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基于生态护坡射流试验的抗冲刷特性研究

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摘要: 植物根系对土体的力学效应是提高边坡抗冲刷性能的重要因素, 为了解植物根系在成片水流下的抗冲刷性能, 以常见的水土保持植物高羊茅和狗牙根为例, 对植物模型边坡进行射流冲刷试验, 对比探讨了不同种类植物根系边坡的冲刷破坏机理。结果表明, 各工况下高羊茅边坡、狗牙根边坡及素土边坡的平均侵蚀深度 ΔD_{AE} 的变化规律具有相似性和一致性, 随冲刷流速增加均呈指数函数增加, 随冲刷角度增加均呈线性函数增加; 各工况下平均侵蚀深度大小普遍为高羊茅 < 狗牙根 < 素土; 各流速下高羊茅的平均侵蚀深度降低值 ΔD_{AE} 略大于狗牙根; 当冲刷角度一定时, 两种植物边坡均在流速为 1.6 m/s 时各角度的 ΔD_{AE} 最大, 流速高于 1.6 m/s 后逐渐降低; 当冲刷流速一定时, 随冲刷角度的增加, ΔD_{AE} 有减小趋势。

关键词: 植物护坡; 模型试验; 水流冲刷; 抗冲刷性能

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1 引言

植物根系能改善土壤结构及其理化性质, 植物根系通过牢固缠绕达到固结土壤结构体的效果, 同时对土壤形成一种紧缚固结包络作用和保护性吸附牵拉作用, 减小水对土壤的分散作用, 继而减少雨水的冲击和径流的冲刷作用, 从而达到提高土壤抗蚀性、维持土体结构稳定和控制水土流失的目的。植物护坡的抗冲刷性能主要体现在抑制径流产生、控制径流规模、减少水流对土壤的侵蚀和抑制泥沙的流失。侍倩等^[1]提出了关于边坡抗侵蚀安全系数的相关理论公式, 可定量计算土壤冲刷造成的侵蚀量变化; 刘窑军等^[2]通过对不同组合形式下的防护边坡进行降雨冲刷试验, 探讨降雨对植被边坡抗侵蚀性能的影响程度, 发现梯坎与草灌结合的护坡形式抗侵蚀性能最好, 其中截留率达 72.3%、阻沙效率达 80.2%; 殷晖等^[3]通过试验直观观测发现植物茎叶可有效削弱雨水对土粒的击打, 较小雨强时, 林冠茎叶产生的截留消能效果最高可达到裸地的 2 倍以上; 陈

举^[4]通过物理模型试验探究了植物根系与河滩坡面结构稳定性和抗冲刷性的关系, 对麦冬草、芦苇和蒿草三种植物的水流、地形、根系形态和冲刷量进行监测, 发现根系结构越发达, 边坡的影响区域越大、抗冲刷性越强等; 孟飞^[5]通过根土复合体的土力学剪切试验和植物模型边坡的渠道冲刷试验, 研究了不同种植密度狗牙根的生物特征量与抗剪切性能的关系, 分析不同种植密度和不同高度的植物冲刷特性和相关关系; 王元立^[6]基于内河航道的防冲机制, 模拟了草皮抗径流冲刷和降雨冲刷, 描述了植物护坡的冲刷破坏过程, 并对破坏程度标准进行了评判, 这对后续河道冲刷研究有一定的参考价值。本文通过设计制作不同岸坡环境的植被边坡模型, 进行多种水流状况下生态护坡措施的射流冲刷试验, 探讨了成片水流下植物边坡的抗冲刷机制, 为实际工程提供了技术支撑和理论依据。

2 研究对象与试验方法

2.1 草种的选择与培育

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在试验设计初期,对郑州市郑东新区的龙子湖、贾鲁河及中牟县周边河流的护坡植物进行实地考察与调研,同时对各渠道收集的植被护坡相关资料进行整理分析,综合研究表明,高羊茅、狗牙根、百喜草、黑麦草四种草系在实际工程中应用十分广泛,有足够的理论基础,比较符合本文基于草根锚固效应的生态护坡抗冲刷机制研究的基本要求^[7]。根据郑州市本地的生态环境及气候,选取高羊茅和狗牙根两种草系作为试验草种的培育对象。

