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Estimation of Impulse Wave Run-up Caused by Underwater Landslide in Dam Reservoirs

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ABSRTACT: Underwater landslide generated waves were studied in a physical laboratory model. Number of 102 sets of laboratory data with a set-up covering all of the three main stages of generation, propagation, and run-up of wave collected in a wide range of effective parameters. An empirical method was presented for prediction of impulse wave run-up caused by underwater landslide in a dam reservoir by using the primary information about slide geometry, initial submergence, still water depth, and sidewalls slopes. The presented method was successfully verified using earlier laboratory-based and analytical equations and an accuracy of ±15% was obtained. The presented method was also applied in a real case study for a dam reservoir in Iran in which, the impulse wave characteristics were available based on a numerical simulation using FUNWAVE as a well-validated model. The similar range of accuracy was obtained in predicted values of impulse wave run-up for the studied real case.

Keywords: Run-up, Impulse wave, Landslide, Dam reservoir, Laboratory investigation.

1 INTRODUCTION

The sudden movement of a large mass due to landslides, shore instabilities, snow avalanches, glaciers and rock falls in reservoirs, lakes and bays can generate large waves. The resulting impulse waves can have a disastrous potential of damage due to run-up along the shore-line and overtopping of dams. Generation and propagation of impulse waves have complex mechanism and may be divided into four parts: slide motion, initial water surface fluctuation induced by energy transfer from landslide to water, impulse wave propagation in the water body and wave run-up along the shores [Harbitz C. B. et al]. Some of earlier works focus only on the impulse wave generation using numerical modeling or laboratory set-up. Some other works focus on both generation and propagation of impulse waves utilizing numerical models [Grilli S. T., and Watts P.] or experimental measurements [Enet F. et al]. Some researches [Lynett P., Liu P. L.] covered the generation, propagation and run-up of impulse waves using numerical models. Ataie-Ashtiani and Malek-Mohammadi examined the accuracy of several available empirical equations for estimating generated wave amplitude in the near field. They showed that these empirical equations overestimate or underestimate the real cases. Based on the observed data from real cases, effective parameters on generated wave amplitude were revealed. To characterize near field wave amplitude based on introduced effective parameters and observed wave amplitude a new empirical equation was proposed and were successfully applied to real cases. The earlier numerical and experimental works about sub-aerial and submerged landslide-generated waves has been summarized by Ataie-Ashtiani and Najafi-Jilani. The only full laboratory set-up which covers all of formation, propagation, and specially run-up of impulse waves has been recently performed by Panizzo et al in a wave tank of 11.5x6x0.8m in which, the impulse waves caused by sub-aerial solid cube sliding on a slope with a range of angle as 16 to 36 degrees.

To the authors' knowledge an experimental set-up covering all of the three main stages of generation, propagation, and run-up for underwater landslide generated waves have not been carried out. It shall be considered that many researchers have experimentally studied the wave run-up independent on the generation source [e.g. Gedik N. et al]. They presented a number of empirical formulas for prediction of wave run-up. But these prediction equations were mainly presented using wave height near to the shore run-up. So the estimation of wave run-up requires the wave simulation in generation and propagation stages and determination the incident wave characteristics prior to the run-up on side walls.

The main objectives of this work are to provide a laboratory-based applicable empirical method to predict the wave run-up caused by underwater landslides especially in dam reservoirs only involving the primary characteristics of landslide, water body conditions and sidewalls slopes. In this regard, a full experimental set up is developed including impulse wave generation, propagation, and run-up. Over 100 laboratory tests performed in a wide range of influenced parameters such as sliding bed slope angle, slide geometry, density, initial submergence, run-up beach slope angle and normal water depth in wave maker tank. The earlier prediction equations have been completely observed and examined in experimental conditions and the differences are discussed.

2 EXPERIMENTAL SET-UP

The experiments have been performed in a wave maker tank with 2.5m width, 1.8m depth and 25m length at Sharif University of Technology. A schematic of the experimental set-up is shown in Figure 1. Two adjustable inclined flat surfaces with a distance of 8m from each other have been installed in the tank. The slope angle of flat surfaces can be changed in a range of 15 to 60 degrees. One of the inclined surfaces operated as the bed for free sliding down of solid blocks and another one for observation of wave run-up. There are transparent windows at the tank walls for observation of the free water surface profile.

