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高地下水位地区透水停车场的水文控制效果

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摘要: 为确定高地下水位地区透水铺装对路面径流的水文控制效果, 在上海市区建造了4个实验性透水铺装单元与1个不透水铺装对照, 其中3个为设有防水衬底的不透型设施分别为透水混凝土铺装(设施Ⅰ)、水泥稳定碎石基层/缝隙透水砖面层(设施Ⅱ)、碎石基层/缝隙透水砖面层(设施Ⅲ), 1个普通缝隙透水砖铺装(设施Ⅳ), 以及1个不透水混凝土对照(设施Ⅴ)。历时1年监测了实际降雨条件下4种实验设施的表面径流、排水管出流流量及表面渗透速率, 考察不同设施的径流总量削减率、峰值削减及峰现延迟能力。结果表明, 缝隙透水砖面层的表面稳定渗透速率明显小于透水混凝土面层, 使用1年后, 2种面层表面稳定渗透速率均明显下降; 4种设施的表面产流均无显著差异; 3种不透型设施的就地消纳水量能力均较弱, 年径流总量控制率分别为24.2%、28.5%、28.4%, 排水管不发生出流的控制降雨量分别为5.2 mm、7.8 mm、7.8 mm; 设施Ⅰ的峰值削减与峰现延迟效果弱于设施Ⅱ及设施Ⅲ, 且3种设施的峰值削减率和峰现延迟时间与降雨强度呈现显著负相关性。

关键词: 透水铺装; 设施构造; 径流削减率; 水文效应; 海绵城市建设

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Hydrological Performance Assessment of Permeable Parking Lots in High Water Areas

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Abstract: In order to evaluate the hydrological performance of permeable pavements in mitigating the surface runoff, four pilot-scale permeable pavement units were constructed in Shanghai and compared with impervious pavements. Three of the permeable facilities with waterproof liners included a pervious concrete pavement (facility I), permeable interlocking concrete pavement using cement stabilized macadam as the base course (facility II) and permeable interlocking concrete pavement using macadam as the base course (facility III). The other two facilities were a conventional permeable interlocking concrete pavement without a liner (facility IV) and an impervious concrete pavement control (facility V). V-notch flow meters, data loggers, and a rainfall meter were mounted to monitor the hydrological data. A double-ring infiltrometer was applied to evaluate the infiltration rate of the pavements. During the one-year experiment, the surface runoff and the underdrain discharge flow rate of the four pilot-scale facilities were continuously monitored in actual rainfall and the total volume reduction, peak flow reduction, and peak concentrating time of different facilities were investigated. The results showed that the surface steady infiltration rates of permeable interlocking concrete pavements were less than those of the pervious concrete, and the surface steady infiltration rates of the two types of surface layers decreased after one year of usage. The surface runoff reduction of the four facilities showed no significant differences. The water volume reduction rate of the three types of facilities was weak. The annual total volume reduction rates were 24.2%, 28.5%, and 28.4%, and the controlled rainfall amounts were 5.2 mm, 7.8 mm, and 7.8 mm. The peak flow reduction rate and the time to the peak flow of facility I were smaller than those of facility II and facility III. The peak flow reduction rate and the time to the peak flow of the three facilities showed significant negative correlation with rainfall intensity.

Key words: permeable pavement; facility structure; annual volume reduction rate; hydrological effect; sponge city development

城市化带来的城区不透水表面的比例提高加剧了城市内涝与面源污染^[1, 2]。低影响开发技术(LID)具有源头分散设置、实施简单、费用较低等特点^[3], 近年来在国内得到高度关注。其中, 透水铺装可广泛应用于广场、停车场以及轻载路面^[4~6], 具有滞蓄、消纳路面径流, 不额外占用土地等优点^[7~9], 在发达国家已得到广泛应用, 是我国大中城市海绵城市建设的主要措施之一。

根据国内相关技术规程, 透水铺装的土基顶面距离地下水位宜大于1.0m^[10]。英国可持续城市排

水手册要求在地下水位与设施底部间距小于1.0m的场合必须使用防渗层(liner)以防止下渗径流污染地下水等问题, 并在铺装结构中设置排水管^[11]。对应的透水铺装设施也称为不透型透水铺装。相比全透型设施, 高地下水位地区的不透型透水铺装的水文控制效果显著降低。国外针对不透型透水铺装的

