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Physical modeling and UVP monitoring yield an efficient protection of a lake reedbed from erosion

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The Lake Geneva revitalisation program includes among various measures the implementing of reedbeds along the artificialized riprap shoreline. The vegetation and its substratum must be protected against wind induced harms due to wave energy and currents. Since embankment-dikes in Suisse lakes are not permitted, according to the Suisse Federal Act on the Protection of Waters (RS 814.20), the Laboratory for Applied Hydraulics (LHA) of HEPIA has been mandated by the *Service du lac, de la renaturation des cours d'eau et de la pêche of Geneva* to carry out a detailed analysis by physical modelling of a double vertical-wall breakwater structure. The metal-wood structure designed by CERA civil engineers had to be optimized at the LHA, to achieve high wave-energy dissipation. In an experimental wave tank of the LHA, reedbed resistance and its substratum erosion potential were tested under 50-year return period wind conditions. The structural strains were also determined, under 100-year return period wind. The breakwater developed at the LHA prevents efficiently the reedbed against wind-wave induced harms and substratum erosion, as verified by Met-Flow UVP probes and described in the present study.

Keywords: physical hydraulic model, Met-Flow UVP probes, reedbed protection, breakwater, lake revitalisation

1. Introduction

The future Cologny reedbed will constitute a revitalisation measure for a portion of the artificialized Lake Geneva shoreline (Fig. 1), and an ecological compensation linked to the planed public access and leisure activities such as bathing. The project fulfils the Geneva renaturation master plan (PDCn 2030) and the Swiss federal laws, and classifies the Cologny revitalisation program as 1st priority.

Figure 5: The revitalisation project is situated on the east bank of the Lake Geneva shore.

The project site extends over 650 m along the Cologny shoreline. The primary lacustrine facilities are, a submerged wave-breaker parallel to the shoreline and a riprap belt defining the edge of the reedbed. Further structures are also planned such as a public access and a recreational platform. The waterbody between the shoreline and the breakwater will also benefit from the protection of the latter.

The lacustrine reedbed has to be protected from threats due to wind induced waves. The innovative breakwater design, developed at the LHA, and the achieved wave energy dissipation yielding an adequate protection of the reedbed are detailed in [1] and [2].

The present paper describes how shears stress on the reedbed substratum is reduced thanks to the breakwater, helping the resilience of the revitalisation measure.

2. Experimental setup

The experimental study was carried at the Laboratory for Applied Hydraulics of HEPIA-Geneva on a physical hydraulic model (Fig. 1) obeying Froude similitude at 1:25 geometrical scale. Scales of typical linked hydraulic parameters are presented in Table 1, where P index stands for prototype (natural condition) and M index designates model.

Table 1 Scales of typical hydraulic variables due to Froude similitude

Wave length L (m), Height h (m), Pressure P (m)	$\frac{L_P}{L_M} = \frac{H_P}{H_M} = \frac{P_P}{P_M} = \lambda$	25
Wave period and time t (s), Wave celerity and flow velocity U (m/s)	$\frac{t_P}{t_M} = \frac{U_P}{U_M} = \lambda^{1/2}$	5
Wave frequency f (1/s)	$\frac{f_P}{f_M} = \lambda^{-1/2}$	0.20

The 6.32 m long and 0.385 m wide wave tank was equipped with an air-piston wave generator. Lake bathymetry was reproduced over a path of 145 m (prototype) from the shoreline. As shown in Fig. 2 and 3, the model of the reedbed was implemented at the leeward extremity of the wave tank, in front of the shoreline. The

reedbed substratum was made of rigid expanded polystyrene, and the vegetation of flexible synthetic fiber planted in the substratum. The breakwater could be placed at various distances from the shoreline. Its modular structure, presented in Fig. 4, allowed several geometrical configurations.

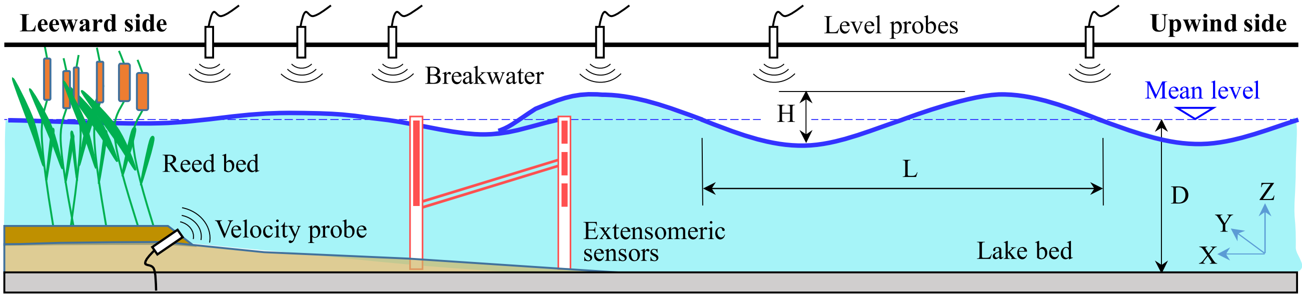

Figure 2. Hydraulic scheme of the physical model (wave tank). Wave propagation from the right to left.

