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黄河上游康杨滑坡堆积体特征及形成机理分析

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摘要: 滑坡堆积体特征及其成因机理是进一步研究滑坡防治及开发利用的基础与前提。位于青藏高原东北缘的黄河上游群科—尖扎盆地内的康杨滑坡属于典型的巨型古滑坡, 其堆积体特征及形成机制在该地区具有典型性和代表性, 具有较高的学术研究价值。结合工程地质钻孔资料, 通过详细的野外调查、粒度分析等方法对康杨滑坡形态特征、形成年代、滑坡体粒度特征及其成因机理进行了研究, 主要认识如下: (1) 康杨滑坡为晚更新世晚期发生的泥岩滑坡, 体积约为 $12.59 \times 10^8 \text{ m}^3$, 为一典型巨型古滑坡, 后壁高耸直立; (2) 滑坡前缘曾滑移至黄河北岸, 堆积体可能堵塞黄河, 后被黄河从中部侵蚀切穿, 目前在黄河北岸仍存留有古滑坡堆积体; (3) 高原抬升和黄河下蚀等作用可能是滑坡发生的背景条件, 降水入渗形成软弱滑带和黄河侧蚀作用可能是触发康杨滑坡的主要因素。

关键词: 康杨滑坡; 发育特征; 成因机理; 群科—尖扎盆地; 黄河上游

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Analysis on the accumulation deposits characteristics and formation mechanism of Kangyang landslide in the upper reaches of Yellow River

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Abstract: The development characteristics and formation mechanism of landslides are the basis and premise for further research on landslide prevention and utilization. Therefore, it is necessary to thoroughly study on the development characteristics and formation mechanism of landslides. The Kangyang landslide located at the Qunke-Jianzha Basin in the upper reaches of the Yellow River on the northeastern margin of the Qinghai-Tibet Plateau, it is a typical and super large scale ancient landslide. Its obvious development characteristics and formation mechanism are more representative in the region and has higher academic research value. Combining with the engineering geological drilling data, detailed field investigation and grain size analysis, the author studied the Kangyang landslide morphology characteristics, formation age, grain size of landslide deposit and its

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formation mechanism. The main conclusions are as follows: 1) Kangyang landslide is a mudstone landslide that occurred in the late Late Pleistocene, with a residual volume of $12.59 \times 10^8 \text{ m}^3$, and the back edge wall is high and upright; 2) Paleoclimate changes may be the key factor triggering the Kangyang landslide. The front edge of the landslide slipped to the north bank of the Yellow River, and the accumulation body may block the Yellow River, which was later cut through by the Yellow River erosion from the middle part. At present, there are still ancient landslide accumulations on the north bank of the Yellow River. 3) The uplift of the plateau and the erosion of the Yellow River may be the background conditions for the occurrence of Kangyang landslide, but the weak sliding zone formed heavy rainfall infiltration and the lateral erosion of the Yellow River may be the main factors triggering the Kangyang landslide.

Keywords: Kangyang landslide; developmental characteristics; formation mechanism; Qunke—Jianzha Basin; upper reaches of Yellow River

0 引言

位于黄河上游的群科—尖扎盆地,地处黄土高原与青藏高原的陡变带^[1],由于长期受新构造运动及气候波动引起的河流侵蚀、切割等因素的影响,滑坡十分发育并以规模大、典型性强而著称,形成了滑坡高易发区,具有较大的研究价值。有研究者对群科—尖扎盆地内滑坡灾害进行了系统研究,取得了较好的成果^[2-3]。多数研究者认为群科—尖扎盆地内滑坡多为泥岩滑坡,此类滑坡具有滑动势能高,残留体积大等特点^[4-6],并研究了盆地内寺门村滑坡及锁子滑坡的发育特征及成因,针对滑坡堆积体的开发、利用以及之后形成的堰塞湖效应进行了探讨^[7-8]。分析了盆地内夏藏滩巨型滑坡的发育期次、演化模式及形成机理^[9]。但对盆地内同样为巨型滑坡的康杨滑坡研究较少,仅开展了部分基础性调查工作^[10],更为详细的研究未见报道。另外,多数学者从

