WATER RESOURCES RESEARCH, VOL. 35, NO. 1, PAGES 311–318, JANUARY 1999

Simulations of cobble structure on a gravel streambed

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Abstract. We present a two-dimensional, time independent, kinematic simulation of a gravel streambed that models impacts between clasts as elastic collisions without momentum transfer between discrete, circular disks. The prototype bed forms that we seek to simulate are the "stone cells" observed in Harris Creek, south central British Columbia. The basic algorithm causes simulated stones to cluster into longitudinal structures that resemble such gravel bed forms as imbricate clusters and cluster bed forms. A modified algorithm incorporating programming rules such as stone rotation, entrainment probability inversely proportional to stone size, and the shielding effects of neighbors causes simulated stones to cluster into structures that resemble transverse ribs. Trials incorporating the rotation rule, with or without additional rules, produce a cobble structure most similar to the prototype. Of all the parameters in the simulation, the number of stones seems to have the most control on the development of an extended surface structure.

1. Introduction

Several computer simulations have been written that model sedimentary features such as gravel-bed topography [*Naden*, 1987], eolian ripples [*Anderson*, 1990], beach cusps [*Werner and Fink*, 1993], stone stripes [*Werner and Hallet*, 1993], and non-periglacial sorted nets [*Ahnert*, 1994]. Most of these simulations attempt to mimic the development of a natural pattern in noncohesive sediments using a computer algorithm that retains the discrete character of the constituent sand or pebbles. Here a similar approach is taken to model the development of a gravel bed form.

We present a two-dimensional, time independent, kinematic model of a gravel streambed using discrete, circular disks that collide with each other as they move downstream. Our algorithm implements gravel entrainment, transport, and deposition using the local configuration of stones and their mutual interactions rather than explicit hydrodynamic conditions. Our approach differs from that of *Naden* [1987], who wrote a one-dimensional queue model that used the velocity profile of the flow and who applied mechanistic entrainment criteria to determine gravel dynamics.

The success of a model can be gauged by how closely its output resembles the prototype phenomenon and by its simplicity. At present, there is no rigorous measure of the similarity between two-dimensional patterns. Therefore we judge the success of our model by a visual appraisal of the similarity between the resulting model output and the prototype, relying heavily on common textures, sorting, packing, and the presence or absence of dominant structures. The prototype gravel bed form is the cobble structure observed in Harris Creek, south central British Columbia [*Church et al.*, this issue] (Figure 1), where stones protruding from the general level of the riverbed define, in plan view, a net-like surface structure termed "stone cells."

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Paper number 98WR01141.
0043-1397/99/98WR-01141$09.00

2. Description of Prototype

Harris Creek is a snowmelt flood regime creek draining a portion of the Okanagan highlands in south central British Columbia. The study reach (Figure 1) is a 60-m-long, 5- to 7-m-wide, extended riffle segment with surface $D_{50} \approx 75$ mm, $D_{84} \approx 110$ mm, and gradient 0.013. We observe that the stone cells form during moderate floods just capable of moving the constituent coarse stones and that the stone cells destruct when stresses exceed ~2 times the threshold stress required to move the same stones. We have observed similar cobble structures in other creeks in southwest British Columbia. We mapped the stones in Figure 1 by viewing low-level air photographs under a stereoscope and by identifying all stones protruding from the streambed by such criteria as their relief, their disturbance of the water surface, and accumulations of leaves and debris in their lee.

Harris Creek's stone cells are made of ridges, one or a few stones wide and one stone high, protruding from the surface armor of the streambed and oriented obliquely, often transverse, to the flow direction. Ridges are typically arcuate or straight in plan view, often 3–20 stones in length, and they typically span 25–75% of the reach width. Ridges appear to have a characteristic spacing of 1–2 m or 5–10 average stone diameters. Individual member stones are subrounded to subangular cobbles and boulders of diverse lithologies with roughly lognormally distributed radii. Their combined, projected cross-sectional area covers ~25% of the total reach area. The structure-forming stones have a median diameter of 20 cm, as measured from Figure 1. This clast size corresponds to the D_{95} of the riffle surficial material [*Church et al.*, 1991], showing that the structure-forming stones are essentially the coarsest stones available in the creek.

