•河流保护与治理•

DOI:10.12454/j.jsuese.202400268

本刊网刊

沟道桩群拦挡多级碎屑流运动特征数值试验

雷　明[1],张　亮[1,2],叶　晨[3],王协康[4*]

(1.东北电力大学 建筑工程学院,吉林 吉林 132012;2.上海建科工程咨询有限公司,上海 200032;
3.集美大学 港口与海岸工程学院,福建 厦门 361000;4.四川大学 山区河流保护与治理全国重点实验室,四川 成都 610065)

摘　要:松散坡体受地震、暴雨等动力作用极易失稳并滑落破碎,引发系列次级滑坡,形成多级碎屑流运动致灾。为降低多级碎屑流的危害,本文在潜在影响区设置桩群以减小碎屑流的破坏力和缩小堆积范围,并基于离散单元法对沟道内桩群拦挡多级碎屑流的运动及堆积过程开展模拟研究。结果表明:首次来沙时,颗粒沿程方向速度随桩群排间距、排数的降低及侧向间距的增加而提高;竖直方向速度随桩群排数的增加和侧向间距的减小而下降,但对排间距并不敏感。桩群的设置能使下游来沙强度降低约47.6%,且下游来沙强度随桩群排间距、排数的增加及侧向间距的减小而下降。同时,下游来沙时间因桩群排数的增加和侧向间距的减小而产生延迟,但对排间距的敏感度较差。另外,桩群排的平均作用力越靠近下游,其峰值越小。以侧向间距3 m、排间距4 m的布置形式为例,首次来沙时,第2、3排平均作用力的峰值仅为首排的17.2%和15.8%,但排间距和排数的变化对其影响较弱;桩群侧向间距的增大对首排平均作用力的峰值影响相对有限,而其余排平均作用力的值会相应提高。再次来沙时,相较于首次来沙,桩群排间距的增加会引起颗粒竖直方向速度明显降低,致使下游来沙时间略有延迟。桩群排平均作用力的初始值随排间距、排数的增加及侧向间距的减小逐渐提升;随着上游的持续来沙,桩群排间距、排数、侧向间距的增加对首排平均作用力的峰值影响并不显著,而其余排平均作用力的峰值会相应增大;颗粒静止后,桩群排平均作用力的峰值随排间距、排数的增加及侧向间距的减小相应提高,且越接近下游其值越大。此外,碎屑流铲刮距离、铲刮深度随桩群排间距、排数的增大和侧向间距的降低而减小,冲击铲刮模式由冲切破坏为主转变为冲切破坏和运动剪切破坏相结合。

关键词:多级碎屑流;桩群;离散单元法;冲切铲刮机制;数值模拟

中图分类号:TV142　　**文献标志码:**A　　**文章编号:**2096-3246(2026)03-0091-11

近年来,中国西南地区频繁遭遇暴雨、地震等自然灾害侵袭。在多重动力因素的共同作用下,边坡震裂松动,雨水渗入其中,致使坡体失稳滑动,形成一种具有高度离散性、破碎性和流动性的集合体称为碎屑流[1–3]。碎屑流以其极快的运动速度和强大的输移能力,常常导致河道淤堵、交通中断、基础设施被掩埋[4–6]。以2017年6月茂县新磨村发生的碎屑流灾害为例,灾害造成10人死亡,73人失踪,大量基础设施被掩埋,河道淤堵近1 km,给当地人民的生产生活带来严重影响[7]。

由于碎屑流具有极强的破坏性,围绕碎屑流运动机理、影响范围及致灾机制等问题的研究一直是地质灾害领域的重要课题[8–10]。在理论分析方面,雷先顺[11]通过分析碎屑流运动中的能量转化规律,在条分法的基础上建立了一种可以描述坡体运动过程的改进黏壶分析模型。詹威威等[12]基于2008年汶川地震中大量碎屑流灾害的野外调查数据,根据逐步回归方法针对碎屑流最大运动距离提出了一种具有较高精度的最优多元回归模型。随着计算机运算性能的显著提升,通过数值计算可以较为真实地模拟坡体从稳定到失稳,再到形成灾害的整个过程,这对灾害的预测具有重要意义。例如,刘春等[13]利用MatDEM软件、基于创新的矩阵离散单元法实现了百万颗粒级的大规模计算,并在此基础上成功地对茂县新磨村发生的碎屑流

收稿日期:2024 – 04 – 16　　**修回日期:**2024 – 06 – 08　　**网络出版日期:**2024 – 07 – 08

基金项目:国家自然科学基金项目(52309081;52239006;52109087);吉林省教育厅项目(JJKH20230144KJ);福建省自然科学基金面上项目(2024J01720)

作者简介:雷　明(1989—),男,副教授. 研究方向:水力学及河流动力学. E-mail:leiming@neepu.edu.cn

* **通信作者:**王协康,研究员,E-mail: wangxiekang@scu.edu.cn

灾害进行模拟。王玉峰等[14]基于MatDEM软件对乱石包高速远程滑坡输移及堆积过程开展了数值试验，从细观角度分析了滑坡的摩擦热效应与滑体流态化运动模式。然而，碎屑流灾害的现场监测数据大多难以获得，针对此类问题的相关理论研究也缺乏统一观点，这时开展物理模型试验便成为研究与验证理论假设、确定数值模拟参数的重要手段。Zhou等[15]通过模型试验分析了泥沙级配、来沙量、沟道坡度等因素对碎屑流运动过程的影响。王贵洲等[16]通过开展系列试验研究了堆积区宽度对碎屑流运动及堆积规律的影响，指出颗粒运动速度、堆积长度与堆积区宽度呈负相关关系。为了对碎屑流灾害进行防控并建立有效的防护结构体系，许多学者围绕各类工程措施开展研究以降低碎屑流的滑动距离和运动速度[17−19]。例如：Chen等[20]将光滑离子流体动力学和有限元相结合对碎屑流对拦挡坝的冲击过程进行了数值模拟，结果显示增加拦挡坝布设数量可以有效提升减灾效果；郜颖超等[21]借助流形元模型对牛圈沟滑坡过程开展模拟研究，计算数据表明在碎屑流路径上布设拦挡坝可使下游的颗粒堆积量大幅下降，且拦截的颗粒数量与拦挡坝高度呈正相关关系。与传统体积庞大的实体拦挡坝相比，桩群具有透水性强、稳定性好、结构简单等优点，因而对于碎屑流灾害的防控具有明显优势[22−24]。如：Bi等[25]基于离散单元法围绕桩群结构对松散坡体的能量衰减过程影响进行仿真研究；陈古华等[26]通过数值计算分析了颗粒级配、桩群距离对颗粒运动特征的影响，从能量观点阐明了桩群动力响应机理。

尽管众多学者围绕碎屑流灾害防治开展了大量研究工作，但针对碎屑流与拦挡结构之间的相互作用机理仍处于研究阶段[27]。特别是对于防护结构拦挡多级碎屑流的研究还较为少见。为此，本文基于离散单元法对沟道内桩群拦挡多级碎屑流的运动及堆积过程开展模拟研究，重点探讨了多级碎屑流条件下桩群结构对颗粒运动速度、下游来沙过程、桩群冲击力和沟床淤积变形的影响，为合理有效地防控多级碎屑流灾害提供科学参考。

