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考虑水沙和风沙过程的海滩-沙丘系统耦合演变数学模型研究综述

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摘要:海滩-沙丘系统耦合演变数学模型同时考虑近岸水沙和风沙过程,可以更好地预测砂质海岸在更大空间尺度上的地貌形态演变,为海岸带保护修复和综合管理提供依据。从概念模型、基于水沙过程的海岸地貌演变模型、海岸风沙输移模型、水沙-风沙耦合模型 4 个方面概述了海滩-沙丘系统耦合演变数学模型的研究进展。现有海滩-沙丘系统耦合演变数学模型可以模拟风暴作用下的海滩-沙丘侵蚀和泥沙交换、供应限制条件下的风沙输移和沙丘发育等物理过程,并初步具备多年时间尺度上的模拟能力,但在适用性、准确性和计算效率等方面仍存在不足,提出该类模型关键物理/生物过程的考虑、计算效率的提高、空间维度的拓展和实际应用的检验等今后的发展方向。

关键词:水沙运动;风沙运动;海滩;海岸沙丘;地貌演变;数学模型

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Review of mathematical models for coupled morphological evolution of beach-dune system considering subaqueous and aeolian sediment transport processes

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Abstract: Mathematical models for coupled morphological evolution of beach-dune system considering both the subaqueous and aeolian sediment transport processes can better predict the sandy coastal evolution on a larger spatial scale, providing the basis for coastal protection and the comprehensive management. This paper summarizes the research progress of beach-dune morphological models, including the conceptual models, the nearshore hydrodynamic and sediment transport models, the coastal aeolian sediment transport models, and the coupled subaqueous and aeolian sediment transport models. The state-of-the-art models can address the storm-induced beach-dune erosion and sediment exchange, as well as the supply limited aeolian sediment transport and the dune recovery on the time scale of years. They are still limited in universality, accuracy and computational efficiency. Four aspects of future research are suggested, including the consideration of key process, the improvement of computational efficiency, the expansion of spatial dimension and the test of practical application.

Key words: subaqueous sediment transport; aeolian sediment transport; beach; coastal dune; morphological evolution; mathematical model

海滩和海岸沙丘是砂质海岸的主要地貌单元[1],具有重要的防灾减灾[2-3]、生态服务[4-6]和休闲娱乐[7]等功能。长期以来,海滩和海岸沙丘被视为两个独立的地貌单元分别进行研究。20 世纪 90 年代以来,随着海平面上升和人类活动的影响越发显著,砂质海岸资源在可持续利用、综合防护与生态修复方面受到了越来

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越多的关注。研究发现,以波浪动力为主的海滩和以风动力为主的沙丘之间存在复杂的物质交换和地貌互馈机制,该机制对整个海滩-沙丘系统的耦合演变具有重要影响[8],该研究方向也成为国际上的研究热点之一[9-12]。近年来,由于我国海岸带保护修复工程涉及一些地区的风沙防治、海滩养护、沙丘重建和植被修复,水动力和风动力共同作用下的海滩-沙丘系统耦合演变研究在国内也开始得到关注并具有较好的工程应用前景[13-14]。

水沙运动、风沙运动和植被效应等复杂物理过程对海滩-沙丘系统耦合演变的影响体现在多个不同的时空尺度上。相比于现场观测和物理模型试验,数学模型研究发展较快。一些学者提出了耦合水沙和风沙过程的数学模型[15-19],模拟年时间尺度上的海滩-沙丘系统演变趋势,并初步探讨了该类模型在全球气候变化下海岸带韧性的提升和综合管理中的应用,但其发展仍受限于对关键物理机制的认识不足和高分辨率验证数据的匮乏[20]。本文从概念模型、基于水沙过程的海岸地貌演变模型、海岸风沙输移模型、水沙-风沙耦合模型 4 个方面对海滩-沙丘系统耦合演变数学模型的研究进展进行综述,并在总结现状的基础上展望未来该类模型研究的发展趋势。

