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古沉积盆地下切引发的泥石流侵蚀和波状流动耦合过程

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摘　要: 青藏高原的持续抬升导致黄河干流下切,带动支流大河坝河溯源下切,使得同德盆地由沉积区变为侵蚀区,泥石流开始群发,研究群发机理对古沉积盆地泥石流的防灾减灾意义重大.通过野外监测结合室内水槽试验,系统分析了同德盆地卵石夹砂沉积层的土力学性质,切沟发育阶段和泥石流的侵蚀、运动过程.卵石夹砂沉积层分选好,磨圆度高,无胶结,利于水流下切和物源能量的累积.大河坝河溯源下切,卵石夹砂物源能量往大河坝河上游传递,导致大河坝河不同河段的切沟发育阶段和泥石流发育趋势不同.卵石夹砂沉积层的厚度和下切深度决定了泥石流的侵蚀强度和发育趋势.水流下切、泥石流侵蚀、卵石夹砂分选和崩滑堵溃过程造成了泥石流龙头能量来源的间歇性和周期性,助推了龙头运动的波动性.

关键词: 泥石流;河流下切;侵蚀;卵石夹砂;波状运动;工程地质;灾害防治.

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Coupling Process of Debris Flow Erosion and Wavy Flow Caused by Incision on Paleosedimentary Basin

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Abstract: Uplift of the Qinghai-Tibet Plateau result in accelerating fluvial incision of the Yellow River. The incision of the Yellow River makes Daheba River, one of the tributaries of the Yellow River, incise quickly on the flat and broad Tongde basin covered by deep fluvial sediments and loess. Tongde basin has changed from sedimentary area to erosion area, and debris flow are developing. The study on the mechanism of debris flow groups occurrence is of great significance to the prevention and mitigation of debris flow in paleosedimentary basins. This paper analyzed the characteristics of sediments soil mechanics, water system of Daheba River and the mechanism of erosin and motion of debris flow through field investigation and physical model. Analysis showed that the Daheba River incised on thick lacustrine sediments and the sediments composed by gravel and sand, good sorting, were beneficial to the formation of debris flow. Under the condition of uplift of Qinghai-Tibet Plateau and rapid incisions of Yellow River, the headward erosion of Daheba River had made the river energy gradually extend upstream. Therefore, different distribution and development characteristics were at different river sections of Daheba River. The thickness and incision depth of pebble sand sediment layer determine the erosion intensity and development trend of debris flow. The intermittent energy source of debris flow head is caused by the process of water flow incision, debris flow erosion, pebble sand separation and collapse, which promotes the fluctuation of debris flow movement.

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Key words: debris flow; river incision; erosion; gravel and sand; wave motion; engineering geology; disaster prevention.

1 研究背景

河流下切是指河床物质受到水流冲刷,河床高程不断降低的现象.自然界大多数山区河流是下切型河流(王兆印,2014),河流下切是山区河网发育和地貌演化的主要动力(Moeyersons *et al.*,2004,2010; Pratt-Sitaula *et al.*,2007),一些构造活跃山区超过80%地形起伏由河流下切引起(Korup *et al.*,2010).青藏高原边缘是典型的河流下切较快的地貌过渡带,众多大江大河流经此区域,水能丰富,河道坡降大,河床耗能不足以抵消河流能量,河流切割强烈,峡谷多,生态环境脆弱(彭建兵等,2004;兰恒星等,2022).群发性泥石流多集中在下切河谷两岸,比如金沙江河谷(唐川等,2006;陈洪凯等,2009;张晨等,2011;陈剑等,2011)、岷江河谷(崔鹏等,2011;崔鹏,2014;范宣梅等,2021)、雅鲁藏布江河谷(蒋忠信,2002;段书苏和姚令侃,2019;高泽民等,2021)、澜沧江河谷(苏鹏程和韦方强,2014;李茂山,2015)、怒江河谷(唐川,2005;罗荣章和徐则民,2016;李旭等,2016;徐慧娟,2016;冯倩倩,2020)、印度河上游河谷(吕立群,2017;梁馨月等,2020)、黄河上游河谷(杜俊等,2014)、白龙江河谷(孟兴民等,2013;黄江成等,2014).河流下切不仅为群发性泥石流提供了物源能量,而且大江大河集中在峡谷内,为泥石流的暴发提供了水源能量.除了火山形成的火山灰地带或者森林火灾形成的灰烬层地带(胡卸文等,2020),国外其他地区的群发性泥石流也集中分布在河流下切的河谷地带(吕立群,2017),比如欧洲阿尔卑斯山脉的Rhone河谷(Kühni and Pfiffner,2001)和Rhine河谷(Turowski and Rickenmann,2009)、新西兰境内的Mathias河谷和Taramakau河谷(Whitehouse, 1983).

河流下切的阶段不同导致群发性泥石流的发育趋势不同(段书苏和姚令侃,2019).河流下切往往导致下游淤积、上游溯源,河流不同河段的下切阶段是不同的.例如雅鲁藏布江、印度河、盖孜河、白龙江在青藏高原边缘处于快速下切阶段,泥石流的群发性加剧(吕立群,2017).怒江大峡谷云南段处于下切向淤积转化的阶段,泥石流的频率在降低、群发趋势在减弱,但是怒江大峡谷西藏段处于加速下切阶段,滑坡灾害比泥石流灾害严重,为群发性泥石流提供了大量物源,泥石流群发趋势在加剧(Lü *et al.*,2021).

