Long-term evolution of heap surface of paste tailings under erosion
/
Evolução a longo prazo de pilha da pasta de rejeitos sujeita a erosão

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ABSTRACT

Many mines are moving from conventional tailings storage facilities to filtered tailings disposal systems. The benefits of these systems include increased water recovery, reduced size of containment landfills, improved facility safety, and reduced environmental impact. In geotechnical terms, the challenges are to find the correct way of waste disposal: whether in piles of dry sandy tailings or co-disposal waste rock. The long-term evolution of the surface of fine and sandy tailings stockpiles is a matter of concern. The goal of this study was to quantitatively evaluate the temporal evolution of a paste tailings pile, using a computational model of landscape evolution. For this, SIBERIA, a simulator of the evolution of landscapes under the action of runoff and erosion, was used. The effect of erosion on a trunk-pyramidal tailings pile with about 21% of slope after long periods of decommissioning (100 and 250 years) was studied. The SIBERIA modelling data considered the surface roughness and the average diameter of the sediment particles and the typical properties of iron ore tailings. The results indicate that for a lower Manning roughness coefficient and larger average apparent diameter of the sediment particles (or clods), the lower the sediment transport will be and, therefore, in the long term, the greater will be the integrity of the tailings pile.

Keywords: mineral paste, *siberia*, modelling, erosion.

RESUMO
Muitas minas estão mudando de instalações convencionais de deposição de rejeitos para sistemas de disposição de rejeitos filtrados. Os benefícios desses sistemas incluem maior recuperação de água, redução no tamanho dos aterros de contenção, maior segurança das instalações e redução do impacto ambiental. Em termos geotécnicos, os desafios são encontrar a maneira correta de destinação dos resíduos: se em pilhas de rejeitos arenosos secos ou codisposição com estéril. A evolução, em longo prazo, da superfície de pilhas de rejeitos finos e arenosos é tema de preocupação. O objetivo deste estudo foi avaliar quantitativamente a evolução temporal de uma pilha de rejeitos, empregando um modelo computacional de evolução da paisagem. Para isso o SIBERIA, simulador da evolução de paisagens sob a ação de escoamento superficial de águas e de erosão foi usado. Foi estudado o efeito da erosão sobre uma pilha troncopiramidal de rejeitos com cerca de 21% de declive após longos períodos de descomissionamento (100 e 250 anos). Os dados para modelagem do SIBERIA consideraram a rugosidade da superfície e o diâmetro médio das partículas do sedimento e as propriedades típicas dos rejeitos de minério de ferro. Os resultados indicam que para menor coeficiente de rugosidade de Manning e maior diâmetro aparente médio das partículas do sedimento, menor será o transporte de sedimentos e, portanto, em longo prazo, maior será a integridade da pilha de rejeitos.

Palavras-chave: pasta mineral, *siberia*, modelagem, erosão.

1 INTRODUCTION

The main function of any waste disposal structure is the long-term safe storage, the waste from the ore beneficiation process, in order to minimize environmental impacts (Martin et al. 2002). The high demand for iron ore associated with improvement in technology for treatment of poorer ores has generated a high production of waste. At the same time, environmental problems originated from mining have greater international media attention after several environmental disaster tailings dam breaks. In this context arises the *thickened tailings disposal* technique or TTD. According to Slotte et al. (2005), the thickened or paste tailings technology has been shown as an effective method of waste disposal in order to increase the water recovery and, especially, as a low-cost alternative to closure tailings dam in addition to retaining possible contaminants. Strictly speaking, it must be considered, additionally, that the geotechnical characteristics of stockpiles often evolve in discrepancy from the initial stacking conditions.

Currently, there are different types of software available to simulate the evolution of the landscape, for example, the software CAESAR (HANCOCK et al., 2015), CHILD (Tucker et al., 2001) and SIBERIA (Willgoose, 2005). Such computational resources can assist in predicting the characteristics of mineral paste landfills, many years after the mine closure, becoming, therefore, tools for evaluating the feasibility of the thickened tailings disposal method.

This study aimed at describing the development of the erosive process after long periods (100 to 250 years) on a paste tailings embankment, considering the deposition slope angle of the paste; the different erodibility values and the average (apparent) diameter of the clod after desiccation by using the Erosion Assessment and Modeling System (EAMS), which is comprised by the software MOSCOW that creates the SIBERIA input files from user given data, the simulator (SIBERIA), and VIEWER for generating the graphics from SIBERIA output files.

