Stabilising the sediment bed in laboratory flumes

Stabilisation des lits de sédiments dans les canaux expérimentaux

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ABSTRACT

Recent laboratory investigations of alluvial channels with loose bed and banks of coarse sand required a method for immobilising or 'freezing' the loose boundary to permit time consuming hydraulic measurements without changes in the boundary geometry. A technique involving spraying separate solutions of sodium silicate and sodium bicarbonate on to a drained channel has been rediscovered, and is reported here. After freezing the changes in geometry and hydraulic roughness are negligible and some results are presented to illustrate this. The equipment and materials costs are low. Furthermore, for freezing a large area the method described has advantages, from a health and safety point of view, over using adhesives or dry cement powder as alternatives.

RÉSUMÉ

Les récentes investigations de laboratoire avec lit érodable et berges en sable grossier, ont nécessité une méthode pour immobiliser ou « geler » la frontière érodable afin de permettre des mesures hydrauliques longues sans changement de la géométrie de la frontière. Une technique utilisant la pulvérisation séparée de solutions de silicate de sodium et de bicarbonate de sodium sur un canal vidangé a été redécouverte, et est rapportée ici. Après le gel les changements de géométrie et de rugosité sont négligeables; ceci est illustré par quelques résultats. L'équipement et les produits ont un faible coût. En outre, pour geler une grande surface, la méthode décrite ici a des avantages certains d'un point de vue salubrité et sécurité par rapport à l'usage des adhésifs ou de la poudre de ciment.

1. Background

During experimental work in the Flood Channel Facility (FCF) with mobile boundaries (at HR Wallingford, UK, during 1994–97) it was necessary to record velocity and Preston tube data, especially near the bed, in order to compare earlier work with rigid boundaries. Thus it was necessary to physically prevent migration of bedforms and 'freeze' the geometry of the loose channel. Draining the channel after some hours of flow with loose boundaries and applying a coating was envisaged, followed by re-establishing the flow in the 'frozen' channel. A sprinkled-on cement covering would be adequate only if it was some millimetres thick, and use of sprayed adhesives (e.g. Khalil [2]) was thought to be too expensive for this 80m^2 area, and too permanent. Both these methods also carry health risks during application to a large area; both coat the surface, affecting geometry and texture to some degree. A less intrusive, practical, economical and safe method was sought.

Vanoni and Nomicos [5] briefly describe a bed freezing technique using aluminium silicate and sodium silicate followed by calcium chloride and finally varnish, which was used successfully in a 250mm wide flume to freeze a mobile bed with little change in grain roughness. Sodium silicate is sometimes used in foundry work to bind sand moulds during the casting process and this idea had also been adapted for experimental work with sediment in the Thames barrier studies at HR Wallingford during the 1970s (Littlewood, pers. comm. [3]). Successful results with Obeche wood chips and Perspex grains were obtained in these studies, though sand was not used. It was of advantage to the FCF experiments to avoid using varnish, which increases air trapping problems, has effect on grain roughness and creates health risks while spraying. The quantities of chemicals in the final FCF technique given below are close to the earlier Thames barrier recipe, but the application method is at least as important as the mixture. Two separate sprayers were used in applying the chemicals, one for the sodium silicate solution and one for the sodium bicarbonate solution. The equipment costs were modest (≈£200 for sprayers) and the chemicals themselves were cheap in bulk (sodium silicate ≈£0.50 per kg, sodium bicarbonate cheaper still).

2. The FCF loose boundary freezing experiments

The first FCF loose bed experiments (undertaken by the University of Newcastle, UK) involved a straight mobile channel region 2m wide and about 40m long, with a near-uniform bedload sand of sub-rounded silica grains. The sediment D_{50} was 0.84mm and σ_D approximately 1.3, where D_{50} was the sieve size passing 50% of the sediment by weight and $\sigma_D = 1/2(D_{84}/D_{50} + D_{50}/D_{16})$. Flow depths of 100mm and flow velocities of about 0.5m/s were to be sustained for several hours over the channel bed and banks after freezing. The bedforms were typically dunes of approximately 1m wavelength and approximately 30mm vertical range. See Valentine *et al* (this issue) [4].

The channel to be frozen was drained so that the water table in the flume was 200–300mm below the bed level. After 12–24 hours, while the sand remained visibly slightly damp, the first coat was applied over the whole area. Table 1 shows the quantities of both solutions that were used for one coat. Sodium silicate and water could be mixed in the sprayer itself, but the sodium bicarbonate solution was made separately beforehand in order to prevent un-

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Table 1. Relative quantities of chemicals used for bed freezing on the FCF, sufficient to cover 80m^2 with one coat.

