TECHNICAL MEMORANDUM Bureau of Reclamation

Cavitation on Stepped Spillways – Lab Studies of Damage Potential

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Introduction

Beginning in the summer of 2009, Reclamation initiated a test program to investigate the cavitation potential of the new auxiliary spillway being designed by the Corp of Engineers for Folsom Dam in Sacramento, CA. This spillway is a novel design that features a high velocity flow exposed to a series of steps at a slope of 1V:2.48H, terminating in a modified type III stilling basin. Testing of a sectional model of the step geometry revealed a high-intensity shear layer above the step tips where turbulent energy production is high. Reduced atmospheric testing within the low ambient pressure chamber (LAPC) allowed for visualization of cavitation structures that would be probable in non-aerated prototype spillway flows. Due to scale effects in simulating the cavitation in this manner, damage to the model resulting from the visualized implosions of cavitation bubbles and vortices typically does not occur.

The test program showed good potential to provide generalized data for stepped spillways and Reclamation's Dam Safety Office and Science and Technology Programs provided additional funds to extend the data to additional slopes. This memorandum will detail lab studies to document cavitation damage to the stepped spillway surfaces based on the cavitation that had been visualized in the LAPC testing. Science and Technology funding was used to complete this task in FY2010.

Methods

Cavitation in hydraulic systems is typically a result of high velocity flow (>15 m/s). When separation from a boundary is forced, as in the skimming flow regime of a stepped spillway, local pressures within the separation and mixing zones are reduced. Typically, the magnitude of the reduced local pressures is a function of the velocity driving the separation. Hence, high velocity flows are generally required to reduce local pressures to the vapor pressure of water and cause cavitation. Cavitation can be created in specialized lab equipment, such as the hydraulic laboratory's LAPC. This facility uses a vacuum pump to reduce and hold the ambient pressure within the chamber at a much reduced level (0.08 atm), figure 1. This lowered ambient pressure then only needs a fraction of the velocity usually required in order to reduce local pressures within the model to the vapor pressure of water. The cavitation parameter or **s**, is used to define conditions or levels of cavitation,

where P_o is the reference pressure, P_v is the vapor pressure of water, **r** is the density of water, and V_o is a reference velocity. Cavitation can easily be visualized at these conditions; however, damage resulting from cavitation has been shown to be a strong function of the actual reference velocity magnitude, not the value of **s**. Stinebring [1976] reported that the pitting rate (a characteristic of cavitation damage) was a function of velocity to the sixth power (V^6). Previous experiences at Reclamation with models in the LAPC have never revealed damage associated with cavitation that has been created at reduced ambient pressures and low velocities.

Initial damage evaluations were attempted using the larger sectional model with a thin lead sheet veneer affixed to the last two steps. The lead sheeting provided a much softer material than the anodized aluminum that the steps were constructed from. Previous experiments with special coatings or paints have also been shown to be effective at times but tend to be very dependent on application technique and curing time.

A smaller sectional model was constructed and the test section was connected to the laboratory's high-head pump facility, figure 2. This pump can deliver up to 0.15 m^3/s at a head of 140 m. The closed channel is very similar to the larger version that had been tested in the LAPC, but the reduced size allows maximum velocities in the test section of over 20 m/s. With a projected prototype step height of 0.914m, the LAPC model featured steps with geometric scales of 16.7 and 33.4; the high-head pump facility used steps with a geometric scale of 64. Steps were machined from aluminum and then sent to be annealed, resulting in the "softest" possible material, i.e. least resistant to damage.

In both instances, the flow was increased to simulate a cavitation parameter of 0.3 and the test was continued for several hours, checking the condition of the model after increments of 1 hour of operation. The test sections were exposed to the cavitation conditions for a total of 6 hours (cumulative time). The tests were run to simulate two different slopes; the Folsom auxiliary spillway 1V:2.48H, and then the reverse of that or a very steep slope, 1V:0.403H.

Results

Testing of the sectional channel in the LAPC revealed no damage to the lead sheet veneer that was glued on the last two steps of the test section. The flow conditions were set to provide a flow **s** of 0.30. The test section was observed at one hour intervals. No pitting or marking of the lead sheet was observed throughout a cumulative time of 6 hours. The mean velocity within the test section was 6 m/s. The steps were reversed in order to simulate a very steep slope and again no pitting or indications of damage were noted. Figure 3 shows the flow conditions captured from high speed video at a frame rate of 2000 frames/sec. They are the mild and steep slopes at the same cavitation parameter.

