

玉树地震滑坡体积、重力势能降与造成的区域质心改变定量研究

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摘要 以玉树地震触发滑坡为例, 开展地震滑坡体积、物质重力势能降与造成的地貌改变量的定量研究。研究表明: (1) 玉树地震使 $2.94 \times 10^6 \text{m}^3$ 物质发生滑动, 研究区内平均(剥蚀)厚度为 2mm。(2) 滑坡物质约从 4140.681~4147.539m 的位置滑向了 4106.394~4113.251m 的位置, 平均垂直下降的高度为 27.430~41.145m。(3) 滑坡造成的物质重力势能降是 $(2\sim 3) \times 10^{12} \text{J}$ 。(4) 假设滑坡堆积物质后来在外力作用下, 全部消亡或被带出了研究区, 则整个区域内的平均高程由 4427.160m 变成了 4427.158m; 若滑坡物质没有被带出研究区, 则研究区内的平均高程不发生任何变化, 与震前的一致。(5) 假设滑坡堆积体后来全部被外力带出研究区, 则整个研究区的质心从 2222.45967m 的位置下降到 2222.45867m 的位置, 质心下降了 1mm; 假设滑坡堆积体保持了滑动后的状态, 则整个区域的质心下降了 0.0066~0.0099mm。

关键词 玉树地震滑坡; 滑坡体积; 重力势能降; 地貌改变量; 区域质心

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Quantitative Study on Landslide Volume, Gravitational Potential Energy Reduction, and Resulting in Regional Centroid Change Triggered by 2010 Yushu Earthquake

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Abstract As the main form of seismic ground response, landslides triggered by earthquake have received much attention in recent years. However, the researches on landslides volume, gravitational potential energy reduction triggered by earthquake and resulting in regional centroid change are almost absent. The aim of the study is to carry out quantitative study on landslide volume, gravitational potential energy reduction, and resulting in regional centroid change triggered by 2010 Yushu earthquake. The results show that (1) the total volume of the 2036 landslides triggered by the Yushu earthquake is $2.94 \times 10^6 \text{m}^3$ and the landslide erosion thickness throughout the study area is 2mm. (2) The materials of these landslides moved from the elevation of 4140.681m~4147.539m to the elevation of 4106.394~4113.251m, resulting in the average dropped distance of 27.430~41.145m. (3) The gravitational potential energy reduction related to the landslides is $(2\sim 3) \times 10^{12} \text{J}$. (4) The average regional elevation of the study area is 4427.160m. The value is constant with the assumption that the accumulation materials retain in situ. Whereas it changes from 4427.160m to 4427.158m under the situation of all landslide materials moved out of the study area. (5) Based on the assumption that all landslide materials moved out of the study area, the elevations of the crust centroid for the study area changes from 2222.45967m to 2222.45867m, that means, due to the landslides the dropping value of crust centroid for the study area is 1mm. Whereas the value is 0.0066~0.0099mm, assuming that the materials retain in situ.

Keywords landslide triggered by Yushu earthquake; landslide volume; gravitational potential energy reduction; landscape change; regional centroid position

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0 引言

作为地震地表响应的主要形式,地震滑坡往往造成大量的人员伤亡与财产损失。近年来,关于地震滑坡的研究,尤其是关于汶川地震滑坡的研究颇受关注^[1]。当前的地震滑坡研究可分为单体地震滑坡研究与区域地震滑坡研究两个方面,单体地震滑坡研究主要包括典型地震滑坡的野外调查^[2-11]、机制分析^[12-24]与数值模拟^[25-41]等方面;区域地震滑坡研究包括建立滑坡空间分布数据库^[42-64]、滑坡空间分布规律研究^[65-83]、危险性评价研究^[84-109]等方面。但是除了一些零星的关于区域性单次地震滑坡体积的研究^[110-115]外,关于滑坡物质重力势能降、造成的地貌改变量与区域质心高程改变的定量研究却几乎是缺失的。因此,本研究具有明确的创新性,研究方法可为同类研究提供参考。

本文以 2010 年玉树地震触发滑坡为实例,基于实地调查,结合高分辨率遥感数据解译和地理信息系统(GIS)技术,开展玉树地震滑坡体积、重力势能降、造成的地貌改变量与区域质心高程改变的定量研究,解决以下 5 个问题:(1) 玉树地震滑坡的总体积,其平均厚度;(2) 滑坡物质滑落的起止位置;(3) 滑坡造成的物质势能降;(4) 滑坡造成的地形地貌改变量;(5) 滑坡造成区域质心位置的高程改变。