工程地质方面着手研究滑坡,取得了丰富的成果^[11-17],但大型的老滑坡及古滑坡的发育多与古气候变化及内动力地质作用有着较为密切的关系^[18-21],前人对于古气候变化及内动力地质作用特别是新构造运动对滑坡的发育及发生所造成的影响研究较少,然而此二者是促使滑坡形成与发展的重要因素^[22]。文章应用 ESR 测年、粒度分析,并结合工程地质钻孔数据及大量的野外调查工作,开展了康杨滑坡堆积体发育特征研究,并对滑坡成因机理进行了探讨分析,以期对群科—尖扎盆地地质灾害多发区防灾减灾提供借鉴与科学依据。

1 康杨滑坡区域位置及概况

康杨滑坡位于青海省黄南藏族自治州北部的群科—尖扎盆地,研究区内地势东西两侧高,中部低,落差大,村庄广布(图 1)。康杨滑坡整体距尖扎县较近,滑坡体中部距县城仅 10.5 km。

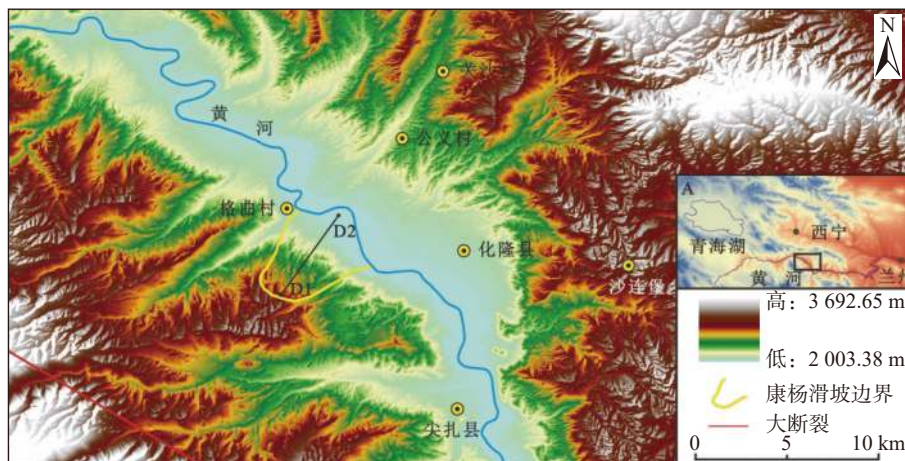


图 1 康杨滑坡所在区域 DEM 高程图 (图 A 为研究区位置图)

Fig. 1 DEM elevation map of Kangyang landslide (Figure A is the regional location map of the study area)

康杨滑坡的滑坡堆积体主要位于黄河南岸,滑坡前缘少部分滑移至黄河北岸,河流相砾石层覆盖其上。现

残存的滑坡堆积体轮廓特征明显,边界整体为圆弧状,西至都藏山及千藏山分水岭处,南部边界则至烂泥滩

河滩沟,前缘坡脚处的格曲村及格曲河滩沟支沟构成康杨滑坡北部边界。尖扎县马克唐镇至康杨镇公路穿越滑坡坡脚,滑坡体后部坐落白日地洲村,现已搬迁见图 2(a),其上可见残存的乡间道路及废弃民居。康杨滑坡为新近系泥岩滑坡,东西横跨约 4.0 km,南北宽约 3.4 km,面积约为 $1.5 \times 10^7 \text{ m}^2$ 。滑坡后壁高耸陡峭,见图 2(b),高近百米,据滑坡后缘 ZK13 工程地质钻孔数据揭示,康杨滑坡后部残留体厚度可达 110 m,中部三个钻孔 ZK3、ZK4、ZK5 揭示残留体厚度约为 80~100 m,位于滑坡前缘的 ZK6 钻孔处残留体厚 52 m,总残留体积约为 $12.59 \times 10^8 \text{ m}^3$ 。



(a) 坐落于滑坡体后部的村庄



(b) 高耸陡峭的滑坡后壁

图 2 康杨滑坡堆积体后部村庄(已搬迁)及滑坡直立后壁
Fig. 2 The village behind the deposits of Kangyang landslide (relocated) and the vertical back wall of the landslide