The reduced-scale sectional model using the high-head pump was operated at a **s** of 0.31, for a total of 6 hours. The mean velocity within the test section was 22.5 m/s. Snapshots of the cavitation present in the high-head facility are shown in figure 4. Pitting was observed after about 2 hours of operation. The number of pits increased with additional time however it was not a linear increase. Figure 5a shows typical damage on the steps. All pitting appeared in the impingement area on the horizontal tread of the steps. A new set of undamaged steps were placed in the test rig in reverse direction to simulate a very steep slope. Only a couple of pits were noted after the 6 hours of operation and these were in the low pressure area on the vertical step face, just below the step tip, figure 5b.

Discussion

The formation of cavitation in hydraulic systems is a fairly common occurrence in spillways with high velocity flows. Typically, cavitation forms in localized areas that have low pressure zones resulting from offsets into or away from the flow. Cavitation on uniformly rough surfaces has received less focus in past research with perhaps the major work still being that of Arndt and Ippen [1983]. Their work showed that cavitation does form on uniformly rough surfaces but that it occurs at lower cavitation numbers than cavitation with a singular irregularity. While there are many documented cases of cavitation and damage to spillway surfaces within the literature, the same cannot be said for stepped spillways.

Stepped spillways, although the concept has been known and used for several thousand years, has only seen a resurgence in modern day designs since about 1970, coinciding with the use of roller compacted concrete (RCC) in dam building. The uniform lifts characteristic of RCC construction provide a direct tie-in to the use of stepped channels as spillways on these structures. Much of the modern day research has been associated with energy dissipation and air entrainment characteristics on stepped chutes. These benefits have also led to some uncertainty about the formation of cavitation and more importantly any damage that may occur. Since the 1950's it has been known that even small concentrations of air within the flow reduce or eliminate damage due to cavitation (Peterka 1953). The use of stepped spillways on high dams has occurred sparingly over the past 40 years and to date there are no documented cases of cavitation damage to any of these structures. Design guidance to date has been somewhat conservative with most structures having limited velocities and specific discharges. Recent designs have sought to far exceed the current recommendations and have driven these present studies to reevaluate possible cavitation and resulting damage.

The specific discharges for the newly designed Folsom auxiliary spillway are an order of magnitude larger than most past designs. The combination of high velocity and high depth has lead to speculation that the flows will not fully aerate, as they commonly do with most stepped spillways. The possible lack of air entrainment and the high velocities have prompted these studies of cavitation formation and damage. The use of the LAPC to visualize cavitation formation at various channel slopes has lead to an interesting finding that damage is very slope dependent. Observations of the mild slope 1V: 2.48H shows that the impact zone on the step tread is an area where coalesced bubbles concentrate, but also a zone where streamwise vortices seem to break up. The steep sloped 1V: 0.403H shows almost no impact on the step tread. The recirculating cavity exists between adjoining step tips. The flow patterns show the majority of the cavitation forms, including vortices, passing over the steps, remaining within the shear layer above the steps.

The damage to the mild sloped steps exhibited the typical incubation period often found when studying damage. No pitting was noted at one hour, but by the second hour, some pitting was evident. The shape of the pits is a bit different from that typical of singular bubble collapse. Elongated erosion holes were found in many locations along the length of the stepped section. The orientation was usually in the streamwise direction or a small angle to that direction. No pits of this type had a lateral orientation. This shape of damage is likely due to vortices imploding close to the step surfaces.

Conclusions

Laboratory testing of stepped channels of differing slopes and roughness heights have shown to exhibit cavitation in the forms of bubble cavitation and vortex cavitation. The vortices are generally in the longitudinal or streamwise direction and likely form on secondary flow interactions. Reduced atmospheric modeling was successful in allowing visualization and measurement of incipient cavitation conditions. Extended testing at low values of the cavitation parameter did not result in any pitting or damage to lead veneered steps within the channel at reduced ambient pressures.