1 计算模型

颗粒在输移过程中的运动方程可表示为：

$$m\frac{\mathrm{d}\boldsymbol{v}_i}{\mathrm{d}t}=m\boldsymbol{g}+\sum_{j=1}^{n_c}(\boldsymbol{F}_{\mathrm{n},ij}+\boldsymbol{F}_{\mathrm{t},ij}) \tag{1}$$

$$I\frac{\mathrm{d}\boldsymbol{\Omega}_i}{\mathrm{d}t}=\sum_{j=1}^{n_c}\boldsymbol{T}_{ij} \tag{2}$$

式(1)、(2)中，m为颗粒质量，$\boldsymbol{v}_i$为颗粒i的平动速度，$\boldsymbol{F}_{\mathrm{t},ij}$，$\boldsymbol{F}_{\mathrm{n},ij}$和$\boldsymbol{T}_{ij}$分别为颗粒$i$、$j$的切向力、法向力和碰撞力矩，$n_c$为与颗粒$i$接触的颗粒数，$I$为转动惯量，$\boldsymbol{\Omega}_i$为颗粒$i$的转动速度，$g$为重力加速度。

颗粒间法向力$\boldsymbol{F}_{\mathrm{n},ij}$可描述为：

$$\boldsymbol{F}_{\mathrm{n},ij}=(-k_{\mathrm{n}}\alpha^{\frac{3}{2}}-\eta_{\mathrm{n},i}\boldsymbol{G}\boldsymbol{n})\boldsymbol{n} \tag{3}$$

式中，$\boldsymbol{n}$为从颗粒i球心到颗粒j球心的单位矢量，$\boldsymbol{G}$为颗粒i、j的相对速度，$\eta_{\mathrm{n},i}$为颗粒i的法向阻尼系数，k_{n}为颗粒i的法向弹性系数，α为法向重叠量。

颗粒间切向力$\boldsymbol{F}_{\mathrm{t},ij}$可表示为：

$$\boldsymbol{F}_{\mathrm{t},ij}=-k_{\mathrm{t}}\boldsymbol{\delta}-\eta_{\mathrm{t},j}\boldsymbol{G}_{\mathrm{ct}} \tag{4}$$

式中：$\boldsymbol{\delta}$为切向位移；k_{t}为切向弹性系数；$\eta_{\mathrm{t},j}$为切向阻尼系数；$\boldsymbol{G}_{\mathrm{ct}}$为滑移速度，表示如下：

$$\boldsymbol{G}_{\mathrm{ct}}=\boldsymbol{G}-(\boldsymbol{G}\boldsymbol{n})\boldsymbol{n}+a_i\boldsymbol{\Omega}_i\times\boldsymbol{n}+a_j\boldsymbol{\Omega}_j\times\boldsymbol{n} \tag{5}$$

式中，$\boldsymbol{\Omega}_i$和$\boldsymbol{\Omega}_j$为颗粒i、j的角速度，a_i和a_j为颗粒i、j的半径。

结合天然沟道比降沿程变化的实际特征，本文构建了由3级坡组成的物理模型，模型如图1所示。模型各级坡段倾角α_1、α_2、α_3分别为50°、20°与0°，对应坡长L_1、L_2、L_3分别为60、60和200 m，沟宽V为20 m。模型中，布设的桩群单桩高度H为3 m，单桩长度a与宽度b均为3 m，试验设置的桩群参数变量包括排间距L_x(4、8、12 m)、侧向间距L_y(3、6 m)与总排数N(1～3)。为探究多级来沙条件下桩群结构对碎屑流运动特征的影响，计算中采用两次加沙的方式模拟多级碎屑流运动过程，首次来沙为颗粒A，再次来沙为颗粒B，质量分别为3.2×10^6 kg和1.6×10^6 kg。结合文献[28−29]，仿真中的相关参数如表1所示，碎屑流颗粒粒径分布如图2所示。

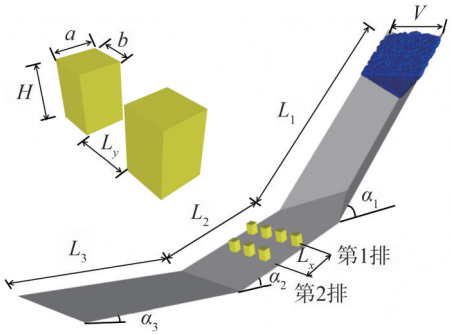


图1 物理模型示意图

Fig. 1 Schematic of the physical model

表1 相关计算参数

Tab. 1 Parameters used for the simulation

模型部件	密度/(kg·m^{-3})	滚动摩擦系数	泊松比	滑动摩擦系数	剪切模量/MPa	碰撞恢复系数
颗粒	2 500	0.15	0.28	0.2	100	0.35
坡面	—	0.15	0.26	0.2	1 200	0.35

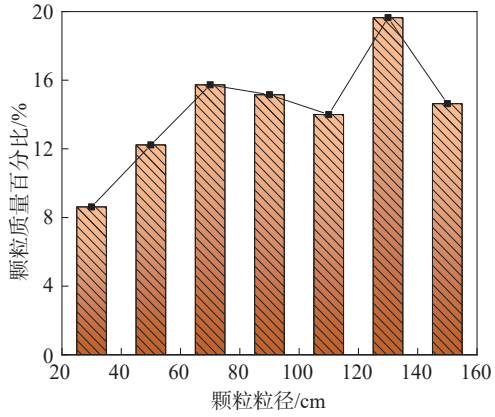


图2　碎屑流颗粒粒径分布

Fig. 2　Particles size distribution in granular flows

2　计算结果分析

本文采用离散单元法对不同桩群结构下碎屑流滑动、堆积过程开展数值试验。为了验证计算模型的准确性，基于文献[30]中的方法对文献[15]中的室内物理模型试验进行数值仿真，碎屑流累积体积的数值计算与文献数据对比如图3所示。由图3可知，数值模拟结果与试验数据较为吻合，表明通过离散单元法模拟碎屑流运动、堆积过程具有较高的可靠性和准确性。

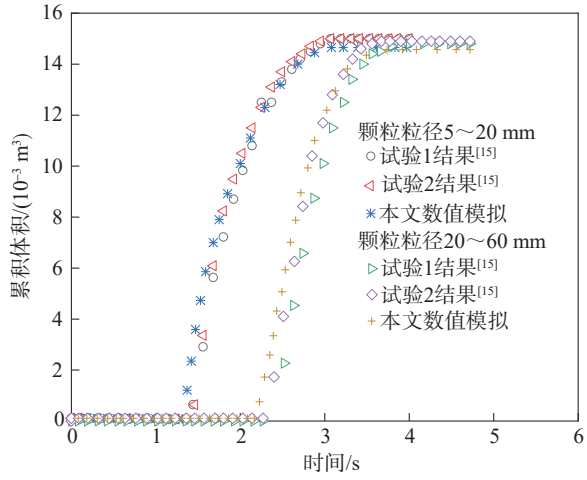


图3　碎屑流累积体积的数值计算与文献数据对比

Fig. 3　Comparison between numerical results of cumulative volume of granular flows and literature data