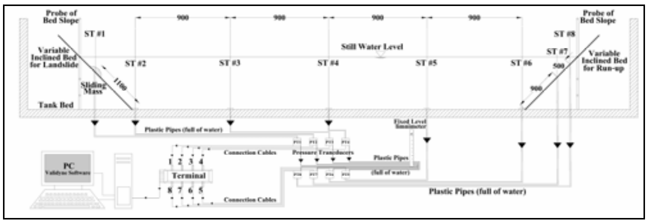

Figure1. The experimental set-up

Figure 2 shows a layout of laboratory tank and experimental set up. Seven solid blocks with different shape, volume and thickness have been used to generate impulsive waves. They have been made of steel plate with 2mm thickness.

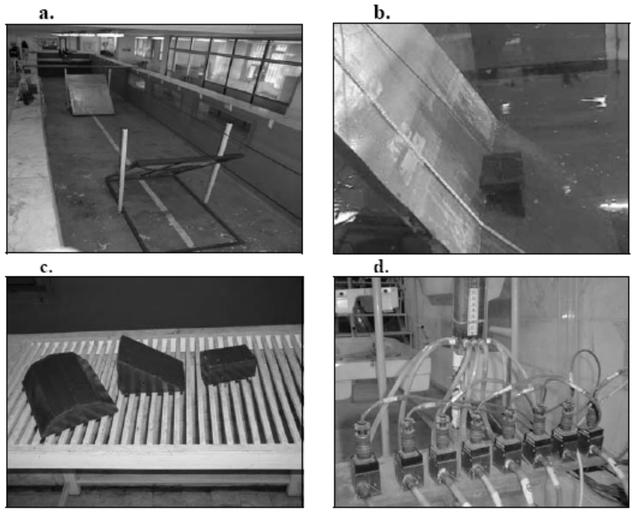

Figure2. a) Laboratory wave tank, sliding and run-up inclined beds, b) triangular rigid block just before sliding, c) sample of rigid blocks, and d) set-up of eight wave gauges

The rigid blocks dimensions are shown in Figure 3. All of the specifications of rigid blocks are given in Table 1 as well.

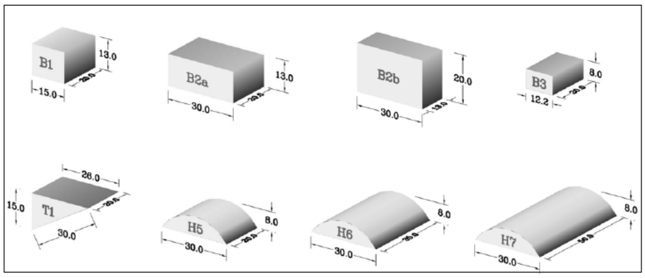

Figure 3. The dimensions of rigid slides

The water surface fluctuations have been measured using eight pressure transducers located at the central axis of the tank. The gauges are

Validyne D15 differential pressure transducers (DPD-D15).

Table 1. The specifications of rigid sliding blocks which are used in experiments

No.	Tag No.	V(m^3)	W_p(kg)	W_i(kg)	W_w(kg)	W_t(kg)	γ(kg/m^3)
		±0.000001	±0.001	±0.001	±0.001	±0.001	±0. 1
1	B1	0.00390	2.37	1.14	3.90	7.41	1900
2	B2	0.00780	3.92	3.10	7.80	14.82	1900
3	B3	0.00195	1.57	0.19	1.95	3.71	1900
4	T1	0.00390	2.84	0.67	3.90	7.41	1900
5	H5	0.00310	2.52	0.27	3.10	5.89	1900
6	H6	0.00540	4.05	0.81	5.40	10.26	1900
7	H7	0.00770	5.58	1.35	7.70	14.63	1900

V : solid block volume; W_w : weight of water
W_p: weight of perimeter steel plate; W_t : total weight of sliding block
W_i : weight of additional insert plate; γ: special gravity [$=W_t/V$]

The accuracy and the range of pressure measurements for each of wave gauges are listed in Table 2. The gauges have been calibrated before beginning of the experiments. Two digital cameras have been used simultaneously to capture the moving pattern of rigid block. One of the cameras applied for side observation and another for photographing from top view. Both of cameras have been focused on the near zone of underwater sliding. In addition, an extra digital camera has been focused on the run-up bed slope to capture the impulse wave run-up on the second inclined bed.

