6 IMPULSE WAVES

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6.1 INTRODUCTION

Waves induced by large masses moving into water are referred to as impulse waves. Given the typically large momentum exerted by such masses, i.e. the product of mass times velocity, the resulting phenomena produce often shallow waves. Water waves can indeed be subdivided into deep water and shallow water waves, the first having a small wave height compared to the still water depth, and the second having a large relative amplitude. Deep water waves are essentially based on a linear theory and are typically wind exerted. They are not further considered here.

Shallow water waves are highly nonlinear and a mathematical approach is complicate. Because of large wave amplitudes, the hydrostatic pressure distribution does not apply, and streamline curvature effects have to be accounted for. A basic wave type is referred to as the *solitary wave* characterized with a single positive wave peak propagating over an otherwise plane surface. An intermediate type between solitary and sinusoidal wave types is referred to as the cnoidal wave, that typically results from large masses plunging into a fluid.

Currently, some information on impulse waves is available, mainly in terms of compact masses plunging into a reservoir. Actual slides involve granulate, mud or snow, and cannot be simulated with a compound mass such as a single block of rock. Impulse waves thus involve a *three-phase flow* containing the slide material, water as fluid and air due to entrainment effects. This complication is certainly a major reason for limited knowledge on this highly interesting but dangerous phenomenon.

Fig.6.1 Vajont arch dam after impulse wave and overtopping in 1963.

Impulse wave into surface waters may originate from earth, rock, snow or glacier movements. All these slides are related to water, such as thunderstorms, avalanches, extreme weather conditions or rythmic water level changes. Slides moving into water bodies damage the region of origin by mechanical fracturing, result in wave action that can destroy shore regions or can even damage infrastructure such as roads, buildings or other near-shore structures. Of particular relevance are destructions in man-made reservoirs because a slide can cause runup or overtopping of a dam that retains a large volume of water. As a result, dambreak may occur with significant damage to downstream regions. Such a scenario occurred at various locations worldwide, but the *Vajont slide* in Northern Italy on October 9, 1963, is certainly the most widely known. Conditions were not all together critical for this incidence although the immense rock avalanche of some 300 Mio m^3 discharged into the reservoir and created an impulse wave of about 100m height. Fortunately, Vajont dam resisted this shock, but a large water volume overtopped it and killed 3000 inhabitants of the downstream located village Longarone (Fig.6.1). The following introduces the main features of impulse waves with regard to disaster resilient infrastructure. This topic is closely related to slides, rock falls and flood waves, and the corresponding contributions should also be consulted.

6.2 FEATURES OF IMPULSE WAVES

Waves generated in water bodies due to momentum release involve three features (Fig.6.2):

① Wave generation due to mass impulse on water body,

② Wave propagation over the water surface, and

③ Wave impact on water boundaries, such as shores or man-made structures, including possible overtopping.

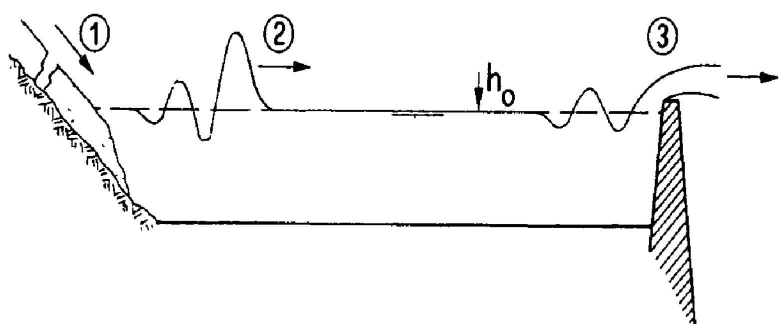

Fig.6.2 Impulse wave mechanisms on reservoir, schematic.