	Sodium silicate mixture	Sodium bicarbonate mixture
Type of sprayer used on the FCF	20 litre knapsack agricultural sprayer	8 litre 'Killaspray' garden sprayer
Volume of chemical	11 litres	-
Mass of chemical	16kg	400g
Volume of water	9 litres	7 litres
Approx. total volume	20 litres	7 litres

Note: sodium silicate (also known as 'water glass', or simply 'crystal') is supplied as a clear viscous liquid in 40-gallon steel drums, or in smaller 20 litre containers. Sodium bicarbonate (or sodium hydrogen carbonate) is a powder obtainable in bulk packs of 25 or 50kg.

dissolved lumps entering the sprayer. Care was taken to achieve a fine spray and keep the spray moving across the bed so as not to disturb the loose sand, especially on the first coat. It was essential that the two mixtures were applied directly to the sand with separate sprayers to avoid mixing the chemicals until they were actually in the sediment. Rinsing the sprayers through with clean water before storing was necessary to prevent the blocking of jets etc. Fig. 1 shows the spraying operation in progress.

Usually 3–5 such coats were applied over 2–3 days, without any artificial drying, in air temperatures of 15–20°C. Successful results in air temperatures below 5°C were also achieved. As a precaution extra radiant heat was applied to the 15m test section by four 2kW photographic lamps in these lower temperatures.

The bonding of sediment formed a surface 'crust' some 10–15 mm thick, which remained almost unchanged in appearance and texture (as the original sand surface), and retained some permeability to water and air. It was important to refill the channel very slowly from the downstream end, as the stream of water over the dry bed tended to seal the surface and trap air, causing local cracking and lifting. Experience was that slow backfilling was the only reliable way to avoid damage on start up. For refilling the FCF the water level was brought up to the downstream invert level as normal; thereafter the frozen bed was backfilled at only 25–50mm of depth per hour, until the whole channel bed was covered with standing water. Once this was completed, bankfull flow could be gradually established within about 30 minutes.

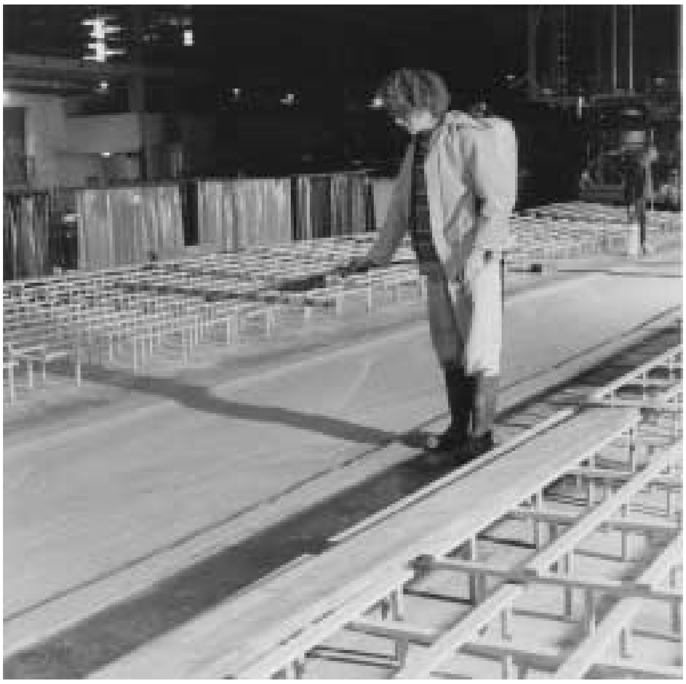

Fig. 1. View of the freezing operation in progress in a typical experiment in the Flood Channel Facility.

3. Properties of the 'frozen' boundary

The bonded surface crust lost some of its strength while wet, but was adequate for Preston tube measurements to be taken with care (the tube had to be placed on the boundary by hand). Detailed velocity measurements and experiments involving injection of coloured sand and fine material into the channel were also made possible. Continuous water flow within the frozen boundary channel for 24 hours or more was possible. Series of tests lasting 2 weeks or more on the same frozen boundary channel were also undertaken, in which cases the flume was drained once or twice and 'top up' applications of 2 or 3 coats of spray were made. Small repairs could also be undertaken while the channel was drained. Repairs utilised either sieved dry cement powder on damp sand, or a plaster of Paris and water mixture which had the advantage of fast drying.

The geometrical changes caused by the above freezing process on the channel bed were barely detectable with the touch sensitive vertical profiling equipment installed on the FCF (accuracy 0.5mm, resolution 0.1mm). Fig. 2 shows a cross-section of a meandering channel at a typical crossover before freezing, and later at the same section, following over 20 hours running with the frozen boundary. It is thought that discrepancies in the plan position of the automatic bed profiler before and after freezing account for much of the observed differences. The profiler head was also able to sink 1–2mm into steep regions of the channel banks and bedforms while they were loose, but not when frozen.