The wave tank was mounted with six UNAM (Baumer) ultrasound level probes placed at six strategic points. A Met-Flow UVP 2 MHz ultrasound velocity probe was installed on the edge of the reedbed, with 30° from horizontal. Table 2 shows the UVP measurement ranges.

Table 2 Measurement ranges of the Met-Flow 2MHz UVP probe.

Velocity range (m/s)	Velocity resolution (mm/s)	Distance range (m)	Spatial resolution (mm)	Acquis. time (ms)	Sampl. frequ. (Hz)
0.09	0.3	3	1.48	132	8
49	193	0.006		1	4170

The breakwater was equipped with HBM SG LE11 50 Hz 2.5 V extensomeric sensors glued at spots where the poles were embedded in the modelled lake-bed (Fig. 4).

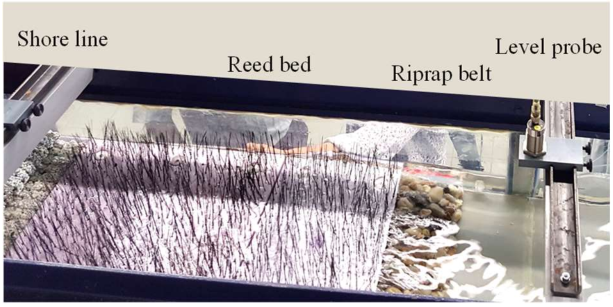

Figure 3: Model of the reedbed in the experimental wave tank. Substratum: rigid expanded polystyrene; vegetation: flexible synthetic fiber; riprap belt: agglomerated gravel.

The primary geometry of the breakwater was provided by CERA engineers. It was designed with two separate vertical walls, facing the waves (Fig. 4). While these walls on the prototype are planed of wooden planks, those of the model were built in metal. The leeward wall is designed with a solid surface and the upwind one with a definite hollow ratio.

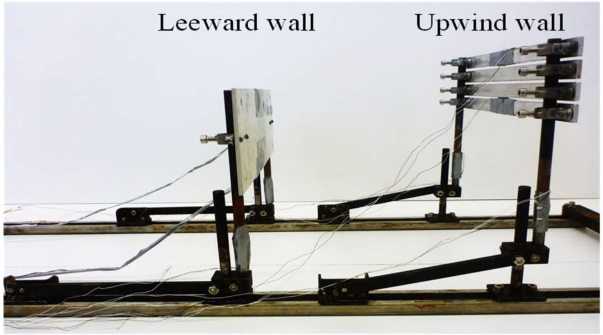

Figure 4: Model of the breakwater, composed of two parallel vertical panels. Extensomeric sensors were glued to the steel spots (S235 European norm EN 10 025 and ECISS IC 1).

On the model, the steel structure of the frame, poles and beams were built of the same material as planned on the prototype (S235 European norm EN 10 025 and ECISS IC 1), in order to achieve a consistent physical comportment due to same specific mass, Young elasticity, Poisson coefficient.

Typical prototype dimensions of the breakwater are presented in Table 3, according to Fig. 5.

Table 3 Typical prototype dimensions of the breakwater.

Bottom of walls above lake-bed, H_1	1.5 – 2.2 m
Wall height, H_2	2.3 – 3.0 m
Wall thickness, T	0.025 m
Upwind wall’s hollow, P	10 - 0 %
Distance between the walls, L_B	6 - 8 m
Beam diameter, D_B	0.3 m

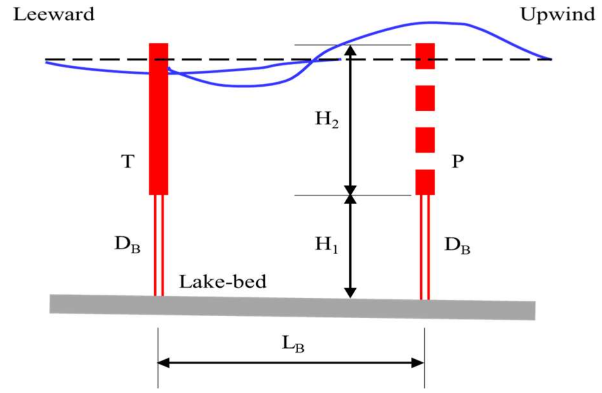

Figure 5: Typical geometric parameters of the breakwater

3. Analysis methods

The velocity measurements were done with a single 2 MHz Met-Flow probe. The sampling path extended over 45 mm. Vertical profiles with horizontal velocity were obtained as the cos30° component of the recorded data.