2.1　桩群结构对碎屑流输移过程的影响

沟道内桩群拦挡多级碎屑流在不同时刻的运动情况如图4所示。由图4可知：碎屑流在经过陡坡加速段后会以较高的速度向前运动，当碎屑流与桩群接触后，在桩群前端有大量颗粒从床面高速飞溅而出，颗粒的运动速度大幅降低。随着时间推移，颗粒进入缓坡段后速度会进一步下降，并最终在床面上静止堆积。再次来沙时，碎屑流不仅与桩群接触碰撞，其前缘还会与首次来沙静止后堆积形成的基底物质发生剧烈冲击并侵入其中，产生明显的冲切铲刮效应。强烈的撞击一方面会引起位于接触部位附近的基底物质在新颗粒的冲击下向前运动，另一方面在向上冲击力作用下部分基底物质会从床面上飞溅起来。随着碎屑流运动过程的持续进行，新颗粒逐渐运动至基底物质的上部，这会对基底物质产生一定的法向作用力和切向作用力，引起强烈的剪切作用。

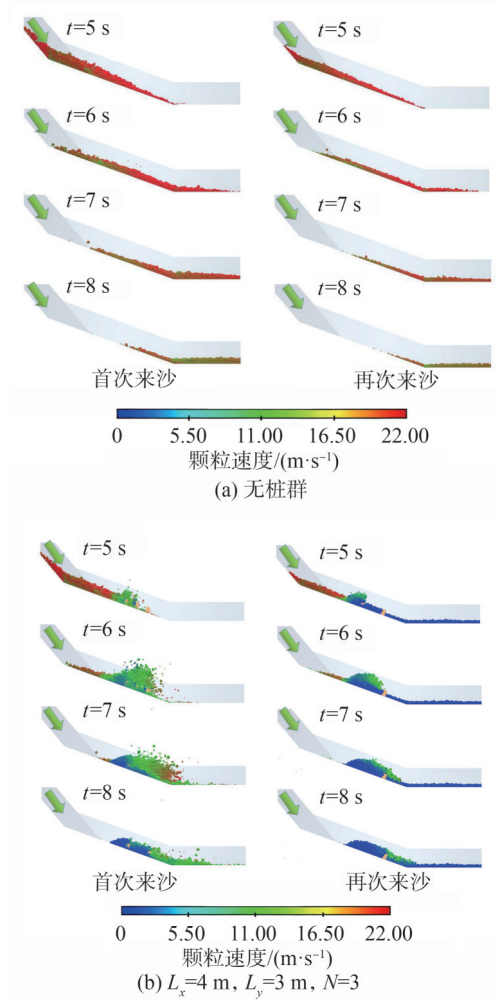
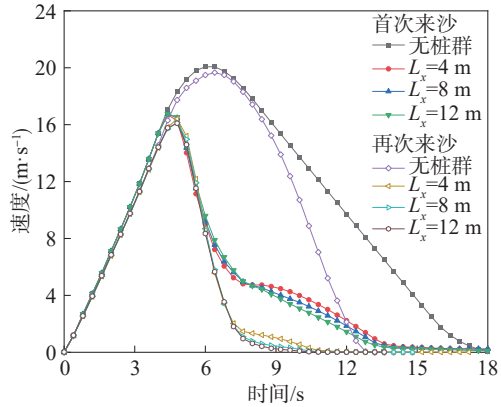


图4　碎屑流不同时刻运动情况

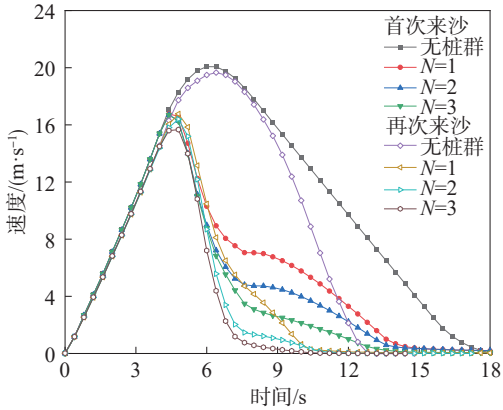
Fig. 4　Motion of granular flows at different times

为探究桩群结构对多级碎屑流能量耗散过程的影响，本文分析了桩群作用下颗粒沿程方向与竖直方向的运动速度变化特征，相关结果分别如图5、6所示。整体而言，多级碎屑流沿程方向与竖直方向速度均呈现先增大后减小的变化趋势，其中，颗粒沿程方向速度大于竖直方向速度，且桩群结构对颗粒沿程方向速度的调控与消能作用更为显著。对比图5(a)、(b)和(c)可知，随着桩群排间距、排数的增加及侧向间距的减小，颗粒沿程方向速度降低，特别对于再次来沙的消能效果更加明显。结合图6(a)、(b)与(c)可发现，首

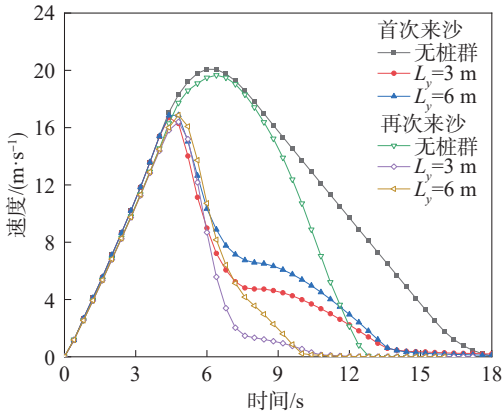
次来沙时，碎屑流与桩群接触会导致颗粒竖直方向速度出现小幅度反弹。随着桩群排数的增加和侧向间距的减小，颗粒竖直方向速度相应降低，而对桩群排间距的变化并不敏感。再次来沙时，碎屑流竖直方向速度随桩群侧向间距的增加而逐渐变大，但与桩群排间距和排数呈负相关关系。此外，由于首次来沙静止后堆积形成的基底物质起到了一定的缓冲作用，再次来沙时颗粒竖直方向速度并未出现明显反弹。



(a) 桩群排间距（L_y=3 m，N=2）



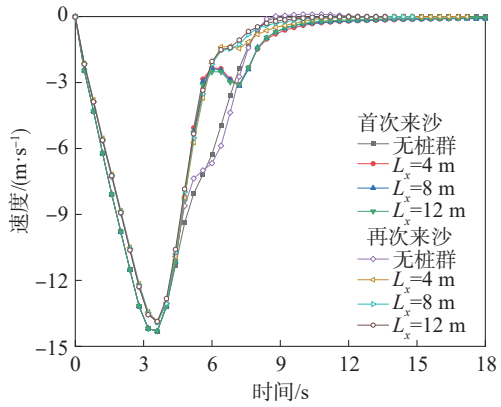
(b) 桩群排数（L_x=4 m，L_y=3 m）



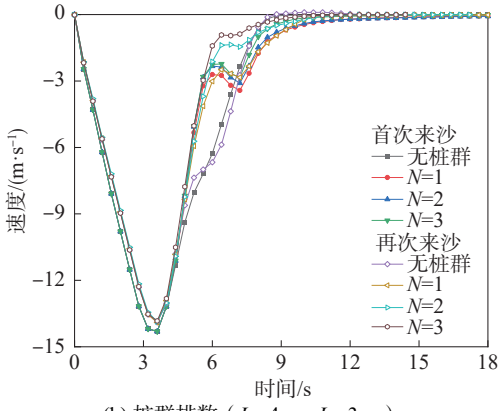
(c) 桩群侧向间距（L_x=4 m，N=2）

图5 桩群对颗粒沿程方向运动速度的影响

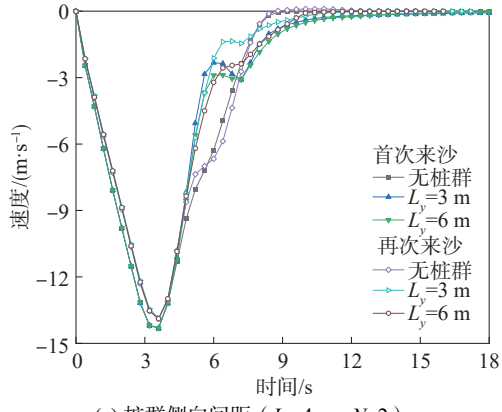
Fig. 5 Effect of baffles on the velocity of particles along the gully



