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土体－大气相互作用下土质边坡稳定性研究

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摘　要： 土体－大气相互作用是指在多种气象要素共同驱动下，地表浅层土体与大气之间进行物质交换与能量传递的复杂过程．受全球气候变化影响，近年来极端气候事件频发．土体的工程性质在日益严峻的气候环境下发生剧烈变化，产生了大量滑坡灾害，给岩土和地质工程领域带来许多新挑战．系统总结了降雨、气温、空气湿度、风以及太阳辐射5个主要气象要素影响边坡稳定性的机制，分析了土体龟裂、地表植被和土体－大气相互作用之间的关联效应．通过介绍各因素在改变边坡稳定性过程中发挥的作用，构建了一个包括气象要素、土体龟裂以及地表植被的土体－大气相互作用分析体系．该体系为今后土体－大气相互作用下土质边坡稳定性研究确定了关键研究问题，所揭示的作用机理可为今后同类研究提供参考．针对该课题的研究现状，笔者提出了今后的研究方向和重点，包括土体－植被－大气相互作用的理论模型、气候作用下冻土坡体失稳机理、极端气候工程地质作用的生态调控措施三个方面．

关键词： 土体－大气相互作用；边坡稳定性；气象要素；土体龟裂；降雨入渗；干湿循环；工程地质．

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Stability of Soil Slope under Soil-Atmosphere Interaction

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Abstract: Soil-atmosphere interaction refers to the complex process of material exchange and energy transfer between the surface shallow of soil and the atmosphere, and this process is driven by a variety of meteorological factors. Due to global climate change, extreme climate events have occurred frequently in recent years. The engineering properties of soil have changed dramatically in the process of increasingly severe climate environment. The change of soil leads to a large number of landslide disasters, which brings many new challenges to the field of geotechnical and geological engineering. In this paper it systematically summarizes the mechanism of rainfall, air temperature, air humidity, wind and solar radiation affecting slope stability, and analyzes the correlation effect among soil cracking, surface vegetation and soil-atmosphere interaction. The mainly conclusions are as follows. (1) There are various ways of slope instability and failure caused by rainfall, including the instability and sliding of slope directly caused by rainfall infiltration, the erosion of rainfall destroys the slope surface, and the swelling and shrinkage failure of expansive soil slope caused by raining and drying cycle. (2) Under the condition of rainfall, the damage degree of soil slope is regulated by both rainfall threshold and soil permeability. (3) The increase of temperature accelerates the process of soil evaporation and shrinkage cracking.

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High temperature environment has an adverse impact on the stability of frozen soil slope. (4) High wind speed, low air humidity and strong solar radiation increase the evaporation rate of soil mass and indirectly enhance the stability of soil slope. (5) The cracks formed by soil cracking become a new channel for water exchange between soil and atmosphere. Cracks increase the evaporation area of soil and increase the evaporation rate of soil. At the same time, cracks provide a priority path for rainfall infiltration, which makes rainfall infiltrates the slope faster and deeper, and destroys the stability of the slope. (6) Through the transpiration of leaves, plants release the water absorbed by roots into the atmosphere and reduce the soil moisture content. Plant roots enhance the water holding capacity of soil and reduce the permeability of soil. At the same time, the root system strengthens the soil in the form of reinforcement, which improves the stability of the slope. In view of the research status of this subject, it puts forward the research direction and focus in the future, including the theoretical model of soil-vegetation-atmosphere interaction, the instability mechanism of frozen soil slope under climate influence, and the ecological regulation measures of extreme climate engineering geology.

Key words: soil-atmosphere interaction; stability of soil slope; meteorological element; soil cracking; rainfall infiltration; wetting-drying cycle; engineering geology.

0 引言

大气中的温室气体含量增加驱动全球气候变化,使得极端天气气候事件出现的频率大大提升(Meehl and Tebaldi, 2004).全球平均表面温度、全球海洋热含量、两极海冰范围3个指标是世界气象组织为评价全球气候状况而制定的基本指标(Trewin *et al.*, 2021),气候基本指标的变化情况反映了全球气候的发展趋势.世界气象组织(World Meteorological Organization, 2021)指出,2011—2020年是有记录以来最热的十年,全球平均表面温度相较于工业化之前的基线值升高了1.2±0.1 ℃;温室气体浓度上升导致地球系统中累积的过剩能量大部分被海洋吸收,增加的能量使海洋升温,海水热膨胀导致海平面上升.由于升温导致的海冰融化更加剧了全球平均海平面的上升.1993年至今,基于测高的全球平均海平面的年上升速率为3.1±0.3 mm,并且上升速率不断增加(Cazenave *et al.*, 2018).根据联合国政府间气候变化专门委员会(IPCC,2018)预测,如果继续以目前的速率升温,全球温升值可能会在2030—2052年达到1.5 ℃;到2100年,全球平均海平面将较1986—2005年均值升高0.26~0.77 m.气候变暖问题是目前全球共同面对的最重要的环境问题之一,也是全球气候正在发生显著变化的佐证.

在全球平均表面温度显著升高、海洋热含量不断提升、海冰融化、两极海冰范围逐渐缩小的气候背景下(Lee *et al.*, 2011; Shepherd *et al.*, 2012; Riser *et al.*, 2016; Chen *et al.*,2020),各种与气候相关的灾害频现.在过去十年里,干旱灾害给欧洲的粮食生产、工业建设、公共卫生等行业带来了巨大的损失(Hemmati *et al.*, 2012; Schewe *et al.*, 2019; Bastos *et al.*, 2020).干旱灾害也是我国面临的主要气象灾害(黄荣辉和周连童,2002).由于干旱导致的土体龟裂会弱化土体的工程性质,更引发一系列工程地质灾害和地质环境问题(唐朝生等,2018;Tang *et al.*, 2021);由于高温热浪和干旱引发的火灾造成了大面积的森林焚毁和基础设施受损(Seidl *et al.*, 2017; Lennon *et al.*, 2017);气候变化导致降雨事件的频率和强度明显提升(Hirabayashi *et al.*, 2013; Fischer and Knutti, 2015; Wood *et al.*, 2016),由强降雨引发的洪水严重威胁人类的生命财产安全(Boulange *et al.*, 2021; Li *et al.*,2021).

频发的极端气候事件也驱动了土体-大气之间愈发强烈相互作用,由此引发了大量的地质灾害,包括滑坡、泥石流、地面沉降等(Hemmati *et al.*, 2012; Sorbino and Nicotera, 2013;Wu *et al.*, 2015; Gariano and Guzzetti, 2016; Rianna *et al.*, 2016;Xu *et al.*,2021b; Tian *et al.*, 2022).众多由于气候变化引起的地质灾害给世界各国的经济带来了重大损失.在各种地质灾害中,滑坡灾害因其分布范围广、发生频次高、造成损失大的特点而受到国内外学者广泛关注(黄润秋,2007).大气对土体的影响主要集中在土体浅部区域(Cui,2022),并且土体-大气相互作用是一个受到包括降雨、气温变化、太阳辐射等多气象要素共同影响的复杂过程(Cui,2021).但目前已有的关于土体-大气相互作用对土质边坡浅表层土体性状影响的研究,大多只关注了单一气象要素,例如Rianna *et al.* (2014)研究了降雨模式在土坡失稳过程中发挥的作用;Liu *et al.* (2019)研

究了大气温度与坡体安全系数的关系.

为了更全面地了解土体－大气相互作用对土质边坡稳定性的影响，以及土坡浅表层土体的工程性质在大气作用下所发生的变化，本文基于大量的文献资料，系统总结了降雨、气温、空气湿度、风以及太阳辐射五个主要气象要素对土质边坡稳定性的影响机制，分析了土体龟裂和地表植被在土体－大气相互作用过程中所发挥的关联效应，提出了今后该课题的研究方向和重点.取得的认识对提升工程地质界应对全球气候变化能力和增强我国滑坡灾害综合防治能力有重要意义.

2　气象要素对土质边坡稳定性的影响

气象要素会对土质边坡稳定性产生影响，是因为在土体表面与地下水位之间存在非饱和带，这部分土体的性质在很大程度上受控于土体与大气之间进行的水分交换与能量传递（Blight, 1997; Alonso *et al.*, 2003）.气候变化正是通过改变地表岩土体的温度场、物质场、结构场，实现对岩土体工程地质特性的影响（唐朝生等，2018）.在各种气象要素作用下，土体表层进行强烈的土体－大气相互作用，包括降雨入渗、水分蒸发、干缩开裂、冻胀融沉等（图 1）（Rahardjo *et al.*, 2010; Ishikawa *et al.*, 2015）.各种相互作用导致土体的含水率、吸力、孔隙比以及强度等关键工程性质参数发生变化，进而影响坡体的稳定性.