1 概 念 模 型

海滩和沙丘两种地貌单元之间的泥沙交换和地貌互馈主要体现在:在风暴大浪和岸滩高水位条件下,沙丘侵蚀的泥沙在海滩上堆积[21-24],潮间带沙坝向岸迁移[25-27],并通过波浪冲流带向海滩和沙丘输送泥沙[28-30];在强风作用下,海滩上一定风区范围内的泥沙被风力搬运到沙丘上,并在沙丘形态和植被等因素影响下发生沉积[31-32]。Psuty[10]较早提出了海滩-沙丘系统相互作用的概念,强调了海岸水动力过程在前缘沙丘演变中所起的作用,包括波浪导致沙丘侵蚀的直接影响和潮汐限制海滩风沙供应的间接影响等。图 1 为海滩-沙丘系统的水沙运动和风沙运动过程示意图。

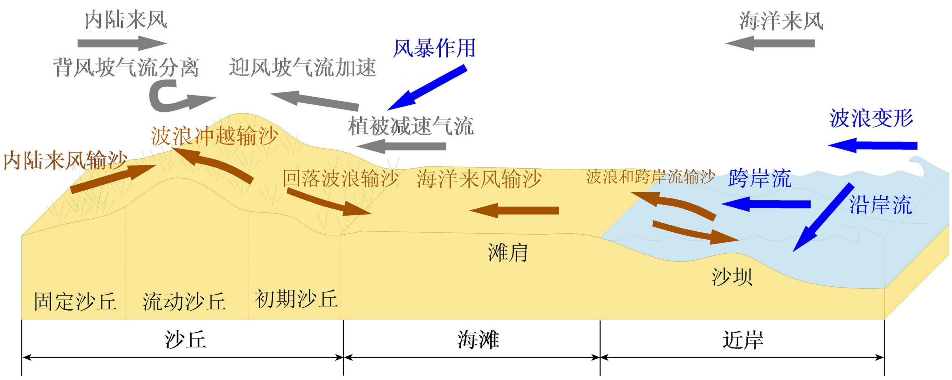

图 1 海滩-沙丘系统水沙运动和风沙运动过程示意图

Fig. 1 Schematic map of subaqueous and aeolian sediment transport processes in a beach-dune system

基于现场调查,一些研究提出了示意性的概念模型[9-10,33-34],尝试在几年到几十年的时间尺度上描述海滩和沙丘的相互作用过程。Short 等[9]认为,沙丘的形成与发展主要取决于海岸动力地貌状态(波浪条件、风力条件、海滩特征、沉积物特性、植被覆盖度等),建立了小尺度(小时至月)的海滩-沙丘相互作用概念模型,并得到 Sherman 等[35]的数值模型验证。Psuty[12]将沙丘形态演变与海滩和沙丘各自的沉积物平衡状态联系起来,建立的中尺度(月至数十年)海滩-沙丘相互作用模型可以预测前缘沙丘的发育。Sherman 等[20]在模型中考虑了稳态泥沙平衡条件,可以解释海平面上升引起的海岸线后退现象及亚临界风速条件。Pye[34]提出的沉积物平衡状态模型还考虑了沿岸泥沙供应率、有效风能以及植被对沙丘形态的影响,并得到 Ruz 等[36]研究结果的支持。董玉祥[37]在总结国外概念模型的基础上,探讨了我国海滩-沙丘系统相互作用研究的发展方向。刘建辉等[13,38-39]分析了福建若干海滩-沙丘系统的沉积物输移特征、地貌变化特征及其动力成因。何岩雨[14]在福建平潭海坛岛强潮海岸调查的基础上,总结了 3 种潮汐-海滩-沙丘系统相互作用模式。

总体来说,这些小尺度和中尺度的概念模型将沙丘的形态演变归因于海滩、近岸状态[9,33]和沉积物平衡状态[12,34]。虽然其中一些模型[9,33]考虑了海滩地貌的动态变化,但此类概念模型难以描述海滩和沙丘耦合演变过程中的复杂动力机制。许多水沙和风沙过程研究[40-42]表明,海滩与沙丘之间的泥沙交换具有显著的

空间变化特征,且在时间上具有间歇性。此外,虽然这些概念模型明确了泥沙输运和交换的各种控制因素,但滩面往往被视为一种静态表面,没有考虑风沙供应能力的变化,限制了模型的预测能力[43]。因此,数学模型的进一步发展需要同时考虑水沙运动和风沙运动过程,模拟泥沙在海滩-沙丘系统中的动态输移。