(a) 桩群排间距（L_y=3 m，N=2）



(b) 桩群排数（L_x=4 m，L_y=3 m）



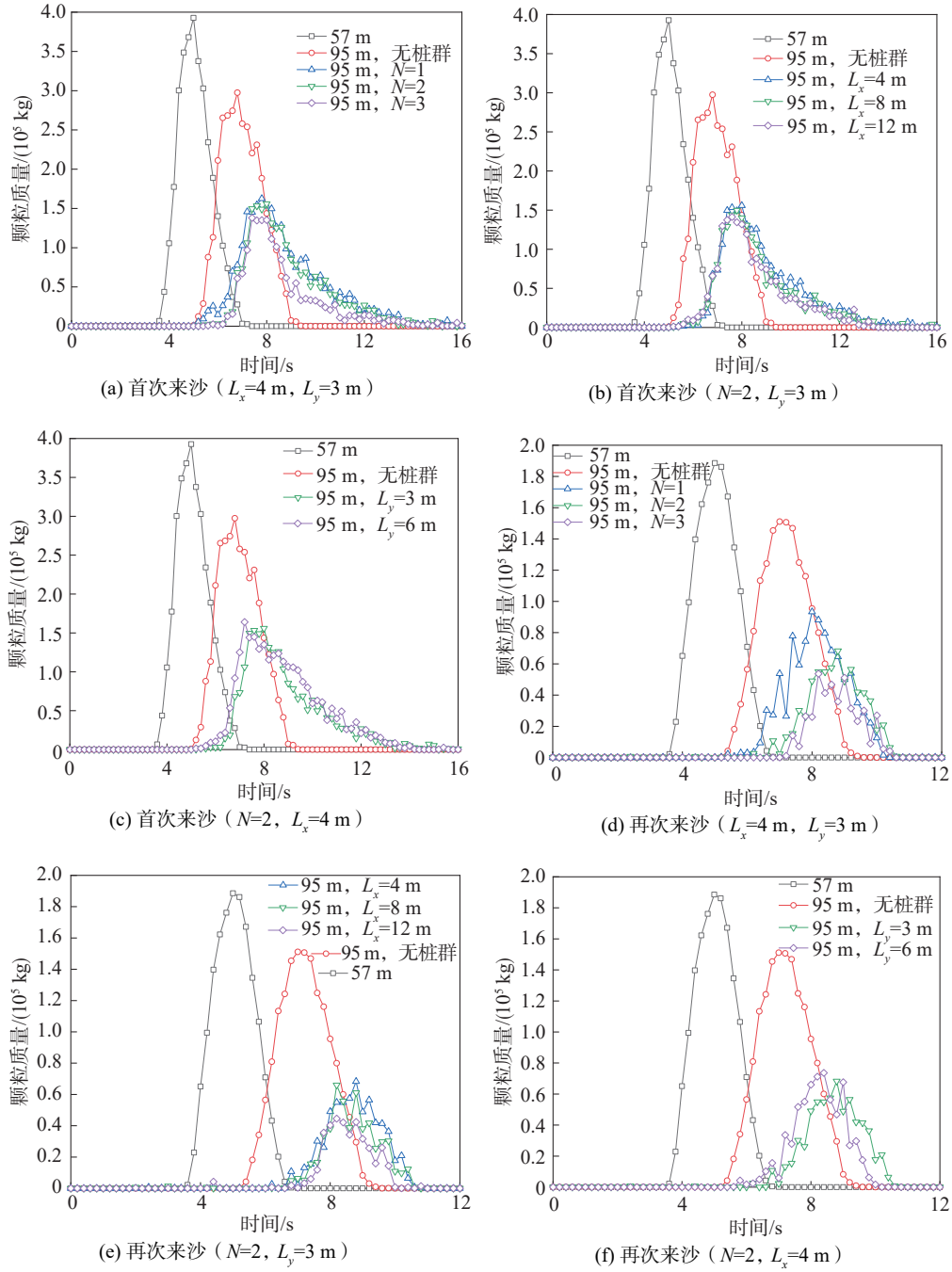
(c) 桩群侧向间距（L_x=4 m，N=2）

图6 桩群对颗粒竖直方向运动速度的影响

Fig. 6 Effect of baffles on the vertical velocity of particles

为了研究桩群结构对多级碎屑流下游泥沙补给过程的调控作用，选取沟道平距为 57 m 和 95 m 的断面作为特征研究断面，桩群对通过研究断面碎屑流质量的影响规律如图 7 所示。由图 7 可知，下游的泥沙补给质量整体上呈现先增大后减小的趋势。桩群的设置不仅使下游泥沙补给强度降低了约 47.6%，还使下游总来沙量大幅下降。由此可见，桩群对于多级碎屑流的输沙过程具有较好的阻滞与调节作用。随着桩群排数的增加和侧向间距的减小，下游泥沙补给的起始时间略有延迟，断面过流的来沙总量与峰值强度均同步降低，且

桩群对后续来沙过程的调控效果尤为突出。另外，随着桩群排间距的增大，首次来沙阶段，下游泥沙补给的起始时间对其敏感度较低，但进入下游的泥沙质量会下降；受首次来沙后沟床淤积变形的影响，后续来沙阶段的泥沙补给起始时间会略有推迟，下游泥沙补给总量与峰值强度也随之进一步降低。