The stone cells can also be described as a framework of smaller stones accumulated and articulated about randomly positioned, larger "keystones" [*Tribe*, 1996]. This can be seen with the help of Figure 1. If all stones with a maximum radius

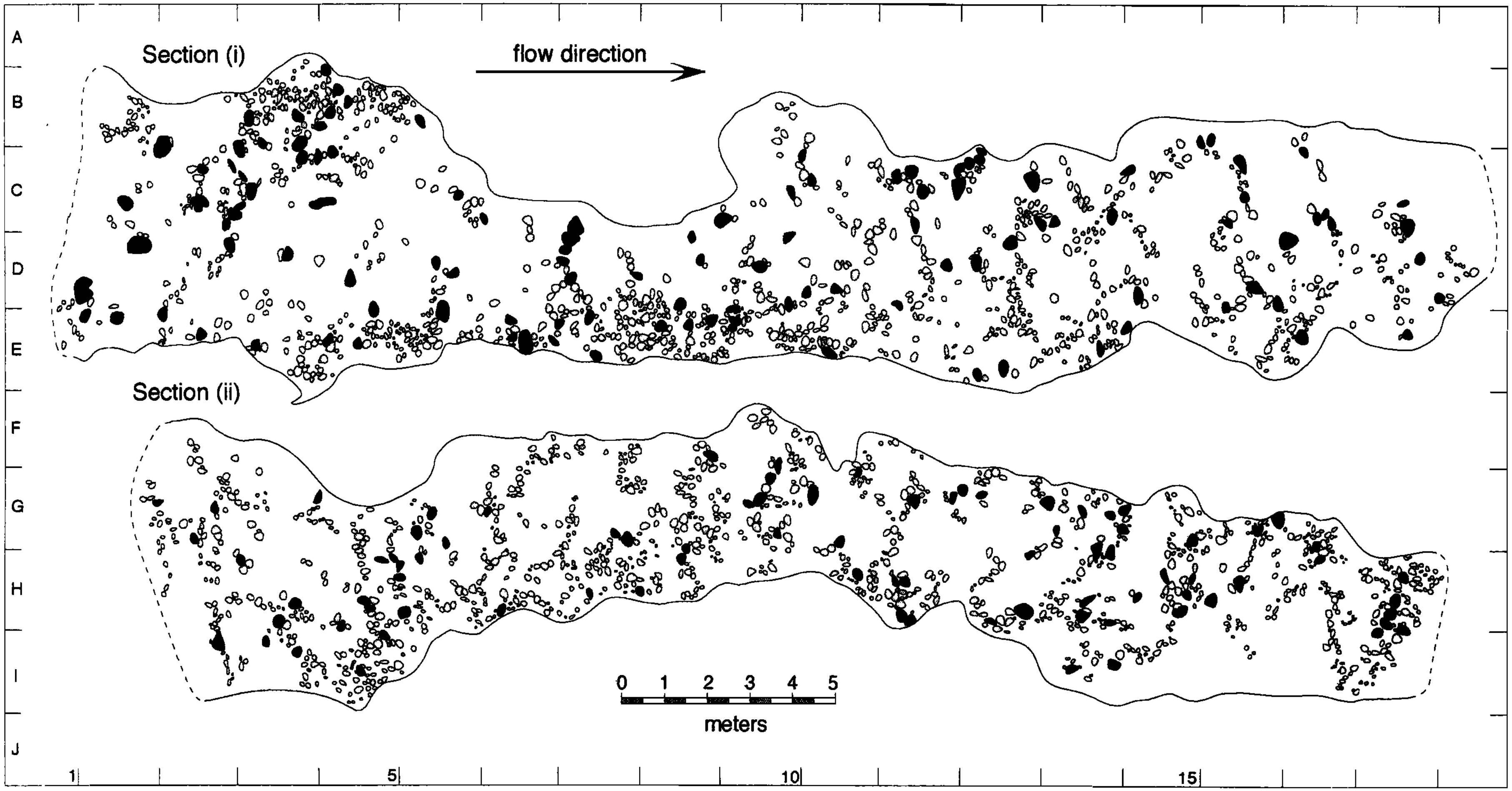

Figure 1. Plan view map of the Harris Creek study reach showing the location of all stones protruding from the general level of streambed. Solid and open stones are those with a maximum radius greater than and less than 12.5 cm, respectively. The stone cells are visible as a network of arcuate stone ridges distributed over the streambed. Section (i) is separated from downstream section (ii) by ~5 m of vegetation cover. Solid lines indicate the lateral boundaries of the reach or vegetation cover, and dashed lines indicate upstream and downstream boundaries. Flow direction is to the right.