2　基于水沙过程的海岸地貌演变模型

水沙运动对海滩-沙丘系统耦合演变的影响主要发生在台风和风暴潮等极端事件的高水位条件下。风暴期间的岸滩总水位成分复杂,是天文潮位、风暴增水、波浪增水、短波爬高和次重力波爬高的叠加。当总水位高于沙丘坡脚高程时,波浪在前缘沙丘上的爬高和回落会引起沙丘的快速侵蚀或崩塌[44]。被侵蚀的沙丘泥沙首先输送到海滩上,再被破波带内的底部离岸流输运到外海[45]。与此同时,海滩剖面形态的变化也会影响风暴波能的沿程分配和频谱演化,进而改变沙丘前方的波流输沙特性。

基于水沙过程的海滩-沙丘地貌演变数学模型已有较多研究,这些模型主要侧重于风暴期间的侵蚀过程。为了节省计算时间并满足大范围模拟,大多数模型[46-50]采用相位平均的短波能量或波作用量守恒方程[51-55]来计算波浪参数的沿程变化,它们的计算精度取决于波浪破碎等不同来源能量耗散的描述[56],并使用参数化的方法来考虑波浪非线性对泥沙运动的影响,可以实现小时到年时间尺度上的模拟[57-58]。然而,这些模型无法考虑次重力波的产生、传播、耗散及其在沙丘上的爬高和反射。相位解析的 Boussinesq 模型[59]或非静压模型[60]可以较好地复演短波和次重力波的传播、破碎、爬高及其非线性特征,但在长周期海岸地貌演变的模拟中仍然存在计算耗时过多的缺陷[61]。目前应用较为广泛的 XBeach 模型[50]对短波平均和次重力波解析的控制方程进行求解时,在模拟风暴期间的海滩和沙丘侵蚀方面具有较好的表现[62-66],但对水下沙坝演变的模拟能力相对欠缺。Zheng 等[67]建立了考虑非线性波浪和底部离岸流互制输沙的海滩剖面演变数学模型 CROSPE,成功复演了海岸沙坝的向、离岸迁移过程,被应用于天然沙坝平衡剖面[68]和人工沙坝平衡剖面[69]的模拟。李文善[70]结合平潭龙凤头岸滩修复工程,使用 XBeach 模型模拟了岸滩风暴侵蚀及常浪恢复过程,并分析了风暴作用下的沙丘地貌响应特征。

目前,相位平均的数学模型仍难以准确地描述冲流带过程,即破波带向岸侧边界[57]到波浪上爬最高点[71-72]这一区域内的水沙运动。一种简化方法是采用经验函数插值获得冲流带内的输沙率分布[73],这种方法的优势在于计算简便,然而由于岸边水深很浅,插值得到的输沙率总是以离岸方向为主,在长时间尺度的模拟中会导致海滩或沙丘的过度冲刷。为了弥补这一缺陷,Roelvink 等[74]引入了滩肩平衡坡度的修正方法。

需要指出的是,在潮汐影响显著的海岸,潮间带沙坝在常浪作用下的向岸迁移是海滩淤积的主要机制之一[75],也是沙丘发育的重要泥沙来源之一[42,76]。由于这个过程涉及破波带动力和冲流带动力在一个潮周期内的相互转化,以及波浪非线性和强破碎紊动对泥沙运动的影响,目前的数学模型都难以模拟这一复杂过程。

3　海岸风沙输移模型

风沙输移与海岸沙丘发育密切相关,其输沙率受到风速、海滩宽度、坡度、湿度、泥沙粒径、滩面形态等许多因素的影响,是海滩-沙丘系统耦合演变的重要物理过程。近年来得到发展的海岸风沙输移模型,尝试将微尺度风沙输移过程与中尺度沙丘形态演变联系起来。这些模型利用长期的风速和风向数据求解风场,结合平衡输沙公式,可以计算从海滩到沙丘的泥沙通量。其中,平衡输沙公式主要建立在实验室数据的基础上,虽然可以通过参数的引入来考虑湿度[77-79]、坡度[80-81]、滩面砾石[82-83]、盐结壳、积雪和植被覆盖等风沙供应限制因素对剪切风速、起动阈值和风沙输运强度的影响,但这些公式在实际海岸复杂环境中的计算精度仍然存在较大的不确定性。