1 玉树地震和触发滑坡

2010 年 4 月 14 日 07:49(北京时间),青海省玉树县发生了 M_w 6.9 级大地震,震中位置为 33.224°N、96.666°E,震源深度为 17km^[16]。据青海省抗震救灾指挥部通报,截至 4 月 25 日 17:00,青海玉树 M_s 7.1 级地震已造成 2220 人死亡,70 人失踪,12135 人受伤,其中重伤 1434 人,约 1.5 万户民房倒塌。2010 年 4 月 14 日的玉树地震触发的地质灾害直接造成 8 人死亡,14 人受伤,直接经济损失约 60 万元^[17-120]。玉树地震发生在青藏高原中部,由于印度板块向青藏高原的推挤作用,导致青藏高原缩短,同时内部的块体沿一些重要的块体边界断裂带发生侧向滑移,造成青藏高原主体向东移动,并在青藏高原内部和块体边界形成不同规模的走滑断裂系与挤出块体。玉树地震就是在这种地质背景下发生的,地震发震断裂为鲜水河断裂带西段的甘孜—玉树断裂带。玉树地震产生了走向约 300°、65km 长的地表破裂带,左旋走滑性质,地表破裂带由一系列挤压鼓包与张裂缝相间排列或雁列式裂缝组成,实测最大水平位错约 1.8m^[121-129]。截至 2010 年 4 月 25 日 15:00,共记录到玉树 M_w 6.9 级地震余震总数为 1467 次,其中 3.0 级以上余震 13 个,包括 6.0~6.9 级地震 1 个,5.0~5.9 级地震 0 个,4.0~4.9 级地震 3 个,3.0~3.9 级地震 9 个。

本文以灾后航空相片与高分辨率遥感影像目视解译为主,辅以野外调查的方法,建立了玉树地震滑坡数据库。玉树地震触发了 2036 处滑坡^[10,11],这些滑坡主要分布在一个以地表断裂带为对称轴、面积为 1455.3km²的矩形区域内(图 1),本文就以这个矩形区域作为研究区。

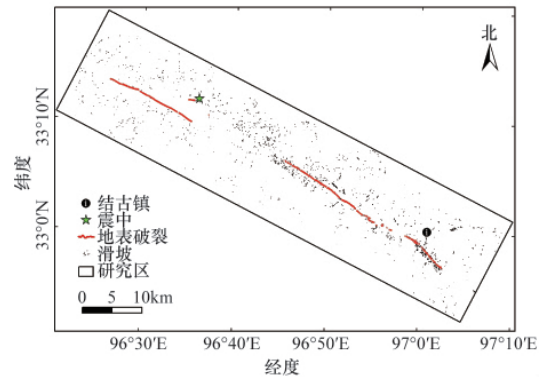


图 1 玉树地震滑坡与同震地表破裂空间分布
Fig. 1 Spatial distribution of landslides triggered by Yushu earthquake triggered landslides and co-seismic surface fault-ruptures

2 玉树地震滑坡的一些属性

开展本文的研究仅标定出单体滑坡的边界远远不够,还需要知道每个滑坡的面积、高、滑坡体滑动前后的质心位置等信息。在标定出滑坡边界的基础上,基于 GIS 技术可以得到每个滑坡体的面积。一般情况下,1:50000 地形图上的等高线与高程点数据对应 20m×20m 分辨率的 DEM 数据,但是玉树地震滑坡中,1320 处滑坡的面积小于 400m²,若是用 20m×20m 的基础栅格数据去统计,连一个栅格的面积都达不到,结果势必会有很大的误差,所以,本文根据 1:50000 的地形图数据插值得到的 5m×5m 分辨率的 DEM 数据,以进行滑坡的属性赋值与空间分布统计。给每个滑坡体赋予最高点高程与最低点高程,作为滑坡体的后壁的高程值与堆积区最低的高程值,这样得到了研究所需的每个滑坡的基本属性值。玉树地震触发的这 2036 个滑坡的总面积为 1.194km²,单体滑坡平均面积为 586.4m²。研究区内滑坡面积百分比 (Landslide Area Percentage, LAP) 为 1.194km²/1455.3km²=0.082%;滑坡点密度 (Landslide Number Density, LND) 为 2036/1455.3km²=1.4/km²。