据前人开展的滑坡 ESR 测年,康杨滑坡形成时间约为 $33.2 \pm 2.5 \text{ ka BP}^{[1]}$ 。由于滑坡形成时间较早,滑体后部及前缘均已被后期改造。

2 康杨滑坡堆积体变形特征

实地野外调查是滑坡研究的关键^[23-26]。调查发现,康杨滑坡边界清晰,滑坡后缘多出现张裂隙,陡坎、冲沟及鼓丘多发育在滑坡体中部及前缘,两侧冲沟规模大,偶见封闭洼地(图 3)。

沿图 1 中 D1—D2 剖面线绘制康杨滑坡横剖面图,滑坡体中部沉积物厚,两测较薄,向上隆起呈拱形(图 4)。滑坡后壁实测坡度 85° ,极为陡峭,风化程度较

高,稳定性较差,发生多处小规模崩塌,致使直立后壁下形成一个坡度较缓的斜面,主要以散落的泥岩、砂岩、黄土等为主。康杨古滑坡的滑坡体由 6 级平台构成,从前缘到后缘依次为 1~6 级,各平台上多见垄岗,以东西向展布居多。滑坡前缘为黄河 II 级阶地,其上可见磨圆度高、分选性好、岩性混杂的砾石。康杨镇坐落在此台面上,台面整体较为平坦,多种植有农作物。在滑坡体前缘第一级平台布设 ZK6 钻孔,由于长期受到冲刷及侵蚀,该平台后端形成一个高 36 m 出露良好的陡坎(图 5),沉积物以砂砾石等为主,黄土层覆盖在其上,由此剖面上沉积物的分布可知滑坡体位于河流相砾石层之上。第二级平台上布设有 ZK4、ZK5 两个钻孔,此平台上宽下窄,ZK4 处宽度为 261 m,至 ZK5 钻孔处缩至 105 m,平台末端宽度仅 78 m,此级平台发育有约深 2 m 的冲沟,冲沟延伸较远,平台上未见明显植被,整体较为松散,上有两处凹陷,一处在 ZK4 钻孔处,另一处在 ZK5 钻孔附近。ZK3 钻孔位于第三级平台之上,平台宽达 322 m,坡度则更缓。第二和第三级两平台间发育有一冲沟,深度较大,可达 30 m 左右,延伸远,附近地表植被较为发育。第四和第五两级平台宽度较第三级平台小,但坡度几乎相同,中间被冲沟分割,冲沟深度不大。第六和第五级两平台有不深的沟壑相隔,第六级平台后部宽度大,曾坐落有白日地州,ZK13 钻孔亦在此处,平台后部向上反翘,上有植被分布,平台前部宽度较后部小,坡度与第五级平台几乎相同。

3 康杨滑坡滑体物质组成及粒度特征

3.1 滑坡体物质组成

该滑坡体岩性组成较复杂,由泥岩、砂岩、砂砾岩、亚砂土及滑坡后壁高台上崩落下的砂砾石、粉砂等物质混杂堆积组成,多呈碎块状。滑坡体后缘至前缘物质组成未见明显规律性,滑坡体上大小块体混杂,整体分选差,小的仅为几厘米,较为完整的大块泥岩长轴可达十余米,块体磨圆度低。

从钻孔揭露的滑体堆积物及冲沟观察来看,后缘一直到前缘呈大多数堆积体杂乱外,仍有部分块体完整性较好,有些泥岩块体达十几米,这些块体在中后部无方向无层次与其它堆积体混杂堆积,层理清楚可辨。整个滑坡体在滑坡体后部呈混杂堆积状态,在滑坡前缘多呈反翘状态(图 5)。