The SIBERIA simulator was chosen because it was considered competent by governments and private agencies (Hancock et al., 2002; Wilson et al., 2006; Walter and Dubreuilh, 2007; Dinwiddie and Walter, 2008; METAGO, 2009; Powers, 2013; Hancock et al., 2015). In addition, it also offers the advantage of being public domain, which is accessible by employing this electronic address http://telluricresearch.com/downloads/index.html for free and it allows customization of its equations for different terrains.

It should be borne in mind the particle diameter considered here actually refers to the typical clod diameter, after the desiccation process and consequent shrinkage cracking. As a matter of fact, the initial process of depositing the tailings in the form of a paste assumes tiny (primary) particles to meet both the production process requirements and the rheological aspects of their ultimate handling operation (transport to the pile).

2 MATERIAL E METHOD

The software EAMS (version 2.09), which consists of the MOSCOW (version 2.04) and VIEWER (version 2.06), and the SIBERIA (version 8.27) were used. Greater detail about conceptual formulations can be found in Willgoose, et al. (1989, 1991a-d), Willgoose (1993, 1994a, b) and Willgoose and Riley (1993, 1998a, b).

In order to work with realistic values, a typical ore tailings deposition system was designed for this study, using tailings from an iron ore processing plant located in the so-called Iron Quadrangle, in the State of Minas Gerais, Brazil. The topographical coordinates of the adopted study area corresponded to the relief of a tailing deposition area in the vicinity of the industrial plant. In turn, Castro et al. (2012) assessed a series of rainfall data collected between 1988 and 2004 from a meteorological station in the municipality of Ouro Preto, sufficiently close to the study area, from the point of view of the climatological regimen, to be adopted as effective in the study area.

A characterization campaign of sample was carried out at Mining Engineering Department from Ouro Preto School of Mine (an academic unit of Federal University of Ouro Preto). The paste studied have median (primary) particle diameter of $d_{50p} = 11.79 \times 10^{-6}$ m, true density $\boldsymbol{d}$ = 3,922.5 kg/m^3 and higher dynamic repose angle equals 12.0°. Figure 1 illustrates the appearance of the paste produced in the laboratory, in accordance with the design criteria for the tailings pile.

Figure 1 — Visual features of a sample of the iron ore tailing under paste consistence.

(Source: Authors' personal files)

As the angle of repose is concerned, values above 15° were obtained by Osorio (2005). If, on the one hand, this increases the storage capacity per square meter of yard, on the other hand, it amplifies the long-term erosion effect. Of course, such a conflict must be resolved in the design phase.

A truncated pyramid-shaped stack has been simulated, as it enhances the erosive process along the sloping edges. The base elevation was 100 m and the top elevation was 172 m.

The tested conditions were ran considering the values of 0.02, 0.04 and 0.06 for the Manning roughness coefficient ($\boldsymbol{n}$), once, for natural channel, we have $0.024 \leq \boldsymbol{n} \geq 0.075$ (Hornberger *et al*., 1998 *apud* Collischonn and Tassi, 2008). On the other hand, as median diameter of clod is concerned, after the natural desiccation and consolidation (cementation) processes are complete, it was tested the following values for d_{50c}: 11.79×10^{-6}, 2×10^{-4} and 2×10^{-2} m.

Other very important parameter is the discharge rate per unit width ($\boldsymbol{q}$). Castro *et. al*. (2012) have determined that for this region the average annual rainfall of 1,610.1 mm, ranging from 1,005.1 mm to 2,512.4 mm. The value of 2,512.4 mm was adopted for this study, representing an extreme condition.

As pointed out by Willgoose et al. (1989), equations for sediment transport used in SIBERIA is derived from the Einstein–Brown equation (Einstein, 1950) for the instantaneous sediment transport, causing $\boldsymbol{m_1}$ and $\boldsymbol{n_1}$ take the values 1.8 and 2.1 respectively.

$$q^* = \frac{q_b}{\sqrt{g \times d_p \times \left(\frac{\rho_s}{\rho_f} - 1\right)}} \tag{1}$$

$$\tau^* = \frac{\tau_b}{g \times d_p \times \rho_f \times \left(\frac{\rho_s}{\rho_f} - 1\right)} \tag{2}$$

$$d^* = d_p \times \sqrt[3]{\frac{g \times \rho_f^2}{\eta^2} \times \left(\frac{\rho_s}{\rho_f} - 1\right)} \tag{3}$$