气象要素对土质边坡稳定性的影响包括直接影响和间接影响（Sidle and Ochiai, 2006）.以降雨为例，直接影响是指降雨强度的变化会使坡体表层土的力学参数发生相应改变，从而影响坡体稳定性；而间接影响是指由于降雨强度的改变，导致坡体所处的环境条件发生变化，包括土坡上的植被生长情况、径流分布等等.由于间接影响的作用时间较长，影响机理复杂，不可预测性强，因此本文主要分析各气象要素的直接影响导致土坡稳定性所发生的变化.

Gariano and Guzzetti (2016)研究发现，在短时间内边坡浅层土体的性状受降雨强度影响最为显著，而该层土体的性状在较长一段时间内同时受到降雨量、气温、风速等参数的影响.Cui *et al.* (2008, 2013)的研究也表明，需要全面考虑空气温度、空气湿度、降水等气象要素对浅表层土体性质的影响，以达到准确分析土体－大气相互作用过程的目的.为全面了解各气象要素对土坡稳定性的影响情况，使用软件 CiteSpace 对 Web of Science 文献库中

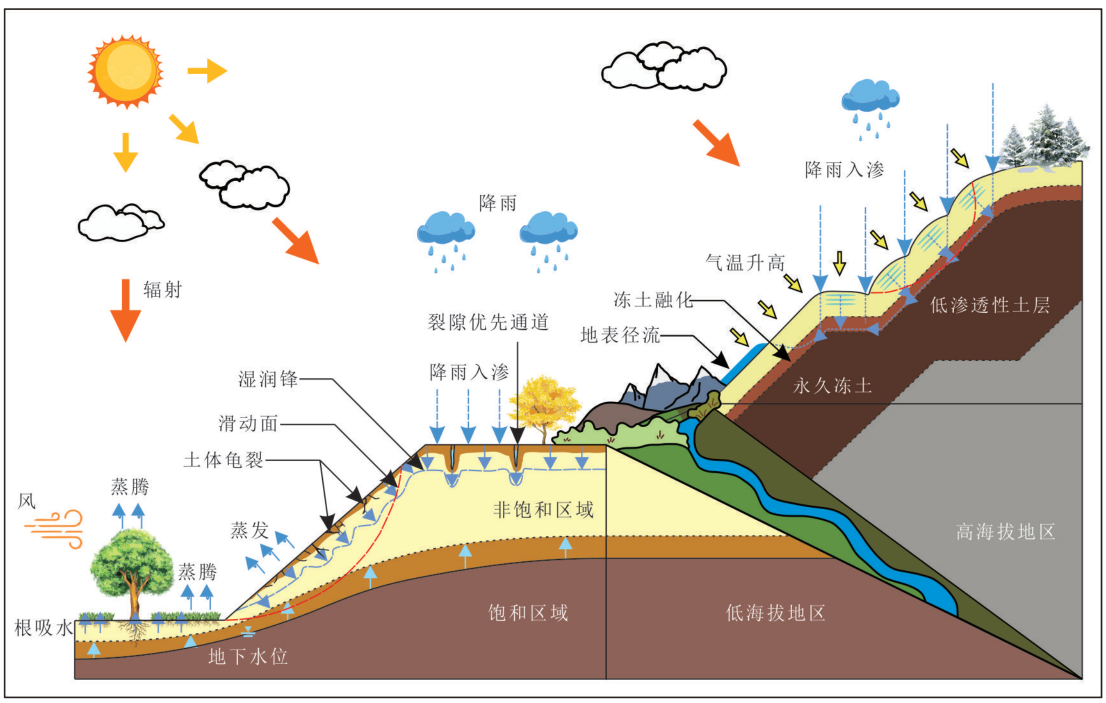

图 1　土体－大气相互作用对土质边坡的影响示意图（改自 Rahardjo *et al.*, 2010; Ishikawa *et al.*, 2015）

Fig.1　Schematic diagram of influence of soil-atmosphere interaction on soil slope (modified from Rahardjo *et al.*, 2010; Ishikawa *et al.*, 2015)

2000年1月至2021年12月间与滑坡有关的英文核心文章进行了统计,图2记录了所有文章中高频出现的关键词,以及各关键词之间的联系.

分析统计结果可以发现,降雨是国内外最常见的诱导滑坡的气象要素,也是国内外学者研究的重点.除了降雨,气温变化、植被等因素也会对土质边坡的稳定性产生影响.下文将着重阐述几个关键气象要素影响土质边坡稳定性及土体工程性质的机理.

2.1　降雨

由降雨导致的土坡浅表层变形破坏主要有3种形式:(1)由水分入渗导致土体抗剪强度降低,坡体失稳滑动;(2)由降雨量季节性变化导致黏土胀缩而引发的变形破坏;(3)由于降雨径流导致的土坡表层侵蚀(Tang *et al.*, 2018a).其中由降雨入渗导致土体抗剪强度降低,坡体直接发生滑动最为常见.

2.1.1　坡体直接失稳滑动　降雨入渗对坡体浅表层稳定性的影响更为显著,降雨易诱发浅层滑坡(殷坤龙, 1987;兰恒星等, 2003).对于该层土体,降雨入渗使得土体含水率升高,孔隙水压力u_w增大,基质吸力(u_a-u_w)降低(黄润秋和戚国庆, 2002; 戚国庆和黄润秋, 2004;Tsai and Wang, 2011).根据Fredlund *et al.* (1978)提出的非饱和土抗剪强度公式(如式(1)),孔隙水压力增大、基质吸力降低将导致土体的抗剪强度随之降低.对于某一特定坡体,存在对应的临界饱和渗透系数和临界降雨条件(Ng and Shi, 1998),当降雨超过某一阈值时,土坡发生滑动的概率激增(Tsai, 2008).

$$\tau_f=c'+(\sigma-u_a)\mathrm{tg}\phi'+(u_a-u_w)\mathrm{tg}\phi^b,\qquad(1)$$

式中:c'为有效粘聚力;σ为法向总应力;u_a为孔隙气压力;u_w为孔隙水压力;ϕ'表示基质吸力(u_a-u_w)不变时,随($\sigma-u_a$)变化而变化的内摩擦角;ϕ^b表示净法向应力($\sigma-u_a$)不变时,随(u_a-u_w)变化而变化的内摩擦角.$\Delta c'=(u_a-u_w)\mathrm{tg}\phi^b$,$\Delta c'$为随($u_a-u_w$)增加的有效粘聚力增量.

基质吸力和孔隙水压力是影响土坡稳定性的重要参数,而土体含水率的变化将直接改变以上两个参数.因此土坡在降雨过程中能否保持稳定,很大程度上取决于坡体的水分入渗量.降雨量和土体入渗性能都会影响降雨过程中的水分入渗量.Green and Ampt (1911)基于水平地表的积水入渗条件提出了Green-Ampt入渗模型,该模型在国内