(a) 首次来沙（L_x=4 m，L_y=3 m）　(b) 首次来沙（N=2，L_y=3 m）

(c) 首次来沙（N=2，L_x=4 m）　(d) 再次来沙（L_x=4 m，L_y=3 m）

(e) 再次来沙（N=2，L_y=3 m）　(f) 再次来沙（N=2，L_x=4 m）

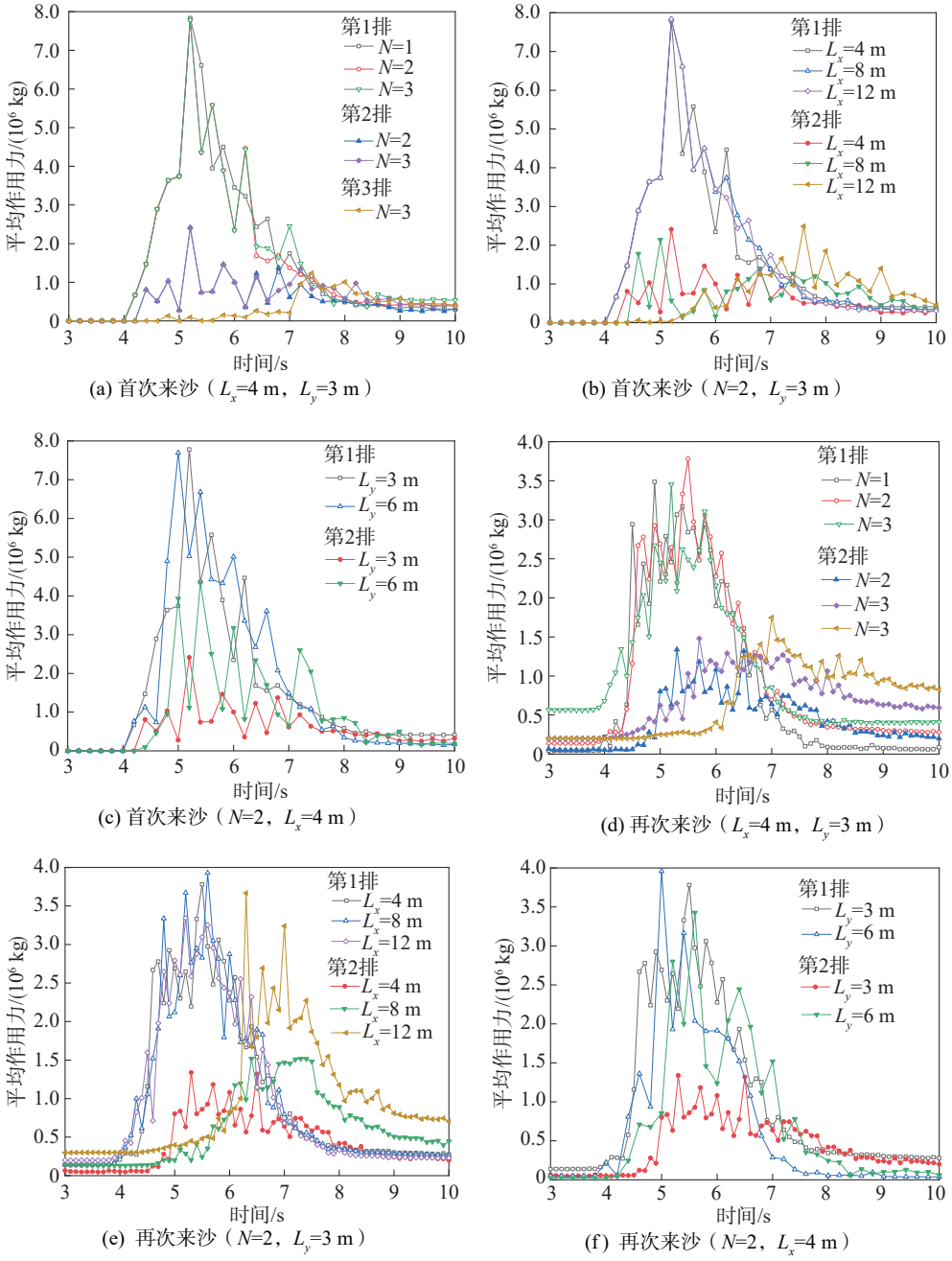
图 7　桩群对通过研究断面碎屑流质量的影响

Fig. 7　Effect of baffles on the quality of granular flows through the research section

2.2　桩群结构对其冲击力的影响

桩群排的平均作用力随时间变化的关系如图 8 所示。由图 8 可知：首次来沙时，当碎屑流前缘与桩群发生接触，桩群排的平均作用力由 0 迅速增加至峰值后逐渐降低，且越靠近下游，桩群排的平均作用力的峰值越小；以桩群侧向间距为 3 m，排间距为 4 m 的布置形式为例，其第 2、3 排平均作用力的峰值约为首排平均作用力峰值的 17.2% 和 15.8%，但桩群排的平均作用力的峰值对于桩群排间距和排数的变化并不敏感；此外，桩群侧向间距的增大对于首排平均作用力的峰值影响较小，其余排的平均作用力的峰值随之增大；再次来沙时，桩群排平均作用力的初始值随排间距、排数的增加及侧向间距的减小逐渐提升；随着上游的持续来沙，桩群排间距、排数、侧向间距的增加对首排

平均作用力的峰值影响并不显著，而其余排的平均作用力的峰值会相应增大；颗粒静止后，桩群排的平均作用力的峰值随排间距、排数的增加及侧向间距的减小相应提高，且越接近下游其值越大。