泥石流的不稳定运动受到沟道物源分布(Berger *et al.*,2011)、泥沙含量(Imaizumi *et al.*,2017)、降雨类型和流量(Kean *et al.*,2013)的影响.三种因素导致泥石流运动不稳定性强烈:(1)降雨汇流过程非线性(Suwa and Ramakoshi, 1999);(2)泥石流在沟道内部由于局部地形造成阻塞和溃决(Xu *et al.*,2009);(3)泥石流本身的力学性质(Phan-Thien and Dudek,1982; 王兆印等,1990),例如龙头颗粒分选导致的泥石流运动阻力的变化(Mangeney *et al.*,2010).沟道物源分为三种方式影响泥石流的不稳定运动过程:(1)沟床揭底;(2)沟床堰塞体溃决;(3)沟岸侧蚀(吕立群等,2015,2016a, 2016b).堵塞体溃决形成的泥石流在地震灾区比较常见(许强,2010;吕立群等,2022),但是崩滑堵塞体的侵蚀过程与沟岸侧蚀存在明显区别:沟岸侧蚀受土体密实度、土壤结构及基质吸力等因素的影响(吕立群等,2017,2018).而堵塞体侧蚀过程由于坝体物质松散、结构强度低,对水流扰动非常敏感,存在对上游来流的蓄积－释放过程(李尧等,2022;Lü *et al.*,2022),水流运动的非恒定性加上物源沿程的非线性补给往往导致泥石流运动的不稳定.同德盆地作为典型的古沉积盆地,卵石夹砂物源巨厚,颗粒分选明显,沟内崩滑体堵溃严重,造成泥石流的侵蚀和运动过程异常复杂.

2 研究区域和方法

2.1 研究区域

同德盆地位于青藏高原东北缘,是青藏高原向大陆内部扩展的前缘部位(张培震等,2003;袁道阳等,2004),面积约3 200 km^2,平均海拔约3 300 m(图1a).由于青藏高原的不均匀抬升,同德地区成为断陷盆地,在外力剥蚀和水流的搬运作用下,盆地开始接收大量沉积物,这些沉积物主要由粒径较小的卵石组成,中间填充大量砂粒,同时第四纪以来风成黄土也在不断堆积(赵振明和刘百篪,2005;杜俊等,2014).120万年前发生的昆黄运动,开始了黄河上游的溯源加长,黄河先后切穿积石峡和李家峡,约15万年前青藏高原发生共和运动,高原持续

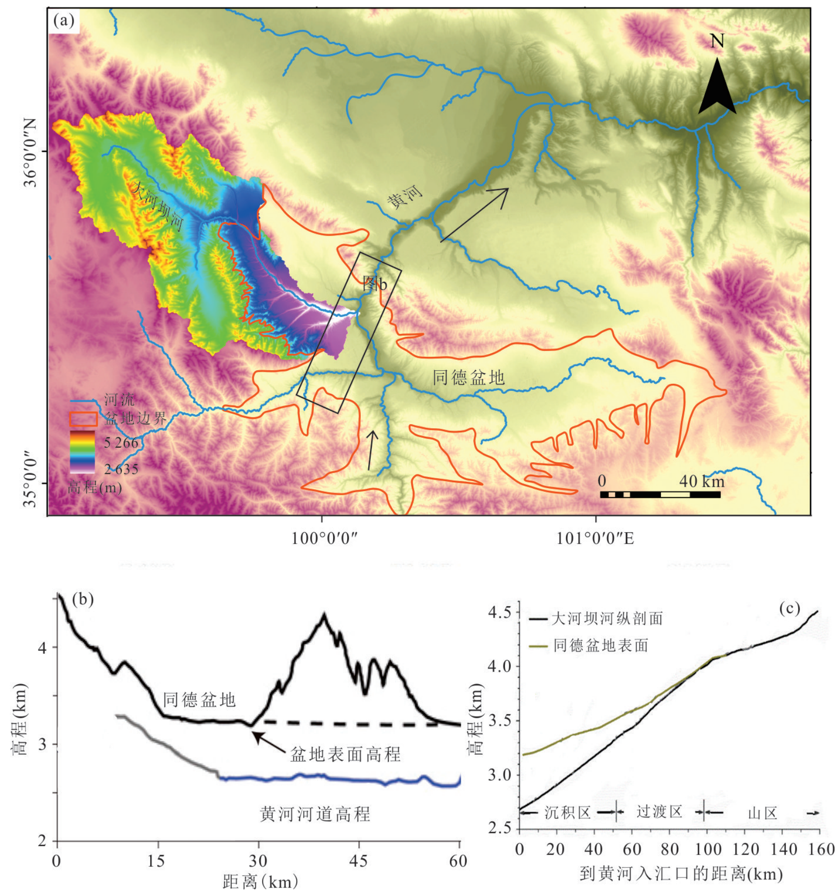

图1　同德盆地，黄河和大河坝河之间的位置关系(a)；最大和最小高程(b；改自 Craddock *et al*., 2010)；大河坝河分段：沉积段，过渡段，山区段(c)

Fig.1　Tongde sedimentary basin, Yellow River and its tributary Daheba River (a); maximum and minimum elevation (b; modified by Craddock *et al*., 2010); three reaches: the sedimentary basin reach, the transition reach, and the mountain reach (c)

隆升，龙羊峡被溯源切穿，黄河进入共和盆地(李吉均等，1996)．约5万年前，黄河抵达唐乃亥一带(刘志杰和孙永军，2007)，黄河在同德盆地下切，下切速率达到4 mm/a(杨达源等，1996；Craddock *et al*.，2010；杜俊等，2014)．黄河干流下切，导致侵蚀基准面下降和支流溯源(图1b)．在这种背景下，支流大河坝河在沉积盆地上快速下切，同德盆地由沉积区变为侵蚀区，泥石流灾害开始群发．