Table 2. The specifications of wave gauges

No.	Gauge station	Sensor technical name	P_{max}	Ac.
1	ST1	DP-15-32-N-1-S-5A	1400	± 3.5
2	ST2	DP-15-32- N-1-S-5A	1400	± 3.5
3	ST3	DP-15-32- N-1-S-5A	1400	± 3.5
4	ST4	DP-15-32- N-1-S-5A	1400	± 3.5
5	ST5	DP-15-22- N-1-S-5A	140	± 0.35
6	ST6	DP-15-22- N-1-S-5A	140	± 0.35
7	ST7	DP-15-22- N-1-S-5A	140	± 0.35
8	ST8	DP-15-22- N-1-S-5A	140	± 0.35

P_{max} : Maximum measurable differential pressure (Δp between two sides of diaphragm) (mm H_2o)
Ac. : Accuracy (mm H_2o)

The range of experimental parameters in performed tests was as bellow:

- Sliding and run-up bed slope angle: 15°≤θ, β≤60°
- Maximum thickness of slide: 8≤T≤20cm
- Slide length along the bed slope: 12.2≤B≤30cm
- Initial submergence of landslide: 2.5≤h_{0C}≤10cm
- Still water depth in wave tank: 50≤h_0≤80cm
- Rigid slide volume: 1950≤V≤3900cm^3
- Rigid slide weight: 3.7≤W≤14.8kg
- Relative thickness of slide: 0.26≤T/B≤0.86
- Relative submergence: 0.08≤h_{0C}/B≤0.82

In total a number of 102 experiments have been carried out with rigid blocks to cover a wide range of parameters. The numbering procedure of tests is illustrated in Figure 4.

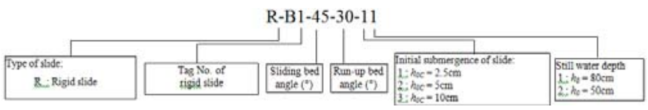

Figure 4. Numbering procedure of laboratory tests

All of the specifications of a test can be recognized based on its number. As seen in Figure 1, the wave gauges have been installed in the generation zone, along the propagation path of impulse waves and lastly on the run-up bed. Figure 5 shows a sample of water surface fluctuations recorded at the wave gauges near to the run-up sidewall. These data have been used as the incident wave characteristics and have been applied to investigate the wave run-up on the inclined bed.

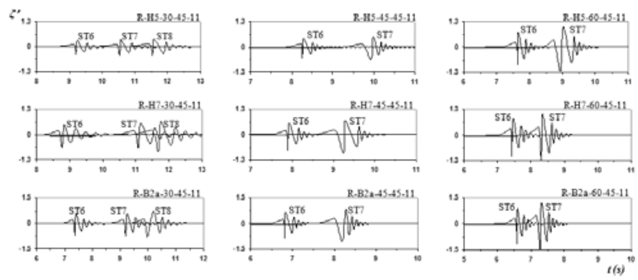

Figure 5. Water surface time series at wave gauges ST6, ST7, and ST8 in various experimental conditions, $\zeta' = \zeta / h_{0C}$

The complete lists of data for a sample of our performed experiments are presented in Table 3.

3 PREDICTION OF IMPULSE WAVE RUN-UP

The laboratory data have been analyzed to provide an empirical method for prediction of impulse wave run-up caused by underwater landslide. The parameters which play main role in determination of wave run-up (R) can be categorized as slide characteristics, parameters of the water body, and specification of the wave run-up sidewalls. Slide characteristics are slide geometry, slide kinematics, density (γ_s), initial submergence before sliding (h_{0C}), and sliding slope angle (θ). The slide geometry can be properly defined with slide length parallel to the bed slope (B) and its maximum thickness (T) [Enet F. et al].