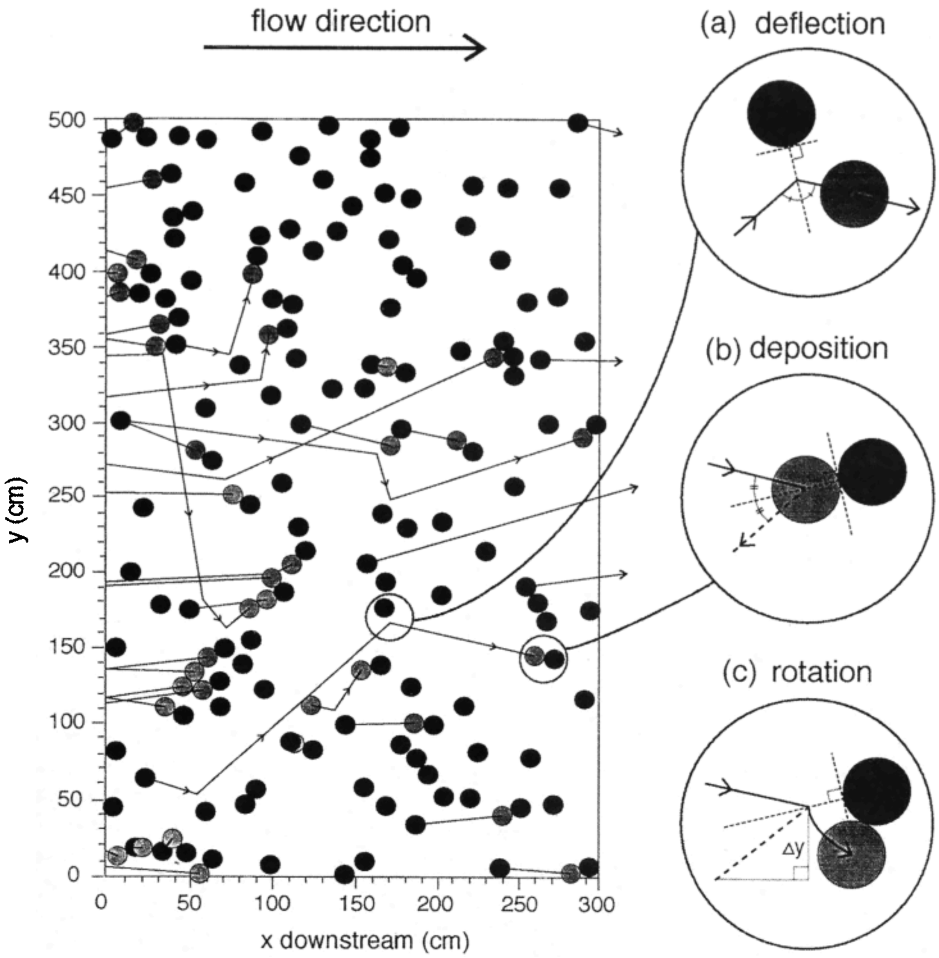

Figure 2. Depiction of the simulated streambed with equal sized, circular stones. Solid circles represent stones placed randomly at the start of an experiment. Entrained stones travel along vectors until stopping as shaded circles behind obstacles. New stones travel along vectors originating on the upstream boundary ($x = 0$). Stones that pass through the reach travel along vectors extending beyond the downstream boundary ($x = 300$). After only 40 entrainments the stones begin to cluster, in this case, into an oblique ridge extending from (35, 110) to (120, 220). Insets detail how the grain interactions are modeled: In the basic algorithm, after colliding with an obstacle, a stone will either (a) deflect downstream or (b) deposit, depending on whether its rebound trajectory has a downstream or upstream component, respectively. Short-dashed lines are the tangent and normal at the impact site. (c) When the algorithm incorporates the rotation rule, a newly deposited stone rotates downstream by a maximum angular amount calculated as the transverse component (Δy) of the rebound trajectory (long-dashed line) multiplied by some factor or until it touches a nearby stone. Flow direction is to the right.

>12.5 cm are removed, the remaining smaller stones constitute primarily quasi-linear ridges. In contrast, if all smaller stones are removed, the remaining stones with a maximum radius >12.5 cm are essentially isolated and scattered quasi-randomly throughout the reach. For this analysis all stones of maximum radius >12.5 cm are those stones not completely covered by circles of that radius.

3. Description of Simulation

The basic algorithm repeatedly chooses a stone at random from all available stones in the simulated reach and entrains it by transporting it along a downstream trajectory. The stone collides with surrounding stationary obstacle stones until encountering one that prevents further downstream movement, at which point the stone is deposited, and another one is entrained (Figure 2). Stone impacts are modeled as elastic collisions between an impinging and a stationary, rigid disk without momentum transfer. The impinging stone will deflect off an obstacle and continue downstream to possible further collisions if its rebound trajectory, calculated as the incoming angle of the transporting stone reflected about the normal to the tangent at the impact site on the obstacle stone, has a downstream component (Figure 2a). If its rebound trajectory has an upstream component, the stone is deposited (Figure 2b).