Impulse waves can be characterized as follows:

- The first wave has normally the maximum wave amplitude, and contains also the maximum energy,
- Waves develop from a highly complex phenomena close to impact location into a gradual surface phenomenon that is amenable to computational analysis,
- Waves decay in height as they travel over a water body of nearly constant depth,
- Typical developed impulse waves are either of solitary or cnoidal wave type, and
- Wave runup and particularly wave overtopping depend on shore conditions and are governed by difficult physical processes.

Given the complications due to various phases and abrupt temporal changes, both the impact an the runup conditions are currently not amenable to prediction, except for hydraulic modeling provided the proper similarity laws are accounted for. Two cases have received particular attention in the past, namely the plane impulse wave and the spatial impulse wave. These are described below.

The *plane impulse wave* was considered under the following conditions (Fig.6.3):

(1) Relative wave smaller than wave breaking limit, i.e. a relative amplitude smaller than 78% of the still water depth,
(2) Relative propagation domains larger than 5 and smaller than around 100 times the still water depth,
(3) Slide velocity larger than about half of wave celerity,
(4) Slide angle larger than about 30° and smaller than 60°, and
(5) Dense slide such as for a rock avalanche but not for exploded material containing much dust.

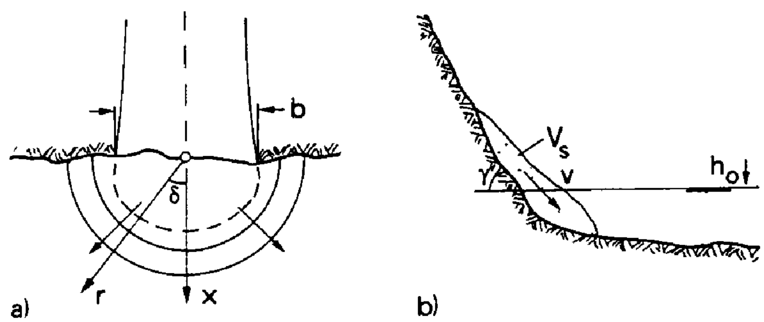

Fig.6.3 Wave generation into reservoir a) plan, b) section.

The maximum wave amplitude relative to the still water depth a_M/h_o depends on four dimensionless quantities, namely the slide angle γ with a large effect, the relative slide volume $V_s/(bh_o^2)$ with an intermediate effect, and the product of density ratio (ρ_s/ρ_w) times the relative distance (h_o/x) with a relatively small effect. The notation is explained in Fig.6.3, and ρ_s and ρ_w are densities of slide and water, respectively. For any given potential slide location, the slide density ρ_s, the slide angle γ and the still water depth h_o can hardly be influenced. The only parameter with a certain degree of variability is the slide volume per unit width V_s/b. The still water depth can of course be reduced for slides that do not immediately occur, provided the water elevation can be drawn down by operating a *bottom outlet*.

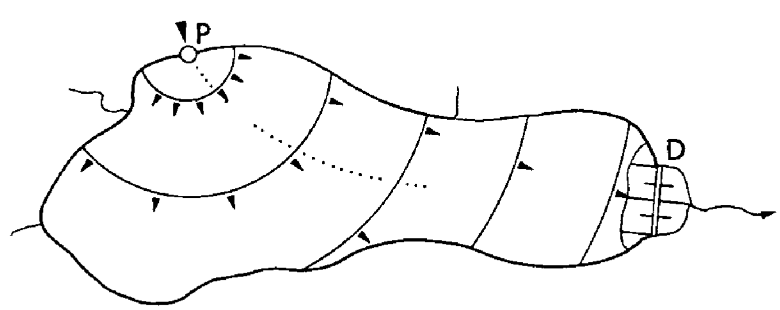

Fig.6.4 Impulse wave generated at point P and propagating towards reservoir shores and dam D.

For a slide running into a reservoir resulting in *spatial impulse wave*, the relative wave amplitude a_M/h_o follows previous characteristics, except of lateral wave propagation (Fig.6.4), and waves propagate radially from the impact location into the water body. The highest wave occurs in the direction of the slide and waves decay .laterally. Because of energy radiation, slides into a 3D water body are much smaller than into the plane reservoir.