草系培育工作于 2019 年 4 月初在位于河南省郑州市郑东新区华北水利水电大学水利水运实验基地进行,在学校未开发区域的天然素土播种草系,按试验要求对所需土样进行风干和杂质筛分,种植前将土体充分湿润,选取优良的种子按相关方案分区域播种。播种量为 $1\ 400\ \text{g}/667\ \text{m}^2$,播后覆盖 $1\sim 2\ \text{cm}$ 厚的细土,并保持土壤湿润。播种后定期除杂草、松土,适当补充有机肥(每 $667\ \text{m}^2$ 撒施 $2\ \text{kg}$ 尿素,夏季不施肥,秋季草坪生长旺盛,适当补充有机肥),在每次施肥后,立即浇水,养护的同时根据天气情况,及时补播。

2.2 试验流程

(1)将高羊茅植物、狗牙根植物和纯素土三种边坡作为对照组,试验前将边坡地上部分的植物茎叶剪掉,只留下约 $1\sim 2\ \text{cm}$ 主茎。

(2)模型由 $1.50\ \text{m}\times 0.90\ \text{m}\times 0.35\ \text{m}$ (长 \times 宽 \times 高)的长方体无盖有机玻璃板粘和而成,坡比为 $1:2.25$,预留了宽 $18\ \text{cm}$ 的底坡,下接泥沙收集装置。

(3)射流系统主要由变频加压泵和自制调节平台组成,变频加压泵功率为 $100\sim 600\ \text{W}$,额定流量 $1\ \text{m}^3/\text{s}$,最大流量 $2\ \text{m}^3/\text{s}$,出流孔口直径为 $4\ \text{cm}$;自制调节平台(图 1)可在地面自由移动,上下伸缩可调节喷头垂直高度,左右旋转可调节水平角度;自制调节平台可固定射流管口并控制射流的方位和角度;射流末端出流管道直径为 $1\ \text{cm}$ 。调节自动调节平台的高度和方位,使射流喷口对应边坡中轴线位置,与水平方向夹角分别为 5° 、 30° 、 60° 、 90° ,自动调节平台距边坡中线 $0.8\ \text{m}$ 。



图 1 自制射流调节平台

Fig. 1 Self-made jet adjustment platform

(4)变频加压泵进水口接通水源,通过增加和减小压强来控制出流流速,利用旋桨式流速仪测量管道出流流速,根据试验流速的大小适当移动射流平台,使其冲射至边坡的流速为设计流速。

(5)射流位置和射流速度调试完毕后,对不同边坡进行 $15\ \text{min}$ 的均匀射流冲刷,设计组次和工况见表 1。

表 1 射流试验工况

Tab. 1 Jet flow test conditions

模型边坡	射流流速/ $(\text{m}\cdot\text{s}^{-1})$	射流角度/ $(^\circ)$
高羊茅	0.8	5,30,60,90
	1.6	5,30,60,90
	2.4	5,30,60,90
	4.0	5,30,60,90
狗牙根	0.8	5,30,60,90
	1.6	5,30,60,90
	2.4	5,30,60,90
	4.0	5,30,60,90
素土	0.8	5,30,60,90
	1.6	5,30,60,90
	2.4	5,30,60,90
	4.0	5,30,60,90

(6)为了保证量测的精准度,边坡射流深度利用高精度测尺进行量测,在试验前期,已在透明的有机玻璃上对边坡高度坡度轮廓进行标识记录,每组次射流试验完成后对边坡各固定测点(图 2)的侵蚀深度、尺度、面积进行测量统计和记录,观察分析植被破坏情况。

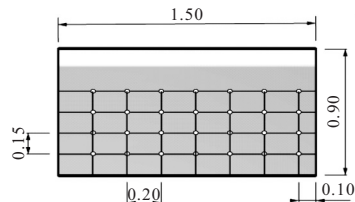


图 2 边坡测点布置图(单位:m)