Table 3. The recorded data in a sample of performed experiments

No.	Test No.	$T(m)$	$B(m)$	S_0 (m)	x_p (m)	H (m)	R (m)
1	R-B1-30-30-11	0.1300	0.1500	0.0932	6.1469	0.0275	0.0597
2	R-T1-30-30-11	0.1300	0.3000	0.1064	6.1469	0.0253	0.0700
3	R-B1-60-45-11	0.1300	0.1500	0.0572	5.4098	0.0336	0.0482
4	R-T1-60-45-11	0.1300	0.3000	0.0642	5.4098	0.0330	0.0609
5	R-B3-30-45-11	0.0800	0.1220	0.1856	6.2220	0.0206	0.0565
6	R-H5-30-45-11	0.0800	0.3000	0.0912	6.2219	0.0153	0.0481
7	R-B3-45-60-11	0.0800	0.1220	0.1007	5.7182	0.0284	0.0479
8	R-H5-45-60-11	0.0800	0.3000	0.0610	5.7182	0.0207	0.0429
9	R-B3-60-30-11	0.0800	0.1220	0.1501	5.4242	0.0418	0.0568
10	R-H5-60-30-11	0.0800	0.3000	0.0934	5.4242	0.0338	0.0545
11	R-H6-30-45-11	0.0800	0.3000	0.1497	6.2219	0.0207	0.0649
12	R-H7-30-45-11	0.0800	0.3000	0.1782	6.2219	0.0246	0.0722
13	R-H6-45-60-11	0.0800	0.3000	0.0870	5.7182	0.0283	0.0532
14	R-H7-45-60-11	0.0800	0.3000	0.0887	5.7182	0.0290	0.0535
15	R-H6-60-30-11	0.0800	0.3000	0.0998	5.4242	0.0357	0.0538
16	R-H7-60-30-11	0.0800	0.3000	0.1047	5.4242	0.0382	0.0577
17	R-B1-45-45-11	0.1300	0.1500	0.0500	5.6828	0.0317	0.0455
18	R-B2a-45-45-11	0.1300	0.3000	0.0657	5.6828	0.0306	0.0665
19	R-B1-15-60-12	0.1300	0.1500	0.0481	6.3035	0.0163	0.0308
20	R-B1-45-60-12	0.1300	0.1500	0.0498	5.3830	0.0271	0.0512
21	R-B2a-15-30-12	0.1300	0.3000	0.1005	6.3035	0.0201	0.0541
22	R-B2a-45-30-12	0.1300	0.3000	0.0696	5.3830	0.0261	0.0708
23	R-B2a-30-45-11	0.1300	0.3000	0.1068	6.1469	0.0257	0.0747
24	R-B2b-30-45-11	0.2000	0.3000	0.0752	6.0419	0.0266	0.0870
25	R-B2a-60-60-11	0.1300	0.3000	0.0764	5.4098	0.0423	0.0673
26	R-B2b-60-60-11	0.2000	0.3000	0.0556	5.3896	0.0430	0.0783
27	R-B2a-30-30-12	0.1300	0.3000	0.1068	5.6276	0.0222	0.0803
28	R-B2b-30-30-12	0.2000	0.3000	0.0752	5.5226	0.0229	0.0899
29	R-B2a-60-45-12	0.1300	0.3000	0.0764	5.2367	0.0359	0.0713
30	R-B2b-60-45-12	0.2000	0.3000	0.0556	5.2165	0.0365	0.0863

Slide kinematics can be defined with initial acceleration (α_0) and terminal velocity (u_t) and the main characteristic of slide kinematics can be expressed as $S_0 = u_t^2/\alpha_0$. Parameters of the water body are water density (γ_w), average still water depth in reservoir (h_0), and acceleration due to gravity (g). The specification of the sidewalls in which, the wave run-up is happened are sidewall slope angle (β), distance of wave propagation (x_p), and specifications of sidewall surface which is assumed impermeable and smooth in this work. Figure 6 shows the definition of all of these effective parameters. All these parameters are combined in a general function that can be written as:

$$f(R, B, T, \gamma_s, h_{0C}, \theta, S_0, \gamma_w, h_0, g, \beta, x_p) = 0 \qquad (1)$$

This physically meaningful equation involved 12 certain number of physical variables, and these variables are expressible in terms of 4 independent fundamental physical quantities. So based on Buckingham π theorem the original expression is equivalent to an equation involving a set of 8 dimensionless variables constructed from the original variables as:

$$f\left(\frac{R}{h_0}, \frac{T}{B}, \frac{\gamma_s}{\gamma_w}, \frac{B\sin(\theta)}{h_{0C}}, \tan(\beta), \frac{x_p}{h_0}, \frac{S_0}{h_0}\right) = 0 \qquad (2)$$

All of the parameters in this formula for a sample of our performed experiments are given in Table 3.