✓ If: t* < 0.182:

$$q^* = \frac{K \times e^{\left(\frac{-0.391}{\tau^*}\right)}}{0.465} \tag{4}$$

✓ If: t* ≥ 0.182:

$$q^* = 40 \times K \times {\tau^*}^3 \tag{5}$$

Where the parameter K is given by:

$$K = \sqrt{\frac{2}{3} + \frac{36}{{d^*}^3}} - \sqrt{\frac{36}{{d^*}^3}} \tag{6}$$

In precedent equations the symbols stand for: $\boldsymbol{q_b}$ — bed flux (volume rate of transport per unit length of surface) [m³/(s.m)]; $\boldsymbol{\tau_b}$ — bed shear stress [Pa]; $\boldsymbol{d_p}$ — particle diameter [m]; $\boldsymbol{\rho_f}$ — fluid density [kg/m³]; $\boldsymbol{\rho_s}$ — solid (particle) density [kg/m³]; $\boldsymbol{g}$ — standard acceleration due to gravity [m/s²]; $\boldsymbol{\eta}$— dynamic viscosity [Pa.s].

The file containing the relief information is made up of a mesh with 107 nodes both in the x-direction and in the y-direction with a spacing of 10 m. Therefore, the area contributing each node is 100 m^2. Dividing this value by the width of the area, it follows that the area contributing for each node by unit wide is 10 m^2/m. Hence, the water discharge per unit width in the period of a year will be: $\boldsymbol{q}$ = 25.124 m³/(m.year) (i. e.: $\boldsymbol{q}$ = 2.5124 m/year x 10 m²/m).

The governing equations of the physical model in SIBERIA are used to simulate the evolution of the drainage network and the contributory catchment areas for each node of an initial mesh or grid. Two variables are solved as a function of the $\boldsymbol{x}$ and $\boldsymbol{y}$ coordinates, namely: the elevation ($\boldsymbol{z}$) and a variable ($\boldsymbol{Y}$), which has two stable attractors, 0 and 1, indicating whether the point in the catchment, $\boldsymbol{P} \equiv (\boldsymbol{x}, \boldsymbol{y})$, is inside an erosive channel ($\boldsymbol{Y} = 1$) or alternatively only on a hillslope ($\boldsymbol{Y} = 0$). Disregarding the tectonic uplift rate, the governing differential equations for elevation and channel indicator functions are (Willgoose et al., 1989):

$$\frac{\partial z}{\partial t} = \frac{1}{\rho_s \times (1 - \epsilon_0)} \left(\frac{\partial q_{sx}}{\partial x} + \frac{\partial q_{sy}}{\partial y} \right) + D_z \left(\frac{\partial^2 z}{\partial x^2} + \frac{\partial^2 z}{\partial y^2} \right) \tag{7}$$

And:

$$\frac{\partial z}{\partial t} = d_t \times \left[\frac{0.0025 \times a}{a_t} \left(-0.1 \times Y + \frac{Y^2}{1 + 9 \times Y^2} \right) \right] \tag{8}$$

The variable $\boldsymbol{d_t}$ stands for the point's constant rate of channel growth. The parameter $\boldsymbol{a}$ is the channel initiation function and $\boldsymbol{a_t}$ are and its threshold. In turn $\boldsymbol{D_z}$ is the diffusivity of the erosive process.

The constitutive equations that as a function of the steepest slope, $\boldsymbol{S}$, are the following ones:

$$a = \beta_5 \times q^{m_5} \times S^{n_5} \tag{9}$$

And:

$$q_s = \beta_1 \times O_t \times q^{m_1} \times S^{n_1} \tag{10}$$

For erosive channels the following equation also holds:

$$Q_c = q \times w = \beta_3 \times A^{m_3} \tag{11}$$

Where $\boldsymbol{A}$ is the catchment area draining to that point in the channel ($\boldsymbol{Y} = 1$)

In turn, the channel width, $\boldsymbol{w}$, is given by:

$$w = \beta_4 \times {Q_c}^{m_4} \tag{12}$$

As a matter of fact, the inflow sediment transport is also obtained from $\boldsymbol{\beta_1}$, $\boldsymbol{m_1}$ and $\boldsymbol{n_1}$. Naturally, the sediment transport rate on the hillslope is lower than within an erosive channel. The O_t coefficient represents this fraction of erodibility decrease (inside a channel: $O_t = 1$). The values found for erodibility parameter (β_1) are described in table 01.