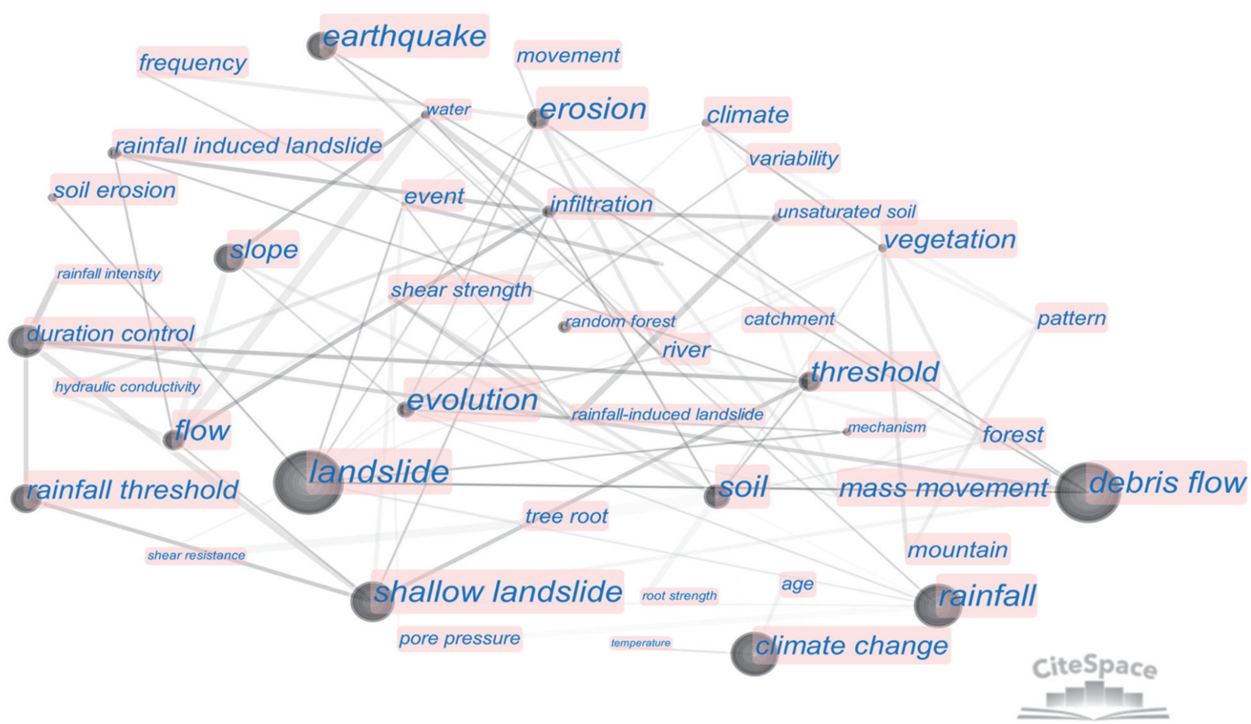

图2　滑坡英文核心文献高频关键词分析

Fig.2　Analysis of high frequency keywords in English core documents of landslide

外的水分入渗研究中得到广泛运用.但该模型假设水分在入渗过程中,土体表面始终被极薄的积水层覆盖,且要求水的入渗率始终等于土体的渗透性能.Mein and Larson (1973)研究了水分入渗土体的几种可能情况,根据降雨强度(I)、土体饱和渗透系数(K_s)、土体允许入渗量(f_p)三个参数对土体的入渗阶段进行了划分,如图3所示.当降雨强度小于饱和渗透系数时($I<K_s$),地表不会出现径流,此时水分的入渗率主要取决于降雨强度,如图3中A线所示;当降雨强度介于饱和渗透系数和土体允许入渗量之间时($K_s<I<f_p$),降雨以较高的入渗率全部渗入土体,此时的入渗率取决于土体的渗透系数,如图3中B段直线所示;当降雨强度超过土体允许入渗量时($f_p<I$),部分降雨无法入渗,在地表形成积水.同时,由于降雨入渗量超过土体允许入渗量,入渗率随之降低,如图3中C段曲线所示.因此Green-Ampt入渗模型不能满足所有状况下的入渗计算,国内外众多学者对该模型进行了改进,Morbidelli *et al*.(2018)对目前提出的各种改进后的入渗模型进行了总结,本文不再赘述.

入渗率即为单位时段渗入坡体内的水量,该物理量反映降雨入渗量的变化(朱伟等,2006).降雨入渗率受坡土体渗透性影响,渗透系数是反映土体渗透性的直接参数,渗透系数对降雨条件下的土坡稳定性影响显著(吴宏伟等,1999).Zhan and Ng (2004)研究发现,渗透系数与基质吸力之间存在很强的相关性.对于可变形的非饱和土,其渗透系数是饱和度、孔隙比等参数的函数(Huang *et al*., 1998).但由于非饱和土的体积变化难以定量衡量,因此国内外没有形成一致结论,确定各因素对可变形非饱和土渗透系数的准确影响.目前大多数研究关注于土体参数对不可压缩的非饱和土渗透系数的影响.因为忽略了土体的体积变化,可以建立渗透系数和体积含水率之间的换算关系.非饱和土的土水特征曲线描述了土体基质吸力和土体体积含水率之间的对应关系,该曲线的形状受到多种因素影响(李志清等,2006),描述该曲线的数学表达式也存在多种形式(Fredlund and Xing, 1994;徐永福和董平, 2002; 包承纲, 2004).由于体积含水率的桥梁作用,非饱和土基质吸力和渗透系数之间的计算也可以通过表达式进行描述,包括线性函数型、幂函数型、指数函数型等(Richards, 1931; Ahuja *et al*., 1980; Philip, 1986).典型的基质吸力与渗透系数对应关系如图4所示(吴宏伟,2017),随着基质吸力逐渐减小,土体渗透系数随之增大.在水分入渗过程中,土体含水率逐渐上升,饱和度提高,基质吸力减弱,渗透系数增加,降雨以更大速率下渗,坡体工程地质特性加速劣化.

在上述水分入渗过程中,除了渗透系数、基质吸力、孔隙水压力等参数的变化会影响坡体稳定性外,气象要素控制的降雨强度、降雨模式、降雨持续时间等降雨条件的变化也会对土坡稳定性产生影响,因为降雨条件决定了降雨入渗过程中的"水量"问题.降雨条件对土坡稳定性的影响也是一个多因素共同作用的复杂过程.降雨强度、降雨持续时间等因素在其中相互协同,共同发挥作用.为了判断降雨诱发滑坡的最低条件,Onodera *et al*. (1974)最早提出滑坡降雨阈值的概念.

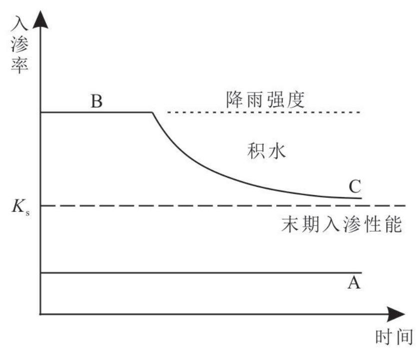

图3　入渗率随时间变化示意图(改自Mein and Larson, 1973)

Fig.3　Schematic diagram of infiltration rate changing with time(modified from Mein and Larson, 1973)

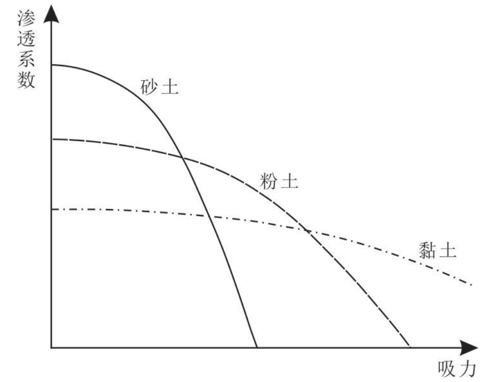

图4　土体渗透系数随吸力变化示意图(据吴宏伟,2017修改)

Fig.4　Schematic diagram of relationship between water permeability and suction(Ng,2017)

当降雨条件达到或超过降雨阈值时，可能触发山体滑坡(Guzzetti *et al.*, 2008).Caine(1980)分析了全球发生的73起降雨诱发滑坡案例，最早提出降雨强度与降雨持续时间的幂函数公式，确定了降雨阈值.降雨阈值对预测降雨型滑坡灾害有指导意义，因此受到国内外学者关注.目前存在两类确定降雨阈值的方法，一类方法是基于区域降雨历史与滑坡数据统计确定区域的经验降雨阈值；另一类是物理基础模型，是以降雨入渗机理为基础，将水文模型运用到边坡稳定性分析中，确定导致边坡失稳的降雨阈值(Wu *et al.*, 2015; 郭子正等，2020).

第一类经验降雨阈值，是将一个大面积区域内诱发滑坡的降雨事件进行汇总，统计降雨的持续时间、降雨强度、累计降雨量、前期降雨量参数，并建立起各参数之间的阈值统计关系.目前应用最广泛的阈值关系为降雨强度－降雨持续时间关系(Caine, 1980; Guzzetti *et al.*, 2007)，该阈值在预测浅层滑坡失稳方面有很好的效果(Segoni *et al.*, 2014).除该阈值关系外还有累积降雨量－降雨持续时间关系、累积降雨量－降雨强度关系(Yang *et al.*, 2020).降雨阈值的物理模型研究开始于20世纪90年代，一些学者在地下水位稳定不变假设下，提出了水利条件引发浅层滑坡的分析模型(Montgomery and Dietrich, 1994; Wu and Sidle, 1995; Borga *et al.*, 1998)，之后国内外学者对相应模型进行了改进修正，针对特定需求，提出了许多更加完善的计算模型.降雨模式会影响水的最大入渗深度与孔隙水压力的变化过程，因此不同降雨模式下的阈值是不同的(Ng *et al.*, 2001).但传统的经验降雨阈值在评价降雨对滑坡的影响时没有考虑降雨模式的作用，因此Tsai采用修正的Iverson模型研究了4种降雨模式对浅层滑坡的影响，得出了不同的降雨阈值(Tsai, 2008; Tsai and Wang, 2011).