To initiate a trial, a percentage of the reach is covered with randomly placed, nonoverlapping stones. The upstream and downstream reach boundaries are open. Any transporting stone that collides with the rigid lateral boundaries of the reach is reflected downstream.

There are several parameters in the simulation:

1. Reach width is set at 5 m, comparable to the average width of the Harris Creek study reach. Reach length is set at

15 m, comparable to the length of each of the two sections in Figure 1 and long enough to buffer upstream and downstream boundary effects. Both parameters can be changed to model different prototypes.

2. The number of stones in a simulation is set by fixing the covered percentage of the reach. For instance, trials that are run at 30% coverage have that number of stones necessary to collectively cover ~30% of the reach area.

3. Stone radii can have lognormal, uniform, or other size distributions. The stones in Figure 3 have lognormally distributed radii with mean and variance similar to the structure-forming cobbles mapped in the Harris Creek study reach. Radius distribution parameters can be changed to model different prototypes.

4. The initial direction of transport for a newly entrained stone is calculated as a normally distributed random number between 0 and 1 multiplied by a factor that sets the angular range of possible trajectories. We use a factor of 10, resulting in initial transport directions that range 10° each side of the downstream direction.

5. The stop criterion is the parameter governing whether a stone deposits or deflects upon colliding with an obstacle. It sets the minimum angular range, from the downstream direction, of rebound trajectories sufficient for deposition. A stop criterion of 90° prohibits upstream transport and is used for all simulations shown here.

6. The duration of an experiment is set by the number of stone entrainments, typically 2000–8000 per trial. An experiment running for 2000 entrainments on 200 stones roughly corresponds to each stone being a candidate for entrainment an average of 10 times.

7. The number of stones can remain constant or change over the course of a trial. All simulations shown here have a constant stone population, maintained by introducing a new stone on the upstream boundary whenever a stone exits the downstream boundary. Aggradation and degradation can be modeled by increasing or decreasing the number of stones in the reach during a trial, respectively.

The basic algorithm was modified in several ways by incorporating one or more "rules" governing entrainment, shielding, transport distance, and grain rotation:

1. The entrainment probability rule entrains a stone only if the stone's radius, factored by a uniform random number between 0 and 1, is less than some criterion. The criterion can be increased or decreased to allow larger stones a greater or lesser chance of being entrained. This rule models the tendency of small stones to be more mobile than large stones at modestly competent shear stresses [*Wilcock and McArdell*, 1997].

2. The neighbor rule entrains only those stones that have few close or touching neighbors, regardless of the size or position of the neighbors relative to the candidate stone. The neighbor criterion is typically set at 2, which prohibits entrainment for stones with two or more touching stones. The neighbor rule models the shielding effect of nearby stones on the entrainment of a candidate stone. If the criterion is increased, the shielding effect of neighbors is correspondingly decreased since fewer stones will satisfy the criterion. This rule implicitly selects on the basis of size since large stones, by virtue of their girth, are more likely to accommodate two or more neighbors and are more likely to fail to mobilize than are small stones.

3. The travel distance rule is based on the empirical result that the travel distance of stones in open positions, that is, not touching nearby stones, varies in inverse proportion to size as

$$L = 1.77(1 - \log D)^{1.35} \quad (1)$$

where $L = L_t/L_{D50\text{subsurface}}$, $D = D_i/D_{50\text{subsurface}}$, and L_t and D_i are the travel distance and diameter, respectively, of the stone in question [*Church and Hassan*, 1992]. Each simulated stone is assigned a maximum travel distance calculated from (1) using $D_{50\text{subsurface}}$ = 10 cm and $L_{D50\text{surface}}$ = 236 cm as scales. Although $D_{50\text{subsurface}}$ is 6 cm in Harris Creek, the higher value of 10 cm is used because this is the size of the smallest, and theoretically the most mobile, stones in the simulation. The entrained stone, providing it glances off one or more obstacles without becoming lodged, travels downstream until its cumulative transport distance has equaled the maximum travel distance assigned to it, at which point it is deposited, often in an open position.