Table 01 — β_1 values

d_{50c}	**11.79 x 10^{-6}**	**2.10^{-4}**	**2.10^{-2}**
0.02	0.01686068	0.04334076	0.000706441
0.04	0.05871231	0.150921293	0.002459969
0.06	0.12181295	0.313122867	0.005103803

SIBERIA algorithms solve these equations on a spatial domain (under boundary condition: $\partial z/\partial p = 0$, where p is the direction perpendicular to the catchment boundary).

Diffusivity D_z refers to sediment transport processes that occur diffusively, such as transport by the action of gravitational force, due to the impact of raindrops on the ground or of airborne sand particles. The values found for diffusivity (D_z) are described in table 02.

Table 02 — D_z Values

***n* [–]**	***d_{50}* [m]** **11,79 x 10^{-6}**	**2 x 10^{-4}**	**2 x 10^{-2}**
0,02	2.15465976	5.538600261	0.090277414
0,06	7.50296109	19.28652631	0.314364213
0,04	15.5667145	40.01458161	0.652224888

The channel initiation function indicates the transition boundary from which erosive channels begin to form at the topographic point under analysis. Several processes can be included as a function of channel initiation, the most common being the runoff (surface) velocity, shear stress due to runoff flowrate, water surgency and groundwater. The values found for the channel initiation function coefficient (β_5) are described in table 03.

Table 03 — β_5 values

***n* [–]**	***d_{50}* [m]** **11,79 x 10^{-6}**	**2 x 10^{-4}**	**2 x 10^{-2}**
0,02	10.4564	10.4564	10.4564
0,06	6.8986	6.8986	6.8986
0,04	5.4089	5.4089	5.4089

Table 04 systematizes all the input parameters used at MOSCOW for simulation.

Table 04 — Parameters used to run MOSCOW

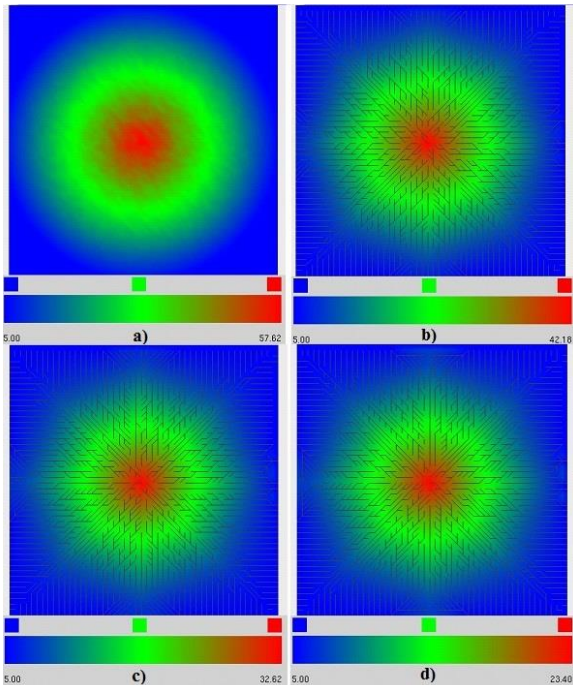
Run Parameters		
RunTime	Duration of simulation (years)	250
InitTimeStep	Time step (years)	1
StatsTime	Period between output of diagnostics statistics	default
Erosion Parameters		
ModeErode	Mode for sediment transport model	0
b1	Coefficient on the fluvial transport relationship	B_1
m1	Exponent on discharge in the fluvial transport relationship	1,8
n1	Exponent on slope in the fluvial transport relationship	2,1
QsHold	Fluvial transport threshold	0
b12	Coefficient on the second fluvial transport relationship	0
m12	Exponent on the second discharge in the fluvial transport relationship	1
Ot	The rate of overland: channel fluvial transport rates	1
Bulk	Bulk density of soil (t/m3)	3.9225
Cover	Vegetal cover factor	1
dZ	Diffusivity of diffusive transport	D_z
dZn	Nonlinearity of diffusive transport	0
dZHold	Diffusive transport threshold	0
Hydrology Parameters		
ModeRunoff	Mode for runoff model	0
ModeDir	Mode for drainage directions model	0
b3	Coefficient on the area in the discharge relationship	1
m3	Power on the area in discharge relationship	1
DTM Parameters		
kx	Easting dimension of the grid (nº of nodes)	107
ky	Northing dimension of the grid (nº of nodes)	107
GridXY	Grid resolution (m)	10
East	Easting of the bottom left-hand corner of the grid (m)	0
North	Northing of the bottom left-hand corner of the grid (m)	0
Channel Parameters		
ModeChannel	Mode for channel model	0
1/at	CIF threshold	0
b5	Coefficient on the Channel Initiation Function (CIF) relationship	β_5
m5	Exponent on discharge in the CIF relationship	0.4
n5	Exponent on slope in the CIF relationship	0.3
a1	Discharge factor between fluvial transport and CIF	1
DTime	Rate of channel formation	1
b6	Coefficient in the channel geometry model	0
m6	Exponent in the channel geometry model	0