虽然确定降雨阈值的目的是评估降雨条件下边坡的稳定性，但经验降雨阈值与降雨阈值物理模型所发挥的作用不尽相同.通过物理模型进行计算，可以准确获得导致某一特定坡体失稳的降雨阈值，以及相应的滑动面等信息(Rossi *et al.*, 2013).但建立物理模型需要详细的岩土参数及水文信息，因此该方法只适用于小范围的降雨阈值确定.基于数据统计的经验降雨阈值不需要获取详细的岩土体信息，便于建立降雨因素与土体滑坡事件之间的对应关系，因此该阈值适用于大面积、区域性的降雨诱发滑坡事件预测.但由于经验降雨阈值数据统计方式的局限性，导致该阈值的精度受到影响.

2.1.2　坡体胀缩变形破坏　在降雨－干旱循环中，坡体表层黏土发生胀缩变形，其特性受到土体矿物组成、微观结构、饱和度变化的影响(Day, 1994; Ferber *et al.*, 2009; Burton *et al.*, 2014).膨胀土富含黏土矿物，是一种高塑性黏土，其对气候变化极其敏感.膨胀土在世界范围内分布广泛，中国也是膨胀土大国(唐朝生等，2018).Shi *et al.*(2002)研究了中国膨胀土的分布特征与各地区膨胀土在组成、性质上的特点.膨胀土具有显著的胀缩性、裂隙性和超固结性(包承纲，2004).土体在吸水后膨胀软化，失水后收缩开裂(郑健龙和张锐，2015)，因为其所含的黏土矿物对水分变化较为敏感，例如蒙脱石、伊利石等都是亲水性黏土矿物，在与水结合后，黏土矿物颗粒表面水膜厚度增加，发生体积膨胀.当土体含水率降低时，土颗粒间基质吸力升高，水化膜变薄，颗粒间距变小，颗粒排列由松散状态变得逐渐密集，颗粒间从“边－面接触”变为“面－面接触”，孔隙比降低，宏观体现为土体收缩(唐朝生和施斌，2011c).根据所含矿物种类及含量、土体结构、压实度等参数的不同，各地区膨胀土的胀缩特性也不完全相同(Shi *et al.*, 2002).

在全球升温，强降雨频发的气候背景下，坡体浅层的膨胀土由于降雨量的季节性变化而经历周期性的干湿循环，不断重复膨胀到收缩开裂的过程.坡表土层原本维持的平衡可能因为某次极端天气气候事件的出现而被打破，发生滑坡灾害.通常情况下，气候作用导致的膨胀土边坡失稳具有浅层性、牵引式、长期性、平缓性和季节性的特点(刘华强和殷宗泽，2010).并且膨胀土坡存在多种破坏机制，较为常见的破坏机制包括：胀缩过程后坡体产生指向坡下的残余变形，随着干湿循环不断累积，在坡肩、坡脚处产生应力集中，最后导致土坡失稳破坏(詹良通，2006)；土体干缩开裂产生的裂隙向下切割坡体表面，深裂隙将土坡划分成不同的强度区域，破坏了坡体结构，使得一定深度内的坡土体由原本的超固结状态变为松散状态.在降雨入渗条件下，裂隙切割形成的坡表土块的抗滑能力不同，坡体发生从局部到整体的变形破坏(刘华强和殷宗泽，2010；Shi *et al.*, 2014)；除降雨引发的膨胀土坡胀缩变形破坏外，季节性冻融使得膨胀土强度降低，膨胀土表面会出现明显的裂隙.膨胀土边坡在

冻融循环后容易发生浅层滑坡(Tang *et al.*, 2018b).因为膨胀土边坡的破坏模式众多,且受到多种因素影响,因此目前针对该类型土坡的稳定性分析以数值模拟为主(Ng *et al.*, 2003; Zhan and Ng, 2004; 陈建斌等,2007).为了提高膨胀土边坡的稳定性,学界也提出了多种治理方案(孔令伟和陈正汉,2012;Abiodun and Nalbantoglu, 2015).

2.1.3　降雨侵蚀坡体　雨滴降落会对坡面产生溅蚀(Smith and Wischmeier, 1962).当降雨强度较大,降雨持续时间较长时,坡体表面出现径流,表面径流导致片蚀的形成(Morin and van Winkel,1996).降雨侵蚀包括3个主要的动力学过程,分别为降雨导致的土颗粒剥蚀过程、坡面径流汇集过程以及表面流输砂过程(付兴涛,2012),其中溅蚀是水侵蚀土体的初始阶段(Fernández-Raga *et al.*, 2017).Kinnell(2005)和Jomaa *et al.*(2012)将"溅蚀"定义为雨滴撞击土颗粒表面,导致部分土颗粒与原有结构分离,在雨滴能量的作用下,分离的土颗粒短距离移动.Fournier(1960)和Descroix *et al.*(2008)将"片蚀"定义为在降雨和地表径流的影响下,坡体表层的细粒土被剥离土体结构.水和固体颗粒的混合物以片状形态流下山坡,坡表土层依次遭到侵蚀.溅蚀和片蚀都是由降雨引起的坡体表面破坏,因此降雨强度、降雨持续时间以及降雨模式等降雨特征是影响两种坡表侵蚀的主要因素(Quansah, 1981).降雨对土坡表层的侵蚀程度同时也受到土层性质影响,特别是土体的渗透性和土颗粒团聚体之间的稳定性(Barthès and Roose,2002).除了降雨特征和土层性质之外,片蚀因为其流动特性而受到地表植被影响较为明显,特别是草对土坡的覆盖作用(Descroix *et al.*, 2008; Bordoloi and Ng, 2020).溅蚀作用导致土体颗粒被抛离原来所在的位置,该作用受到坡度影响较为显著.受到溅蚀作用的土体颗粒可能向各个方向运移,飞向坡下的颗粒数量随着坡度的增大出现先增大后减小的变化过程(Fu *et al.*,2011).

降雨侵蚀使得坡表土层变薄,同时坡体原有的土颗粒团聚体也因为侵蚀作用而发生解体(Chalise *et al.*,2019).降雨侵蚀的主要作用对象为土坡表面的细粒土,因此随着细粒土的逐渐迁移,土坡表层的持水能力会发生变化,土中有机质减少,植被生长条件随之恶化.在土体强度降低、粒度变化以及植被生长受限等多重因素作用下,坡体的稳定性也随之降低.

降雨除了直接导致坡表土层变性、变形直至失稳破坏,还有可能复活休眠的古滑坡.强降雨频发使得河流流量增加,河水位上涨.极端干旱气候下河水位降低.河水位的升降作用使得河流对河岸的侵蚀作用增强,导致河岸失稳坍塌.河岸的失稳趋势传递至坡体,可能激发休眠的古滑坡(李松林等,2020).但这个过程是一个受到自然环境调节的复杂过程,土体－大气相互作用在其中所发挥的作用有待进一步明晰(Gariano and Guzzetti,2016).

2.2　气温

在土体－大气相互作用过程中,气温变化不会对土坡的稳定性直接造成不利影响,但会控制与之相关的过程,例如土体的蒸发速率、土体的收缩开裂过程以及高海拔地区的冻土状态等.

土体的蒸发速率同时受到大气条件与土体特性影响,气温是影响土体蒸发特性的重要环境因素之一(Tang *et al.*, 2011).气温升高会导致坡体表面土体的蒸发速率显著提高.Song *et al.*(2014)通过试验研究发现,土体的蒸发速率受到气温影响,气温越高,土体蒸发越快;同时蒸发过程中土体温度和空气温度有很强的相关性.唐朝生等(2011b)通过试验将初始饱和土体的蒸发过程划分为3个阶段,分别为常速率阶段、降速率阶段以及残余阶段,如图5所示.