Fig. 2 Layout of measuring points on slope

2.3 数据处理方法

为保证量测的精准度,利用高精度测尺量测边坡射流深度,在每组次冲刷试验完毕后,利用高精度测尺对固定位置的测点进行量测并求出平均值,即为平均侵蚀深度 D_{AE} :

$$D_{\text{AE}} = D_{\text{TE}}/n \quad (1)$$

式中, D_{TE} 为各测点冲刷深度累加值,cm; n 为测点个数, $n=28$ 。

平均侵蚀深度降低值(较素土边坡) ΔD_{AE} 为:

$$\Delta D_{\text{AE}} = D_{\text{AE}}(\text{无根土壤}) - D_{\text{AE}}(\text{有根土壤}) \quad (2)$$

各冲刷流速梯度、冲刷角度梯度下的平均侵蚀深度降低值(较素土边坡)百分比 P_{RD} 为:

$$P_{\text{RD}} = [\Delta D_{\text{AE}}/D_{\text{AE}}(\text{无根土壤})] \times 100\% \quad (3)$$

3 植物坡面平均侵蚀深度 D_{AE} 变化特征

3.1 各射流角度下射流流速的变化规律

各种工况下射流冲刷试验的平均侵蚀深度 D_{AE} 见表 2。由表 2 可看出,不同冲刷流速及角度下各植物边坡的平均侵蚀深度,变化不一,其中素土边坡的平均侵蚀深度明显大于高羊茅边坡和狗牙根边坡。

表 2 各工况下坡面平均侵蚀深度 D_{AE}

Tab. 2 Average erosion depth D_{AE} of slope surface under various working conditions

草种	流速 $/(m \cdot s^{-1})$	D_{AE}/cm			
		冲刷 角度 5°	冲刷 角度 30°	冲刷 角度 60°	冲刷 角度 90°
高羊茅	0.8	2.1	2.3	4.8	5.7
	1.6	2.9	3.5	5.1	6.4
	2.4	3.8	5.9	7.6	10.8
	3.2	7.1	8.4	9.7	13.8
	4.0	8.1	9.2	12.5	14.9
狗牙根	0.8	3.2	4.8	5.6	5.9
	1.6	3.8	4.9	6.1	8.5
	2.4	5.4	6.8	7.9	11.5
	3.2	7.8	9.6	10.8	15.7
	4.0	8.5	9.8	11.5	13.6
素土	0.8	3.4	5.4	7.8	10.5
	1.6	5.3	6.5	8.9	13.4
	2.4	6.3	8.9	10.6	13.5
	3.2	8.3	10.8	10.6	14.9
	4.0	10.3	11.8	13.2	15.9

图 3 为四种冲刷角度下平均侵蚀深度随冲刷流速的变化曲线。由图 3 可知,在冲刷角度一定的情况下,高羊茅植物边坡、狗牙根植物边坡、自然素土边坡随射流流速的变化规律有较大的相似性,三种边坡的平均侵蚀深度与射流流速均呈指数函数关系,即随流速增大其冲刷深度越大(相关拟合方程见表 3),同时随流速的增大平均侵蚀深度变化速率增大。结合数据分析,四种冲刷角度下不同流速对应的平均侵蚀深度数值的总体变化趋势为素土 > 狗牙根 > 高羊茅。从坡面破坏机理

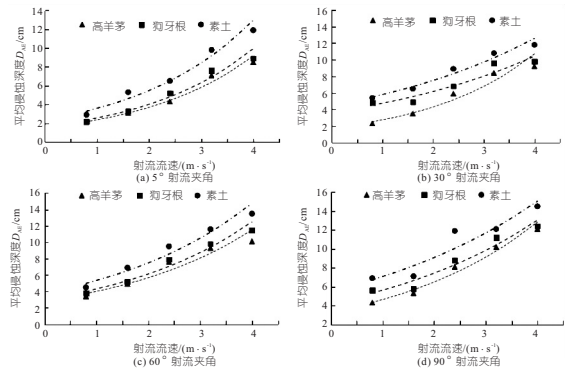


图 3 射流流速与边坡的平均侵蚀深度关系

Fig. 3 Relationship between jet velocity and average erosion depth of slope

表 3 不用冲刷角度下边坡射流流速与对应平均侵蚀深度 D_{AE} 拟合关系式

Tab. 3 Fitting relationship between jet velocity of slope and corresponding average erosion depth