The measured flow velocity and calculated bed shear-stress were compared to critical values, for both initial and project states. The reedbed substratum is considered as composed of sand and silt with moderate cohesion. The critical bed shear stress is expressed by Eq. 1.

$$\tau = \rho \left(\frac{U_x \cdot \kappa}{ln\left(\frac{11 \cdot h}{k_S}\right)} \right)^2 \tag{1}$$

with:

ρ,	density of water,
U_x,	horizontal flow velocity,
κ,	von Kármán's constant (typically: 0.408),
h,	water column above the substratum,
k_S,	roughness height.

4. Preliminary data

Lake Geneva bathymetry was obtained from specific GIS data. The Lake's water level is regulated at its emissary in Geneva by the Seujet hydropower plant. The typical winter water level is 371.60 m.a.s.l.. During spring, snowmelt fills back the lake to the typical maxima of 372.30 m.a.s.l., lasting seven months. The historical extreme maxima corresponds to 372.70 m.a.s.l., attained a second time in Mai 2021.

Wind data were obtained from MétéoSuisse. Due to its 16 km fetch (Fig. 1), the determinant wind at Cologny is the northeast Bise. Duration curves of distinct return periods of the Bise were considered according to [3]. The dimensionless wave variables were determined with the JONSWAP method (Joint North Sea Wave Observation Project) [4], expressed as a function of the determinant dominant wind, the local bathymetry and shoaling conditions, as follows.

5. Modelling results

All results are hence presented with prototype values corresponding to natural i.e. project conditions.

The calibration of the physical model was first carried out. The simulations were done under stationary condition with sinusoidal homogeneous waves. Wave propagation was frontal to the breakwater to attain a maximum mechanical stress on its structure and effort on the reed bed.

Six water levels were applied for all tests, between the 372.70 m.a.s.l. extreme high-level of the lake and the 371.45 m.a.s.l. extreme low level.

The initial state was first simulated, without the breakwater, but the reedbed implemented in the model. For the project state, the experimental series were run by systematically adjusting the breakwater's geometry to achieve an efficient energy dissipation (see [2] and [1]).

The measured velocity range on the model is 0-0.4 m/s, and the velocity resolution is 10 mm/s (see Fig. 7 and 9). According to Table 1, these ranges fit in the UVP measurement range. The uncertainty of the measurement results is below 1 %.

5.1 Initial state

Reedbed behavior and soil erosion analysis at the initial state (without breakwater), were done for 50-year return period. Typical prototype values were: H = 1.0 m, wave height, L = 23.8 m, wave length, 1/f = 4.05 s, wave period.

During the flux phase, pointing to the shore, $KMnO_4$ dye tests showed a slight slowing down of the wave induced flow, due to the vegetation. The Met-Flow probe installed at the upwind edge of the reedbed, revealed a systematic characteristic velocity profile, as shown in Fig. 7 (solid line), with a near parabolic velocity distribution.

In Fig. 7 (dashed line), a typical velocity profile corresponding to the reflux phase is presented. While the main flow tends to backflush, the vegetation induces an eddy flow with a reversed current close to the substratum.

During both flux and reflux, the wave induced current close to the bed seems to slow down.

The typical horizontal component of the measured velocity converted to prototype value varies between $U_x = 1.5$ m/s and 2.0 m/s, oscillating from flux to reflux. Due to these measured values the calculated shear stress (Eq. 1) varies between $\tau = 4.94$ and 8.78 N/m².

Former analysis [5] reported a critical flow velocity comprise between $U_{cr} = 0.5$ to 0.6 m/s for erosion of sand substratum, and $U_{cr} = 0.3$ to 0.4 m/s for mud. Critical stress reported for sand erosion (Eq. 1) is about $\tau_{cr} = 0.3$ to 0.35 N/m², and about $\tau_{cr} = 0.2$ to 0.25 N/m² for mud.

In the light of the foregoing, it is noteworthy that without a breakwater both flow velocity and shear stress exceed the critical values, demonstrating the erosion of the reedbed's substratum. The impoverishment of the soil yields an inevitable destruction of the reedbed, which must be avoided in order to sustain the projected ecological revitalisation measure. A protecting breakwater is therefore needed.