3 RESULTS AND DISCUSSION

None of the calculations conducted for the pile with mean diameters of the sediment particles, ***d_{50c}***, ranging from 11.79 x 10^{-6} m to 2 x 10^{-4} m presented the results generated by SIBERIA viewable by VIEWER, indicating the absence of the pile after the minimum period of analysis, 100 years. This indicates the necessity of a covering system, for instance, such as rockfill with mine overburden, and a suitable vegetation cover to avoid runoff and erosion in long term basis.

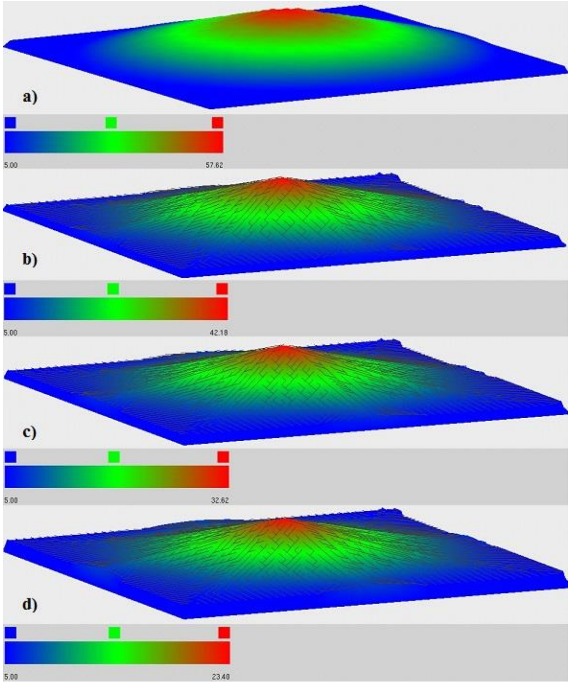
By comparing the top view of the paste piles simulated with average diameter of sediment particles (actually clods), ***d_{50c}***, of 2 x 10^{-2} m (after desiccation, consolidation and shrinkage resulting a dry cracked mass), after 100 years and the starting corresponding piles, one sees that the higher the Manning roughness coefficient), the higher the sediment transport (Figure 2).

Figure 2 — Surface view: Comparison between initial heap (a), and the analysis after 100 years with apparent median size d_{50} of $2x10^{-2}$ m and n = 0.02 (b); n = 0.04 (c); n = 0.06 (d).



This potentiation of sediment drag promotes a rounded look to the stacks, as can be seen in Figure 3, resulting in a greater accumulation of material near the base of the structure.

Figure 3— Side view: Comparison between initial heap (a), and the analysis after 100 years with apparent median size d_{50} of $2x10^{-2}$ m and n = 0.02 (b); n = 0.04 (c); n = 0.06 (d).



The same results can be seen to the piles of tailings whose average diameter of sediment particles, d_{50}, is $2x10^{-2}$ m after 250 years, but more intense. In consequence the erosion grid will be more developed (Figures 4 and 5).

Figure 4 — Surface view: Comparison between initial heap (a) and the analysis after 250 years with apparent median size d_{50} of $2x10^{-2}$ m and n = 0.02 (b); n = 0.04 (c); n = 0.06 (d).