边坡类型	冲刷角度/ $^\circ$	回归趋势线方程	相关度 R^2
高羊茅	5	$y = 1.490 2e^{0.453 1x}$	0.986 0
	30	$y = 1.847 6e^{0.435 2x}$	0.958 0
	60	$y = 2.804 6e^{0.352 3x}$	0.938 1
	90	$y = 3.285 8e^{0.340 5x}$	0.977 6
狗牙根	5	$y = 1.616 4e^{0.453 7x}$	0.977 3
	30	$y = 2.313 5e^{0.383 6x}$	0.939 6
	60	$y = 3.005 7e^{0.356 1x}$	0.971 2
	90	$y = 4.235 2e^{0.281 0x}$	0.939 9
素土	5	$y = 2.319 0e^{0.429 8x}$	0.963 2
	30	$y = 2.746 8e^{0.407 6x}$	0.953 2
	60	$y = 3.792 8e^{0.339 6x}$	0.957 6
	90	$y = 5.482 7e^{0.252 3x}$	0.886 5

上来看,高羊茅和狗牙根在冲刷深度超 8 cm 后,增加其冲刷深度变化速率有加快趋势。

3.2 各射流流速下射流角度对应的平均侵蚀深度 D_{AE} 变化规律

图 4 为五种冲刷流速下冲刷角度与平均侵蚀

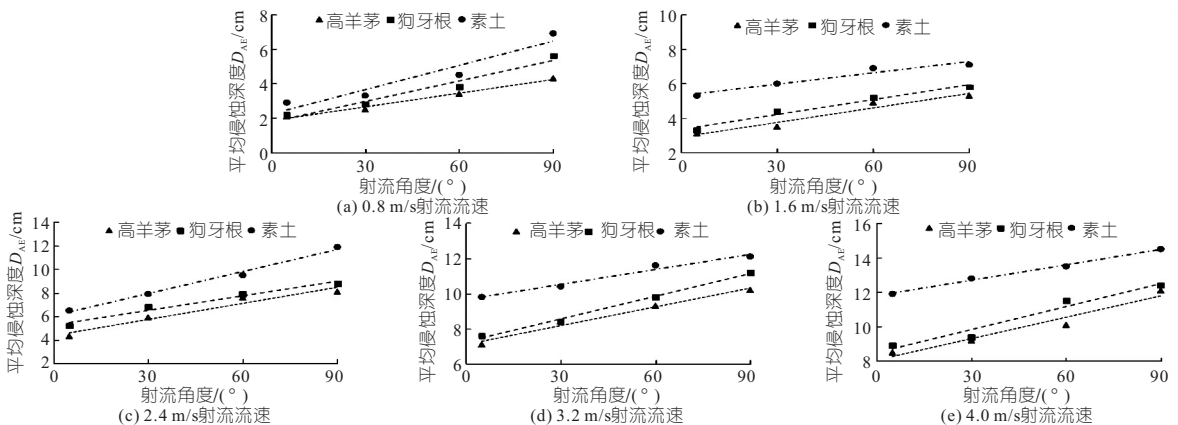


图 4 射流角度与边坡平均侵蚀深度关系

Fig. 4 Relationship between jet angle and average erosion depth of slope

深度 D_{AE} 的变化关系。由图 4 可知,在冲刷流速一定的情况下,高羊茅边坡、狗牙根边坡、自然素土边坡随冲刷角度变化规律具有一致性,三种工况的平均侵蚀深度均与射流角度呈线性函数关系(随冲刷角度的增大其平均侵蚀深度越大相关拟合方程见表 4)。相同流速下,冲刷角度达 90° 时平均侵蚀深度最大,这说明水流流向与坡面形成的方位对坡面的侵蚀具有一定影响,当水流顶冲刷面时造成的冲刷破坏最大。对比三种工况下平均侵蚀深度数值,各冲刷流速下随角度变化平均侵蚀深度分布大小基本为高羊茅 < 狗牙根 < 素土,其中高羊茅与狗牙根较接近。