3 玉树地震滑坡体积

前人多用构建滑坡体积与面积的回归关系式去求取区域滑坡的体积,这些关系式均是体积与面积的幂律关系式。本文从文献^[111,130-147]中找到了 20 个区域滑坡体积与面积的关系式,其形式均可表示为

$$V_{is} = \sum_{i=1}^n \alpha A_i^\gamma \quad (1)$$

式中, V_{is} 为滑坡总体积; n 为滑坡总数量; i 为滑坡序号; α 与 γ 为系数,不同文献中的取值不同。根据不同文献中的公式计算的体积相差颇大,最大值达 4.74×10⁷m³,最小值仅 7.47×10⁶m³,但是多数结果集中在 (1~5)×10⁶m³ 之间,且在中值 3×10⁶m³ 附近。所以,本文选择最接近这一范围的中值,基于 Larsen 等^[136]的方法, α 取值 0.186, γ 取值 1.35,最后得到滑坡

总方量 $V_k=2.94 \times 10^6 \text{m}^3$, 以下的研究均是基于这一体积结果进行的。滑坡总面积为 1.194km^2 , 那么这些滑坡体的平均厚度约为 $2.94 \times 10^6 \text{m}^3 / 1.194 \text{km}^2 = 2.46 \text{m}$; 而研究区的总面积为 1455.3km^2 , 那么研究区内平均地震滑坡剥蚀厚度约为 $2.94 \times 10^6 \text{m}^3 / 1455.3 \text{km}^2 = 2 \times 10^{-3} \text{m}$, 即因玉树地震滑坡直接造成的平均剥蚀量为 2mm 。

4 玉树地震滑坡造成物质势能降

4.1 滑坡质心的两种假设

研究滑坡造成的物质势能降, 必须知道每一个滑坡体的滑前质心位置与滑后质心位置, 精确地完成这一工作显然是不现实的。但是可以知道每个滑坡体区域内的最大高程值与最小高程值。为此, 首先用 H 代表滑坡堆积物最低的高程值, h 代表滑坡体的高度, 也就是整个滑坡体从滑坡后壁最高处(山峰)到最低处的高差。既然无法获得每个滑坡体滑动前后质心的精确位置, 那么进行如下假设: (1) 滑坡质心下降最小值的假设。假设滑坡的滑源区高度为 $h/2$, 滑前质心的高程位于滑源区中间位置, 那么滑前的质心高程为 $H+(3h/4)$; 假设堆积物的高度也是 $h/2$, 质心的高程位于堆积物高程的中间位置, 则滑后的质心为 $H+(h/4)$, 那么该滑坡的物质就从 $H+(3h/4)$ 滑到 $H+(h/4)$ 位置, 下降了 $h/2$ 的滑坡高度; (2) 滑坡质心下降最大值的假设。假设滑坡的滑源区高度为 $h/4$, 滑前的质心的高程位于滑源区中间的位置, 那么滑前的质心高程为 $H+(7h/8)$; 假设堆积物的高度也是 $h/4$, 质心的高程位于堆积物高程的中间位置, 那么滑后的质心为 $H+(h/8)$, 该滑坡的物质就从 $H+(7h/8)$ 位置滑到了 $H+(h/8)$ 位置, 下降了 $3h/4$ 的滑坡高度。之所以做这样的假设, 是因为根据经验估计、现场考察与影像判断, 几乎所有滑坡体滑前与滑后的质心大概位置均在上述范围内。

这样, 结合玉树地震滑坡数据库中每个滑坡体的高程最大值和最小值, 即可求出每个滑坡体质心位置的垂直降低量, 进而进行玉树地震触发所有滑坡物质势能降研究。

4.2 势能降

依据滑坡质心位置的两个假设进行玉树地震滑坡势能降最大值与最小值的计算。计算公式为

$$Ep_k = \sum_{i=1}^n m_i g h'_i \quad (2)$$

式中, Ep_k 为玉树地震滑坡总势能降, m_i 为第 i 个滑坡质量, g 为重力加速度, h'_i 为第 i 个滑坡滑前质心到滑后质心的垂直距离。

取滑坡物质密度 $\rho=2500 \text{kg/m}^3, g=9.8 \text{m/s}^2$ 。

第一种情况(势能降最小值):

$$h'_i = [H_i + (3h_i/4)] - [H_i + (h_i/4)] = h_i/2$$

第二种情况(势能降最大值):

$$h'_i = [H_i + (7h_i/8)] - [H_i + (h_i/8)] = 3h_i/4$$

因此, 势能降最小值为

$$Ep_{k\text{min}} = \sum_{i=1}^{2036} m_i g h'_{i\text{min}} = \sum_{i=1}^{2036} m_i g h_i / 2 = 1.976 \times 10^{12} \text{J}$$