Testing at near prototype velocities (>20 m/s) on annealed aluminum did result in pitting and elongated holes within the impact zone on the 1V:2.48H steps. The aluminum steps were exposed to a velocity of 22 m/s for a period of 6 hours. Consistent damage from step to step was observed. Still images show similar cavitation patterns as were observed in the larger LAPC modeling. The steep slope showed little if any damage. A couple of pits were observed on the annealed aluminum steps on the vertical face just below the step tip. This zone corresponds to an extreme low pressure zone identified by other researchers (Amador, et.al. 2009). The damage that occurred was in the absence of any air entrainment and so it is yet to be seen if prototype damage will occur in the presence of naturally entrained air.

References

Amador, A., Sanchez-Juny, M., and Dolz, J. (2009). *Developing Flow Region and Pressure Fluctuations on Steeply Sloping Stepped Spillways,* J. Hydraulic Eng., 135(12), pp. 1092-1100.

Arndt, R.E.A. and Ippen, A. (1968). *Rough Surface Effects on Cavitation Inception.* J. Basic Eng., June 1968, pp. 249-261.

Stinebring DR, (1976). *Scaling of cavitation damage,* MS thesis. Penn. State Univ.

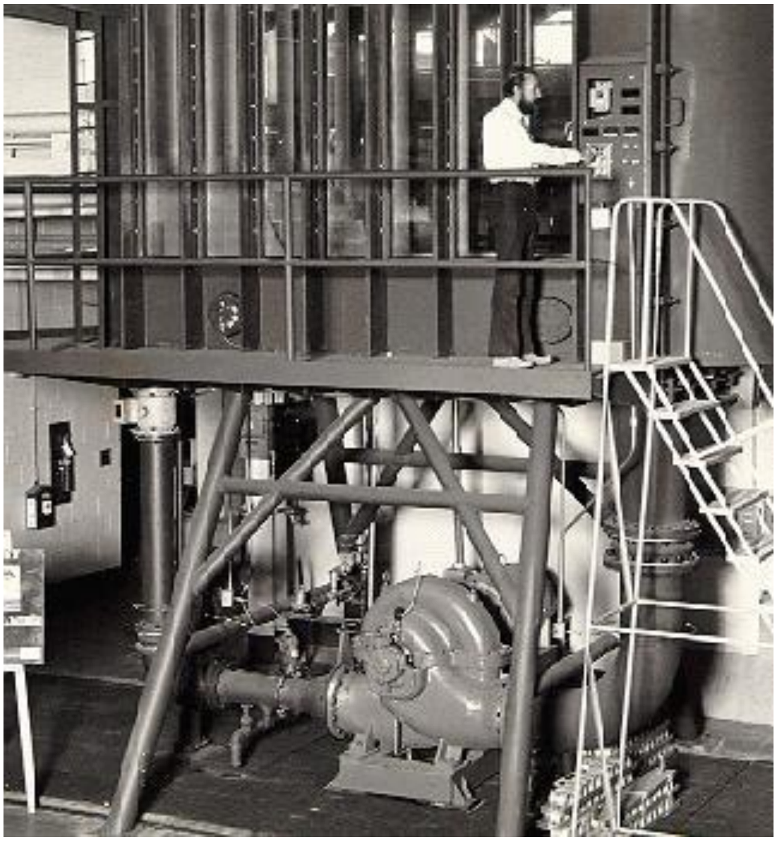


Figure 1: Low ambient pressure chamber (LAPC). An enclosed recirculating vacuum chamber for studying cavitation in hydraulic structures.