常速率阶段的蒸发速率随着气温的升高显著提升,并且达到降速率阶段的时间明显缩短.蒸发处于常速率阶段时,土体温度与大气温度处于相对平衡状态.气体与土体之间进行能量交换,当气温

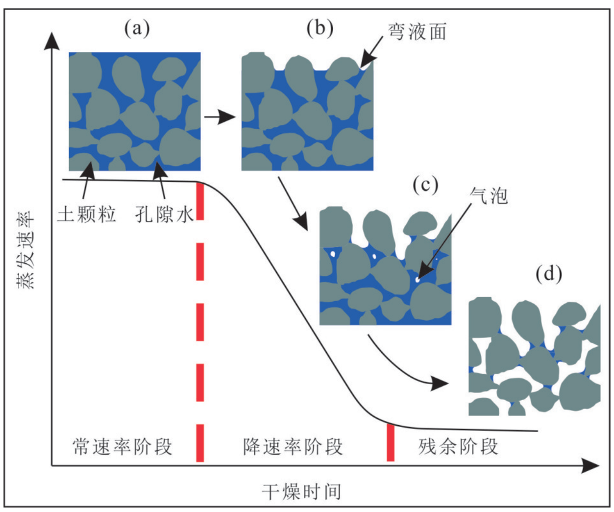

图5　土体蒸发阶段划分(据唐朝生等,2011b修改)

Fig.5　Schematic showing the three stages of evaporation from soil(Tang *et al.*, 2011b)

较高时，土体温度随之升高．温度升高使得土体之中的水分子热运动更加剧烈，更多的水分子获得足够多的能量，以水蒸气的形式释放到空气中，完成蒸发（唐朝生等，2011b）．常速率阶段的蒸发速率主要受大气条件控制，当蒸发进入降速率阶段后，土体的蒸发速率主要受基质吸力等土性因素影响．Tang *et al.*（2021）总结了目前已有的各种水分蒸发模型，其中较为基础、得到广泛运用的模型为Penman模型．

Penman（1948）基于能量平衡的方法，提出了蒸发速率的计算模型，相关原理如公式（2）～（10）所示．该模型考虑了土体表面与空气之间的温度差、蒸汽压梯度，将该模型运用到土体表面的蒸发计算，取得了良好的效果．

Cummings and Richardson（1927）提出地表接收的辐射能（H）主要在蒸发（E）与加热空气（K）过程中耗散，如公式（2）．而蒸汽的运移和空气热涡流扩散的机理相近，蒸发受到蒸汽压梯度（e_s-e_d）控制，热涡流扩散受到温度场（T_s-T_a）控制．因此蒸发速率与加热空气能量之间可以写为比值关系，如公式（3）．

$$H=E+K, \tag{2}$$

$$K/E=\beta=\gamma(T_s-T_a)/(e_s-e_d), \tag{3}$$

式中：H为地表接受的净辐射能，辐射能在蒸发与加热空气过程中耗散；E为蒸发速率，单位为mm/d；β为Bowen比例系数；T_s，T_a分别为某时刻下的表面温度和露点温度，单位为℉；e_s，e_d分别为对应温度下的表面饱和蒸汽压和露点饱和蒸汽压，单位为mm•Hg；γ为干湿表常数．

将公式（2）与公式（3）结合得到土体表面蒸发速率的表达式，如公式（4），此时的蒸发速率是相较于露点蒸汽压而言的．在土体蒸发过程中，蒸发的驱动力为大气与土体之间的蒸汽压梯度，因此需要进一步建立蒸发速率与空气蒸汽压之间的关系．

$$E=\frac{H}{(1+\beta)}=\frac{H}{1+\gamma(T_s-T_a)/(e_s-e_d)}. \tag{4}$$

根据Dalton在18世纪提出的蒸发速率计算经验公式（Brutsaert，1975）（如公式（5），公式（6）），土体表面的蒸发速率E和空气蒸发速率E_a之间存在比值关系（如公式（7））．

$$E=(e_s-e_d)f(u), \tag{5}$$

$$E_a=(e_a-e_d)f(u), \tag{6}$$

$$\frac{E_a}{E}=1-\frac{(e_s-e_a)}{(e_s-e_d)}=1-\phi, \tag{7}$$

式中：e_a为气温下的饱和蒸汽压，单位为mm•Hg；$f(u)$为水平风速的函数；E_a为当表面饱和蒸汽压等于空气饱和蒸汽压（$e_s=e_a$）时的空气蒸发速率，单位为mm•Hg；$\phi=(e_s-e_a)/(e_s-e_d)$．

将$T=T_a$时的蒸汽压梯度－温度梯度曲线斜率定为Δ，如式（8）．则根据公式（4）、公式（7）对公式（8）进行整理，得到相对于空气蒸汽压的土体表面蒸发速率计算公式（9），进一步整理得公式（10）．

$$T_s-T_a=(e_s-e_d)/\Delta, \tag{8}$$

$$\frac{H}{E}=1+\frac{\gamma(e_s-e_a)}{\Delta(e_s-e_d)}=1+\frac{\gamma\phi}{\Delta}, \tag{9}$$

$$E=(H\Delta+E_a\gamma)/(\Delta+\gamma). \tag{10}$$

通过公式（8）和公式（9）可知，土体表面温度与空气温度对蒸发速率的影响显著．空气温度越高，即（T_s-T_a）越小，蒸汽压梯度－温度梯度曲线的斜率Δ越大，H/E的比值越接近1，蒸发所消耗的能量占辐射能比例越大，蒸发速率越快．除温度与蒸汽压差外，其他因素也会影响土体蒸发．Lee and Pielke（1992）研究发现，土体表面的相对湿度对土体的蒸发效果影响显著．Wilson *et al.*（1994）基于Penman提出的蒸发公式，完善了土体－大气相互作过程中蒸发通量的计算公式，进一步考虑了土体表面相对湿度对水分蒸发的影响．

黏土的干缩开裂过程也受到气温影响．Tang *et al.*（2010）研究发现，土体产生裂隙时的临界含水率w_{lc}随着气温的升高而逐渐提升．蒸发过程中，土体含水率降低，吸力增加，并在表面产生张拉应力场，当张拉应力超过土体抗拉强度时，土体产生裂隙（唐朝生等，2012）．可以预见，当黏土从较高含水率开始蒸发时，高气温环境中的土体开裂比低气温环境中的开裂更迅速，开裂时的土体含水率更高．根据前文的介绍，土体开裂对于坡体的稳定性是不利的．因此从土体收缩开裂角度分析，气温升高导致土体收缩开裂进程加快，对于坡体稳定性产生了负面影响．除此之外，温度升高会降低土体的基质吸力和持水能力（Tang and Cui，2005；Cheng *et al.*，2020；Cui，2022），提高土体的渗透性，从而使降雨更多、更快、更深地入渗到坡体内部．气温升高导致坡体表面的温度场发生变化，使得坡体内部水分发生重分布，对土坡的稳定性产生影响．同时温度变化会导致土体内水分的粘滞系数等微观参

数发生变化,也会影响土坡的稳定性(Cheng and Tang, 2021).

大气温度升高会对高海拔地区的冻土状况以及积雪融化过程产生影响.在积雪地区,升高的平均气温使得土坡表层的积雪更快融化,并以融水的形式入渗土体,增大了土体的孔隙水压力,降低了土体的抗剪强度(Huggel *et al.*, 2010; Daanen *et al.*, 2012; Subramanian *et al.*, 2017).对于季节性冻融的坡体,冬季降温导致土体冻胀,土层向上隆起;夏季升温,冻土表层融化,坡体表面发生垂直沉降,出现典型的"冻胀融沉"现象(Ishikawa *et al.*, 2015).坡体浅表层的冰透镜体在气温升高后逐渐融化,融化后的坡表水分向坡体内部渗透.处于高海拔寒区的土坡,其内部一定深度处的冻层受气温变化影响较小,处于永久冻结状态.水分无法透过永久冻层继续向坡内传递,在永久冻层表面水分逐渐积累(Koch *et al.*, 2013; Bring *et al.*, 2016).因此永久冻层表面形成了高饱和度、低摩擦阻力和低抗剪强度的滑动面(Zimmermann and Haeberli, 1992),使得坡体易在该面发生失稳滑动,如图1和图6所示.气温升高,深层永久冻土的融化扩大了上部季节性活动层的厚度,为土中水的运移提供了更多的路径,增强了各个地下水层之间的联系,促进了各层之间的物质、能量交换(Walvoord and Kurylyk, 2016; Gariano and Guzzetti, 2016; Patton *et al.*, 2019).我国青藏高原常见的热融滑塌型斜坡失稳就是由于气温升高导致冻土融化造成的(牛富俊等, 2004).

