometry of the waterbody. While Mohammed and Fritz (2012) studied the edge wave propagation at a straight beach extending the sliding plane, McFall and Fritz (2016, 2017) also included edge waves on the curvilinear shoreline of a conical island. At Chehalis Lake, these edge waves had a lower but nonetheless significant runup compared to the waves for $\gamma = 0^\circ$ (Roberts *et al.* 2013). The experimental setup of this study resembles the tip of a headland, since it is not bounded by an inclined shoreline, and edge waves were not accounted for. Heller *et al.* (2012) conducted experiments in a wave basin with confining side walls, adjusted to a basin side angle θ . For θ between 30° and 90° , with $\theta = 0^\circ$ representing a 2D flume, no significant effect on the maximum wave features was found at $\gamma = 0^\circ$. Edge waves strongly depend on the bathymetry and topography of the water body and require a case-by-case assessment. The maximum relative wave propagation distance reached in the experiments was $r/h \approx 16$. While this upper limitation of the propagation distance is not sufficient to cover long distances in oceans, it is suitable for smaller confined basins, e.g. bays or fjords. The lower limit of r/h is directly defined by the impact radius R_0 . The approach by Heller *et al.* (2009) states $r/h = 5$ as global lower limit. Therefore, the present approach involving R_0 allows for the prediction of impulse wave characteristics closer to the impact location (Fig. 11).

Eqs. (9), (14), and (16) describe the initial wave amplitudes at the impact radius R_0 for $\gamma = 0^\circ$. Parameter P , introduced by Heller and Hager (2010) based on 2D experiments, is included in all three equations. The results of this study indicate that P is also applicable to the generation and propagation of impulse waves in 3D. However, the relative slide width B has to be included as an additional parameter, since P solely accounts for the unit momentum transfer from the slide to the water column. The effective slide impact angle α_{eff} is also added as an additional parameter. Although it is already included in P , it has a strong influence in spatial environments. The features of 3D impulse waves therefore are based on these of 2D impulse waves and extended by typical 3D wave parameters as previously described.

Fig. 22. (a) Measured impact radii $R_{0,0^\circ, meas}$ versus predicted $R_{0,0^\circ, pred}$ (Eq. 23) and (b) measured initial first wave crest amplitudes $A_{0,c1, meas}$ versus predicted $A_{0,c1, pred}$ (Eq. 22); values predicted with equations by Bregoli *et al.* (2017)

Bregoli *et al.* (2017) proposed for the maximum wave amplitude a_{max} and its distance x_{max} from the impact location

$$a_{max} / h = 0.118(S)^{0.459} \left(\frac{l_s}{h} \right)^{0.463} F^{0.554} \triangleq A_{0,c1} \quad (22)$$

$$x_{max} / h = 3.97(S)^{0.198} \left(\frac{m_s V_s^2}{\rho_w g b l_s h^2} \right)^{0.277} \triangleq R_{0,0^\circ} \quad (23)$$

Eqs (22) and (23) correspond to the relative initial wave amplitude $A_{0,c1}$ (Eq. 9) and the relative impact radius $R_{0,0^\circ}$ (Eq. 6) for a single wave propagation angle $\gamma = 0^\circ$, respectively. In Fig. 22, Eqs (22) and (23) by Bregoli *et al.* (2017) are applied to predict the dataset of this study. The slide length is substituted with $l_s = m_s / sb\rho_s$. While the measured relative impact radii $R_{0,0^\circ}$ for $\gamma = 0^\circ$ are in good agreement with the prediction, the predicted relative initial wave amplitudes $A_{0,c1}$ are largely underestimating the measured values. Compared to $R_{0,0^\circ}$, the equation for x_{max}/h by Bregoli *et al.* (2017) does not include the effect of the slide impact angle α . While Kamphuis and Bowering (1970) found an only minor effect of α on the generated wave magnitudes, Heller and Hager (2010) included its effect into the impulse product parameter P . In addition, the equation for a_{max}/h does not include the effect of the slide mass m_s , the slide width b , and again α , which may explain the observed deviations.

Eqs. (12), (15), and (17) include the initial amplitudes describing the spatial wave propagation process with the relative surrogate wave propagation radius R^* and the wave propagation angle γ as polar coordinates. $R^* = 0$ is equivalent to the impact radius R_0 and the equations are defined for $R^* \geq 0$. The wave amplitude decay processes are described by exponential functions, also contained in Hughes (1993) for different wave attenuation equations as well as by Bregoli *et al.* (2017) in their relations describing impulse wave propagation for $\gamma = 0^\circ$. While the exponential function in Eq. (12) includes a factor of -0.4 , Eq. (17) has a lower factor of -0.1 , indicating that a_{c2} is subject to a smaller wave decay rate than a_{c1} . However, the initial first wave crest amplitude $A_{0,c1}$ (Eq. 9) is generally larger than the second $A_{0,c2}$ (Eq. 16). In combination with the different decay rates, the ratio of A_{c1} to A_{c2} is subject to permanent variation during propagation. To describe the wave crest and trough shapes along γ , hyperbolic secant functions were selected based on experimental observations (Fig. 10). Their exponents include α_{eff} and R^* as governing parameters accounting for the lateral spreading during wave propagation. A slightly different exponent to describe this effect was originally introduced by Heller *et al.* (2015).