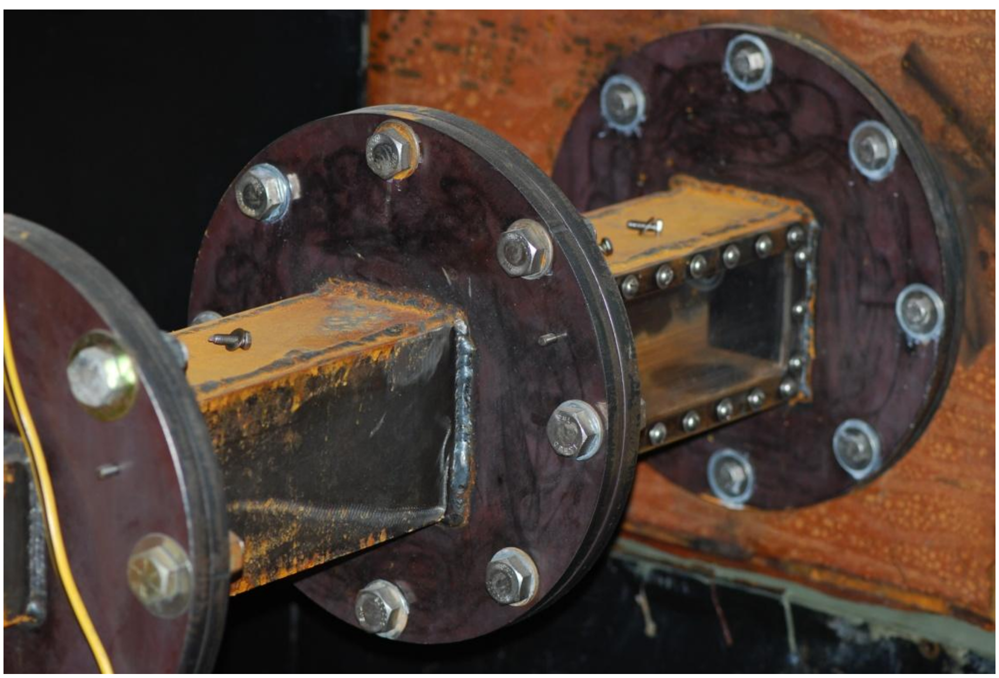
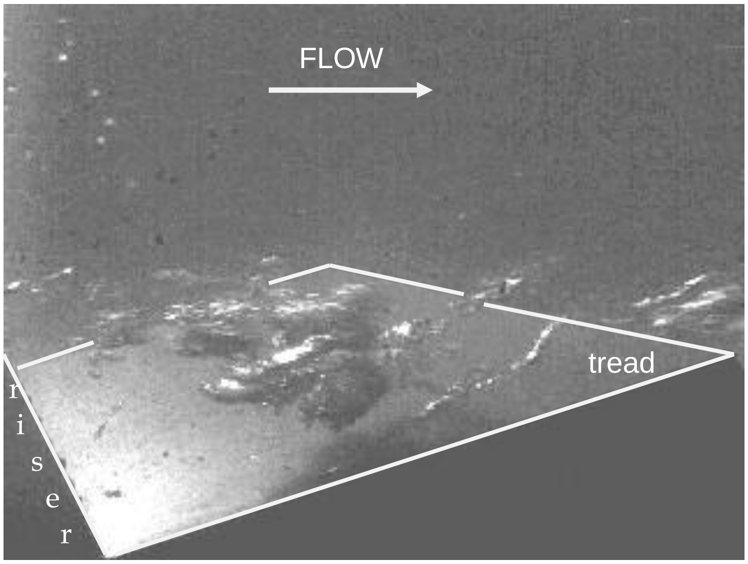
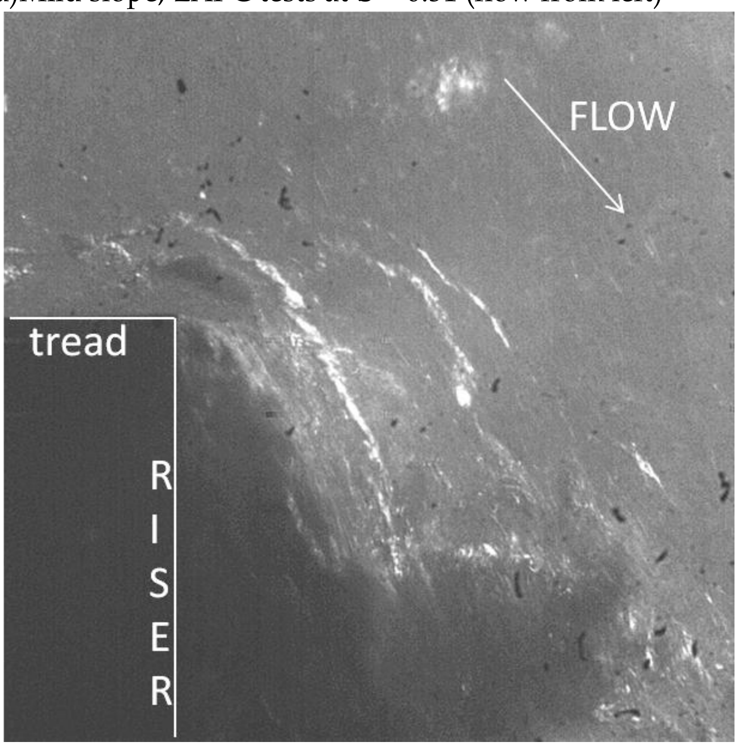


Figure 2: Test section of high-head pump facility. Stepped inserts are placed within the lengths shown.