4. The grain rotation rule allows newly deposited stones to rotate downstream about the center of the obstacle by a maximum angular amount proportional to the transverse component of the stone's rebound trajectory (Δy in Figure 2c). This component, which is between 0 and 1, is translated into an angular rotation amount by multiplying it by some factor. Using this rule, if a stone stops directly upstream of an obstacle, the transverse component of its rebound trajectory is small, and the stone will rotate a small or negligible amount. In contrast, if a stone stops somewhat adjacent to an obstacle, its transverse component will be larger, allowing the stone to rotate a greater amount downstream. All trials shown here that incorporate grain rotation use a factor of 45, which allows stones to rotate up to 45° downstream. The transverse component of the rebound trajectory is assumed to be proportional to the tangential momentum at impact, a quantity that may be conserved during grain interactions according to *Naden* [1987].

The simulation was written with the Think C++ For Macintosh compiler by Symantec, version 7.0. All work was performed on a Macintosh Quadra 605 personal computer. Execution times for the results displayed here varied from 2 to 4 hours.

4. Simulation Results

A representative example of the model results using the basic algorithm (Figure 3a) shows that the simulated stones tend to cluster into longitudinal, single-file stone lines, occasional oblique stone lines, and rare equant stone clusters. The simulated bed forms have a flow parallel pattern, not the strong transverse pattern seen in the Harris Creek bed form.

The influence of the parameters on the final bed forms was examined by initiating trials of the basic algorithm while varying only one parameter at a time. Bed forms made of stones with lognormally distributed radii tend to be more compact and, in some cases, more oblique than bed forms made of stones with identical radii, which tend to form strictly longitudinal, single-file stone lines. Trials using lognormally distributed stone sizes with differing size distribution parameters resulted in similar longitudinal bed forms. In trials in which newly entrained stones had initial transport directions that ranged up to 45° either side of downstream, the bed forms tend to be more arcuate and less longitudinal, in some cases, than those resulting from trials in which initial transport directions ranged only 1° from downstream, although the difference is minor. Varying the stop criterion from 90° to 30° has little effect on the bed forms although, intuitively, this change may be expected to stop more stones than before and thereby to favor more transverse clustering.