大河坝河流经同德盆地的中心区和边缘区，上游延伸到山区(图1a)．盆地中心区卵石夹砂沉积层巨厚，大河坝河没有切穿沉积层，基岩未出露；盆地边缘区沉积层较薄，大河坝河切穿沉积层到达基岩，并发育基岩河床结构．根据大河坝河两岸出露岩层的不同，大河坝河分为下游沉积段(盆地中心区)，中游过渡段(盆地边缘区)和上游山区段(无卵石夹砂沉积层)(图1c)．

2.2　研究方法

2.2.1　泥石流识别和沟道地貌特征测量　首先区分泥石流沟和非泥石流沟．泥石流沟道密度大(图2a，2b)，沟头不断后退(图2c)，沟道中下游漏斗状的断面表明正在经历快速下切阶段(图2d)．工程治理的沟道无疑是泥石流沟道，对于没有治理的沟道，可通过扇体区分(图2e，2f)．泥石流扇体粗颗粒多，分选差，有侧堤，坡降大(3°～16°)(图3e)；洪积扇颗粒均匀，分选好，坡降低(1°～2°)(图2f)．利用DEM提取沟道的汇水面积和纵比降．对于沟长通常较短的支沟，流域高程沿程变化的精度至关重要，利用高精度的差分GPS测量了沟道的高程，精度达到了1 mm，确保了数据的可靠性．

2.2.2　泥石流野外监测和运动参数计算　图2b和2c是一条活跃的泥石流沟(沟口坐标：35.51917°N，100.02190°E)，离入汇黄河的河口11.4 km，在沟道内安装了监测预警设备．2016年7月8日、14日和26

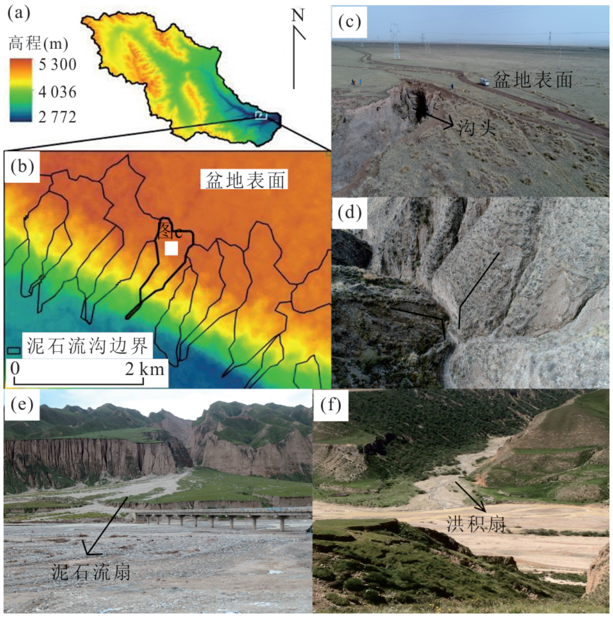

图2 泥石流沟的地貌特征

Fig.2 Geomorphic characteristics of debris flow gully

a.大河坝河河谷;b.泥石流沟流域形状;c.监测沟道;d.监测断面;e.泥石流扇;f.洪积扇

日分别暴发了3次泥石流,8日的泥石流被完整记录下来,8日和14日泥石流暴发前后的沟道纵剖面高程使用RTK进行了测量,并通过拉格朗日法和欧拉法计算了某断面(图2d)泥石流的运动过程.拉格朗日法是通过跟踪龙头的位移和时间来计算速度的变化;欧拉法是通过观测某一断面泥石流经过时,卵石夹砂混合物中卵石经过断面时位移随时间的变化来计算速度.需要指出的是,流速计算比较粗糙,因为运动距离的估算不够精确,但运动过程足以说明其波状的运动特点.

2.2.3 泥石流侵蚀和运动过程模拟 泥石流沟道两岸崩滑物源丰富,颗粒为卵石和细沙,卵石磨圆度较好,有一定的分选,显示了良好的搬运特性,粒径总体较小,中值粒径不超过1 cm,沟道横断面多为梯形.用梯形断面水槽来模拟泥石流侵蚀和运动过程,试验水槽长12 m,宽0.6 m(图3).实验泥沙采用粗砂(5~40 mm)和细沙(0.5~2.0 mm)来分别模拟沉积盆地的卵石夹砂物源(图3d和3e).上游水箱放水侵蚀泥沙形成泥石流,采用6个流量参数(6.72、13.38、25.65、36.21、47.36、53.53 L/s)代表6种降雨强度下泥石流沟道的汇水流量.试验几何相似率1:20,流量缩小比尺$1:20^{2.5}$,模拟流域面积1 km^2,试验相似律和流量参数的选取原则和计算方法可参考吕立群等(2017,2018).