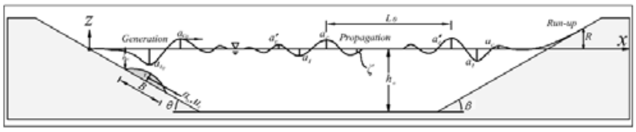

Figure 6. Definition of impulse wave characteristics at three main stages: generation, propagation and run-up in performed experiments

As it can be seen in Equation (2), the slide density "γ_s" is clearly considered as a separate parameter that significantly influences the impulse wave characteristics and also the wave run-up. Slide density is included in a distinct dimensionless group which will be involved in the run-up prediction Equation. Landslide kinematics is also strongly affected by slide density. So to minimize the scale effects in experiments and to simulate the moving pattern of slides due to their density completely same as in the real condition, the effect of bed friction on the moving pattern of blocks and also on the generated wave is minimized. The inclined sliding bed was completely lubricated and all of the tests were repeated at least two times. The recorded data of slide motion was examined and reported when the recorded time-variable location of block mass center had negligible changes. The sliding surface was smooth and was also lubricated in order to provide a frictionless slope. Therefore, the blocks could slide freely on the slope only due to their density. For quantitative controlling of density effects on sliding in laboratory and to provide a reliable prediction equation for the impulse wave run-up, it is necessary to determine the slide law of motion experimentally. The moving pattern of underwater slides is captured with a digital camera in 25 frames per second. The location of mass center of slides is determined during sliding down at 0.04 s time step on a regular perpendicular mesh with 1mm adjusted at the transparent walls of experimental wave tank. The location is measured parallel to the bed slope and the S–t curve is determined where S is the slide mass center location and t is time. The u–t and α–t curves are found from S–t curve by two-step time derivation where u is the slide velocity and α is its acceleration. Based on u–t and α–t curves, the main parameters of slide kinematics, u_t (terminal velocity) and α_0 (initial acceleration) are determined. The characteristic length for slide kinematics, S_0 is defined as $S_0 = \frac{u_t^2}{\alpha_0}$ [32] where C_d and C_m are the shape related coefficients of slide consist of drag and added mass coefficients, respectively. The characteristic time of slide motion is also defined as $t_0 = \frac{u_t}{\alpha_0}$. The moving equation of slides in experiments is captured in the tests and compared [6] with the well-validated law of motion $S(t) = S_0.\ln(\cosh(t/t_0))$ presented by Grilli and Watts [13-15, 9, 32, 33, and 34] for sliding down underwater landslides and a good agreement is obtained [6]. It is concluded that the effect of slide density on the waves in laboratory is completely modeled same as it influences the impulse wave in the real conditions.

Using multiple-nonlinear regression method for analysis of recorded data in performed experiments, the following formula obtained for estimation of impulse wave run-up caused by underwater landslide in a dam reservoir.

$$\frac{R}{h_0} = 0.126(\tan(\beta))^{-0.45}\left(\frac{x_p}{h_0}\right)^{-0.44}\left(\frac{S_0}{h_0}\right)^{0.6}\left(\frac{T}{B}\right)^{0.75}\left(\frac{B\sin\theta}{h_{0C}}\right)^{0.97}\left(\frac{\gamma_s}{\gamma_w}\right)^{0.3} \quad (3)$$

The parameter "x_p" which indicated in Equation (3), is propagation distance of leading impulse wave. This parameter is previously used by other researches which focused on the estimation of wave specifications in far-field [19]. "x_p" is the flat distance from wave generation point (sliding centre of mass) to the point on reservoir sidewall in which, the wave run-up is requested. It shall be noted that the proposed empirical formula is applicable especially for dam reservoirs, where the wave propagation distance is limited. The validation range of the presented empirical equation is too wide to be practical for dam reservoirs. Similar limitations were indicated by others [16, 18] and it is not any limitation for the universal value of the expression. The validation range of empirical equation (3) is $0.6 \le h_0/h_1 \le 1.5$ where h_1 is the still water depth near to the run-up sidewall. Besides, the presented method is only valid in short-distance propagated impulse waves as $x_p/h_0 \le 14$. As it can be seen in prediction Equation (3), the impulse wave run-up in dam reservoir is estimated based on slide geometry and kinematics, water body conditions and sidewalls slopes.