基于以上分析,对于土质边坡而言,气温升高导致蒸发速率增加,使得坡体表面的平均含水率降低,相应基质吸力升高.需要更大的降雨强度以及更长的降雨持续时间才会使土坡失稳破坏,即降雨阈值提升.单纯从加速土体蒸发、降低土体含水率角度分析,气温升高对提高土坡稳定性而言起到了积极作用.但由于气温升高使得土体收缩、开裂的速率明显提升,土体会在更高的含水率下开裂.土体开裂破坏了坡体的完整性,为土－气之间的水分交换提供了新路径,对于坡体稳定性而言又十分不利.特别是对高海拔寒区而言,气温升高导致积雪、冻土融化,融水、降雨向坡体内部渗透过程中无法穿透低渗性冻层,冻层表面易发生滑坡.

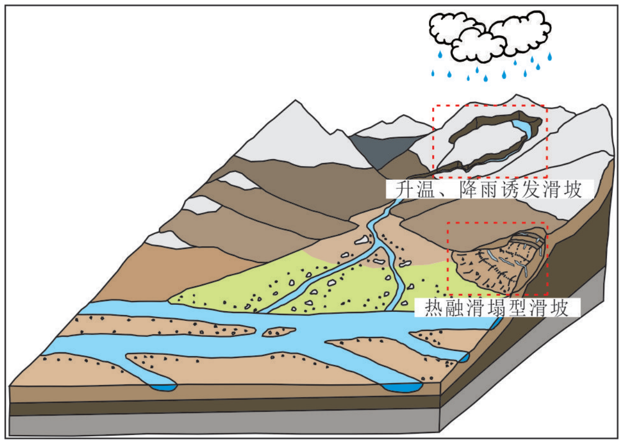

图6　土体－大气相互作用下的冻土地区滑坡示意图(据 Patton *et al.*, 2019 修改)

Fig. 6　Schematic diagram of landslide in permafrost area under soil-atmosphere interaction (modified from Patton *et al.*, 2019)

2.3　空气湿度、风、太阳辐射

空气湿度、风、太阳辐射3个气象要素在土体－大气相互作用过程中所发挥的最直接作用就是改变土体的蒸发条件(Pan and Mahrt, 1987),影响土体与大气之间的物质、能量交换过程,进而影响坡体表层土的性质.土体与大气之间的相对湿度差值决定了土体中的水分子是否能够逃逸出土体表面,进入大气(唐朝生等,2011a).Song *et al.*(2016)通过环境箱监测了风速、气温、空气相对湿度对土体蒸发过程的影响.研究发现,土体蒸发过程和空气相对湿度变化过程有相同的三阶段性,变化规律大致相似,证明空气相对湿度是影响土体蒸发速率的因素之一.唐朝生等(2011b)通过试验验证,土体的蒸发速率取决于土体表面与大气之间的蒸汽压梯度,即相对湿度差值.蒸汽压梯度越大,蒸发速率越快.同时空气湿度会影响土体裂隙的发育情况,Zeng *et al.* (2022)研究表明,空气湿度提高,裂隙会在更高的含水率下发育,即 w_{tc} 提升;降低空气湿度,使得土－气界面的湿度梯度增大,会促进裂隙的发育.

水分从土中逸出后,进入空气中的自由流动区,该区域即土－气界面的扩散边界层.增加风速会使得该区域内的对流强度增加,热量和质量传递更为频繁(Davarzani *et al.*, 2014).Crozier (2010)研究发现风速的提高会增强土体的蒸发,从而影响土体含水率,对边坡稳定性产生影响.Davarzani *et al.* (2014)研究了风温、风中的水汽浓度对土体蒸发量的影响,发现吹过土体表面的风越干燥,水汽浓度含量越低,土体蒸发速率越快.风的作用还会对积雪的融化速度产生影响(Crozier, 2010),根据前文

的介绍,积雪融化也会对土坡稳定性产生不利影响.太阳辐射为土体的蒸发过程提供了能量驱动,更强的太阳辐射会增强蒸发速率(Guthrie *et al.*, 2010).Blight(2009)建立了太阳辐射能量和蒸发量之间的对应关系,用以评估辐射量对于裸土蒸发的影响.Teuling *et al.*(2009)对全球接受的太阳辐射量和地表蒸散量进行统计分析,发现二者之间具有很好的同步关系,即太阳辐射强度波动会影响地表的蒸散作用.Selim and Kirkham (1970)比较了风与辐射对于蒸发速率的影响,发现在同等蒸发能量下,风的作用对于蒸发的影响要强于辐射的作用.

3　土体龟裂发挥的作用

土体干缩开裂(龟裂)是土体－大气相互作用的结果.同时土体龟裂形成的裂隙参与到土体－大气相互作用的各个过程之中,协同改变土体性质,影响土质边坡稳定性.

唐朝生带领团队就土体的干缩开裂问题进行了大量研究,通过室内试验、原位监测、数字图像处理、数值模拟等一系列手段,探究了土体在干燥过程中收缩开裂的机理,分析了影响土体干缩开裂的因素,提出了预测土体龟裂的力学模型,研发出了一套可以处理龟裂图像、自动获取裂隙参数的软件系统CIAS.除此之外还将激光扫描、高密度电阻率成像(ERT)、热红外成像、CT、光纤监测、人工智能、数值图像相关(DIC)、粒子图像测速(PIV)等多种先进技术运用到土体裂隙观测分析中,建立了一整套土体龟裂研究方法体系(Tang *et al.*, 2010, 2012, 2019, 2020;唐朝生等,2012;冷挺等,2016;曾浩等,2019; Cheng *et al.*, 2020; Xu *et al.*, 2021a; Lin *et al.*, 2022; Tian *et al.*, 2022; Zeng *et al.*, 2022).通常情况下,土体的抗剪强度、粘聚力等力学参数在土体干缩开裂过程中会受到显著影响,同时裂隙的形成破坏了土体的完整性,为水分迁移提供了优先路径.

裂隙在土－气水分交换过程中发挥了通道作用.降雨入渗以及土水蒸发对土体－大气相互作用而言至关重要,这两个作用过程伴随着诸多的土体条件、气象参数变化,涉及土体－大气之间的物质交换与能量传递.土中形成的裂隙提供了更大的蒸发面积(Adams and Hanks, 1964),同时裂隙的产生影响了土中水分的分布,裂隙周围土体含水率较高,与空气之间的蒸汽压梯度更大,蒸发速率更快(Ritchie and Adams, 1974; Cui, 2022).Adams and Hanks(1964)和Hatano *et al.* (1988)研究表明,裂隙处的蒸发量在土体总蒸发量中所占比例很大,特殊情况下甚至可以达到50%左右.因此土体裂隙对于蒸发过程的影响是不可忽视的.Tang *et al.*(2011)将表面裂隙率(R_{SC})这个指标应用于土体开裂监测,来量化土体表面的裂隙发育程度.表面裂隙率(R_{SC})是指在不同含水率下,土体表面裂隙面积与试样总表面积的比值.Poulsen *et al.*(2020)通过试验研究发现,除了风速提升会显著增加蒸发速率外,裂隙宽度、裂隙间距、裂隙深度以及裂隙发育方向4个因素都会对土体的蒸发速率产生影响,但影响强度依次减弱.Selim and Kirkham(1970)通过试验研究发现裂隙宽度会对土体的蒸发速率产生影响.Poulsen(2022)研究发现在恒定风速、恒定裂隙间距条件下,裂隙宽度对于蒸发速率的影响不是线性增强的关系,蒸发速率随着裂隙宽度的增加出现一个先增大再减小的变化过程.因为裂隙宽度是裂隙特征中对蒸发影响最为强烈的因素,因此目前大多研究只关注了裂隙宽度,而裂隙间距、裂隙深度以及裂隙发育方向影响蒸发方面的研究较少.Song *et al.*(2016)和Cui(2022)通过环境箱、现场试验等手段,监测并分析了黏土体在土体－大气相互作用过程中所发生的变化.其中土体蒸发过程中产生的裂隙增加了蒸发面,增强了空气条件对土体的影响.Song and Cui(2020)提出了一个含裂隙黏土蒸发情况的计算模型.