该滑坡滑床后壁较陡,中前部一直很缓,根据野外调查,滑面切穿黄土在滑坡前缘沿基岩顶面剪出,滑体

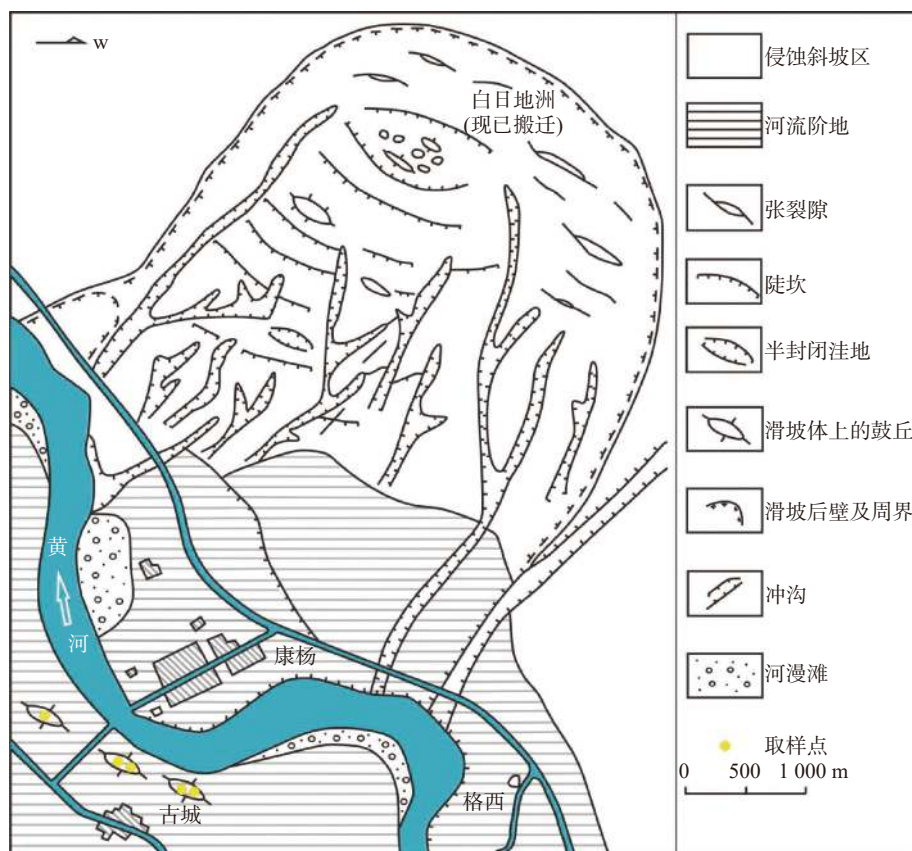


图 3 康杨滑坡平面图

Fig. 3 The plan of Kangyang landslide

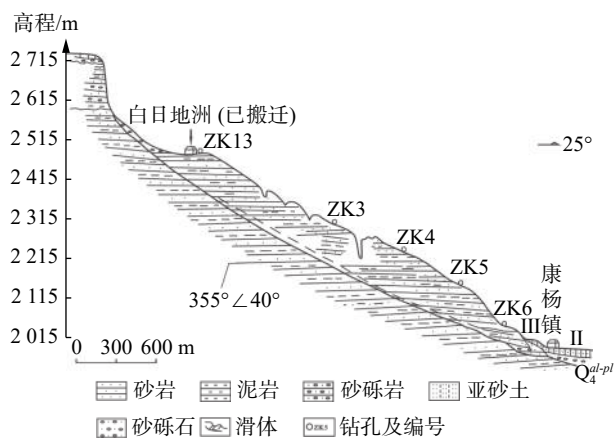


图 4 康杨古滑坡剖面图 (剖面位置见图 1)

Fig. 4 The profile of Kangyang ancient landslide (the location is in Fig.1)