4 COMPARISON WITH EARLIER PREDICTION EQUATION

In this section, the presented prediction equation is compared with the run-up equations in the previous works. Based on the general characteristics of impulse waves caused by underwater landslide, solitary waves or combinations of negative and positive solitary-like waves are often used to simulate the run-up and shoreward inundation of these waves. Similar pattern of combined positive-negative solitary waves with a main higher-order leading wave is recognized in our experimental work. So, the main empirical equations for estimation of solitary wave run-up are used here and the results are compared with the measured data and also presented prediction equation. For further investigations, the periodic wave run-up is also investigated here. The run-up amplitude for a periodic incident wave on a beach can be analytically calculated in a simplified manner using nonlinear shallow water wave equations in a one-horizontal dimension. This analytical approach was clearly indicated in the basic and pioneer work of Carrier and Greenspan (1958) for periodic wave run-up on a beach. The maximum wave run-up (R_{max}) is determined as [Carrier, G.F., Greenspan, H.P.]:

$$\frac{R_{max}}{A_0} = 2\sqrt{\pi}\left(\frac{\omega^2 h_0}{g\alpha^2}\right)^{\frac{1}{4}} \quad (4)$$

Here A_0 is the amplitude of the incident wave with frequency ω on still water depth h_0. The water depth on the sloping beach is defined with $h(x) = -\alpha x$. Using the similar analytical approach and considering some modification, the run-up of a periodic wave on a sloping beach along the cross section of bay with ($m_{(horizontal)}:1_{(vertical)}$) for lateral direction y was determined by Golinko et al using Gamma function as Equation (5).

$$\frac{R_{max}}{A_0} = \frac{2\sqrt{\pi}}{\Gamma(1+1/m)} \left(\frac{m}{m+1}\right)^{\frac{1}{2m}+\frac{1}{4}} \left(\frac{\omega^2 h_0}{g\alpha^2}\right)^{\frac{1}{2m}+\frac{1}{4}} \qquad (5)$$

Equation (5) reduces to (4) for the plane beach where m→∞. According to our experimental conditions, equation (4) is used here to determine the impulse wave run-up in our performed laboratory tests and the results are compared with measured values and also presented prediction equation. Moreover, the following run-up equations for non-breaking solitary wave run-up over impermeable smooth bed have been also considered.

- Hall and Watts (1953) Equation

Hall and Watts (1953) predicted wave run-up as:

$$\frac{R}{H} = K(S_s)\left(\frac{H}{h_0}\right)^{(a(s)-1)} \qquad (6)$$

where *R* is the wave run-up, *H* is the incident wave height, h_0 is the still water depth, S_s is the run-up sidewall slope and *K* and *a* coefficients can be determined as follow (Equation 7):

$$\begin{cases} K(S_s) = 11S_s^{0.67} \text{ and } a(S_s) = 1.90S_s^{0.35} & \text{for } 0.09 < S_s \le 0.20 \\ K(S_s) = 3.05S_s^{-0.13} \text{ and } a(S_s) = 1.15S_s^{0.02} & \text{for } 0.20 < S_s \le 1.0 \end{cases}$$

- Synolakis (1986, 1987) Equation

Synolakis (1986, 1987) presented the well-known run-up law as:

$$\frac{R}{h_0} = 2.831\left(\frac{H}{h_0}\right)^{1.25} .\sqrt{\cot\beta} \qquad (8)$$

where β is the run-up sidewall slope angle. Some researches [Gedik N. et al] experimentally examined this empirical equation and good accuracy has been obtained.

- Müller (1995) Equation

Müller (1995) presented an empirical equations involving incident wavelength as:

$$\frac{R}{h_0} = 1.25\left(\frac{\pi}{2\beta}\right)^{0.2}\left(\frac{H}{h_0}\right)^{1.25}\left(\frac{H}{L_0}\right)^{-0.15} \qquad (9)$$

where L_0 is the non-breaking wave length.

- Li and Raichlen (2001) Equation

Li and Raichlen (2001) implied a minor modification in Synolakis (1986) run-up low as Equation (10).

$$\frac{R}{h_0} = 2.831.(\cot\beta)^{\frac{1}{2}}\left(\frac{H}{h_0}\right)^{\frac{5}{4}} + 0.293.(\cot\beta)^{\frac{3}{2}}\left(\frac{H}{h_0}\right)^{\frac{9}{4}} \qquad (10)$$

As it will be explained, the results come from this prediction equation in our performed experiments are too near to the Synolakis (1986).