3 结果

3.1 卵石夹砂沉积层厚度和下切深度对泥石流发育趋势的影响

泥石流大部分分布在沉积区,少部分在过渡区,山区没有泥石流发育(图4).沉积区泥沙淤积厚度在大河坝河与黄河的交汇口达到660 m,但是目

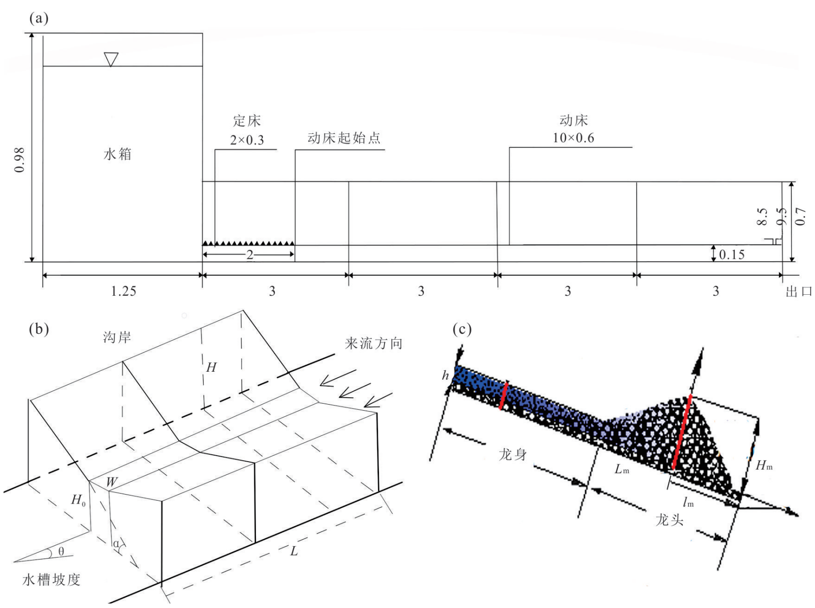

图3 试验模型

Fig.3 Experimental model

a.侧视图;单位:m;b.断面图;c.龙头和龙身

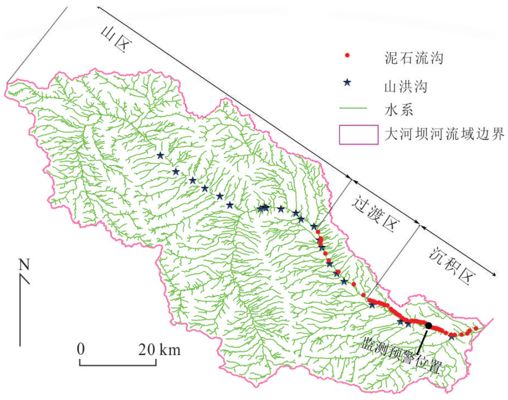

图 4　大河坝河泥石流分布

Fig.4　Debris flow distribution

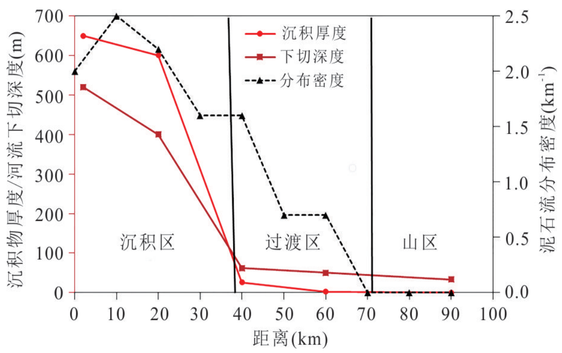

图 5　泥石流分布密度和沉积层厚度与河流下切深度之间的关系

Fig.5　Debris flow density, sediment thickness and incision depth

前沉积层只被切穿了 520 m. 沉积层可以分为两层：上层薄薄的黄土层，下层巨厚的卵石夹砂层. 离入汇口 20 km、40 km、70 km 和 100 km 处，沉积层的厚度分别为 600 m、70 m、16 m 和 2 m，大河坝河在中游切穿盆地进入基岩，下切基岩的深度达到了 5 m（图 5）. 泥石流沟群的线密度（每 1 km 范围内泥石流沟群的数量）与沉积物的厚度呈现正相关的关系，在大河坝河下游的密度最大，可达到 1.5 个/km. 随着上游沉积层厚度的减小，泥石流沟群的线密度在降低. 在 40～70 km 范围内密度较低，70 km 上游没有泥石流.

大河坝河两岸的泥石流发育需要一定的集水面积，最小集水面积为 0.1 km^2（图 6），小于 0.1 km^2 或者大于 3 km^2 的沟道一般是以山洪的形式搬运颗粒物质. 对位于大河坝河上游山体发育区的支沟进行测量，发现在同样集水区面积和沟道比降的条件下，也难以暴发泥石流. 因为在大河坝河上游沉积物厚度和总量较少，同样雨量的条件下没有足够的沉积物供给. 所以沉积层厚度（决定物源储量）、集

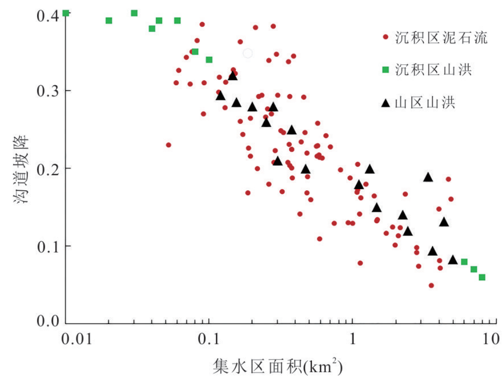

图 6　泥石流和山洪集水面积和沟道坡降

Fig.6　Gully gradient vs. gully drainage area for debris-flow and non-debris-flow gullies

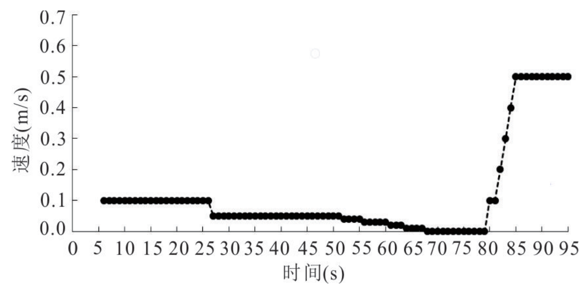

图 7　野外监测泥石流龙头速度（拉格朗日法）

Fig.7　Velocity of the head of the debris flow based on a Lagrangian analysis

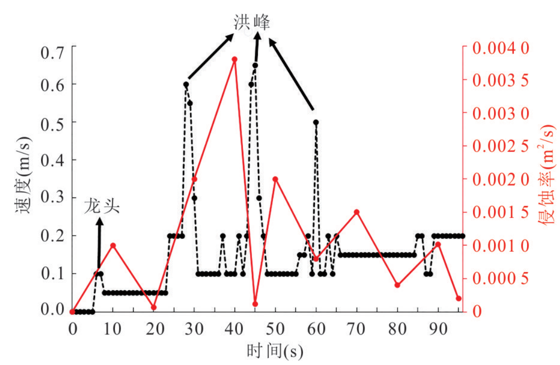

图 8　野外监测泥石流经过某断面（见图 2d）的速度和侵蚀率（欧拉法）

Fig.8　Velocity of the body of the debris flow while passing through section (indicated in Fig.2d) based on an Eulerian analysis

水区面积（决定集水能量）和河流下切的程度（决定支沟比降）共同构成了泥石流发育的条件.