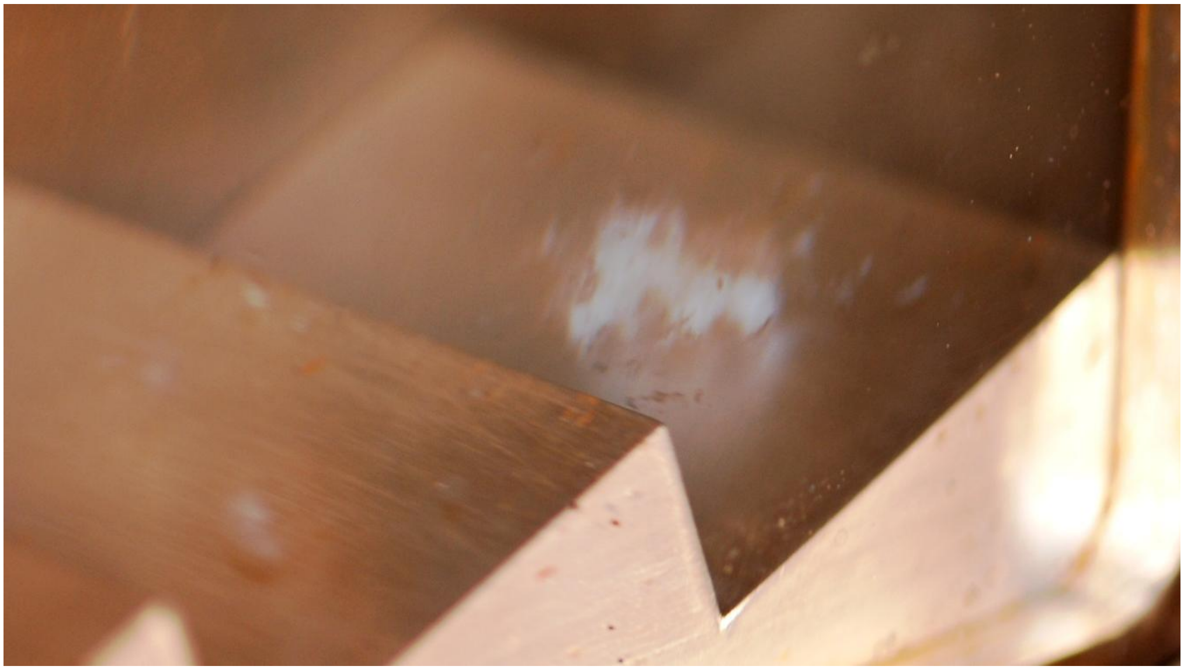


a)Mild slope, LAPC tests at **s** = 0.31 (flow from left)