- Hughes (2004) Equation

Hughes (2004) performed some laboratory experiments and introduced the momentum flux of incident wave as an effective parameter for wave run-up. He predicted wave run-up over impermeable smooth bed as:

$$\frac{R}{h_0} = 1.82(\cot\beta)^{\frac{1}{5}}\left(\frac{M_F}{\gamma_w h_0^2}\right) \qquad (11)$$

The dimensionless momentum flux of incident wave introduced as:

$$\frac{M_F}{\gamma_w h_0^2} = \frac{1}{2}\left[\left(\frac{H}{h_0}\right)^2 + 2\left(\frac{H}{h_0}\right)\right] + \frac{N^2}{2M}\left(\frac{H}{h_0}+1\right)\left\{\tan\left[\frac{M}{2}\left(\frac{H}{h_0}+1\right)\right] + \frac{1}{3}\tan^3\left[\frac{M}{2}\left(\frac{H}{h}+1\right)\right]\right\}$$

where *M* and *N* are empirical coefficients and can be determined as:

$$M = 0.98\left\{\tanh\left[2.24\left(\frac{H}{h_0}\right)\right]\right\}^{0.44} \qquad (13)$$

$$N = 0.69\tanh\left[2.38\left(\frac{H}{h_0}\right)\right] \qquad (14)$$

The presented equations in previous works have been applied to calculate the wave run-up in our performed experimental tests. Then, the results are compared with measured data of wave run-up and also with the results of presented prediction Equation (3). The comparison can be seen in Figure 7. The correlation of predicted and measured data in our performed laboratory tests are generally good and the maximum deviation from measured data is about ±15%. In further investigation on Figure 7, it can be concluded that the run-up prediction equations which developed based on the solitary-like assumptions of incident waves are in a generally better agreement with measurements. So it can be seen that the assumption of solitary-like waves for submarine-landslide-generated waves can be more reliable for estimation of wave run-up or shore inundation; as it was mentioned before.

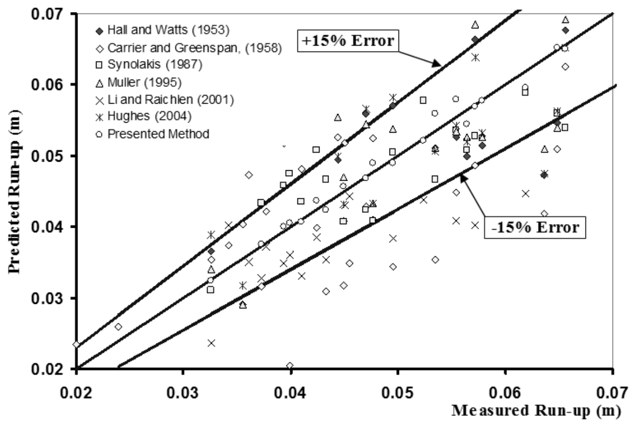

Figure 7. Verification of presented equation for estimation of wave run-up comparing to the earlier works

The main preference of the presented prediction equation (3) is to estimate the run-up only using slide specifications, water body conditions and run-up sidewall slope. But for application of the previous equations, the impulse wave characteristics near to the run-up slope should be provided, so the modeling of generation and propagation of impulse wave are required.

5 APPLICATION OF PRESENTED METHOD IN A REAL CASE

In this section, we apply the presented prediction method in a real dam reservoir which is located in northwest of Iran. For verification of presented equation, we used the results of numerical modeling of impulse wave generation and propagation in dam reservoir came from FUNWAVE as a well-validated model [Malek-Mohammadi S.]. It shall be considered that the potential landslides are very close to the normal water level and the major part of them is located underwater and the characteristics of submerged slide can be clearly recognized for them. Although Ataie-Ashtiani and Malek-Mohammadi were considered the slide potential as sub-aerial but the impact velocity of slides could not be empirically determined because of the slide real location and they used a minimum value for slide impact velocity as 0.3 m/s based on earlier works recommendation and estimate the initial wave height and length. It is considerable that if we use the latest well-validated underwater impulse wave empirical equations for estimation of initial wave characteristics caused by three potential slides, the results are very close to which obtained by Ataie-Ashtiani and Malek-Mohammadi with maximum deviation as ±5%. So the initial wave specification as well as results of numerical simulation of wave propagation using FUNWAVE can be used here.

The wave height recorded in numerical model at some gauges located near to the reservoir sidewalls and dam body. Then we apply the latest previous empirical equations for estimation of wave run-up over reservoir sidewalls and dam body. The results are compared with simple prediction equations presented in this work (Equation 3) which estimates the wave run-up without any need to numerical modeling of generation and propagation of impulse wave. The dam reservoir and potential landslides are shown in Figure 8. It is named as Shafaroud Dam and located in Guilan province in northwest of Iran. As it can be seen, three potential landslides are recognized in reservoir sidewall.