势能降最大值为

$$Ep_{k\text{max}} = \sum_{i=1}^{2036} m_i g h'_{i\text{max}} = \sum_{i=1}^{2036} m_i g 3h_i / 4 = 2.964 \times 10^{12} \text{J}$$

最终得到玉树地震滑坡的势能降为 $(2\sim 3) \times 10^{12} \text{J}$ 。

5 玉树地震滑坡前后滑坡物质绝对高程

滑坡滑动前后的物质绝对高程计算公式为

$$H_k = \left(\sum_{i=1}^n V_i E_i \right) / V_k \quad (3)$$

式中, H_k 为所有滑坡体的平均高程, V_i 为第 i 个滑坡的体积, E_i 为第 i 个滑坡质心高程。

同样, 按照假设的两种滑坡滑动前后的质心位置分别计算。当滑坡体滑动前后的质心位置分别在 $3h/4$ 与 $h/4$ 时, 滑前平均高程为

$$H_1 = \left(\sum_{i=1}^{2036} V_i (H_i + 3h_i/4) \right) / V_k = 4140.681 \text{m}$$

滑后平均高程为

$$H_2 = \left(\sum_{i=1}^{2036} V_i (H_i + h_i/4) \right) / V_k = 4113.251 \text{m}$$

计算结果表明, 滑坡物质从 4140.681m 的位置滑到了 4113.251m , 落差为 27.430m 。

当滑坡前后的质心取 $h/8$ 与 $7h/8$ 时, 滑前平均高程为

$$H_1 = \sum_{i=1}^{2036} V_i (H_i + 7h_i/8) / V_k = 4147.539 \text{m}$$

滑后平均高程为

$$H_2 = \sum_{i=1}^{2036} V_i (H_i + h_i/8) / V_k = 4106.394 \text{m}$$

表明了滑坡物质从 4147.539m 的位置滑到 4106.394m , 落差为 41.145m 。

可以说, 滑坡物质从 4140.681m 的位置滑向 4113.251m , 或从 4147.539m 的位置滑向 4106.394m , 平均垂直下降高度为 $27.430 \sim 41.145 \text{m}$; 或者也可以这样表述, 这些滑坡体约从 $4140.681 \sim 4147.539 \text{m}$ 的位置滑向 $4106.394 \sim 4113.251 \text{m}$ 的位置, 平均垂直下降高度为 $27.430 \sim 41.145 \text{m}$ 。

6 区域高程与质心改变量

关于区域高程与质心改变量研究分两种情况, 一是假设这些滑坡物质均在震后被外力带到研究区以外, 在研究区内区域高程与质心改变研究中, 假设这些物质消亡了; 另一种是假设这些物质在滑动后均保留在当时的位置上。

6.1 假设堆积体被全部带出研究区

整个研究区面积为 1455.3km^2 , 其高程范围是 $3589.710 \sim 5181.360 \text{m}$ 。平均高程计算公式为

$$E_{\text{aver}} = \sum_{i=1}^a E_i / a \quad (4)$$

式中, E_{aver} 为研究区平均高程, a 为研究区内栅格数量, i 为栅格序号, E_i 为该栅格高程。

研究区平均高程为 4427.160m, 滑坡堆积体的平均厚度为 2mm, 则地震之后的平均高程较震前下降了 2mm, 为 4427.158m。

假设整个研究区的密度是一致的, 以海平面作为参照平面, 则整个研究区质心高程为

$$H_{\text{cen}} = \frac{1}{2} \left(\sum_{i=1}^a E_i^2 / \sum_{i=1}^a E_i \right) \quad (5)$$

式中, H_{cen} 为整个区域质心高程。

震前的质心位置为 $1/2 \times (19678369.100/4427.160) = 2222.45967\text{m}$ 。

震后, 假设滑坡物质全部被带出研究区外, 即这些物质全部消失, 则研究区平均下降 2mm, 质心位置计算公式为

$$H_{\text{cen}} = \frac{1}{2} \left(\sum_{i=1}^a (E_i - 0.002)^2 / \sum_{i=1}^a (E_i - 0.002) \right) \quad (6)$$

震前的质心位置为 $1/2 \times (19678351.39\text{m}^2/4427.158\text{m}) = 2222.45867\text{m}$, 质心下降了约 0.001m, 也就是 1mm。