裂隙的存在会影响土体的储水能力,并加速降雨的入渗过程,因为裂隙为水的入渗提供了优先路径.不同的裂隙宽度、深度、空间分布和连通性会对降雨入渗的效果产生影响(Krzeminska *et al.*, 2012).袁俊平和殷宗泽(2004)研究了水在裂隙中运移对非饱和膨胀土坡的影响.通过研究发现,裂隙深度是影响水入渗速率的最主要因素,裂隙的存在对膨胀土边坡的稳定性构成了威胁.Louati *et al.*(2021)研究了干湿循环过程中,土体裂隙开合对渗透系数的影响.提出一种分形模型来预估土体在干湿循环不同阶段的渗透系数.Zhang *et al.*(2021)研究了降雨入渗过程中的土体裂隙优先流对边坡稳定性的影响.使用全尺寸试验模型还原了现场发生失稳的黏土边坡.通过数字图像处理技术和水文传感仪器监测了坡体在降雨－蒸发循环中裂隙的发育过程和坡体的参数变化.揭示了裂隙优先流造成

土坡破坏的机理:降雨可以通过裂隙快速进入坡体,但裂隙尖端深层土的渗透系数较小,因此在裂隙尖端附近形成局部滞水区.导致裂隙附近深层土的含水率迅速升高,孔隙水压力增大,抗剪强度降低,滞水区附近的低渗土层成为坡体强度的薄弱部分,滑坡失稳易在该区域发生,该过程如图7所示.染料示踪剂常被用来监测土体裂隙中的优先流运移,Zhang *et al.*(2014)基于该方法研究发现裂隙可以使水入渗到更深的地层,因此优先流可能会导致深层滑坡的发生.Pei *et al.*(2020)和 Khan *et al.*(2017)通过有限元的方式研究裂隙中的优先流对膨胀土边坡稳定性的影响,在研究中发现由于土体渗透性的变化,确实会在某些裂隙尖端出现滞水区,降雨通过裂隙入渗对土坡稳定性产生负面影响.

4　植被发挥的作用

植被是土体－大气相互作用过程中的中间介质,是影响土体性质的关键因素,在改变坡体稳定性方面发挥了重要作用.比如,植物根系会从周围土体吸收水分,降低土体含水率,并以加筋的形式对周围土体进行加固.此外,植物根系还会改变土体的渗透性、持水性.叶片会增加蒸腾面积,为土－气之间的水分交换提供通道.

Philip(1966)提出了土体－植被－大气连续体(SPAC)概念,将土体得失水过程融入植被－大气的水循环中,形成了完整的水分运移系统,并提出用水势的概念来量化各系统中水的运移情况.土体向大气输送水分的方式包括两种,分别为蒸发和蒸腾.蒸发是水从土体表面逸出后,以水蒸气的形式进入土－气之间的扩散层边界.蒸腾作用是根系从土中吸水后,通过植物叶片的气孔将水释放到大气中(Bordoloi and Ng, 2020).土体的蒸发量与植被的蒸腾量之和称为蒸散量(Gardner, 1960).Schlesinger and Jasechko(2014)统计表明,植被蒸腾在全球水循环中发挥了重要作用,每年的植被蒸腾量约占全球蒸散量的60%～80%,植被蒸腾对于降低坡体含水率而言至关重要.坡体表面,土体－植被－大气相互作用中的水循环过程如图8所示.吴宏伟(2017)提出将植物特征参数化,用以定量评价植物在土体－大气相互作用过程中所发挥的作用,定义了叶片面积指数(LAI)、根表面积指数(RAI)等参数.叶片面积指数(LAI)是指单位土地面积下叶片的总单面投影面积;根表面积指数(RAI)是指在特定深度纵向截面上根系表面积与水平方向上根伸展区域面积的比值.

蒸腾作用是植物在土体－大气相互作用过程中发挥的重要作用.水分被植物根系吸收后,会经由植物的内部结构运送到叶片,满足植物叶片在蒸腾作用中对水的需求,避免叶片脱水(McElrone *et al.*, 2013).植物的蒸腾作用是由浓度梯度和气流驱动的水汽输送,受到包括大气温度、空气湿度、太阳辐射以及空气流等气象要素影响(Zhu *et al.*, 2022).对于某些植物而言,根系所吸收的水分超过90% 会从叶逸出(Hopkins and Hüner, 2009).Garg *et al.*(2015)对比了植物蒸腾与土体蒸发对土体基

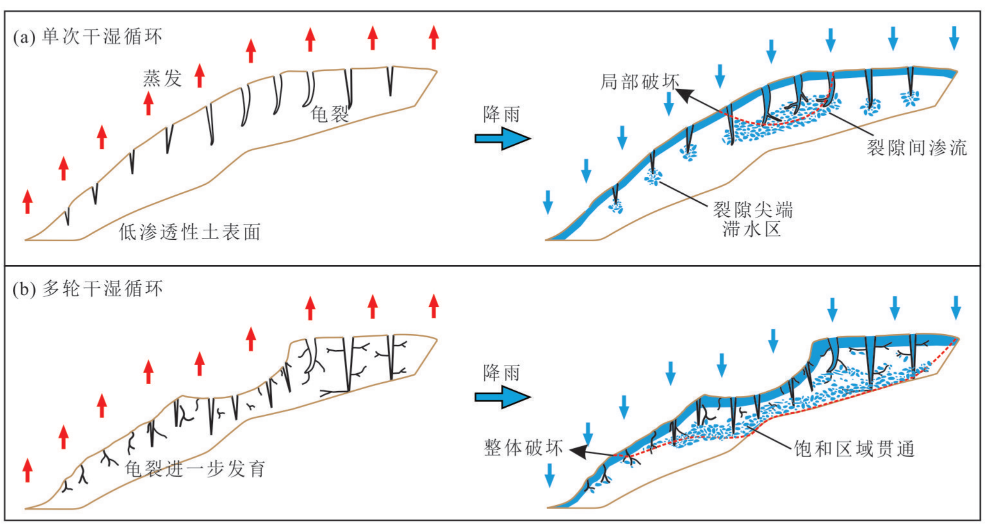

图7　裂隙优先流诱发土质边坡破坏示意图(据 Zhang *et al.*,2021修改)

Fig.7　Schematic diagrams of soil slope failure induced by crack dominant flow(modified from Zhang *et al.*,2021)

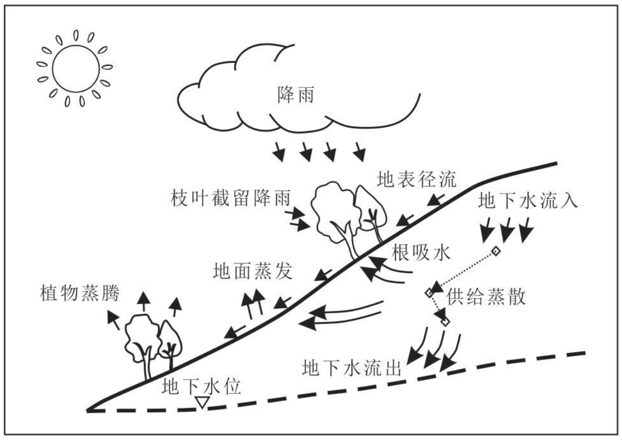

图8 土体-植被-大气相互作用中水循环示意图(据吴宏伟,2017修改)

Fig.8 Schematic diagram of water circulation in soil-vegetation-atmosphere interaction (modified from Ng,2017)

质吸力的影响,研究结果表明对于七叶石斛这种特定植物而言,由蒸腾作用引起的土体吸力变化比裸土蒸发有明显提升,特别是当叶片面积指数更大时,蒸腾作用对吸力的影响更为显著.植物的蒸腾作用效果受到众多因素调节.植物的叶片面积指数、植株种植间距、植物的根表面积指数,乃至土体的压实度都会对植物的蒸腾作用效果产生影响(吴宏伟,2017).Ni *et al.*(2016)研究了树木与草混合种植进行蒸腾作用时,树木间距对两种植物生长情况的影响.发现当树木的种植间距过小,会使得树间草的生长受到抑制,树木的叶片面积指数也会因此受限.植物的根表面积指数会影响植物的吸水效果,进而影响根系向叶片供水,影响植物的蒸腾作用(吴宏伟,2017).根系的形态及埋深都会改变其影响蒸腾作用的效果(Zhu *et al.*, 2018).蒸散作用导致的土体基质吸力增加和植物根表面积指数线性相关,树木种植间距过小对植物的根系生长不利,因此植物蒸腾作用与土体基值吸力增加也受到限制(Ni *et al.*, 2016).Ng *et al.* (2021)研究了植物形态对根系吸水能力的影响,对比了同一树种在5种不同植株高度条件下吸水能力的区别,研究发现,在相同的生长环境下,根区大小在垂直和水平方向上均与植株高度呈正相关,单位根长的吸水能力与叶片面积指数和根表面积指数之间的比值有关,比值越大,单位根长的吸水能力越强;植物根系的吸水能力越强,对于植物蒸腾越有利.