(a) 首次来沙（L_x=4 m，L_y=3 m）　(b) 首次来沙（N=2，L_y=3 m）

(c) 首次来沙（N=2，L_x=4 m）　(d) 再次来沙（L_x=4 m，L_y=3 m）

(e) 再次来沙（N=2，L_y=3 m）　(f) 再次来沙（N=2，L_x=4 m）

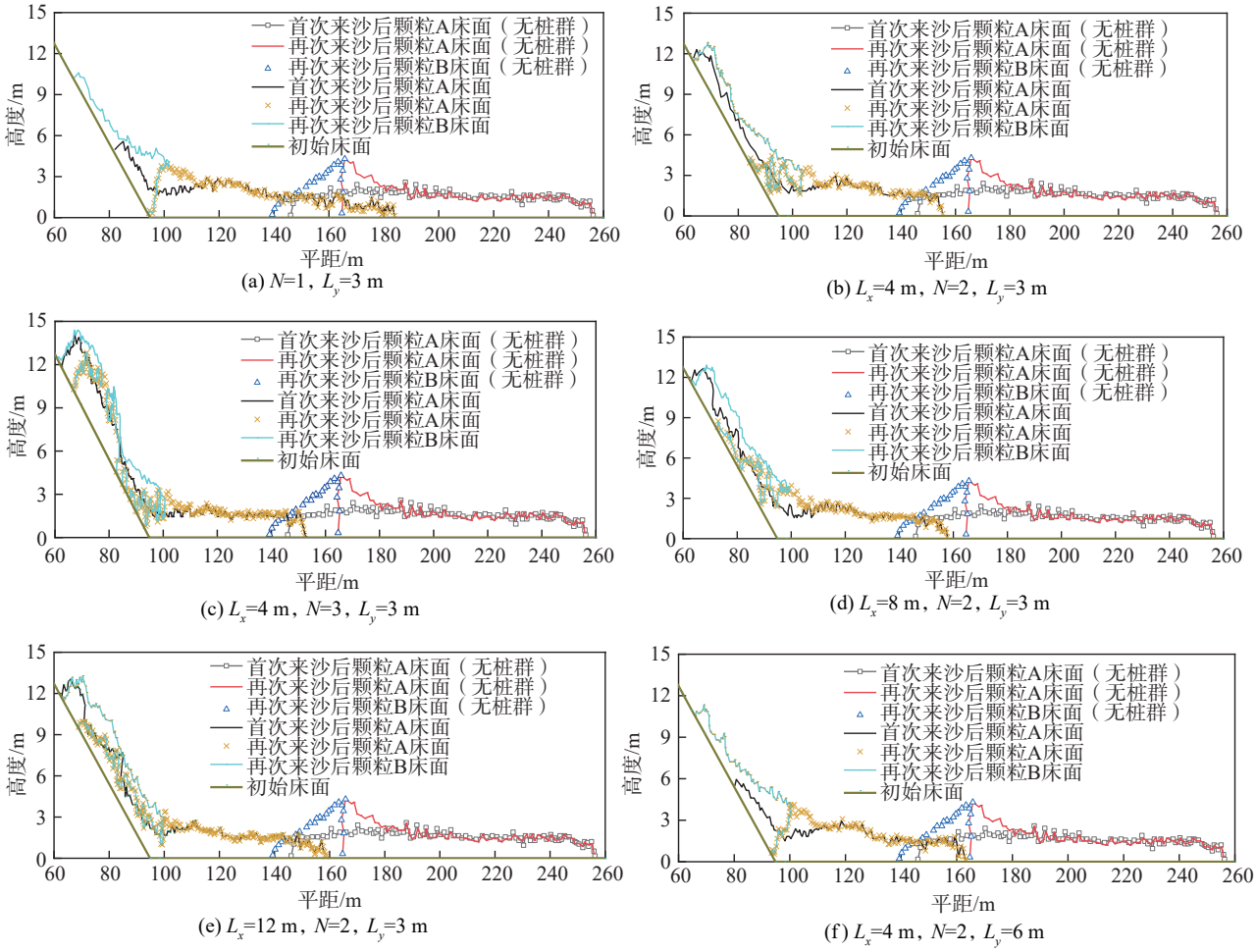
图8　桩群布设方式对其排平均作用力的影响

Fig. 8　Influence of baffles arrangement on the average force per row

2.3　桩群结构对碎屑流床面淤积变形的影响

多级碎屑流具有较强的冲切铲刮效应，这种效应主要体现在对基底物质的冲切破坏和运动剪切破坏上。冲切破坏通常发生在碎屑流的前端，是指基底物质在巨大的作用力下发生的破坏铲刮。运动剪切破坏常见于碎屑流的中后部，是指基底物质在切向力的作用下发生的破坏铲刮[31]。为探究桩群结构对沟道内颗粒堆积规律的影响，图9展示了不同桩群结构下多级碎屑流的最终堆积形态。由图9可知，首次来沙后颗粒的堆积形态较为平坦，再次来沙时新颗粒会对首次来沙形成的基底物质产生强烈的冲切铲刮作用，巨大的碰撞力致使冲击部位附近的基底物质发生破坏并被推动向前。在强烈的冲击碰撞作用下，新颗粒的动能严重耗散致使大量泥沙在碰撞部位附近堆积，从而显著增加了该区域的淤积厚度。设置桩群后，碎屑流的能量损失进一步增大，运动速度显著降低，致使其堆积位置整体向上游方向移动。随着桩群排间距、排数的增加和侧向间距的减小，桩群

对碎屑流的阻碍效率大幅提高，下游来沙量明显下降，多级碎屑流的铲刮距离和铲刮深度相应降低，冲击铲刮模式由冲切破坏为主转变为冲切破坏和运动剪切破坏相结合。



(a) N=1，L_y=3 m　(b) L_x=4 m，N=2，L_y=3 m

(c) L_x=4 m，N=3，L_y=3 m　(d) L_x=8 m，N=2，L_y=3 m

(e) L_x=12 m，N=2，L_y=3 m　(f) L_x=4 m，N=2，L_y=6 m

图9　不同桩群结构下颗粒的最终淤积形态

Fig. 9　Final sediment deposition morphology with different baffle configurations

3　讨　论

松散坡体在动力因素影响下失稳滑动会导致后续坡体抗滑能力大幅下降，引发一系列次级滑坡，形成多级碎屑流运动致灾。目前，对于多级碎屑流的防控方法主要有：监测预警预报措施、工程措施及生物防治措施[32]。由于工程措施具有适用范围广、施工速度快、防治效果显著等优点，使得工程措施被广泛采用。为此，本文围绕沟道桩群拦挡多级碎屑流运动特征开展模拟研究。

当前，针对松散坡体运动过程的计算模型主要分为两大类：连续介质模型与非连续介质模型[29]。连续介质模型将松散坡体看作连续体，通过连续介质理论来计算松散坡体输移过程。尽管连续介质模型具有理论发展成熟、计算效率高、应用范围广等优点，但其无法获得颗粒之间相互挤压碰撞等细节变化，因而在模拟多级碎屑流运动特征上存在明显不足[6]。与连续介质模型相比，非连续介质模型既能描述松散坡体的整体运动情况，又能获得坡体在滑动过程中内部破坏特征，在非连续介质模型中离散单元法的应用较为广泛[25−26]。故本文基于离散单元法重点探讨了多级碎屑流条件下桩群结构对颗粒运动速度、下游来沙过程、桩群冲击力和沟床淤积变形的影响。

天然滑坡碎屑流的物质组成较为复杂，有小到几毫米的砂石，也有大到数米的漂石，有着广泛的粒径分布[27]。但随着颗粒数量的增加，数值仿真的计算量会大幅提升，故仅对粒径范围在30～150 cm内的多级碎屑流的输移及堆积过程进行仿真计算。模拟中，只进行2次加沙，并未考虑颗粒级配、来沙量、颗粒形状、沟道宽度、沟道坡度等因素对于沟道内桩群拦挡多级碎屑流的影响。此外，多级碎屑流对拦挡结构的冲击力往往是巨大[25]，本文在计算中将桩群视为刚体来研究其布设方式对于多级碎屑流拦挡效果的影

响，未考虑桩群的变形效应。但在实际状态下，多级碎屑流的巨大作用力极易造成拦挡结构变形甚至破坏，因此如何构建满足防护要求的拦挡结构仍有待深入探索。

4 结 论

本文采用离散单元法模拟了沟道桩群对多级碎屑流的拦挡过程，重点探究了桩群结构对颗粒运动特性、下游泥沙补给规律、桩群冲击荷载及沟床淤积变形的影响。结论如下：

1）首次来沙阶段，颗粒沿程方向速度与桩群排间距、排数呈负相关，与侧向间距呈正相关；颗粒竖直方向速度则随桩群排数增加、侧向间距减小而递减，且对排间距的变化并不敏感。桩群结构可有效削减下游泥沙补给强度，该强度随排间距、排数增大及侧向间距减小逐步降低；下游泥沙补给启动时刻也会随桩群排数增加与侧向间距收窄而产生滞后，排间距对其影响则相对微弱。此外，桩群各排平均冲击力峰值沿程向下游方向持续衰减，排间距和排数的变化对该衰减特征无显著影响；增大侧向间距对首排桩群荷载峰值增幅有限，但可明显提升后续各排的平均冲击力峰值。

2）再次来沙阶段，相较于首次来沙，桩群排间距的增大可使颗粒竖直方向速度显著下降，并导致下游泥沙补给起始时刻出现小幅滞后。各排平均作用力的初始值随排间距、排数的增大及侧向间距的减小而升高；上游持续输沙过程中，排间距、排数和侧向间距的增大对首排桩群荷载峰值影响微弱，但会使后续各排平均冲击荷载峰值相应增大；颗粒静止堆积后，各排平均作用力峰值随排间距、排数增大及侧向间距减小而升高，且整体呈现沿程向下游逐渐递增的分布规律。

3）桩群结构对碎屑流的沟床侵蚀效应具有显著调控作用。增大桩群排间距与排数、减小侧向间距可有效缩短铲刮距离、降低铲刮深度，同时使沟床破坏模式由冲切破坏为主转向冲切破坏与运动剪切破坏共同主导的复合模式。

参考文献：

[1] Qin Panpan, Huang Bolin, Li Bin, et al. Hazard analysis of landslide blocking a river in Guang'an Village, Wuxi County, Chongqing, China[J]. Landslides, 2022, 19(11): 2775–2790.