3.2　泥石流波状流动规律

野外监测表明（图 7）：龙头和龙身区分明显，龙身处伴随有堵溃现象，不断有洪峰从龙身传递能量给龙头；龙头运动时走时停，可以分为波动期和非

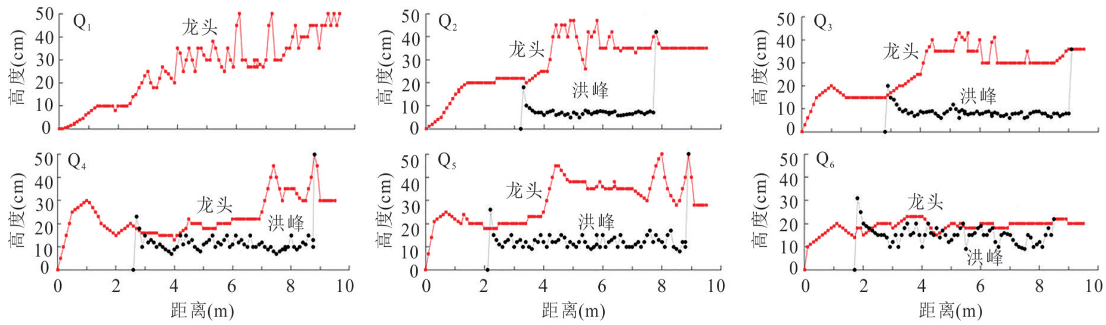

图 9　泥石流龙头和龙身洪峰高度

Fig.9　Height of debris flow head and flood on the body

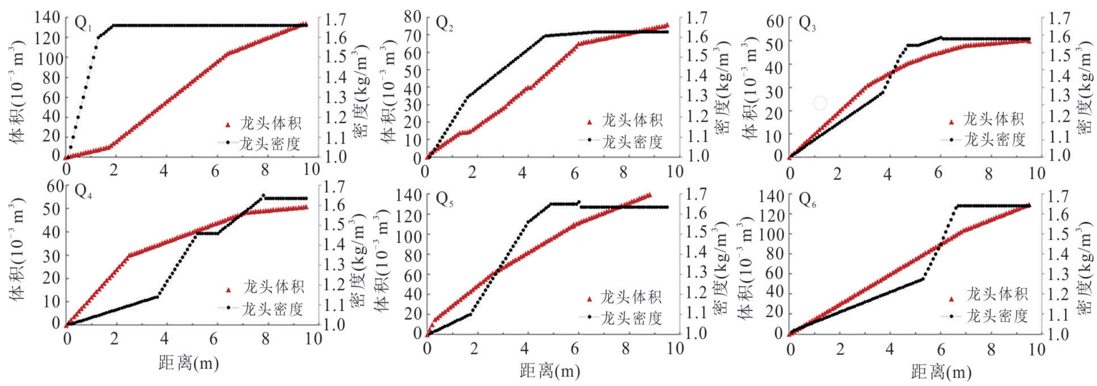

图 10　泥石流龙头体积和密度

Fig.10　Volume and density of debris flow head

波动期.在波状期,龙头运动速度低(6~79 s),甚至降低为0(79~80 s),但是龙身由于堵溃形成的洪峰速度不会减弱,且持续把泥沙从龙身传递给龙头,导致龙头不断膨胀,形成附加坡降,当附加坡降达到足够大时,龙头失稳加速前行(80~91 s),龙头由波状期进入运动期.如此反复,构成了泥石流的波状运动特征.图 8 是用欧拉法测得的泥石流流经监测断面处时的流速过程:龙头首先以低速通过,在 20~95 s之间,不断有洪峰以较高速度通过,由于速度较高,龙身的侵蚀速率反而大于龙头.

实验可以模拟龙头的波状运动,龙身处洪峰流速相对平稳(图 9).龙身不断向龙头输沙,龙头的体积不断膨胀,密度不断增大(图 10).

3.3　泥石流的下切侵蚀过程

野外监测表明(图 11):泥石流的侵蚀作用主要发生在龙身,因为龙身存在崩滑—堵溃的现象,崩滑对侵蚀加速起到了关键作用.卵石夹砂岸坡易崩滑,规模小、数量大,占据了沟底大部分断面(图 11a,11b),泥石流暴发后新的崩滑体会及时补充沟底(图 11c),有些崩滑体并没有完全被泥石流搬运到下游(图 11d),残余崩滑体和新的崩滑体累

图 11　泥石流沟内崩滑体

Fig.11　Gully morphology and sediment availability in the gully

a.暴发前崩滑体; b.暴发后崩滑体; c.暴发前堰塞体; d.暴发后残留堰塞体

加堆积在沟底,为下次泥石流提供物源材料.