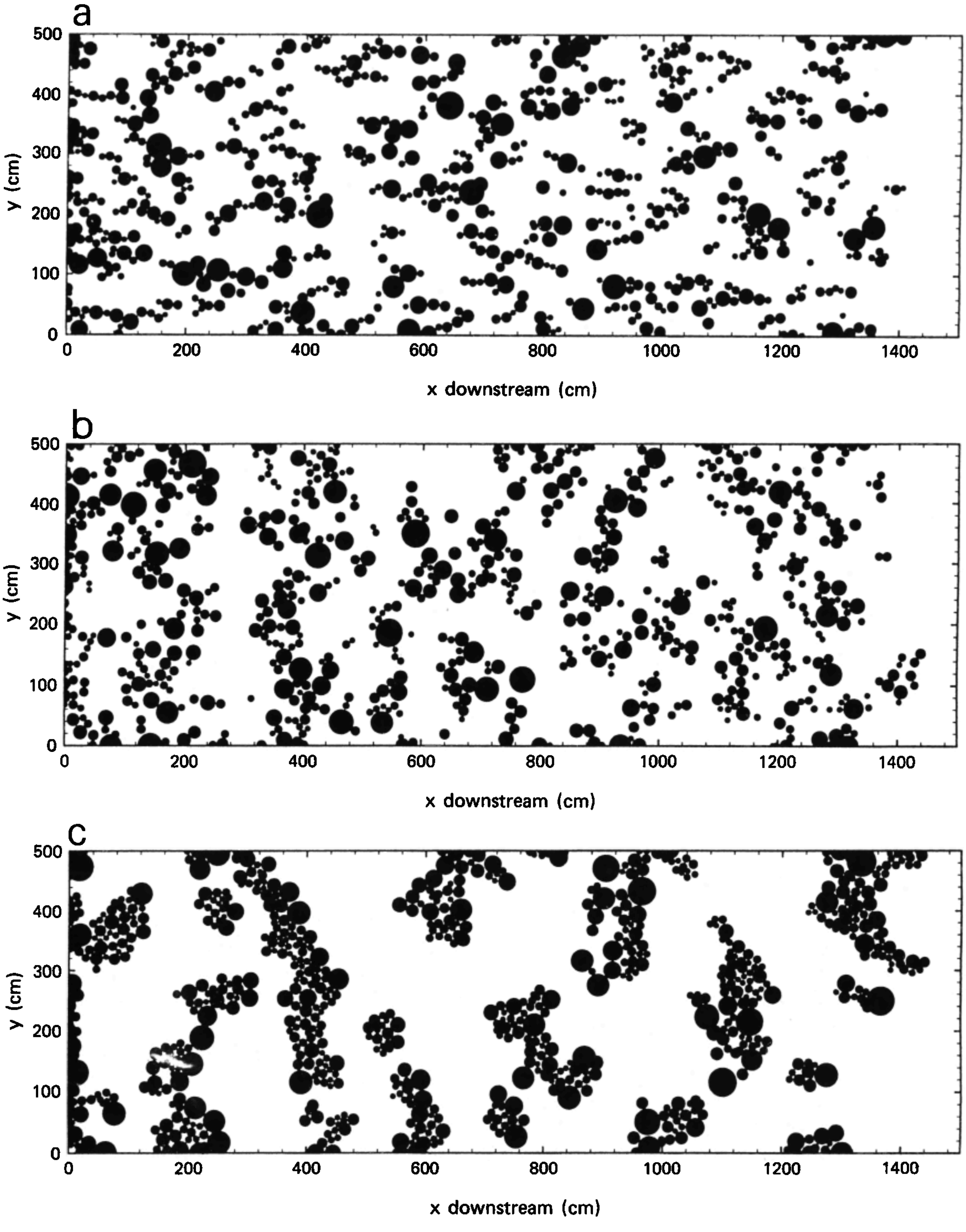

Figure 3. (a) Final configuration of a trial using the basic algorithm with the following parameters: 716 stones cover 30% of the bed for 5000 entrainments duration. Single-file stone lines dominate, resulting in a flow parallel pattern. Flow direction is to the right. (b) Final configuration of a trial incorporating grain rotation with the following parameters: 716 stones cover 30% of the bed for 6000 entrainments duration. Loose oblique ridges develop with a transverse fabric. Flow direction is to the right. (c) Final configuration of a trial incorporating grain rotation, entrainment probability, and neighbor rules with the following parameters: 835 stones cover 35% of the bed for 6000 entrainments duration. Tightly packed stone ridges develop with a strong transverse fabric. Flow direction is to the right.

We found that of all the parameters the number of stones in a simulation had the greatest influence on the bed forms made with the basic algorithm. In trials with 5–10% coverage, longitudinal, single-file stone lines and equant stone clusters dominate with lesser oblique stone lines. Stone lines rarely extend more than 5–10 stones in length and seldom intersect with adjacent clusters or lines. When coverage increases to 20–30%, longitudinal stone lines and loose, oblique ridges, both of order 10 stones, develop. Equant stone clusters are less common. Stone lines and ridges sometimes merge with adjacent similar structures and when viewed on the scale of the entire reach, result in a weakly developed cellular structure reminiscent of the prototype, although lacking a transverse fabric. Finally, trials with 40% or greater coverage develop frequent, longitudinal stone lines and loose, oblique ridges of varying width. These structures tend to merge with each other and with rare equant clusters to such an extent that any cellular structure that may have been visible on a bed with fewer stones becomes indistinct.

The influence of different rules on the final bed forms was examined in trials that incorporated each rule separately. Trials incorporating only the entrainment probability rule result in stones that tend to form longitudinal ridges and stone lines. Because this rule selects on the basis of size, the more mobile smaller stones tend to accumulate upstream of the more stationary larger stones. The flow parallel bed forms do not resemble the prototype.

When the algorithm incorporates only the neighbor rule, the stones tend to develop into longitudinal ridges and stone lines. If the neighbor criterion is set at a high value, such as 3 or more, single-file stone lines develop. If the neighbor criterion is decreased to 2, ridges several stones wide tend to develop. The resultant bed forms resemble Figure 3a more than they resemble the prototype.

Trials incorporating only the travel distance rule result in primarily longitudinal stone lines with rare, loose, oblique stone ridges. Because this rule allows some stones to be deposited in open positions, looser structures develop, on the reach scale, than those in simulations for which each stone is deposited flush against an obstacle. Again, flow parallel bed forms that do not resemble the prototype dominate.

When the algorithm incorporates only the grain rotation rule, oblique or transverse, loose stone ridges develop. Longitudinal stone lines and equant stone clusters are not as often nor as well developed as they are with the basic algorithm. If a large enough number of stones is used, the stones can develop into an extended cellular structure (Figure 3b) that resembles the Harris Creek prototype to a greater degree than does the basic algorithm.