[2] Luo Gang, Chen Xinan, Zhang Qian, et al. Failure mechanism and sedimentary characteristics of a catastrophic rockslide avalanche induced by the 2008 Wenchuan earthquake[J]. Landslides, 2023, 20(1): 25–38.

[3] Lei Ming, Xu Zexing, Zhao Tao, et al. Dynamics of loose granular flow and its subsequent deposition in a narrow mountainous river[J]. Journal of Mountain Science, 2019, 16(6): 1367–1380.

[4] Bao Yiding, Sun Xiaohui, Zhou Xin, et al. Some numerical approaches for landslide river blocking: Introduction, simulation, and discussion[J]. Landslides, 2021, 18(12): 3907–3922.

[5] Bi Yuzhang, Wang Dongpo, Yan Shuaixing, et al. Research on the blocking effect of baffle-net structure on rock avalanches: Consider the influence of particle splashing[J]. Bulletin of Engineering Geology and the Environment, 2023, 82(7): 277.

[6] Lei Ming, Xu Zexing, Liu Xingnian, et al. Numerical simulation of deformation process and accumulation state of loose materials under seismic action[J]. Advanced Engineering Sciences, 2018, 50(3): 240–246. [雷明, 许泽星, 刘兴年, 等. 地震作用下松散体变形过程及堆积形态的数值模拟[J]. 工程科学与技术, 2018, 50(3): 240–246.]

[7] Xu Qiang, Li Weile, Dong Xiujun, et al. The Xinmocun landslide on June 24, 2017 in Maoxian, Sichuan: Characteristics and failure mechanism[J]. Chinese Journal of Rock Mechanics and Engineering, 2017, 36(11): 2612–2628. [许强, 李为乐, 董秀军, 等. 四川茂县叠溪镇新磨村滑坡特征与成因机制初步研究[J]. 岩石力学与工程学报, 2017, 36(11): 2612–2628.]

[8] Lei Ming, Yang Po, Wang Yikui, et al. Numerical analyses of the influence of baffles on the dynamics of debris flow in a gully[J]. Arabian Journal of Geosciences, 2020, 13(19): 1052.

[9] Wang Dongpo, Bi Yuzhang, Li Qinze, et al. Kinetic response analysis of different types of baffle submitted to rock avalanches based on discrete element method[J]. Environmental Earth Sciences, 2021, 80(17): 600.

[10] Jian Fuxian, Cai Zhengyin, Guo Wanli. Laboratory-scale investigation of the material distribution characteristics of landslide dams in U-shaped valleys[J]. Journal of Mountain Science, 2023, 20(3): 688–704.

[11] Lei Xianshun. Model test and theoretical study of the landslide–debris flow[D]. Hefei: Hefei University of Technology, 2016. [雷先顺. 滑坡–碎屑流模型试验与理论研究[D]. 合肥: 合肥工业大学, 2016.]

[12] Zhan Weiwei, Huang Runqiu, Pei Xiangjun, et al. Empirical prediction model for movement distance of gully-type

rock avalanches[J]. Journal of Engineering Geology, 2017, 25(1):154–163.[詹威威,黄润秋,裴向军,等.沟道型滑坡–碎屑流运动距离经验预测模型研究[J].工程地质学报,2017,25(1):154–163.]

[13] Liu Chun, Fan Xuanmei, Zhu Chenguang, et al. Discrete element modeling and simulation of 3-dimensional large-scale landslide-taking xinmocun landslide as an example[J]. Journal of Engineering Geology, 2019, 27(6):1362–1370.[刘春,范宣梅,朱晨光,等.三维大规模滑坡离散元建模与模拟研究–以茂县新磨村滑坡为例[J].工程地质学报,2019,27(6):1362–1370.]

[14] Wang Yufeng, Ming Jie, Feng Zhiyi, et al. Research on the fluidized propagation and frictional heating effect of the Luanshibao rock avalanche[J]. Chinese Journal of Rock Mechanics and Engineering, 2022, 41(Supp 2):3174–3186.[王玉峰,明杰,冯止依,等.乱石包高速远程滑坡流态化运动模式及摩擦热效应研究[J].岩石力学与工程学报,2022,41(增刊2):3174–3186.]

[15] Zhou Jiawen, Yang Xingguo, Hou Tianxing. An analysis of the supply process of loose materials to mountainous rivers and gullies as a result of dry debris avalanches[J]. Environmental Earth Sciences, 2017, 76(13):452.

[16] Wang Guizhou, Gong Wenping, Xing Lei, et al. Model tests of run-out and deposition process of land-slide debris considering influence of depositing zone width[J]. Journal of Engineering Geology, 2023, 31(5):1637–1647.[王贵洲,龚文平,邢磊,等.考虑堆积区宽度影响的滑坡碎屑流运动与堆积过程物理模型试验研究[J].工程地质学报,2023,31(5):1637–1647.]

[17] Yuan Dong, Liu Jinfeng, You Yong, et al. Experimental study on the performance characteristics of viscous debris flows with a grid-type dam for debris flow hazards mitigation[J]. Bulletin of Engineering Geology and the Environment, 2019, 78(8):5763–5774.

[18] Wang Zhuang, Liu Daochuan, You Yong, et al. Characteristics of debris flow impact on a double-row slit dam[J]. Journal of Mountain Science, 2023, 20(2):415–428.

[19] Feng Zhujun, Wang Xiuli, Ran Yonghong. Dynamic impact of boulders on different types of concrete dam[J]. Journal of Mountain Science, 2022, 19(10):2920–2934.

[20] Chen Hongxin, Li Jin, Feng Shijin, et al. Simulation of interactions between debris flow and check dams on three-dimensional terrain[J]. Engineering Geology, 2019, 251:48–62.

[21] Gao Yingchao, Wei Wei, Jiang Qinghui. Simulation of movement of high-speed and long run-out landslide rock avalanche and the disaster reduction effects of retaining-wall based on the numerical manifold modelling[J]. Advanced Engineering Sciences, 2020, 52(6):40–48.[郜颖超,位伟,姜清辉.基于流形元模型的高速远程滑坡碎屑流运动规律与拦挡结构减灾效果研究[J].工程科学与技术,2020,52(6):40–48.]

[22] Ng C W W, Choi C E, Song D, et al. Physical modeling of baffles influence on landslide debris mobility[J]. Landslides, 2015, 12(1):1–18.

[23] Gong Sixia, Zhao Tao, Zhao Jidong, et al. Discrete element analysis of dry granular flow impact on slit dams[J]. Landslides, 2021, 18(3):1143–1152.

[24] Yang Haiqing, Haque M E, Song Kanglei. Experimental study on the effects of physical conditions on the interaction between debris flow and baffles[J]. Physics of Fluids, 2021, 33(5):056601.

[25] Bi Yuzhang, Du Yanjun, He Siming, et al. Numerical analysis of effect of baffle configuration on impact force exerted from rock avalanches[J]. Landslides, 2018, 15(5):1029–1043.

[26] Chen Guhua, Han Peifeng, Wang Yueming, et al. Discrete element simulation of retaining effect of retaining piles on debris flow of landslide[J]. Journal of Railway Science and Engineering, 2022, 19(1):129–140.[陈古华,韩培锋,王月明,等.拦挡桩群对滑坡碎屑流挡流效果的离散元模拟[J].铁道科学与工程学报,2022,19(1):129–140.]