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现场实验报道很少,已有的研究显示不透型透水铺装的水文效果较差^[12].而长三角等地区的地下水埋深很小,渗透铺装应该使用防渗层,透水铺装的实用性受到影响.此外,随着使用时间推移,透水铺装面层渗透速率因堵塞显著下降,影响设施对表面径流的削减效果^[13~15].应对堵塞的方法主要为高压冲洗和真空吸尘^[16],缝隙透水砖铺面堵塞后可通过吸出填充缝隙的砂砾重新扫砂,维护更新方便,目前在发达国家受到推崇.

为考察在高地下水位地区不同面层及结构层组成的透水铺装设施的水文控制效果,本文建造了4种不同构造的应用规模透水铺装,其中3个为底部设置防渗膜的不透型设施,在实际降雨条件下考察透水铺装在长期使用过程中的水文控制效果.

1 材料与方法

1.1 实验设施

位于同济大学校园内一处停车场的实验设施包括2个不透型缝隙透水砖铺装、1个不透型透水混凝土铺装(上海格林路得公司建造)、1个全透型透水砖铺装及1个不透水混凝土铺面对照,5个单元的面积均为6 m×6 m且无额外汇水面积,各设施边缘设置高3 cm的混凝土镶边以消除来自相邻铺面的径流.在距离设施约10 m处设置1个地下水观测井,用于地下水位的观测.设施表面标高3.28 m,现场实测地下水位高程变化范围2.23~2.84 m.5个单元的具体结构组成与编号见表1,其中,设施Ⅱ的水泥稳定碎石基层在结构强度上优于设施Ⅲ的碎石结构层.设施Ⅰ、设施Ⅱ与设施Ⅲ的底部均设有HDPE防渗膜(200 g·m⁻²),并于锥型截面的底部设置DN75穿孔排水管.设施Ⅳ为无防渗膜的全透型透水铺装,用以与设施Ⅱ、设施Ⅲ对比表面产流与结构稳定情况.混凝土缝隙透水砖的缝隙宽度为3~4 mm,缝隙面积约占设施表面积10%.设施Ⅱ与设施Ⅲ在找平层下垫有无纺土工布.各设施面层均做出1%~2%的坡度,并于低端设置宽约10 cm的排水边沟以收集表面产流,通过排水管接入临近的观测井,观测井面积为2.5 m×1.2 m.

1.2 水文数据采集

各设施底部出流与表面径流分别连接到置于观测井中的60°三角堰,各三角堰上方设置超声波液位计(MIK-ES)并连接至数据记录仪(MIK204D),连续记录堰上水头,数据采集间隔为1 min.参照规程计算得到各设施底部出流及表面径流的流量过

程^[17].在距离实验地点约100 m处屋顶安装SL3-A翻斗式雨量计(精度0.1 mm)监测场地的降雨情况,降雨数据采集间隔为1 min.各设施表面渗透速率及土基层渗透速率使用双环渗透仪测量.面层测量前使用油灰将双环与待测铺面之间缝隙堵住,持续读取内环液位,读数间隔根据液位下降速率而定,达到稳定阶段的渗透速率为饱和渗透速率^[15, 18].

表1 实验设施结构组成

Table 1 Structure of the facilities for the experiment			
编号	构造	深度/mm	结构材料
0	面层	150	普通水泥混凝土
	结构层	300	粒径20~40 mm碎石
Ⅰ	面层	150	透水混凝土
	结构层	300	粒径20~40 mm碎石
Ⅱ	面层	60	混凝土缝隙透水砖
	找平层	20	粒径0.5~1.0 mm粗砂
	基层	150	5%水泥+粒径15 mm以下碎石的水泥稳定碎石
	垫层	200	粒径20~40 mm碎石
Ⅲ	面层	60	混凝土缝隙透水砖
	找平层	20	粒径0.5~1.0 mm粗砂
	基层	150	粒径15 mm以下碎石
	垫层	200	粒径20~40 mm碎石
Ⅳ	面层	60	混凝土缝隙透水砖
	找平层	20	粒径0.5~1.0 mm粗砂
	基层	150	粒径15 mm以下碎石
	垫层	200	粒径20~40 mm碎石

1.3 数据统计与计算方法

采用SPSS 20对实验数据进行统计.其中,使用Games-Howell法对各设施径流削减率以及表面产流削减率进行方差分析,并使用Pearson相关系数法进行降雨强度和前期晴天数与各设施峰值削减率和峰现延迟时间的相关性分析.