In the context of hazard assessment, the predicted wave characteristics act as input parameters to estimate the impact at the shoreline. Besides wave crest amplitudes, also the wave height, the wave period, and the wave length are accounted for, e.g. by Müller (1995). Among various water wave types (Heller 2008), the solitary wave causes runup heights with the highest elevation (Synolakis 1989). Impulse waves exhibit features of wave types within the range of intermediate-water to shallow-water waves depending on the generation process (Fritz *et al.* 2004, Heller and Hager 2011). The measured wave crest celerities of this study are presented in relation to solitary waves (Eqs. 20 and 21). While the first wave crest propagates at approximately 95% of the solitary wave celerity, the second wave crest reaches 70%. The celerity reduction from the first to the second wave crest is on average 26%. This is a slightly higher reduction than 18% to 23% observed by Mohammed and Fritz (2012) and 23% by McFall and Fritz (2016).

The videometric measurement system allows for a quasi-continuous representation of the water surface and consequently a high number of data points. This measurement technique allowed for adaptively tracking the newly introduced impact radius r_0 . Another advantage of the high number of data points is highlighted by the box plots in Fig. 13, Fig. 15, and Fig. 17. These plots allow for assessing the evolution of the impulse wave features as well as their respective scatter along the polar coordinates r/h and γ .

Conclusions

Impulse waves were generated in a hydraulic laboratory wave basin and their spatial propagation patterns tracked with a videometric measurement system. The following wave features were extracted from the water surface contours: the amplitudes of the first wave crest and trough as well as the second wave crest, the height and period of the first wave, and the celerities of the first and the second wave crest. Empirical dimensionless equations are proposed to predict the magnitude of these wave features based on the slide impact velocity, the slide mass, the slide thickness, the slide width, the slide impact angle, and the stillwater depth as governing parameters. The main findings are:

- The impulse product parameter, originally derived from 2D wave flume experiments, in combination with the slide width and the additional effect of the slide impact angle, is suitable to quantify the spatial impulse wave generation and propagation features.
- The impact zone close to the slide impact location is influenced by the collapse of the impact crater, strong turbulence, and arbitrary distortion of the water surface, while in the wave propagation zone, distinct characteristics of the outgoing wave train, e.g. amplitudes, become quantifiable.
- The transition from the impact zone to the wave propagation zone is confined by the impact radius r_0 , which is governed by the slide characteristics; the spatial extent of r_0 is approximated by an ellipse.
- The crest and trough shapes of the spatially propagating wave train is approximated by a hyperbolic secant function featuring an exponent accounting for the lateral spreading of the wave crest during propagation.
- The wave decay is approximated by an exponential function; the first wave crest amplitude is thereby subject to a higher wave decay rate than the second wave crest amplitude.
- While the first wave crest propagates at 95% of the solitary wave celerity, the second does at only 70%.

The equations derived in this study allow for predicting impulse wave magnitudes at a specific location relative to the wave source based on the governing slide parameters. In combination with equations from literature describing the wave impact, e.g. runup heights, a preliminary hazard assessment for potential landslide generated impulse wave events at prototype scale may be conducted.

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Notation

$A_{0,c1}$	Relative initial first wave crest amplitude for $\gamma = 0^\circ$ [-]
$a_{0,c1}$	Initial first wave crest amplitude for $\gamma = 0^\circ$ [m]
$A_{0,c2}$	Relative initial second wave crest amplitude for $\gamma = 0^\circ$ [-]
$a_{0,c2}$	Initial second wave crest amplitude for $\gamma = 0^\circ$ [m]
$A_{0,t1}$	Relative initial first wave trough amplitude for $\gamma = 0^\circ$ [-]
$a_{0,t1}$	First wave trough amplitude for $\gamma = 0^\circ$ [m]
A_{c1}	Relative first wave crest amplitude [-]
a_{c1}	First wave crest amplitude [m]
A_{c2}	Relative second wave crest amplitude [-]
a_{c2}	Second wave crest amplitude [m]
$a_{\max}$	Maximum wave amplitude for $\gamma = 0^\circ$ by Bregoli <i>et al.</i> (2017) [m]
A_{t1}	Relative first wave trough amplitude [-]
a_{t1}	First wave trough amplitude [m]
b	Slide width [m]
c_{c1}	First wave crest celerity [m s^{-1}]
c_{c2}	Second wave crest celerity [m s^{-1}]
d_g	Grain diameter [mm]
F	Slide Froude number [-]
g	Gravitational acceleration [m s^{-2}]
h	Stillwater depth [m]
H_1	First wave height [m]
l_s	Slide length (Bregoli <i>et al.</i> 2017) [m]
M	Relative slide mass [-]
m_s	Slide mass [kg]
n	Number of data points [-]
P	Impulse product parameter [-]
r	Radial wave propagation distance [m]
R^*	Relative surrogate radial wave propagation distance [-]
r^*	Surrogate radial wave propagation distance [m]

R^2	Coefficient of determination [-]
R_0	Relative impact radius [-]
r_0	Impact radius [m]
S	Relative slide thickness [-]
s	Slide thickness [m]
t	Time [s]
T_1	First wave period [s]
V_s	Slide centroid velocity [m s^{-1}]
x	transverse coordinate [m]
$x_{\max}$	Distance from the impact location of $a_{\max}$ by Bregoli <i>et al.</i> (2017) [m]
y	streamwise coordinate [m]
Y_1	Relative first wave height [-]
z	vertical coordinate [m]
α	Slide impact angle [$^\circ$]
α_{eff}	Effective slide impact angle, $\alpha_{\text{eff}} = (6/7)\alpha$ [$^\circ$]
γ	Wave propagation angle [$^\circ$]
Δ_{meas}	Deviation of measured values from predicted
η	Water surface displacement [m]
θ	Basin side angle [$^\circ$]
ρ_g	Grain density [kg m^{-3}]
ρ_s	Bulk slide density [kg m^{-3}]
ρ_w	Water density [kg m^{-3}]

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