6.3 IMPULSE WAVE RUNUP AND OVERTOPPING

Consider a water body of still water depth h_o containing an impulse wave of amplitude a_M and propagation velocity c_w. To estimate the potential of damage, the runup characteristics on a shore must be known. With L_w as the wave length (Fig.6.5) between $0.5 \leq h_o/L_w \leq 2$, the runup height $R=r/h_o$ depends essentially on the relative wave height h_M/h_o and slightly on the runup angle β and the relative wave length L_w/h_M. The *runup height* may be somewhat reduced when increasing the runup angle to, say, 90°. Wave breaking occurs if the index $tan\beta/(h_M/L_w)^{1/2}<3$.

An analysis of VAW data summarized by Vischer and Hager (1998) shows that

$$\frac{r}{h_M} \cong 1.25 \left(\frac{\pi}{2\beta} \cdot \frac{L_w}{h_o}\right)^{0.20} \tag{6.1}$$

This indicates that the runup height increases significantly with the maximum wave height, and slightly with the product $[L_w/(\beta \cdot h_o)]$. To control runup, one may practically adjust only the wave height h_M, therefore.

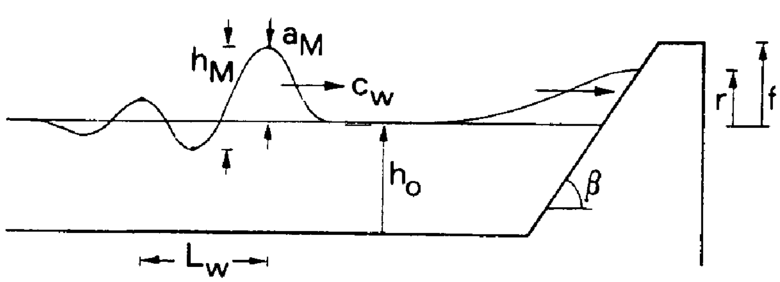

Fig.6.5 Wave runup on dam or shore, definition of variables.

Reservoirs with a dam downstream are particularly endangered because *dam overtopping* can occur in addition to wave runup. Fig.6.6 shows a definition sketch with L_d as crest width, r as runup height on a hypothetical shore of angle β, and f the freeboard under still water conditions. The *effect of freeboard* can be described as

$$V_d/V_o = (1-f/r)^2, \tag{6.2}$$

with V_d=overtopping volume, and the reference volume

$$V_o = C_1(gh_M^6h_o^2t_w^2)^{2/9} \tag{6.3}$$

where C_1= a constant of the order 0.6, depending on the crest geometry. The overtopping period varies mainly with the wave period $t_w=L_w/c_w$ where $c_w=[g(h_o+a_M)]^{1/2}$ is the propagation velocity. Both wave runup and wave overtopping are based on a plane approach flow. Roughening a shore has practically no effect on both wave runup and overtopping characteristics.

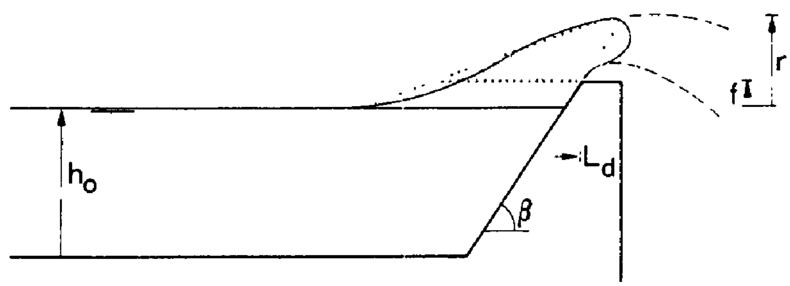

Fig.6.6 Overtopping of dam with (···) overtopping volume.