[27] Zhang Ruixiao. Impact effect and accumulation characteristics of landslide interact with protective structure[D]. Mianyang: Southwest University of Science and Technology, 2020.[张睿骁.滑坡碎屑流对防护结构的冲击效应及堆积特征研究[D].绵阳:西南科技大学,2020.]

[28] Bi Yuzhang, Wang Dongpo, Fu Xianlei, et al. Optimal array layout of cylindrical baffles to reduce energy of rock avalanche[J]. Journal of Mountain Science, 2022, 19(2): 493–512.

[29] Zhao Chuan, Fu Chenghua. Numerical simulation of movement characteristics of debris flow based on DEM[J]. Advances in Science and Technology of Water Resources, 2017, 37(2):43–47.[赵川,付成华.基于DEM的碎屑流运动特性数值模拟[J].水利水电科技进展,2017,37(2):43–47.]

[30] Cheng Hao, Han Peifeng, Su Youwen. Sliding and accumulation characteristics of loose materials and its influencing factors based on discrete element method[J]. Acta Physica Sinica, 2020, 69(16):159–174.[成浩,韩培锋,苏有文.基于离散元方法的松散体滑动堆积特性及影响因素分析[J].物理学报,2020,69(16):159–174.]

[31] Lu Pengyuan, Hou Tianxing, Yang Xingguo, et al. Physical

modeling test for entrainment effect of landslides and the related mechanism discussion[J].Chinese Journal of Rock Mechanics and Engineering,2016,35(6):1226–1232.[陆鹏源,侯天兴,杨兴国,等.滑坡冲击铲刮效应物理模型试验及机制探讨[J].岩石力学与工程学报,2016,35(6):1226–1232.]

[32] Wang Zaijun. The distribution of landslide thrust between arched double-row anti-slide piles and its engineering application[D]. Changsha: Central South University, 2013.[王在军.拱形双排抗滑桩拱形双排抗滑桩滑坡推力分配计算及其工程应用[D].长沙:中南大学,2013.]

Numerical Experiment on the Motion Characteristics of Multiple Granular Flows Blocked by Baffles in a Gully

LEI Ming[1], *ZHANG Liang*[1,2], *YE Chen*[3], *WANG Xiekang*[4*]

(1.School of Civil Engineering and Architecture, Northeast Electric Power University, Jilin 132012, China;
2.Shanghai Jianke Engineering Consulting Co., Ltd., Shanghai 200032, China;
3.College of Harbor and Coastal Engineering, Jimei University, Xiamen 361000, China;
4.State Key Laboratory of Hydraulics and Mountain River Engineering, Sichuan University, Chengdu 610065, China)

Abstract:

Objective Under the influence of earthquakes and rainfall, loose slopes are highly prone to instability and sliding, triggering a series of secondary landslides and forming multiple granular flow disasters. Baffles are installed in the potential impact areas to reduce destructive forces and limit the accumulation range, and the motion characteristics of multiple granular flows blocked by baffles in a gully are analyzed using the discrete element method to reduce or avoid the hazards of multiple granular flows.

Methods The influence of the baffle structure on the transport process of multiple granular flows was investigated through numerical simulation. Due to the inability of the continuous medium model to capture detailed information such as particle squeezing and collision during multiple granular flows, the discrete element method, which belongs to the discontinuous medium model, was used for the numerical simulation. Firstly, the calculation method was validated. The physical model reported in the literature was established, and numerical simulations were conducted using the experimental conditions described in the same literature. The accuracy and reliability of the calculation method were assessed by comparing the calculation results with the experimental data from the literature. Secondly, due to significant variations in channel gradient at different locations, the physical model used in the calculation adopted a three-stage slope configuration, and the baffle structure was installed at the position of the second slope. The impact of the baffle structure on the blocking effect of multiple granular flows was obtained by modifying the arrangement of the baffles. Finally, the motion and accumulation of multiple granular flows were calculated using the three-dimensional discrete element method. Based on the analysis of the numerical data, the motion characteristics of multiple granular flows blocked by baffles in a gully were examined.

Results and Discussions During the first sediment supply, the particle velocity along the gully increased with wider lateral spacing but decreased as the spacing and the number of rows increased. The vertical particle velocity decreased as the number of rows increased and the lateral spacing decreased, but it remained relatively insensitive to changes in row spacing. The baffles reduced the downstream sediment supply intensity by approximately 47.6%. The downstream sediment supply intensity exhibited a negative correlation with both the spacing and the number of rows, while it showed a positive correlation with the lateral spacing. The downstream sediment supply time was delayed as the number of rows increased and the lateral spacing decreased, whereas the sensitivity to row spacing remained relatively low. In addition, the closer the location was to the downstream, the smaller the peak average force on the rows became. For instance, considering the baffle arrangement with a lateral spacing of 3 m and a row spacing of 4 m, the peak average force on the second and third rows was only 17.2% and 15.8% of that on the first row. However, the effect of variations in spacing and the number of rows on this parameter remained relatively weak. An increase in lateral spacing has a limited impact on the peak average force on the first row, while the peak average force on the other rows rises accordingly. When particles were supplied again, compared to the first sediment supply, an increase in row spacing caused a corresponding decrease in particle vertical velocity, and the downstream sediment supply time was slightly delayed. The initial value of the average force on the rows increased as the spacing and the number of rows increased, but it showed a negative correlation with the lateral spacing. As the sediment supply continued, increases in spacing, the number of rows, and lateral spacing had a relatively minor impact on the peak average force on the first row. In contrast, the peak average force on the other rows increases accordingly. After particle accumulation, the peak average force on the baffles gradually increases as the spacing and the number of rows increase, and as the lateral spacing decreases, and the closer the location is to the downstream, the greater the peak average force becomes. In addition, the distance and depth of the entrainment process decrease with increases in spacing and the number of rows, and

with decreases in lateral spacing, and the entrainment mode shifted from impact failure to a combined mode of impact failure and shear failure. The material composition of granular flows is highly complex, ranging from a few millimeters of sand to several meters of boulders, with a wide particle size distribution. However, the computational cost increases significantly as the number of particles increases. Therefore, the study only conducted simulations for particle diameters ranging from 30 to 150 cm. The influence of particle shape, particle size distribution, channel width, and channel slope on the motion characteristics of multiple granular flows blocked by baffles in a gully was not considered in the simulation. The impact force of multiple granular flows on protective structures remained extremely large. In this study, the baffle structure was treated as a rigid body to investigate its protective effect against multiple granular flows. However, in practical situations, the large forces generated by multiple granular flows could cause deformation or damage to the protective structure. Therefore, the design of protective structures that meet practical requirements needs further investigation.

Conclusions The results demonstrate that the installation of baffles in the potential impact area of multiple granular flows can reduce their destructive force and limit the accumulation range. The effects of baffles on particle motion velocity, downstream sediment supply, impact force, and sediment deposition patterns studied in the study provide a scientific basis for baffle design for the effective prevention and control of multiple granular flow disasters in mountainous areas.

Key words: multiple granular flows; baffles; discrete element method; entrainment mechanism; numerical simulation

（编辑　张　琼）

引用格式: Lei Ming,Zhang Liang,Ye Chen,et al.Numerical experiment on the motion characteristics of multiple granular flows blocked by baffles in a gully[J].Advanced Engineering Sciences,2026,58(3):91–101.[雷明,张亮,叶晨,等.沟道桩群拦挡多级碎屑流运动特征数值试验[J].工程科学与技术,2026,58(3):91–101.]