The hydraulic roughness changes were minimal and close to the limits of experimental error. Table 2 gives stage, Manning's n, and mean velocity as calculated for two straight channels before

Table 2. The effect of the freezing process on hydraulic roughness. Two experiments with the near-uniform sediment boundary channel in the FCF.

Channel	45 l/s straight bankfull channel		25 l/s straight bankfull channel	
Boundary	Loose	Frozen	Loose	Frozen
Stage, mm	62.1 ±1.5	60.6 ±1.9	44.7 ±1.0	45.4 ±0.7
Manning's n	0.0145 ±0.0005	0.0135 ±0.0007	0.0135 ±0.0004	0.0139 ±0.0003
Velocity (m/s)	0.427 ±0.010	0.436 ±0.012	0.371 ±0.008	0.366 ±0.006

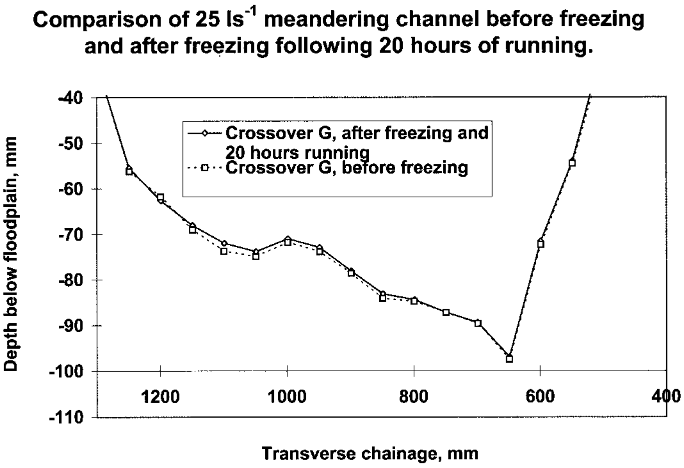

Fig. 2. Comparison of the cross-section at a typical crossover in a meandering channel before freezing, and after freezing and 20 hours running.

and after the freezing process.

Table 3 outlines the conditions where the technique described is known to have been used successfully to date (information for the last two rows kindly supplied by Sarah Catmur, Queen Mary and Westfield College, UK, and Mervin Littlewood, HR Wallingford, UK, respectively).

4 Re-establishment of the loose bed

The removal of the frozen crust was performed manually in the FCF, lifting it gently with the help of a shovel slid underneath the frozen level, so as to remove pieces as large as possible. Bags of the removed crust were then lifted away using an overhead gantry. A significant amount of material was wasted in the process, in order to minimise the contamination of the loose sand remaining in the FCF (equivalent to about 10mm depth in addition to the frozen 10-15mm thick crust). However it was possible to break

Table 3. Known sediments and experimental conditions in which the sodium silicate/sodium bicarbonate spraying technique has been used.

Sediment	Experiment type	Depth	Velocity	Duration and Comments
Near-uniform silica sand, D_{50} 0.84mm	FCF. Straight and meandering, frozen banks and bed.	0.04-0.1m	up to 0.6m/s	Many days with minor repairs and 1 or 2 recoats; in excess of 24 hours continuous running.
	FCF. Straight, frozen bed alone. (both flat bed and bed with very large bedforms)	0.2-0.3m	0.4-0.8m/s	Progressive failure after several hours, better with periodic recoating. Large, steep bedforms problematic.
Non-uniform calcite sand, D_{50} 1.5mm and $\sigma_D \approx$ 3.2	FCF. Meandering, frozen bed alone.	0.15m	0.4m/s	Many days with minor repairs and 1 or 2 recoats; in excess of 24 hours continuous running.
Obeche wood chips (≈0.5mm) or Perspex grains (≈1mm)	Thames barrier models. Rigid prototype mouldings covered with a layer of sediment.	≈0.05m	≈0.1m/s	Several days on one application, no repairs needed.

up, sieve and wash the frozen sediment and return it to a loose granular state with very little change in the grading curve. Crushing the crust with a large roller and pumping it through the FCF sediment return system was very effective in breaking it down; experimental quantities were then wet sieved by hand with a large 2mm mesh sieve. No attempt was made to test the practicality of this procedure for large quantities (i.e. of the order of tonnes) of spent crust as the necessary equipment for washing and sieving was not available.

5 Conclusions

After the successful application of the sodium silicate /sodium bicarbonate spray freezing technique it was possible to undertake an extensive program of measurements in a large sediment flume, with the roughness and geometry of the previously loose boundary channel preserved. Some preliminary results of this work were presented by Benson et al. [1].

Modern laser and ultrasonic velocimetry has reached the stage were sampling times and sample volumes below the scale of the bedforms or even the sediments used in laboratory flumes are available. This method of immobilising sediment boundaries in laboratory channels promises to be of value in the study of sediment-flow interaction with such instruments.

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