Assuming an average value $h_M=1.5a_M$ allows further elaboration of Eq.(6.3) for $L_w \cong h_o$ as

$$V_o = C_2\left(a_M^2 h_o\right)^{2/3}\left(1-\frac{a_M}{2h_o}\right) \tag{6.4}$$

The relative reference volume V_o/h_o^2 depends thus exclusively on the relative wave amplitude a_M/h_o. Note that V_o corresponds asymptotically to the overtopping volume for $(f/r)\rightarrow 0$.

6.4 CONSEQUENCES FOR INFRASTRUCTURE

6.4.1 Reservoir overtopping

The infrastructure endangered by impulse waves is located along a reservoir shore for wave runup, and downstream of the reservoir for wave overtopping. The latter scenario can be compared with a *dambreak* and may not directly be countered. The only measure against a dambreak is defining hazard zones, such as *zone 1* for immediate danger where there is no chance for evacuation, because of the dam proximity. Accordingly, no important infrastructure may be erected in this zone. In *zone 2*, evacuation within a short time is possible though not simple. This zone should not be accessible for population and infrastructure for strategic purposes. In *zone 3* only slight damages due to dambreak floods are expected, and evacuation is strictly possible. Procedures of evacuation should be trained with the population involved, and future infrastructure should be so designed that damages do not lead to significant conflicts, such as for access roads to villages endangered, supply lines or buildings of higher priority. The general recommendations given for protection against flood waves should be consulted, because the dambreak wave is a kind of extreme flood wave. Certainly a key mode of protection against dambreaks is the *dam safety technique*, involving regular control of all dam facilities, including monitoring of slides and settlements, geotechnical displacements, seepage flow and adopting hydrologic changes.

6.4.2 Wave runup

Impulse waves may damage infrastructure mainly by wave runup, except for extremely large slides into a practically full reservoir resulting in overtopping. According to Eq.(6.1) the runup height r is mainly influenced by the wave amplitude h_M, which depends significantly on the slide angle γ, the slide volume per unit width and the relative distance of slide impact to runup location x/h_o. For large slides only the *reservoir depth* h_o can be influenced if a bottom outlet is available. It will be hardly possible to reduce the relative slide volume by widening the slide, as also the slide angle. In order to reduce the reservoir level from an originally full reservoir that corresponds to the design condition (worst case scenario) the *temporal slide prediction* is of outmost importance. Again, one may distinguish between three cases:

(1) The slide occurs completely unexpectedly. This may be due to poor management or surveyance, or due to extreme thunderstorms. Then reservoir drawdown is impossible, and the slide may cause large scale damage. For cases with a proper management, the latter incident cannot happen because responsibility would restrict the reservoir filling elevation.
(2) The slide is predicted but within such a short time of occurrence that no significant reservoir drawdown can be introduced. Then all people and perhaps material of general value have to be safed.
(3) The slide occurs within days or weeks, depending on meteorological conditions mainly. Then, reservoir drawdown should be initiated to a degree that the downstream community is not endangered, but losses in values may be accepted. The latter scenario is closely related to modern dam safety, and should be the usual case. A slide has to be monitored and controlled by adequate engineering methods. Cases (1) and (2) have to be excluded.

Case 3 is, to be sure, more or less the only strategy to counter impulse waves. For the other two cases, there is practically no method of defense, given the enormous potential of energy set free by impulse waves. A way to protect strategically significant access roads are tunnels, rather than roads along shores. This concept is often dictated in Alpine countries because of extremely large slopes. If an access is strategically determining, this concept can largely contribute to reducing damages. For example, a *bottom outlet gate* has to be operated under all other conditions, because it will ultimately reduce damages of impulse waves. If such a gate gets squeezed, or does not move because of power supply shutdown, an complete emergency concept can fail.