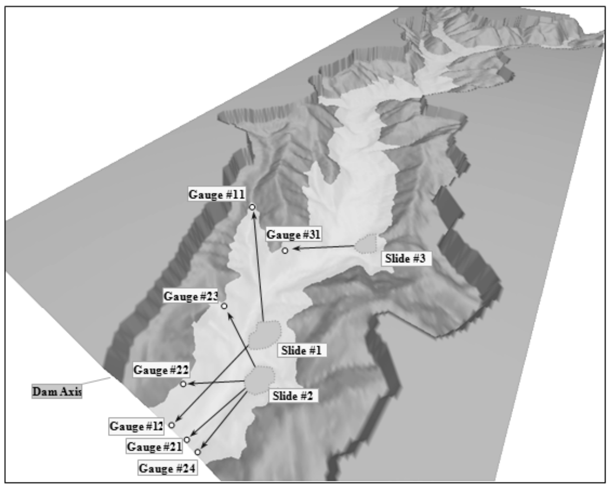

Figure 8. Shafaroud Dam reservoir (Iran), location of potential landslides and wave gauges applied for estimation of impulse wave run-up

The specifications of landslides are presented in Table 4. The Figure shows each of potential slides with corresponding wave gauges.

Table 4. Characteristics of three potential landslides in Shafaroud Dam reservoir (real case in Iran)

Slide No.	Length B (m)	Thickness T (m)	Density γ (-)	Submergence h_{0C} (m)	Bed slope θ (°)	Drag coef. C_d (-)	Added mass coef. C_m (-)	Terminal velocity u_t (m/s)	Initial acceleration α_0 (m/s^2)	Characteristic of motion S_0 (m)
1	380	15	2.7	35	30	1.7	1	54.1	2.2	1299
2	235	25	2.7	30	30	1.7	1	42.5	2.2	803.4
3	140	30	2.7	20	25	1.7	1	30.2	1.9	478.6

The water surface fluctuations caused by each of underwater landslides and wave run-up on the reservoir sidewalls have been numerically recorded at corresponding wave gauges using FUNWAVE. The numerical –based run-up has been compared with present prediction equation. The comparison is presented in Table 5. As it can be seen, the accuracy of presented method is acceptable. The mean error of estimated values of impulse wave run-up in the studied real case is about 9.6% and it shows the reliability of presented method.

Table 5. Results of presented method for impulse wave run-up in real case study (Shafaroud Dam reservoir), comparison with the latest previous prediction equation

Gauge No.	Reservoir specifications			Incident wave characteristics (FUNWAVE results)			Wave Run-up		Error (%)
	Propagation distance x_p (m)	Average depth h_0 (m)	Run-up slope β (°)	Positive amplitude a_c (m)	Negative amplitude a_t (m)	Incident wave height H (m)	Numerical Results	Presented method	
11	750	90	20	5.2	2.9	8.1	20.2	21.5	6.4
12	850	90	40	4.5	2.2	6.7	13.8	14.0	0.8
21	500	90	40	5.2	3.3	8.5	18.0	20.2	12.3
22	600	90	45	4.7	2.7	7.4	14.9	17.3	15.8
23	900	90	40	3.3	3.3	6.6	13.6	15.6	14.8
24	450	90	40	6.0	3.0	9.0	19.2	21.2	10.3
31	550	90	30	6.2	4.5	10.7	25.2	21.7	14.1

6 CONCLUSIONS

Over 100 laboratory tests have been performed to investigate the impulse wave run-up caused by underwater landslide in a dam reservoir. The experimental set up includes impulse wave generation, propagation and run-up and covers a wide range of effective parameter such as slide specifications, initial submergence, still water depth and run-up slope. The measured data have been used to present an applicable method for estimation of impulse wave run-up. The required data in prediction method is only slide specifications, water body conditions and specifications of run-up sidewalls of reservoir. The present method has been successfully verified using well-validated prediction equations for wave run-up in earlier works. A maximum error about ±15% has been obtained in presented method. The prediction equation is also applied in a real case study in which, the water surface data and wave run-up are available at some wave gauges near to the sidewalls from numerical modeling using FUNWAVE as a well-documented model. A good accuracy is obtained in all real case studies at various distances from source point and at various slide conditions. So, the reliability and applicability of presented prediction equations has been generally confirmed in laboratory and real case conditions.

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