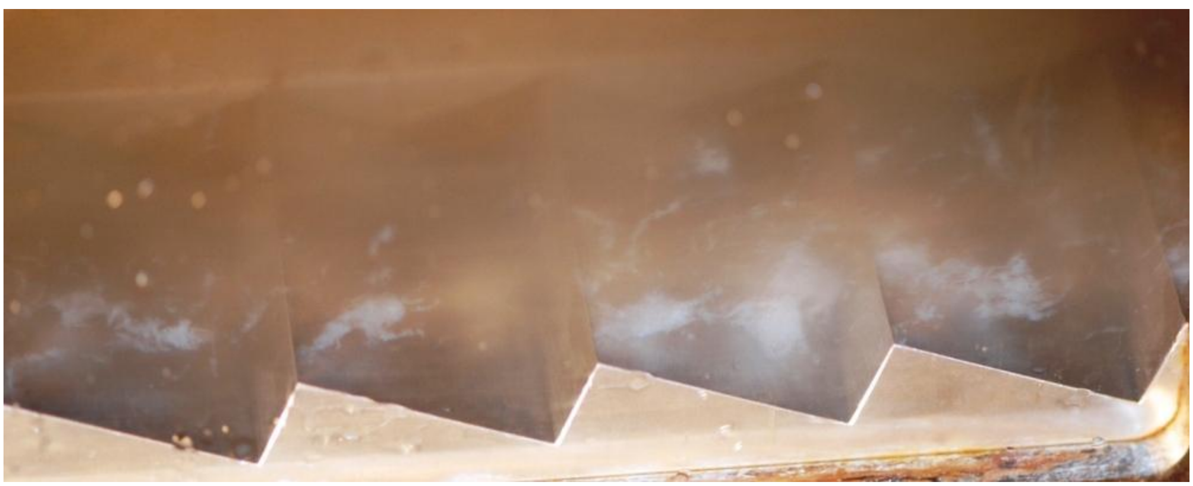


a) Steep slope, LAPC tests at **s** = 0.32 (flow from top left)

Figure 3: Steps within the LAPC, captured from high-speed video running at 2000 frames/s. Mild slope appears with the step tread at 21.9-degrees to the horizontal – such that a line connecting the step tips is horizontal. In the steep slope picture, the camera was rotated to provide a horizontal tread.

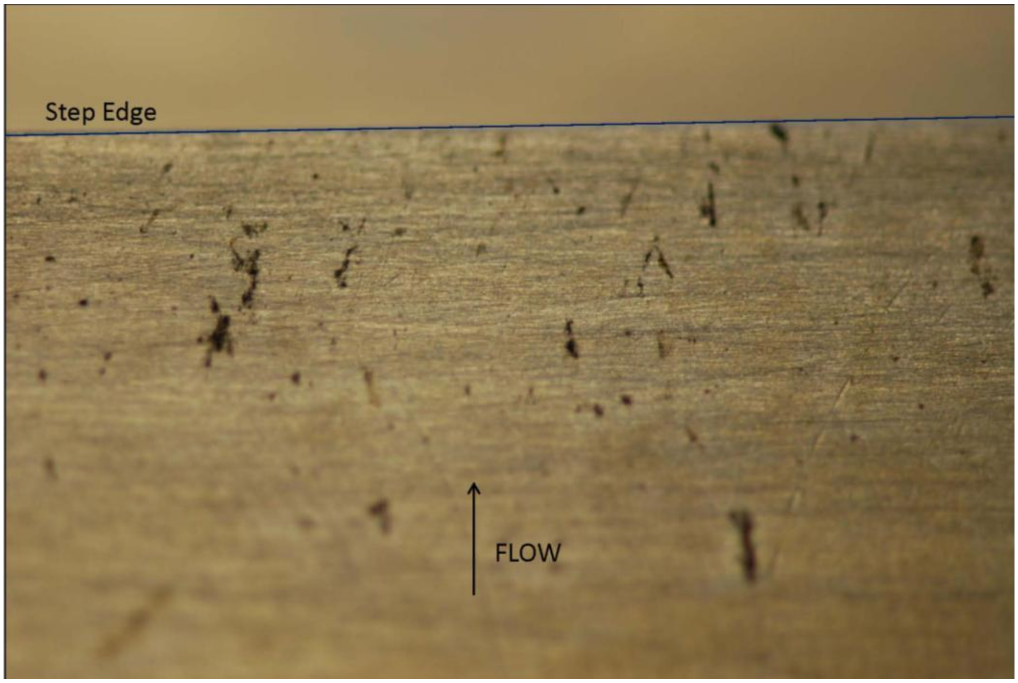


a) Snapshot of cavitation on mild slope in the impact zone.



b) Snapshot of cavitation on the steep slope, note cavitation seems to be generated more at the step tips.

Figure 4: Steps in high-head pump test facility. Photos with digital camera at a shutter speed of 1/60th s. The speed of capture is not enough to provide the sharp detail of the flow structures.



a) Close up of damage to a step after 6 hours of operation at 22 m/s, on the mild slope (1V:2.48H) depth of pits varies but none are very deep. Most interesting features are the elongated voids in basically a streamwise orientation.

b) Close up of step after 6 hours of operation at 22 m/s, on the steep slope (1V:0.4025H). Little if any pitting occurred. No elongated damage as in (a) shown above.

Figure 5: Close-ups of damage to the annealed aluminum steps in the high-head facility after 6 hours of exposure to velocities of 22 m/s (**s** ~ 0.3).