6.5 RESERVOIR DRAWDOWN

A relevant question related to impulse waves is the *drawdown capacity* of a reservoir. If a general reservoir shape is considered that is controlled by a bottom outlet, the time t required for drawing down an initially full reservoir of depth H_o to depth H(t) can be given as

$$t/t_* = \frac{1}{\delta-0.5}\left[1-(4/H_o)^{\delta-0.5}\right]. \qquad (6.5)$$

Here $t_*=V_o/[C_dA(2gH_o)^{1/2}]$ is a reference time with δ=reservoir shape factor, V_o=full reservoir volume, C_d=discharge coefficient, approximately equal to 0.60, and A=bottom outlet area. Typically a value $\delta=2.5$ may be used, with extremes $\delta=1.5$ for bucket-shaped, and $\delta=3.5$ for V-shaped reservoirs. Eq.(6.5) thus simplifies to

$$t/t_* = \frac{1}{2}\left[1-(H/H_o)^2\right]. \qquad (6.6)$$

To reduce the reservoir elevation by 10% and 50%, say, one would use $t/t_*=0.10$ and $t/t_*=0.38$, respectively. A full reservoir drawdown requires $t/t_*=0.50$.

Consider a reservoir volume $V_o=10^7m^3$ with a reservoir depth $H_o=10^2m$. For a cross-sectional area of the bottom outlet $A=10m^2$, one has $t^*=2.5\cdot10^7/[0.60\cdot10\cdot(2\cdot10\cdot10^2)^{1/2}]$ =93'200s=1.08d. Such a small reservoir might thus be drawn down to 90% and 50% elevation heights within t=2·5h, and 10h, respectively, and might be completely emptied within one day. If the reservoir had a smaller depth but the same volume t_* increases accordingly. The time scale is thus dictated by t_*, that is drawdown of a reservoir is fast for:

- Small reservoir volume V_o,
- Large bottom outlet section A,
- Large reservoir depth H_o.

For a given reservoir, one may only influence parameter A, and a *large bottom outlet* is required for rapid reservoir drawdown.

6.6 RECOMMENDATIONS

Impulse waves can have a desasterous potential of damage combined with a significant degree of uncertainty. There are practically only two procedures to protect infrastructure: (1) evaluation of a emergency scheme by assuming the most critical combination of parameters, and (2) analysis of reservoir drawdown in terms of reservoir and downstream flow characteristics. In addition the following items may be added:

(1) Reservoirs with a potential to impulse waves should be controlled with a *bottom outlet*. If a bottom outlet is missing, its addition must be seriously considered, not only to counter impulse waves but also in terms of general dam safety, reservoir sedimentation and a more flexible reservoir management. If a bottom outlet is available, the drawdown features should be evaluated in terms of drawdown time and tailwater floods.

(2) Strategic *access roads* should be protected from floods and impulse waves by road tunnels. Also, electric power supply lines have to be so arranged that power is available even during large floods. A bottom outlet whose outlet gates cannot be moved is strictly of no value. The addition of an emergency power system based on fuel can be considered as an alternative. Given the extreme pressure forces exerted on outlet gates, its operation should be periodically tested.

(3) *Research activities* in impulse waves are currently small, given the complex interactions of geology, rock and ice mechanics, soil mechanics and hydraulics. The latter item has received particularly scarce attention, and questions relating to the effect of approach slide velocity, slide mixture characteristics, effect of air entrainment or momentum transfer during impact on the water body are not yet treated at all. To the author's knowledge, VAW has currently one of the few research activities worldwide on impulse waves, and it is hoped that the current experimental approach will be extended by a numerical research study to predict far-field effects of impulse waves on reservoirs.

Impulse waves are one of the spectacular but also one of the very dangerous natural hazards, therefore. Its knowledge should definitely be improved by an appropriate funding. This report aims to outline the possible procedures and to indicate directions which should be taken to reduce damages of lives and values.

REFERENCE

- Vischer, D.L., Hager, W.H. (1998). *Dam hydraulics*. John Wiley & Sons: Chichester, New York.