2016年7月8日和14日泥石流暴发前后的沟道纵剖面高程变化表明(图 12):泥石流沟道下游明显淤积,中上游由于崩滑体及时补充,平均高程变化不大,这说明了沉积盆地下切区泥石流的侵蚀以沟岸侧蚀为主.实验证明了同样的规律:足够物源条

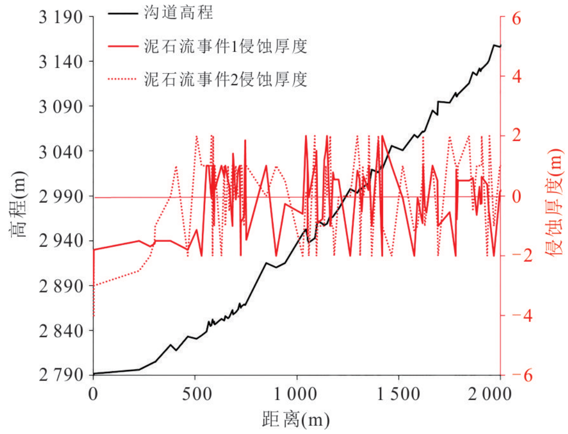

图 12　泥石流侵蚀厚度

Fig.12　Erosion thickness by debris flow

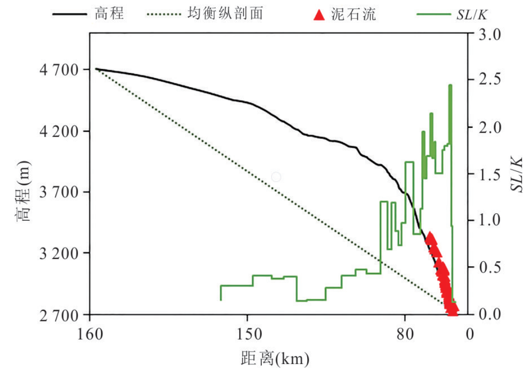

图 13　大河坝河泥石流分布与坡降指数之间的关系

Fig.13　Debris flow distribution and SL/K

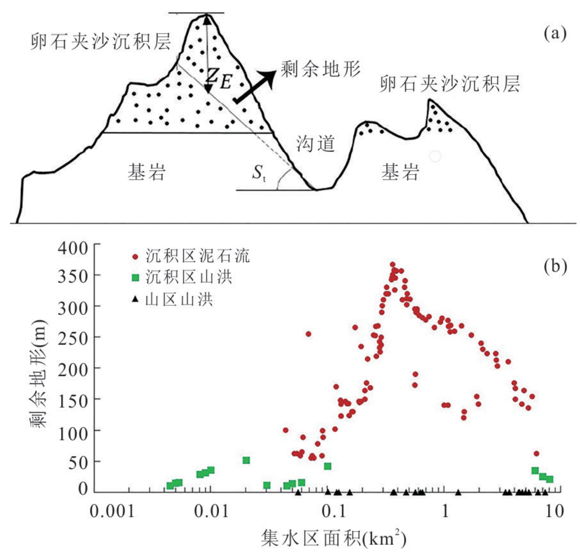

图 14　大河坝河泥石流剩余地形高度

Fig.14　Excess topography vs. gully drainage area for debris-flow and flood gullies

件下,泥石流龙头泥沙主要来自沟岸侧蚀,流量越小,侧蚀所起的作用越大,小流量条件下,流速不足以起动沟底的泥沙颗粒形成泥石流,需要靠沟岸重力侵蚀提供泥石流克服阻力耗能所需的能量.

4　讨论

4.1　大河坝河溯源下切对泥石流发育的影响

标准化的河流坡降指数 SL/K($H=c-k\times\lg(L)$;$SL=(\Delta H/\Delta L)\times L$)是反映河流下切阶段的参数,$H$ 为河流各段的高程,L 为河段沿着河道至源头的距离,c 为常数,K 为均衡剖面指数.大河坝河标准化的河流坡降指数 SL/K 从沟口到山体发育区由高变低($k=766$,$c=4\ 700$),表明了河流下切刚刚到达过渡区(图 13).泥石流沟群的线密度沿大河坝河逐渐降低(图 5)的原因有两个:(1)沉积物厚度降低导致崩滑体体积量减少;(2)大河坝河溯源下切刚刚到达过渡区两岸物源能量降低.

卵石夹砂地层岩性力学性质差,根据固结排水三轴剪切试验,内摩擦角在 30°左右,30°斜面以上的卵石夹砂不稳定.Blöthe *et al.*(2015)引入剩余地形高度(Z_E)的概念(图 14a),来评价不稳定岩土体的规模.Z_E 是指单位流域面积上山体表面和临界破坏角度面之间的不稳定岩土体的高度.图 14b 是同德盆地泥石流沟群的剩余地形高度值,这表明汇水面积 0.5~1.0 km^2 内的剩余地形高度大,这与泥石流高频暴发汇水范围高度吻合,山洪沟道的剩余地形高度要低得多,不足以提供物源能量形成泥石流(图 14b).

4.2　泥石流侵蚀和分选加强龙头波状流动的力学机理

试验表明:泥石流运动过程中卵石夹砂颗粒分选明显,卵石往龙头集中,细砂往龙身集中,随着龙头的膨胀,密度越来越大,摩擦系数也越来越大.龙头总应力(σ)波动性的增长表明了龙头的不稳定性.孔隙水压力(P)伴随着总应力的增大而增大,但是孔压的增长速率远没有总应力增长的速率快(图 15),所以龙头的摩擦阻力($\tau=(\sigma-P)\mathrm{tg}\varphi$)不断增大.当龙头阻力达到一定程度,加速度($a=g(\sin\theta+J')-\tau/\rho_m H_m+P/\rho_m V_m$;Lü *et al.*, 2017)越来越小,运动停滞,需要增加附加坡降($J'(x)=-\partial H_m/\partial x\approx H_m(x)/l_m(x)$;Lü *et al.*, 2017)来提供动力(图 16a),这样周期性的动力平衡和再平衡是泥石流波状运动的力学机理.汇水流量