表 4 不同角度下射流流速与对应平均侵蚀深度 D_{AE} 拟合方程

Tab. 4 D_{AE} fitting equation of jet flow velocity and corresponding average erosion depth at different angles

边坡类型	冲刷流速 / ($m \cdot s^{-1}$)	回归趋势线方程	相关度 R^2
高羊茅	0.8	$y=0.0265x+1.8516$	0.9859
	1.6	$y=0.0281x+2.8985$	0.9477
	2.4	$y=0.0456x+4.3650$	0.9444
	3.2	$y=0.0429x+7.2636$	0.9941
	4.0	$y=0.0413x+8.0639$	0.9507
狗牙根	0.8	$y=0.0396x+1.7699$	0.9595
	1.6	$y=0.0289x+3.3379$	0.9695
	2.4	$y=0.0414x+5.2582$	0.9696
	3.2	$y=0.0356x+7.1046$	0.9809
	4.0	$y=0.0444x+8.4954$	0.9593
素土	0.8	$y=0.0468x+2.2346$	0.9176
	1.6	$y=0.0220x+5.3091$	0.9405
	2.4	$y=0.0626x+6.0542$	0.9901
	3.2	$y=0.0284x+9.6607$	0.9757
	4.0	$y=0.0298x+11.7980$	0.9940

3.3 坡面平均侵蚀深度降低值 ΔD_{AE} 变化规律

射流流速和角度与平均侵蚀深度降低值百分比 P_{RD} 变化见图 5。

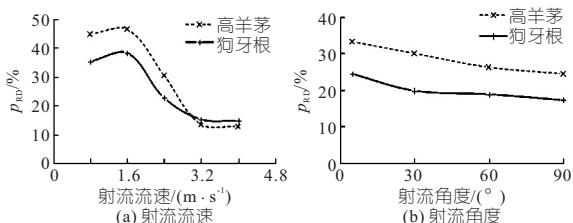


图 5 射流流速和角度与坡面平均侵蚀深度降低百分比 P_{RD} 变化

Fig. 5 P_{RD} change of jet velocity and angle and average erosion depth reduction percentage of slope

由图 5 可知,当冲刷角度一定时,高羊茅的 P_{RD} 普遍较大,最高可达 52%,狗牙根最高则为 37%,这反映种植物边坡较素土边坡具有较好的抵抗垂直侵蚀的能力,且高羊茅的抗侵蚀效果总

体上优于狗牙根;两种植物边坡均在流速低于 1.6 m/s 时各角度的 ΔD_{AE} 较大,流速高于 1.6 m/s 后, ΔD_{AE} 逐渐降低,表明随冲刷流速增至某个极限后,草系固土抗侵蚀性能减弱。当冲刷流速一定时,高羊茅、狗牙根的 P_{RD} 平均变幅分别为 17%、14%,这反映种植植物的边坡较素土边坡具有一定的抗侵蚀性能。根据变化趋势可知,随冲刷角度的增加, P_{RD} 有减小趋势,说明渠道来流与坡面形成夹角增大会降低根系土的抗侵蚀性能。

4 结论

a. 高羊茅边坡、狗牙根边坡、素土边坡的平均侵蚀深度随冲刷流速增加均呈指数函数增加,随冲刷角度增加均呈线性函数增加。流速和角度变化梯度下平均侵蚀深度大小为高羊茅 < 狗牙根 < 素土,各角度下平均侵蚀深度随流速的增幅为素土 < 狗牙根 < 高羊茅;随冲刷角度的增加均呈线性增加。

b. 各流速下高羊茅的平均侵蚀深度降低值 ΔD_{AE} 普遍略大于狗牙根;当冲刷角度一定时,冲刷流速为 1.6 m/s 时两种植物边坡各角度的 ΔD_{AE} 最大,流速高于 1.6 m/s 后则逐渐降低,当冲刷流速一定时,随冲刷角度的增加, ΔD_{AE} 有减小趋势。