海岸风沙输移模型的一大重点是海滩和沙丘上方的风场建立。目前常用的高效风场模型[84]通过线性求解雷诺平均的 Navier-Stokes 方程[85-86]计算海滩和前缘沙丘上的剪切应力分布,可以合理描述地形变化引起的边界层气流扰动。但稳态模式的风场计算方法并不适用于陡坡或地形急剧变化的情况[18],而更精细的计算流体力学方法[87-90]可以提高模型的适用性,但会显著增加计算时间。此外,模型只能考虑风向与岸线相互垂直的情况,斜向风作用下的剪切应力场模拟需要设置与岸线斜交的剖面[90]或采用旋转网格[91]。

除了风速,海岸风沙输移强度也受到风区长度、滩面湿度和滩面形态等因素的控制,这些因素被称为风沙输移的供应限制因素。一些研究者认为风区长度[92]是风沙输移过程的主要供应限制因素,并将可侵蚀滩

面上的输沙率随顺风距离的增加称为风区效应。Bauer 等[92]开发的模型将平衡输沙公式与风区效应结合起来,认为未达到平衡时的输沙率受实际风区长度与临界风区长度比值的控制。Delgado-Fernandez 等[93]建立的模型考虑了滩面湿度对临界风区长度的影响。Hage 等[94]建立的 Aeolus 模型通过地下水模块确定湿度变化,可以较好地复演风沙输移的时间变化规律,但模型预测能力取决于影响临界风区长度的湿度阈值的确定。

另一方面,de Vries 等[95]尝试直接采用泥沙可利用率代替风区长度量化时空变化的风沙供应能力,并结合一维平流方程建立了供应限制条件下的风沙输移模型(图 2)。AEOLIS 模型[96]通过划分网格单元对海床进行离散,并对海滩粗化过程、水动力混合过程、泥沙组分在空气与海床中的相互作用进行建模,计算时空变化的泥沙可利用率。该模型通过解析风沙搬运的多重分形问题来模拟泥沙起动,而不是直接采用参数化的风速阈值,但该模型没有考虑地形对气流的影响。

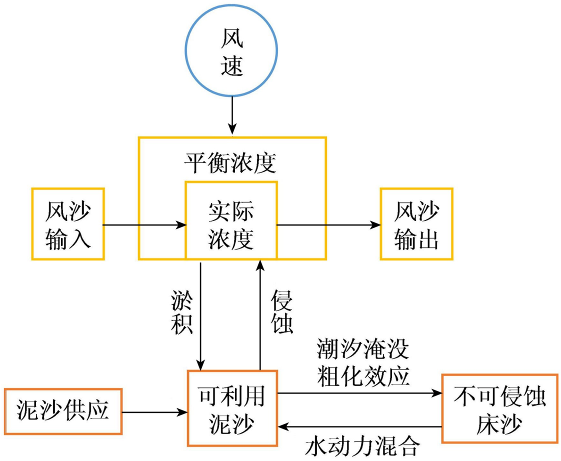

图 2 供应限制条件下的风沙输移模型概念

Fig. 2 Conceptual representation of the supply limited model for aeolian sediment transport

4 水沙–风沙耦合模型

海滩–沙丘系统的地貌形态演变是水沙过程和风沙过程耦合作用的结果。泥沙在水动力作用下输送到海滩,在风动力作用下输送到沙丘,又会在风暴浪侵蚀或离岸风作用下输送回海滩和近岸。近年来,一些学者尝试开发耦合水沙过程和风沙过程的数学模型(表 1),这些模型通常包括水沙运动模块、风沙输移模块和植被模块(图 3)。首先通过水沙运动模块(如 XBeach 模型[50])来模拟波浪、水流及其作用下的泥沙输运过程,然后通过植被模块计算植被参数的动态时空变化,再利用考虑植被效应和供应限制因素的风沙输移模块(如 AEOLIS 模型[96])计算风场动力和风沙输沙率。各个模块在每个时间步中交换动力、地形和植被信息,耦合求解水动力和风动力作用下的海滩–沙丘地貌形态演变。