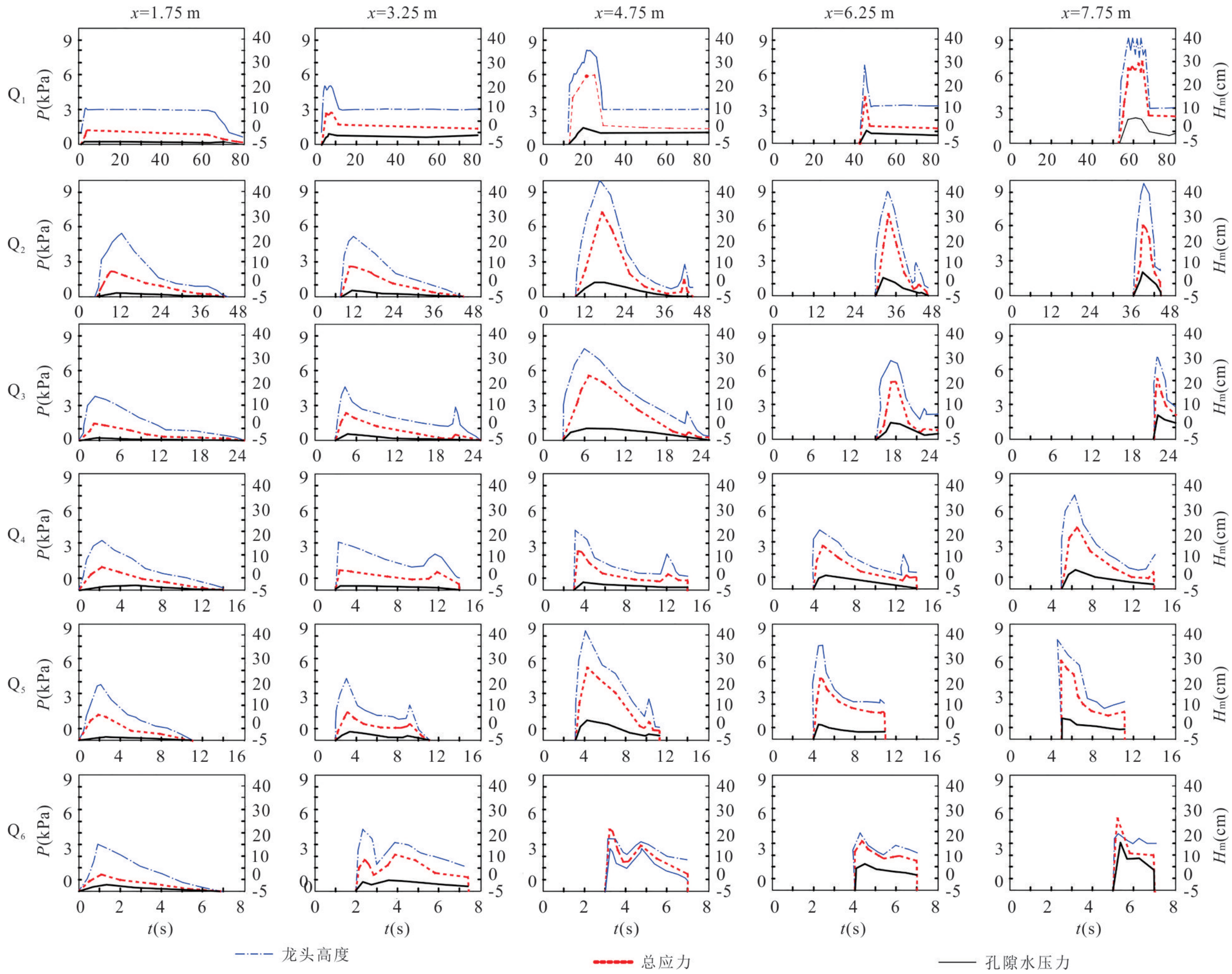

图15　泥石流龙头高度、孔压和正压力

Fig.15　The debris head height, pore pressure and total normal pressure

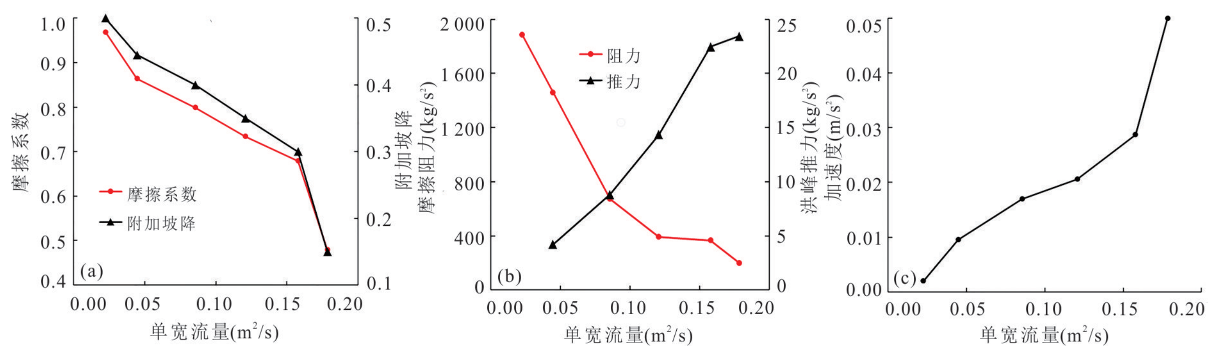

图16　泥石流龙头阻力、洪峰推力和龙头加速度

Fig.16　Head resistance, push press by the body and acceleration of the head

越大，摩擦系数越低（图16a），但是龙身对龙头的推力（$P=\rho_f(u_f-u_m)^2h$；Lü *et al.*, 2017）越大（图16b），所以流量越大泥石流龙头的加速度越大（图16c）．其中，ρ_m是龙头的密度，$\rho_m=c_g\rho_g+c_w\rho_w$；$\theta$是沟道坡降；下标g和w分别代表了颗粒相和水流相．