Trials that incorporate grain rotation, entrainment probability, and neighbor rules produce transverse and oblique, tightly packed, stone ridges (Figure 3c). Repeated experimentation reveals that although the entrainment probability and neighbor rules both affect the chances of a stone becoming entrained, the neighbor criterion has the greater influence on the final bed forms. All other criteria and parameters being equal, decreasing the neighbor criterion from 3 to 2 results in stones that pack together more tightly and form stone ridges several grains in width, as opposed to single-file ridges. If the neighbor and entrainment probability rules are changed such that they increasingly inhibit the entrainment of smaller stones, that is, if the neighbor criterion is set to the lowest possible setting of 2 and the entrainment criterion is decreased to an appropriate amount, the resulting bed forms tend to form tightly packed, equant stone clusters that persist over the course of a trial and become so firmly established that the bed appears to develop a stable configuration.

5. Discussion

Trials that incorporate the grain rotation rule, with or without one or more additional rules, produce cobble structures with a transverse fabric that resemble the prototype to a greater degree than do the results of trials excluding the grain rotation rule. The grain rotation rule when used alone, produces loose, transverse bed forms whereas when it is used in conjunction with one or more other rules, it results in tighter, more closely clustered bed forms.

The version of the algorithm incorporating the grain rotation, entrainment probability, and neighbor rules results in arcuate and transverse stone ridges that resemble the form and sorting of the Harris Creek bed form. The tendency of small stones in Figure 3c to accumulate in the spaces between and behind large stones is reminiscent of Harris Creek's framework of small stones accumulated about large keystones. The sorting appears to be largely the result of the entrainment probability rule. Although Harris Creek's ridges appear to be thinner than the simulated ridges in Figure 3c, this may be due to the subjective decision of whether or not to include a given stone in the map of Figure 1 as well as to the tendency of smaller stones to lie below the water surface and escape notice.

The importance of the grain rotation rule was recognized only after considerable experimentation with parameters and other rule combinations produced continually unsatisfactory results. Little is known regarding the extent of grain rotation in natural gravel systems. Intuitively, rotating a stone to a position adjacent to an obstacle may predispose the stone to be reentrained into the flow. Yet in our model the effect is to favor the development of transverse structures. Transverse ribs are commonly thought to be initiated and maintained by the interaction of hydraulic jumps and sediment accumulations [*Koster*, 1978]. However, flow measurements of Harris Creek at structure-forming flows never approach a Froude number greater than unity, indicating that Harris Creek's transverse structures were not formed by the same mechanism that is thought to form transverse ribs.

Both the neighbor and entrainment probability rules act to prohibit equal mobility of stones. The most realistic bed forms develop with entrainment probability and neighbor criteria that balance the chances of a stone encountering a cluster with the chances of a stone leaving the cluster. If the entrainment of smaller stones is inhibited, the chances of clustering are increased for stones of all sizes. It is possible that given the right initial conditions, such a trial can result in a bed configuration that reaches a static state because no stone satisfies the criteria for entrainment: most stones have too many neighbors, the larger stones are too big to be entrained, and smaller stones are too close to one another to move anywhere.

As was the case with the basic algorithm, for different rule combinations the number of stones appears to be the parameter with the greatest effect on the resultant bed forms. In simulations incorporating grain rotation, entrainment probability, and neighbor rules, trials with stones covering 30–40% of the reach (Figure 3c) produce bed forms that tend to ramify throughout the reach and intersect each other, forming a somewhat cellular structure with a relatively strong transverse component. Trials with fewer stones form widely spaced, equant clusters that fail to intersect each other. Trials with more stones form more linear, transverse ridges that merge so frequently with nearby ridges that an extended cellular structure is destroyed. Because the stones cluster together tightly with this rule combination, a greater number of stones is needed to produce extended bed forms than is needed with other rule combinations.

Even though trials using the basic algorithm, as well as trials using rule combinations excluding the grain rotation rule, fail to produce bed forms resembling Harris Creek's stone cells, they do generate other realistic gravel bed forms. For instance, single-file and multiple-file, longitudinal stone lines resemble imbricate clusters and multiple obstacle clusters [*de Jong and Ergenzinger*, 1995], respectively. Equant stone clusters resemble cluster bed forms [*Dal Cin*, 1968; *Brayshaw*, 1984]. Of course, the circular, two-dimensional simulated stones cannot properly imbricate. Other realistic bed forms generated with either the basic or modified algorithms include diagonal ribs, transverse ribs [*Gustavson*, 1974; *Martini*, 1977], and mature and destroyed lobate ribs [*de Jong and Ergenzinger*, 1995].