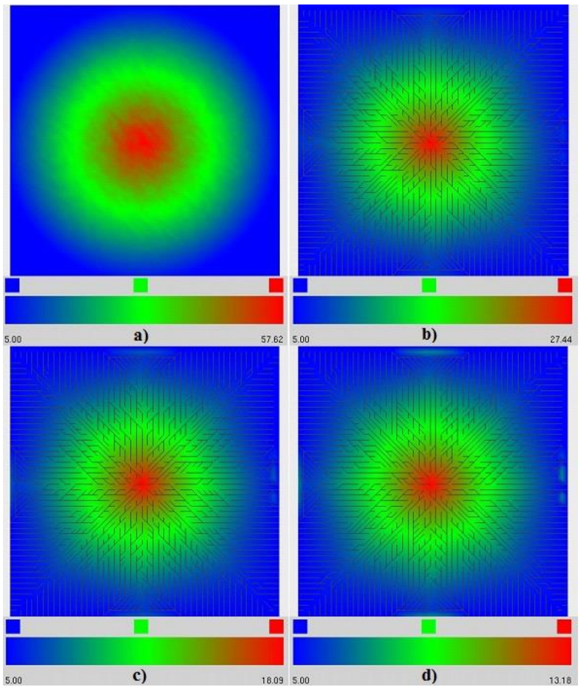
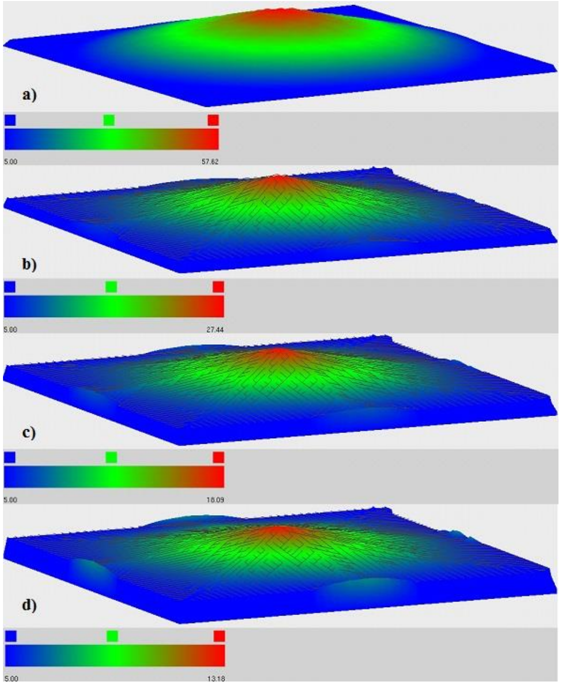


Figure 5 — Side view: Comparison between initial heap (a) and the analysis after 250 years with apparent median size d_{50} of $2x10^{-2}$ m and n = 0.02 (b); n = 0.04 (c); n = 0.06 (d).



4 CONCLUSION

This study indicates that, for values d_{50} ranging from 11.79 x 10^{-6} m and d50 — 2 x 10^{-4} m, there will be no residual pile after 100 years. Regardless of the value of the Manning roughness coefficient is understandable because, due to the extremely fine grain sediments, it will be easier unhook the particles from the structure, increasing the particle transport process, resulting in no pile after the minimum period of analysis, 100 years. This result implies the necessity in the closure plan of implement a cover system to avoid erosion and to guarantee the long-term stability of the pile.

The results for samples having apparent median size (***d_{50}***) of 2 x 10^{-2} m show the importance of maintaining control over the value of the Manning coefficient, since the greater the value of n, the surface will be rougher, a fact which implies greater shock/contact between the runoff water and the inclined surface, facilitating the drag of sediment particles. This result corroborates the results above. The apparent median particle size (***d_{50}***) of 2 x 10^{-2} m resulted from the surface paste particles size after dissection process and this grain do not have stability for long term. Therefore, a cover system is need from time to time in order to avoid erosion process in the constructed pile.

During the construction life of piles from paste tailings, binding additives, or other mitigating devices are required, in order to ensure the lowest possible Manning coefficient by reducing the surface roughness and increasing interparticular cohesion (even by induced cementation), as well as the average diameter of the resulting clods.

As a final remark, it should be borne in mind that the dynamic and complex effect of vegetation cover, and other interactions with the local biota over the years, was not taken into account in the simulations carried out in this work.

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DECLARATION OF INTEREST

The authors declare no conflict of interest

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