表 1 水沙–风沙耦合数学模型

Table 1 Numerical models for coupled subaqueous and aeolian sediment transport

数学模型内容		DUBEVEG[15]	XBeach-Duna[17]	Windsurf[18]	CS[97]
地貌演变时空尺度		时间尺度:年至数十年 空间尺度:岸线至前缘沙丘向陆 50 m 范围	时间尺度:年至 10 年 空间尺度:闭合水深至前缘沙丘	时间尺度:年 空间尺度:闭合水深至前缘沙丘	时间尺度:年至百年 空间尺度:闭合水深至前缘沙丘
模型组成		海洋动力过程模块 DECAL 风沙模块[98-99] DECAL 植被模块[98-99]	XBeach 水沙模块[50] Duna 风沙模块[17]	XBeach 水沙模块[50] CDM 陆域形态模块[100] AEOLIS 风沙模块[96]	沙丘侵蚀模块 沙坝–滩肩耦合模块 风沙输移模块
水沙运动	水动力模拟		波作用量守恒方程; 水流动量守恒方程	波作用量守恒方程; 水流动量守恒方程	
	泥沙模拟	平衡剖面方程	泥沙对流扩散方程[101]	泥沙对流扩散方程[101]	平衡沙坝体积假定
	冲流带过程	波浪爬高能量耗散模型	次重力波爬高与侵蚀	次重力波爬高与侵蚀	理论公式[102]
风沙输移	风场模拟	跨岸均匀分布	雷诺平均的 N-S 方程 线性解[84]	雷诺平均的 N-S 方程 线性解[84]	跨岸均匀分布
	风向	仅考虑与岸线垂直的风向	仅考虑与岸线垂直的风向	旋转网格法[90]求解斜向风场	考虑斜向风的风区效应
	风沙输移	风沙输移概率模型[99]	一维线性对流方程	一维线性对流方程	考虑风区效应的风沙输移模型[103]
植被效应	植被参数	植被覆盖率	植物高度[100]或覆盖密度[104]	植物高度[100]	
	植被演变考虑因素	植被的埋深和侵蚀耐受极限以及沉积平衡	植被的埋深和侵蚀耐受极限以及自然生长的时间尺度	距海岸线距离以及沉积平衡	

植被在水沙过程和风沙过程中都具有重要影响。水位和地形变化会影响植被演变[4],而植被冠层施加的阻力会减小风的剪切速度,促使风沙沉积[105]。耦合模型使用简单的参数化方法描述植被分布与演变,包

括植被的自然生长与埋深、侵蚀的耐受极限等,并通过植物高度[100]或覆盖密度[104]的时空变化来确定植被对风速的影响。然而,这些植被参数的合理确定和解释往往是难点,需要对植被在不同盐度、温度等环境中的季节性演化规律有更深入的研究。

多模块嵌套耦合的 Windsurf 模型[18]整合了近岸水沙运动模型 XBeach[50]、与植被相关的陆上形态动力学模型 CDM[100]和风沙输移模型 AEOLIS[96],成功模拟了 1 a 内的沙丘发育和海滩高程变化,但模型运行时间较长,且假定局部质量守恒,未考虑外部沉积物的输入。另一方面,Keijsers 等[15]开发的沙丘、海滩和植被演变的元胞机模型 DUBEVEG 采用简单的启发式解来描述沙丘与邻近海滩之间的相互作用,适用于复杂沙丘形态形成的模拟,但无法考虑局部风场与地形的相互作用。