除了蒸腾作用,土体中的植物根系会改变土体性质,同时植物根系还在土中起到了加筋作用,增强了土体的力学强度.Leung *et al.*(2015)比较了百慕大草和鸭脚木对土体入渗率和渗透系数的影响.研究发现植物根系会降低水分入渗土体和在土中运移的能力,对于维持土体基质吸力有利.植物根系对土体的加筋作用是通过增加根系与土体之间的摩擦力,提高土体的抗拉强度与抗剪强度.吴宏伟等人在此基础上,进一步研究了与植物根系共生的真菌对抗拉强度提升的贡献.试验发现,由于真菌与植被之间的互利共生关系,可以明显提升根系的发育量,更多的根系发育在土体中,对于提高土体抗拉强度是有益的(吴宏伟,2017).

由于坡体表面植被的存在,使得浅层土的水分依靠蒸腾通道迅速散失,实现降低土体孔隙水压力,提高土体基质吸力的目的,增强了坡体的稳定性.更大的叶片面积指数,更适宜的草、树种植间距以及更大的根表面积指数都能够达到增强蒸腾作用的效果,从而更好地维持坡体稳定.此外,由于植物根系降低了土体的渗透性,使得水分更难渗进坡体,提高了表层土的抗渗能力;植物根系的加筋作用,以及根系和微生物之间的互利共生关系,使得土体抗拉强度、抗剪强度明显提升,对于提升土坡稳定性而言发挥了积极作用.

5 总结与展望

5.1 总结

本文从土体-大气相互作用角度出发,基于大量文献资料,系统总结了降雨、气温、空气湿度、风、太阳辐射5个主要气象要素以及土体龟裂、植被特征影响边坡稳定性的机制,得到的主要认识如下:

(1)降雨是导致土质边坡滑动、破坏的最主要因素.降雨入渗导致坡体浅表层土的含水率升高,孔隙水压力增大,基质吸力降低,土体的抗剪强度随之降低,坡体易发生失稳滑动.降雨-干旱循环导致土体产生胀缩变形,在多轮干湿循环后,土质边坡可能因为残余变形累积量过大而失稳滑动,也可能因为胀缩循环后坡表产生大量的深裂隙,破坏了坡体的完整性,降低了坡体的强度.降雨侵蚀坡体表面,通过点蚀和片蚀作用将坡体表层的细粒土冲刷带走,降低了土体的持水性、抗渗性,改变了植被的生长环境,破坏了原有的团聚体结构,进而降低了坡体的稳定性.

(2)降雨诱发滑坡受到土体渗透性以及降雨阈

值调控.降雨强度与土体饱和渗透系数的相对大小决定了降雨能否迅速渗进土体.只有当降雨强度小于土体饱和渗透系数时,雨水才能全部渗进土体,否则将在坡表形成径流.随着雨水不断入渗,土体的基质吸力降低,渗透系数有增大的趋势,更加快了水的入渗过程.降雨阈值可以用来评估当前的降雨条件是否会威胁坡体的稳定性.存在两种确定降雨阈值的方式,一类是通过数据统计获得经验降雨阈值;另一类是通过物理模型确定降雨阈值.

(3)大气温度升高使得坡体浅表层土的温度随之提升,土中水分子的热运动更加剧烈,更易逃逸出土体表面进入大气.该过程使得土体的蒸发速率加快,蒸发时程明显缩短.气温越高,蒸发过程所占的太阳辐射能量比例越大,蒸发速率越快.气温升高加速了土体的收缩开裂过程,降低了土体的基质吸力与持水能力,影响了坡体表面的水分分布,劣化了坡体的力学性质.同时,气温升高使得高海拔地区的冻土、积雪融化,季节性冻融效果增强,因此诱发了一系列的坡体破坏.

(4)空气湿度、风、太阳辐射3个气象要素都会影响土体的蒸发过程.空气与土体表面的湿度梯度是土体蒸发的驱动力,空气湿度越小、土体表面湿度越大,则蒸发速率越快.同时空气湿度还会影响土体开裂过程.风速越快,风中水汽浓度越低,土体蒸发越快.太阳辐射越强,地表接受的能量越多,土体的蒸发速率越高.单纯从土体蒸发角度考虑,蒸发速率越大,坡体表面的土体含水率越低,基质吸力、抗剪强度越高.因此高风速、低空气湿度以及强太阳辐射3个要素通过加速蒸发增强了土质边坡的稳定性.

(5)土体龟裂是造成坡体失稳破坏的重要因素.龟裂形成的裂隙为土－气之间的水分交换提供了通道,同时裂隙还破坏了坡体的完整性,弱化了坡体的力学性能.土体裂隙增大了蒸发面积,加速了土体的蒸发.裂隙宽度、裂隙深度、裂隙间距等裂隙参数都会影响蒸发效果,其中裂隙宽度是最主要的影响因素.降雨条件下,裂隙成为雨水入渗的优先路径.裂隙的存在使得雨水入渗到更深的土层,并在裂隙尖端形成滞水区,各裂隙尖端的滞水区彼此联通,形成滑动面,导致土坡失稳.

(6)植被在提升坡体稳定性方面发挥了积极作用.植物通过叶片的蒸腾作用将根系吸收的绝大多数水分释放到空气中.根系吸收水分,降低了周围土体的含水率,提高了土体的基质吸力.同时,根系的存在使得土体的渗透性降低,持水能力提升,不利于降雨入渗.植物根系在土中起到了加筋作用,提高了土体的抗拉、抗剪强度,增强了坡体的稳定性.植物的种植间距和种类等因素都会影响叶片、根系的发育.根系的形状、埋深、表面积以及叶片面积指数等因素会影响植物的蒸腾作用.

5.2　展望

系统掌握各气象要素对土质边坡稳定性的影响,对于提升岩土与地质工程行业在极端气候条件下的防灾减灾能力有重要意义.尽管学界围绕土体－大气相互作用影响土质边坡稳定性这一问题已经开展了较多研究,取得了一定的研究成果,但该课题仍存在部分方向需要进一步攻关.笔者认为今后有必要对以下几个方向做重点研究:

(1)土体－植被－大气相互作用理论模型.土体－植被－大气相互作用是一个受气象要素、植被特征以及土体特性等多方面因素共同影响的复杂过程.已有的评估单一气象要素影响土体性质的理论模型无法实现对土体－植被－大气相互作用复杂体系的准确描述,因此需要建立包括土体参数、气象参数以及植被参数的完整评估模型来量化各参数在相互作用过程中的变化.通过模型计算土体参数对极端气候事件的响应,判别土体性质的劣化程度,对于提升灾害预警能力有现实意义.

(2)气候作用下冻土坡体失稳机理.目前国内外有关冻土地区土质边坡滑动机理的研究不够深入,特别是我国关于冻土地区坡体稳定性研究起步较晚.我国的多年冻土面积较大,主要分布在青藏高原、东北、中西部山区等高海拔地区(金会军等,2000).这些高原冻土和高山冻土受全球升温影响,更易发生滑坡等地质灾害.因此对于冻土地区边坡滑动机理的深入研究是十分有必要的.

(3)极端气候工程地质作用的生态调控措施.土体的工程地质特性在极端气候作用下劣化,为保证坡体稳定,传统方式采用锚固、格构、排水沟等土工构筑物对边坡进行改造.虽然实现了护坡的目的,但对生态环境产生了不利影响.在"推进生态文明,建设美丽中国"的时代背景下,更加低碳环保的土体改性技术应当被运用到坡体治理中,包括植被对坡土体的改性及加固,微生物成矿土质改性技术等(Tang *et al*., 2020).植被提升坡体稳定性的功能已经在国内外大量工程案例中得到验证.应用微生

物成矿土质改性技术可以提升土体的抗旱性,抑制降雨侵蚀土体,维持土体在极端气候作用下的稳定(Liu *et al.*, 2021; Cheng *et al.*, 2021).生态调控措施对于提升坡体稳定性有利,但如何定量评价调控效果是今后需要继续探究的方向.

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