6.2 假设堆积体保留在原地

在地震后的短时间内, 这些物质只是堆积在坡脚位置, 并未被外力带出研究区。假设堆积体均保持刚滑动后的状态, 高程的变化是多少? 不论多少滑坡发生的滑动, 滑源区的高程降低, 堆积区的高程增加, 研究区的物质总量没有变化, 所以整个研究区的平均高程并没有任何变化。

虽然研究区平均高程没有变化, 但是因为滑坡体的势能降, 整个区域的质心高程还是有所改变的。考虑第一种质心位置, 这些滑坡平均从 4140.681m 的位置堆积到 4113.251m 的位置, 平均下降了 27.430m。如上面假设这些物质全部消亡的计算结果, 即高程从 4140.681m 变为 0m, 整个区域的质心下降了约 1mm。那么这种堆积体保留原地情况下的质心下降值为 $1\text{mm} \times (27.430\text{m}/4140.681\text{m}) = 0.0066\text{mm}$ 。

对于第二种质心位置, 滑坡物质从 4147.539m 的位置滑到 4106.394m, 平均下降了 41.145m。那么质心下降值为 $1\text{mm} \times (41.145\text{m}/4147.539\text{m}) = 0.0099\text{mm}$ 。

整个研究区的质心高程下降值为 0.0066~0.0099mm, 这一值与假设堆积体被外力全部带出研究区相比相当微小, 几乎可以忽略不计。

7 分析与讨论

从滑坡体积与面积的关系式来看, 不同的关系式得到的结果相差颇大。而目前求取区域滑坡体积的方法几乎均是构建滑坡体积与面积的幂律关系式, 这种方法的误差较大, 为了求得更精确的玉树地震滑坡体积(剥蚀量), 后期工作计划实测一些玉树地震滑坡体积, 进而构建滑坡体积与滑坡长、

宽、高、坡度、岩性等的关系式^[48]

$$\ln V_{\text{is}} = \alpha \cdot f_{\text{lithology}} \cdot f_{\text{slope}} \cdot f_{\text{earthquake}} \cdot f_{\text{aspect}} \cdot (\beta \ln L + \gamma \ln W + \delta \ln H) \quad (7)$$

式中, V_{is} 为单体滑坡的体积; $\alpha, \beta, \gamma, \delta$ 为常数; $f_{\text{lithology}}, f_{\text{slope}}, f_{\text{earthquake}}, f_{\text{aspect}}$ 分别为该滑坡对应的岩性、坡度、地震参数、坡向因素; L, W, H 分别代表单体滑坡的长、宽、高。

在进行地震滑坡势能降研究中, 对滑坡体滑动前后质心位置的上限与下限的确定均是基于经验的, 缺乏有说服力的严格的实证, 后期需要加强这方面的研究。在区域质心改变量研究中, 将研究区块体假设为密度一致的连续块体, 这与实际情况也会有一定的差别。但是对于区域性质的地震滑坡研究来说, 本文研究方法与结果的可靠性仍然足以满足需要, 可为其他地震事件触发滑坡研究提供参考。

8 结论

通过实地调查, 结合高分辨率遥感数据解译和地理信息系统(GIS)技术, 对玉树地震触发滑坡的滑坡体积、物质重力势能降与造成的地貌改变量进行定量研究, 得到下列结论。

(1) 玉树地震使 $2.94 \times 10^6 \text{m}^3$ 物质发生滑动, 即玉树地震滑坡体积(剥蚀量)为 $2.94 \times 10^6 \text{m}^3$, 研究区面积为 1455.3km^2 , 平均(剥蚀)厚度约为 $2 \times 10^{-3} \text{m}$, 即 2mm。

(2) 滑坡体从 4140.681~4147.539m 的位置滑向 4106.394~4113.251m 的位置, 平均垂直下降高度为 27.430~41.145m。

(3) 滑坡造成的物质重力势能降是 $(2 \sim 3) \times 10^{12} \text{J}$ 。

(4) 假设滑坡堆积物质后来在外力作用下, 全部消亡或被带出了研究区, 整个区域内的平均高程由 4427.160m 变为 4427.158m; 若滑坡物质没有被带出研究区, 则研究区内的平均高程不发生任何变化, 与震前的一致。

(5) 假设这些物质后来全部被外力带出研究区, 则整个研究区的质心从 2222.45967m 位置下降到 2222.45867m 位置, 质心下降了 0.001m, 即 1mm; 假设滑坡堆积体保持了滑动后的状态, 则整个区域的质心下降了 0.0066~0.0099mm。这一值与假设堆积体被外力全部带出研究区相比相当微小, 几乎可以忽略不计。

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