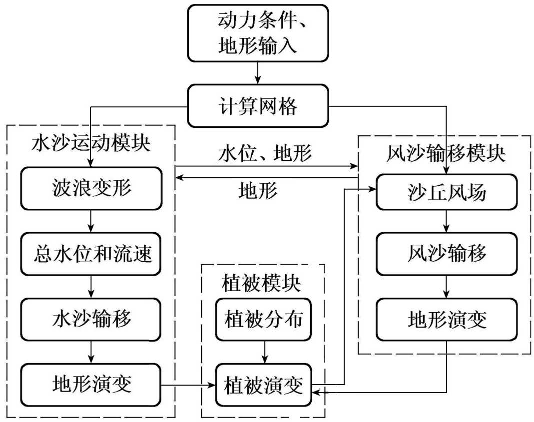

图 3　水沙-风沙耦合模型计算流程示意图

Fig. 3　Computational flow chart of the coupled subaqueous and aeolian sediment transport model

更大时间和空间尺度下的模拟往往需要采用降低复杂性的方法,如聚焦于关键过程的模型简化[106-107]、地貌形态加速技术[108]和输入缩减技术[109-110]。Hanson 等[111]和 Larson 等[16]修正了 Sbeach 模型[73],实现了以风力强度和海滩尺度为参量的沙丘恢复简化求解。Hallin 等[19]基于经验性海滩剖面演变模型 CS[97],添加了考虑泥沙可利用性的风沙输运公式,以及海平面上升引起海岸线后退的 Bruun 法则[112],通过海岸形态和输沙公式的简化,可以实现 10 a 至百年尺度的高效模拟。CS 可以预测一些海岸带综合管理中比较关心的参数,如海岸线变化、沙丘高度和体积变化等。然而,简化后的模型难以用于研究潮间带沙坝、侵蚀陡坎等一些较为复杂的地貌形态演变。XBeach-Duna 模型[17]综合采用地貌加速因子和输入缩减技术,通过最小化沙丘模型,考虑地形对气流的扰动,以兼顾物理过程和计算效率的方式实现 10 a 尺度上的海滩-沙丘系统耦合演变模拟,但其广泛适用性仍需要更多的现场实测资料验证。

5　研究展望

近年来,随着海岸风沙运动研究的发展,耦合水沙和风沙过程的海滩-沙丘系统耦合演变数学模型可以考虑风暴作用下的海滩-沙丘系统侵蚀和泥沙交换、供应限制条件下的风沙输移和沙丘发育等物理过程,并初步具备多年时间尺度上的海滩-沙丘系统耦合演变模拟能力,但在适用性、准确性和计算效率等方面仍存在不足。在今后的研究中,需关注以下 4 个方面:

a. 关键物理/生物过程的考虑。在持续深入研究水沙过程和风沙过程相互作用的基础上,应进一步研究冲流带水沙运动规律及其高效模拟方法、沙丘植被对风沙输移的定量影响以及植被生长响应过程,考虑在模型中纳入地表水-地下水的相互作用、多动力作用和多泥沙来源的海滩床面沉积及其对风沙输移的促进/制约效应等。这些过程的考虑有助于改进模型的可靠性和适用性,但也依赖于更多的现场观测和对机制的认识。

b. 计算效率的提高。基于复杂过程建立的海滩-沙丘系统耦合演变数学模型往往需要大量的输入参数和较长的运行时间,除了模型简化、形态加速和输入缩减技术等计算方法的改进外,聚焦于导致沙丘体积和海滩宽度发生显著变化的主导事件,量化事件类型、事件次数和时间顺序对地貌演变的影响,也有助于简化数值模拟过程,提高计算效率。

c. 空间维度的拓展。现有的海滩-沙丘系统耦合演变数学模型大多局限于向、离岸方向上的一维剖面,较少考虑沿岸方向上的水沙和风沙过程,这可能是模型计算结果和实测数据之间存在误差的原因之一。建立平面二维模型,研究斜向动力驱动、沿岸不均匀条件下的海滩-沙丘地貌系统演变是今后发展的一个重要趋势。

d. 实际应用的检验。现有模型已基本具备模拟海滩-沙丘系统中长期耦合演变的能力,但与现场实测资料的对比验证仍远远不足。此外,从服务工程应用的角度出发,今后的数学模型研究需更多考虑海平面上升、人工采砂、海岸构筑物、海滩养护、阻沙栅栏、植被修复、休闲娱乐设施等重要的自然和人为因素对海滩-

沙丘系统长期演变的影响。

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