参照文献[19],本文中年轻流总量控制率按式(1)计算:

年轻流总量控制率 =
$$\frac{\text{降雨量} - \text{底部出流} - \text{表面产流}}{\text{降雨量}} \quad (1)$$

2 结果与分析

2.1 监测降雨事件

在2016年1~12月的监测期间内,共发生了雨量≥0.5 mm的降雨事件76场,累积降雨量1597.4 mm,远高于上海市1 200 mm的多年平均降雨量.其中,雨量<10 mm的降雨事件共34场,设施Ⅰ发生底部出流场次为10场,设施Ⅱ与设施Ⅲ发生底部出流场次均为8场;雨量≥10 mm的降雨事件共42

场,3种不透型设施均发生底部出流。

2.2 表面渗透速率

4种设施采用的2类面层在实验开始与结束阶段的表面渗透速率测定结果见图1,随测定时间延续趋于稳定的渗透速率为介质饱水之后的稳定渗透速率。可知缝隙透水砖面层的表面稳定渗透速率均明显小于透水混凝土面层,这与Kumar等^[20]的实测结果相近,缝隙透水砖面层的渗透主要通过砖块之间的缝隙进行,过水面积较小,因此渗透速率小于依

靠孔隙渗透的透水混凝土面层^[21]。各设施使用1a后面层损坏情况均不明显,但表面渗透速率下降显著^[22],缝隙透水砖面层后期渗透速率已达不到规范要求的 $1 \times 10^{-4} \text{ m} \cdot \text{s}^{-1}$,透水混凝土面层的渗透速率下降幅度大于缝隙透水砖面层,仅为初始值的1/20。由于灰尘与泥土在砖块间缝隙以及混凝土孔隙表面沉积^[23],并且找平层粗砂容易发生板结现象^[24],导致铺面渗透通道堵塞,表面渗透速率明显下降。