滑床为新近系砂泥岩, 扰动后成碎裂状。灰白色块体状砂岩和紫红色泥岩呈近水平层理, 遇水易泥化, 稳定性较差。

3.2 滑坡体及其上覆黄土粒度特征

粒度测试是对沉积物各组分进行定量研究的重要方法, 可以辅助开展沉积物多组分分布特征的研究, 进而可以对沉积物形成时所蕴藏的动力机制条件的探索

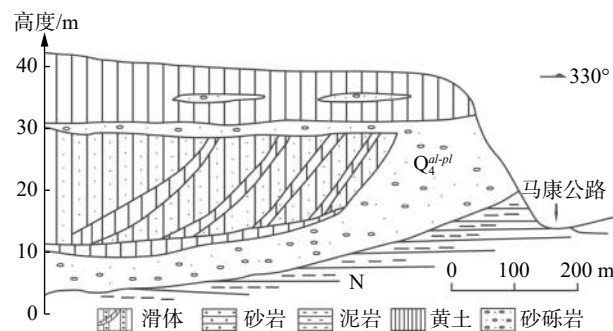


图 5 康杨古滑坡前缘横剖面图

Fig. 5 Cross section of the front edge of Kangyang ancient landslide

提供一定的依据^[27-29]。滑坡堆积体上的物质亦为沉积物, 由多个组分组成, 各组分分布特征明显。5 个粒度样品取自康杨滑坡前缘 (表 1、图 6), 取样过程遵循标准取样流程^[30]。粒度样品在中国科学院新生代地质与环境重点实验室应用 Mastersizer 3 000 激光粒度仪测试完成, 整个过程遵循前人标准试验方法^[31]。

根据样品粒度测试结果并加以计算分析, 绘制粒度频率曲线, 可知黄土与滑坡体二者的频率曲线区别明显 (图 7), 粒度曲线差异明显, 这与人所得结论一致^[27]。进一步研究发现黄土的粒度曲线呈现双峰模式, 优势组

表 1 康杨滑坡粒度样品信息

Table 1 Information of grain size samples of Kangyang landslide

样品编号	海拔/m	样品类型
KY01	2 098	阶地上覆黄土
KY02	2 116	滑坡堆积物
KY03	2 097	滑坡堆积物
KY04	2 098	滑坡堆积物
KY05	2 097	滑坡堆积物

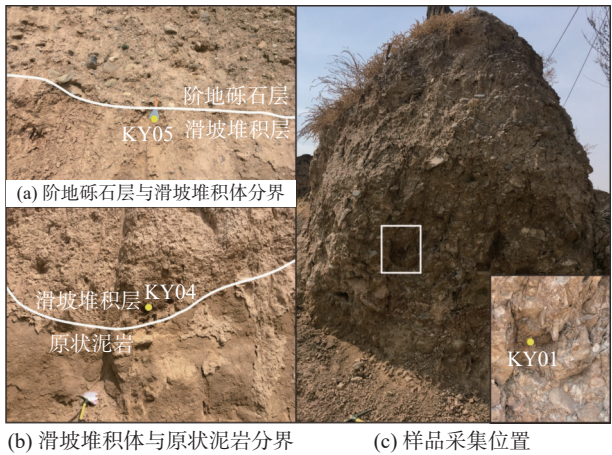


图 6 康杨滑坡前缘粒度样品采集位置图

Fig. 6 Sampling location of grain size at the front edge of Kangyang landslide

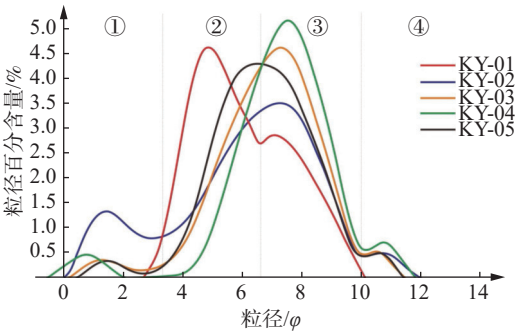


图 7 康杨滑坡粒度样品频率分布曲线图

Fig. 7 Frequency distribution curves of grain size samples of Kangyang landslide

分为 4~8 φ , 滑坡体粒度样品曲线则多表现为 3 峰并存, 优势组分多为 4~10 φ , 这得到了前人在临近区域所做研究的证实^[8]。同时依据前人有关滑坡堆积物粒度组分的分析方法^[27], 发现康杨滑坡 5 个粒度样品均可分为 4 个组分, 即<3.3 φ 为水成悬浮组分, 此组分粒度最大; 3.3~12 φ 为风成悬浮组分, 其中 3.3~6.5 φ 为粗粒组分, 6.5~10 φ 为中粒组分, 10~12 φ 则为细粒组分。