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Study on Internal Economic Operation of Large Hydropower Station Based on Load Optimal Distribution Table

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Abstract: Dispatching operation of hydropower station is in face of the large capacity and large units, unit control new scheduling features such as irregular more limits and more complicated operation requirements. To aim at power station safe, stable and economic operation, a model of economic operation inside the station was established to realize optimal load distribution of hydropower station units under various operation conditions. The optimal output range of each unit under different head was analyzed. The optimal load distribution rule of the power station was studied, and the economic operation model of the station was established. Based on the economic operation model of the station, the optimal load distribution table was designed. The optimal load distribution result table of the power station under different loads, different heads, and different unit commitment was proposed to guide the real-time economic scheduling of the power station. Taking Hongjiadu station as an example, the results show that the model can reasonably arrange the start-stop sequence and number of units according to the real-time load instruction, and give real-time start-stop suggestions of units. It can obtain the optimal load distribution combination of the proposed unit under various working conditions, reduce the monthly average water consumption rate by 0.18%, reduce the adverse working conditions such as frequent start-stop and frequent crossing of the vibration zone by 9.5%, ensure the efficiency of the unit operation, and improve the economic benefits of the power station.

Key words: station economic operation; real time scheduling; optimal load distribution; adverse conditions; parallel dynamic programming

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Research on Anti-scouring Characteristics Based on Ecological Slope Protection Jet Test

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Abstract: The mechanical effect of plant roots on soil is an important factor in improving the erosion resistance of slopes, and the relevant research on the impact resistance of plant roots under water flow at home and abroad is in a blank spot. In this paper, the common soil and water conservation plants tall fescue and dogtooth roots were selected as the research objects, and the jet erosion test was carried out on the slope of the plant model, and the erosion failure mechanism of the root slope of different species of plants was compared. The main conclusions are as follows: the variation law of the average erosion depth ΔD_{AE} of high fescue slope, dogtooth root slope and plain soil slope under different working conditions is similar and consistent, and it increases exponentially as a function with the increase of erosion flow velocity and linear function with the increase of erosion angle. The average erosion depth under various working conditions was generally as follows: high fescue < dog tooth root < plain soil; The average erosion depth of high fescue at each flow rate decreased slightly ΔD_{AE} slightly greater than that of dog tooth root. When the scouring angle was fixed, the ΔD_{AE} of each angle was the largest when the flow rate was 1.6 m/s, and the flow rate was higher than 1.6 m/s, and gradually decreased. When the erosion flow rate is constant, there is a decreasing tendency ΔD_{AE} increase with the increase of the scouring angle.

Key words: plant slope protection; model test; water erosion; anti-scour performance

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Structural Safety Analysis and Design Method for Different Types of Tunnel Plug of Large Diversion Tunnel

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Abstract: The diversion tunnel plug is a key project for the safety of water conservancy and hydropower projects. Wedge-shaped plugs are widely used in engineering. There are many calculation methods for columnar plug, but not so much for the wedge-shaped plug. Based on the design scheme of the diversion tunnel plug in Karot power station, this paper carried out the theoretical and numerical simulation analysis. Through the force analysis of the wedge, the calculation method of the hydraulic pressure bearing capacity of the wedge-shaped plug was proposed. The comparative analysis of wedge and columnar plug safety was carried out by three-dimensional elastoplastic numerical simulation. The result shows that the maximum deformation under the calibration water level of the wedge-shaped plug was 0.8 mm, and its overload safety factor was 1.08 times that of the columnar plug. By comparing the numerical simulation with the formula calculation results, the rationality and accuracy of the calculation method for the bearing capacity of the wedge-shaped plug were verified. The research results have important guiding value for the design of wedge-shaped block.

Key words: diversion tunnel; tunnel plug; wedge-shaped plug; columnar plug; numerical simulation