但是野外监测设备指示：泥石流龙头波动运动过程中，多个洪峰在龙身出现（图8），给龙头提供的推力（$P=n\rho_f(u_f-u_m)^2h$）应该是间断的，导致龙头加速度波动性加强，其中h是洪峰高度，n是洪峰数量．水槽试验中仅仅模拟出一个洪峰，

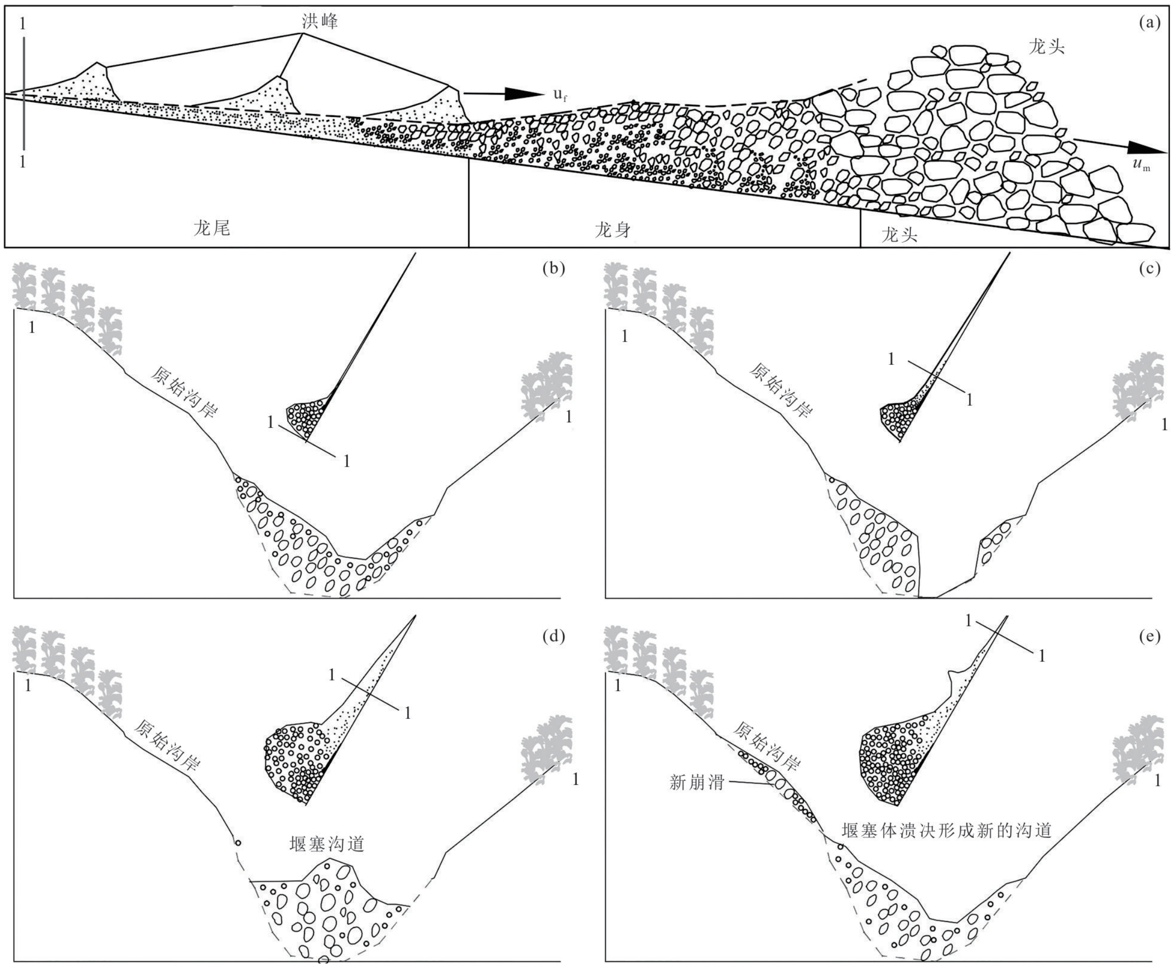

图 17　泥石流侵蚀下切和波状运动耦合示意

Fig.17　Schematic diagram of coupling of debris flow incision and motion

所以龙头的波动性没有野外泥石流龙头波动性强烈．另外野外泥石流在侧蚀过程中，不断有崩滑堵塞现象，导致龙身洪峰对龙头的推力较高，也是野外泥石流波动性强的原因（图 17）．

5　结论

不同于山区泥石流，同德盆地作为古沉积盆地，卵石夹砂磨圆度好，崩滑物源丰富，泥石流暴发频率高．黄河下切带动大河坝河溯源下切，使得同德盆地由沉积区变为侵蚀区，泥石流形成条件由沟道下切深度和卵石夹砂沉积层厚度共同决定．一方面，河流下切巨厚的卵石夹砂沉积层，为泥石流发育提供了物质和能量来源；另一方面，河流切穿盆地边缘到达基岩，抑制物源能量向上游传递．所以大河坝河下游泥石流密度高，中游泥石流密度低，上游泥石流不发育．沟道内卵石夹砂的下切侵蚀、崩滑和堵溃加强了泥石流运动的波动性．野外监测和室内试验表明泥石流在波动过程中，卵石夹砂分选明显，卵石集中在龙头，下切侵蚀和堵溃现象主要发生在龙身，导致龙身多个洪峰出现．龙身洪峰流速大于龙头流速，将泥沙和动力断续的从龙身传递到龙头，使得龙身对龙头的推力和龙头卵石的附加坡降出现间断性的变化，从而导致龙头波状运动．

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