4 康杨滑坡成因机理浅析

导致滑坡发生的因素较为复杂。对青藏高原及黄河上游的研究认为, 临近区域发生的地质灾害会对青藏高原的构造变形产生一定的响应。古气候变化研究认为, 古滑坡发育及形成演化往往与全球性气候变化耦合程度较高^[32]。

4.1 内动力地质作用

地貌可对内动力地质作用产生明显的响应, 而新构造运动是内动力地质作用重要的表现形式^[33-34]。多数学者认为共和运动致使黄河上游河段产生较为强烈的抬升, 随着黄河的持续侵蚀, 在黄河上游地区两岸形成高陡直立边坡。群科—尖扎盆地发育有尖扎北断裂带, 整体距康杨滑坡较近, 且研究区内小规模断裂多, 在青藏高原发生频繁构造活动的情况下, 会使得群科—尖扎盆地内活动断裂发生地貌差异抬升, 为滑坡形成提供了高陡的地形条件, 同时断裂活动可能会引发地震, 形成大量裂隙及表生滑动构造, 进一步促成滑坡的发生。

4.2 外动力地质作用

气候波动对滑坡形成的影响受到诸多学者的关注^[35-39], 在 40~30 ka BP, 青藏高原及邻近区域因岁差周期等因素的影响形成高温大降水事件^[40], 致使温度升高, 冰雪消融, 加之降水增多, 加剧了黄河的切割与侵蚀, 进一步促成了临空面的形成。另外, 降雨量的增加导致入渗水量增多, 滑坡体载荷增大, 加剧滑坡发生的可能性。

4.3 斜坡临空面促滑作用

群科—尖扎盆地多发育高陡直立边坡。黄河不断侵蚀斜坡坡脚, 随着时间的推移, 高陡边坡因自身重力较大而向侵蚀岸倾斜, 并开始产生滑移。前缘在历经长时间的流水侵蚀后, 形成临空面, 同时坡脚应力集中现象开始显现, 汇集的雨水沿节理、裂隙、孔隙等入渗, 致使饱和层形成, 不仅使滑体整体重量陡增, 而且加剧软弱结构面及软弱结构带等的软化程度, 进而使应力集中区发生连通及贯穿, 坡体发生大面积失稳, 在重力作用下发生向下滑动, 滑体滑移至黄河左岸, 使黄河东移, 出现滑坡前缘凹岸、凸岸并存, 但因滑体堵塞黄河时间短, 未因此形成大规模的堰塞湖。

综上, 滑坡发生前, 康杨滑坡所处的斜坡段为黄河侵蚀岸(凹岸), 坡脚在河水不断侵蚀下, 高耸的岩质斜坡在重力作用下向河谷方向变形, 产生位移, 前缘局部地段冲刷、侵蚀强烈, 形成较大滑坡临空面; 坡脚应力集中急剧增加; 加之, 降水在地表汇集, 沿垂直节理面、

风化裂隙面入渗,不仅增大了坡体重力,而且在基础结构面上形成饱和层,不断软化形成坡体内部的软弱带,并与坡体应力集中区贯通,坡体整体失稳。在重力作用下沿其滑动,并在坡脚处形成滑坡。因此,笔者认为断裂活动等内动力地质作用对于黄河上游地貌格局演化具有明显控制作用,但气候变化中的降水入渗形成软弱滑带和黄河侧蚀作用可能是触发黄河上游群科—尖扎盆地康杨滑坡形成的主要因素。

5 结论

通过详细的野外调查、粒度测试及遥感解译等方法,初步分析了位于黄河上游群科—尖扎盆地内康杨滑坡的发育特征及成因机理,取得如下认识:

(1)康杨滑坡后壁高陡直立,具有滑动距离远、残存体积大等特点,滑坡堆积物粒度样品频率曲线及粒度参数均与黄土特征不同,滑坡体粒度多由 4 个组分组成。

(2)康杨滑坡发生于晚更新世,前缘滑体滑移至黄河北岸,在黄河北岸残留有古滑坡堆积体。

(3)黄河侧蚀作用和降水入渗形成软弱滑动带可能是诱发康杨滑坡发生的主要因素。

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