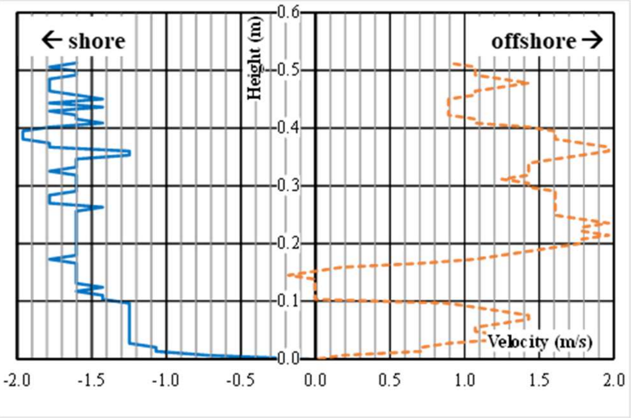

Figure 7. Horizontal U_x Met-Flow UVP velocity profiles (prototype values). Solid line: flow over the reedbed is pointing the shore. Dashed line: backdraft flow pointing mainly offshore, with a reversed flow close to the substratum, revealing the influence of reeds.

5.2 Project state

The wave tank equipped with the breakwater is presented in Fig. 7. The most relevant breakwater layout yields a near 70% wave energy reduction over the reedbed.

Substratum erosion potential is estimated on the basis of recorded velocity profiles. The two characteristic flow shapes shown in Fig.9 reveal a velocity pattern typically weaker than under initial state (Fig. 7). During backwash, flow encounters a reversed current near the bottom (Fig. 9 dashed line), due to the vegetation.

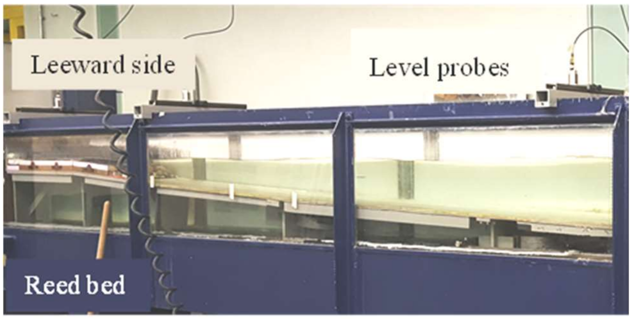

Figure 8. Wave tank during project state simulation. The breakwater yields a significant wave energy dissipation at its leeward stretch.

The typical horizontal component of the measured velocity under 50-year storms, converted to prototype value varies between $U_x = 0.35$ and 0.55 m/s, oscillating from flux to reflux. Due to these measured values the calculated shear stress (Eq. 1) varies between $\tau = 0.27$ and 0.66 N/m². These values are close to or lower than reported critical ones for sand erosion ($U_{cr} = 0.5$ to 0.6 m/s; $\tau_{cr} = 0.3$ to 0.35 N/m²).

Kármán constant of Eq. 1 may vary between 0.35 and 0.42 in flows over mobile sediment beds. With $\kappa = 0.42$, instead of 0.408, the maximum shear stress would not change significantly ($\tau = 0.70$ N/m²). The systematic shading effect of the reed vegetation may also help to protect its proper substratum even under 50-year storms.

The designed breakwater yields an efficient protection of the reedbed and its substratum against erosion.

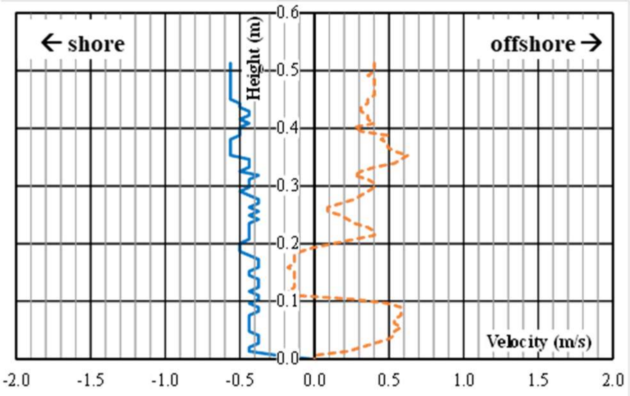

Figure 9. Horizontal U_x Met-Flow UVP velocity profiles (prototype values). Solid line: flow over the reedbed is pointing the shore. Dashed line: backwash flow pointing mainly offshore, with a reversed flow close to the substratum, revealing the influence of reeds.

6. Conclusion

The presented study carried out, on a physical model at the LHA of HEPIA in Geneva, on the protection of a reedbed yielded the following achievements:

- Without a breakwater the reedbed of Cologny should suffer from harms due to wind induced waves.
- Former papers [1] and [2] point out that the innovative double-wall breakwater developed by CERA engineers and tested at the LHA will protect the reed bed, by dissipating the wave energy about 70%.
- The present paper demonstrates, with the help of Met-Flow UVP measurements and calculated shear stress, that the breakwater yields also an efficient protection of the reedbed substratum.

In conclusion, the innovative breakwater can be constructed off shore Cologny, to guarantee a resilient reedbed.

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