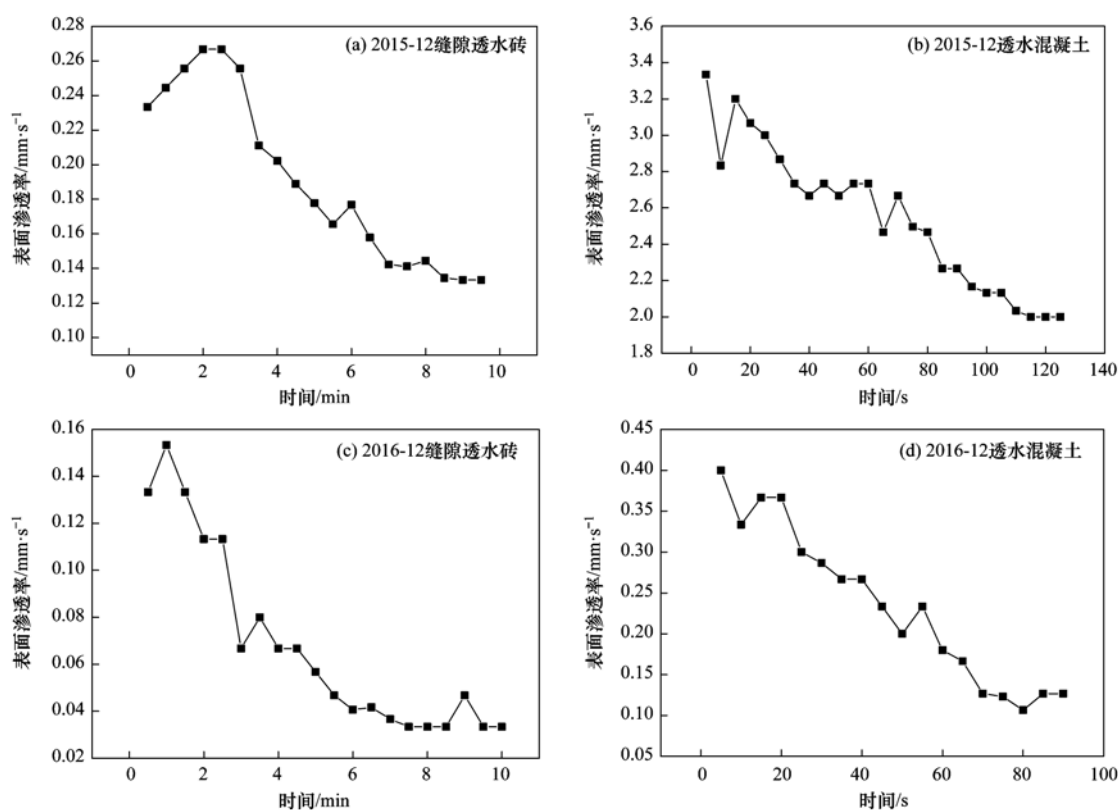


图1 2种面层实验前后期的表面渗透速率

Fig. 1 Surface infiltration rate of two types of surface layers before and after the experiment

2.3 径流削减情况

2.3.1 表面径流

不同降雨事件下4种设施不同降雨事件表面产流量的分布见图2。设施下坡端的混凝土边沟面积约占设施表面积1.7%,设施表面产流中有部分来自不透水的边沟,因此实际表面产流小于测量值。经过修正,设施I、II、III在整个监测期间的累积表面产流总量分别为48.1、69.6、75.8 mm,不同实验阶段各设施的表面径流相对降雨量的平均削减率见表2。各设施实验前期除去边沟部分外,几乎无表面产流。在产流降雨事件中,透水混凝土的削减率与缝隙透水砖面层无显著差异($P > 0.05$);在缝隙透水砖面层设施中,沿地面坡度纵向排列的砖块铺

设方式影响了径流经缝隙的下渗几率,部分径流未及时下渗便沿砖块表面流过,使得在降雨强度小于表面渗透速率条件下仍有少量径流产生。因此,砖块人字形铺设方式有利于协调面层强度与下渗效果。其中全透型的设施IV的径流削减率与设施II和设施III无显著差异($P > 0.05$)。由于实验现场地下水位距设施表面0.44~1.05 m,距离设施底部尚有空间,且设施底部原有杂填土平均渗透速率为 $1.4 \times 10^{-5} \text{ m} \cdot \text{s}^{-1}$,因此设施IV可通过底部渗透有效削减径流,在就地消纳降雨方面优于底部不透水设施。然而,下渗水直接进入含水层存在明显的污染地下水的风险^[25]。实验后期各设施径流削减率小于前期且存在显著差异($P < 0.05$),大雨期间径流削减

率小于小雨且存在显著差异 ($P < 0.05$), 这是由于各设施后期表面渗透速率大幅下降, 大雨期间会产生更多未及时下渗便沿坡度排出的径流。

2.3.2 次降雨出流情况

按照降雨量 $< 10\text{ mm}$ 、 $\geq 10\text{ mm}$ 且 $< 25\text{ mm}$ 、 $\geq 25\text{ mm}$ 这 3 种情况, 分别讨论不同设施的出流量控制效果。3 种降雨量降雨事件的典型出流过程如图 3 所示。不同降雨事件中 3 种设施的底部出流的折算径流深度分布见图 4, 设施 I、II、III 监测期底部出流总量分别为 1 162.5、1 072.3、1 067.6 mm。图 3 中各设施在 3 种降雨量下对底部出流的削减率如表 3 所示, 底部出流削减率为相对设施 0 产生径流量的减少比例。随着降雨量的增大, 各设