Simulated stones cluster together rapidly. Cobble clusters after trials of 8000 entrainments duration do not significantly differ from those arising from 2000 entrainments with two exceptions. First, the number of stones in open positions on the streambed decreases with increasing elapsed simulation duration in those simulations that do not use the travel distance rule. Providing the travel distance rule is not used and given a sufficiently long duration, every stone in the reach will be entrained and will come to rest flush against another stone, leaving no isolated stones. Second, the effects of the upstream and downstream boundary conditions become more pronounced with increasing elapsed simulation time. Over time, the upstream margin tends to clog up with stones, and the downstream margin tends to empty of stones. However, these effects are confined to the extreme ends of the reach, and since the reach is of a sufficient length, they do not bear on the bulk of grain interactions that occur in the reach interior. Utilizing periodic boundary conditions, that is, making the reach a seamless track by joining the upstream and downstream boundaries, may alleviate these effects.

Models are frequently used as approximations to real-world phenomena. Even though the physical principles governing a phenomenon may be fairly simple, the mathematical expression of the physics is often too complex for analytic solution. Reasonable numerical approximations can often be made, but they introduce their own set of difficulties. The situation is further complicated by the randomness of initial and boundary conditions, nonlinearities, the effect of noise in the real-world system, and multiple degrees of freedom. Consequently, a simulation model may be the only viable means to approximate a phenomenon. This is especially true in the case of cobble-gravel transport since empirical tracer studies are hampered by the problem of clast retrieval and flume experimentation is hindered by scale effects.

Yet simulation models also have inherent limitations. For instance, our simulation incorporates several parameters that together constitute a vast parameter space, only a small portion of which has been examined owing to computational limitations. Furthermore, the simulation is a discrete model of a gravel streambed built using a reductionist approach to sediment transport. The primary assumption is that gravel transport can be realistically modeled in two dimensions as elastic collisions between disks on a smooth plane. The size and direction of transport of the impinging stone and the size and position of the obstacle stone are the variables bearing on whether the stone deposits behind or glances off the obstacle. The precise shear stress exerted by the flow, the exact shape and packing of the grains, and the irregular bed surface over which they migrate, otherwise considered important though complicating factors in the initiation and cessation of sediment transport, are not treated explicitly in this model. Nonetheless, the success of our model suggests that it is a reasonable approximation of gravel interactions.

Regardless of inherent limitations, a successful model invites speculation about how the real world operates. In our case, results suggest that the kinematics of gravel interactions may be important in the development of certain gravel bed forms such as cluster bed forms and imbricate clusters. Furthermore, the development of an extended, cellular stone structure may depend on the number of active stones in the reach. In comparison, local flow conditions may be relatively unimportant.

6. Conclusions

A section of the Harris Creek streambed displays stone cells, variably oriented cobble ridges with a strong transverse alignment, that outline a cellular surface structure in plan view. The constituent smaller stones compose a framework accumulated and articulated about randomly positioned, large keystones.

The gravel-bed simulation presented here models grain impacts as elastic collisions between two-dimensional disks without momentum transfer, somewhat like a sticky shuffleboard game. The basic algorithm is capable of generating realistic longitudinal gravel bed forms such as cluster bed forms and imbricate clusters, yet transverse structures are rare. It is an adequate representation of gravel streambed kinematics and serves as a suitable framework upon which to introduce more complicated entrainment, transport, and deposition criteria.

Incorporating the grain rotation rule into the basic algorithm results in bed forms with a transverse fabric. Incorporating grain rotation, entrainment probability, and neighbor rules results in bed forms with a strong transverse fabric and sorting similar to the Harris Creek prototype.

Reproducing Harris Creek's stone cells was the motivation for the suite of experiments presented here. It may be possible to extend this model to simulate coarse sediment transport in more general situations. The sediment transport capacity of the model can be monitored during the course of a trial and can conceivably be related to tracer studies. Future work may include refining some of the rules such as the neighbor rule, which can be improved by distinguishing the effects of neighbor stones on the basis of their size and position relative to the candidate stone. At present, the most critical future work involves developing a measure to quantitatively assess the similarity between variable, two-dimensional, spatial patterns.

Acknowledgments. This work was supported by a University of British Columbia Graduate Fellowship. We acknowledge helpful comments on the manuscript from Rob Ferguson, Peter Wilcock, and an anonymous reviewer and the especially acute discussion from Kurtis Halingten. The suggestion to incorporate grain rotation was made by Simon Tait of Sheffield University.

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(Received July 21, 1997; revised January 12, 1998; accepted April 3, 1998.)