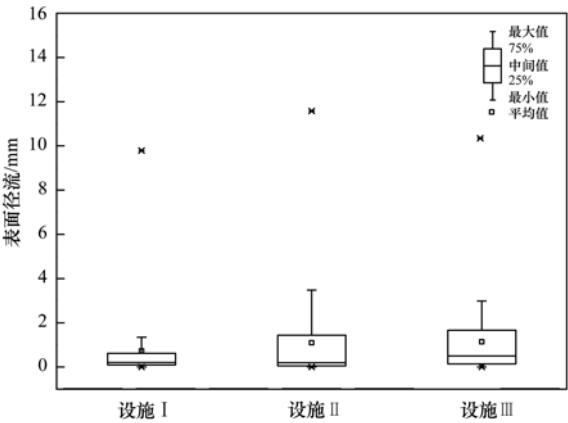


图 2 各设施不同降雨事件下表面产流量的分布
Fig. 2 Distribution of surface runoff of each facility in different rainfall events

表 2 4 种设施表面产流相对降雨量的平均削减率

Table 2 Average reduction rate of surface runoff of four facilities

设施	2016-01 ~ 2016-06 平均削减率/%		2016-07 ~ 2016-12 平均削减率/%	
	降雨量 $< 25\text{ mm}$ (28 场)	降雨量 $\geq 25\text{ mm}$ (10 场)	降雨量 $< 25\text{ mm}$ (30 场)	降雨量 $\geq 25\text{ mm}$ (8 场)
I	98.8	97.5	91.6	86.4
II	95.4	92.4	84.9	80.0
III	96.0	92.9	85.3	80.5
IV	97.6	94.6	88.7	84.2

表 3 不同降雨量降雨事件底部出流削减率¹⁾/%

Table 3 Discharge reduction rate in different rainfall events/%

降雨量	设施 I	设施 II	设施 III
$< 10\text{ mm}$ (34)	30.9	37.2	39.4
$< 25\text{ mm}$ 且 $\geq 10\text{ mm}$ (24)	24.0	30.6	29.2
$\geq 25\text{ mm}$ (18)	18.1	19.3	20.4

1) 括号中表示对应降雨事件场次

施的出流量、峰值及峰现时间与对照设施的差异明显降低。

2.3.3 各设施年径流总控制率与控制降雨量

统计监测期间所有降雨事件的设施底部出流以及表面产流情况, 按式 (1) 得到 2016 年各设施的年径流总量控制率。3 种不透型设施由于底部有防渗层, 径流控制能力均较弱^[26, 27], 年径流总量控制率分别为 24.2%、28.5%、28.4%。设施 II 与设施 III 年径流总量控制率相近, 不存在显著差异 ($P > 0.05$), 因此缝隙透水砖铺装的控制率可合并表示, 且表明加入 5% 水泥的水泥稳定碎石结构层对设施的径流削减能力没有影响。设施 I 的年径流总量控制率明显低于另外 2 种设施 ($P < 0.05$), 这可能是由于透水混凝土面层的多孔结构虽能迅速渗透排除表面径流, 但不能有效滞蓄径流^[28]; 而设施 II 与设施 III 由于面层混凝土砖和粗砂找平层可滞蓄入渗径流, 加强了降雨结束之后的蒸发作用^[29], 因此具有

较好的径流削减效果。

3 种设施在所有监测事件中的降雨量、出水总量关系见图 5。不同前期间隔等降雨特性条件下, 设施 I、设施 II 和设施 III 可以直接控制的降雨量分别为 5.2、7.8、7.8 mm, 设施出流量与降雨量线性方程的斜率分别为 0.82、0.78、0.79。可知, 透水混凝土设施在相同降雨情况下相比设施 II 与设施 III 产生更多出流。根据图 5 得到的关系式可大致从降雨量推算出流量, 并且将设施 II 与设施 III 合并, 可得混凝土砖缝隙透水铺装的拟合方程为 $V_{\text{出水}} = 0.78V_{\text{降雨量}} - 3.38$ ($8.2 \leq V_{\text{降雨量}} \leq 91.5$, 单位 mm)。值得注意的是, 由于 2016 年为异常丰水年, 且大雨较往年多, 根据图 5 中的方程由降雨量推算所得的出流量结果偏大。根据 1984 ~ 2004 年上海市的次降雨量概率密度函数积分得到上海的降雨量概率累积曲线; 并根据文献 [19] 提供设计降雨量计算方法, 由 2016 年次降雨数据计算次降雨量与年度径流

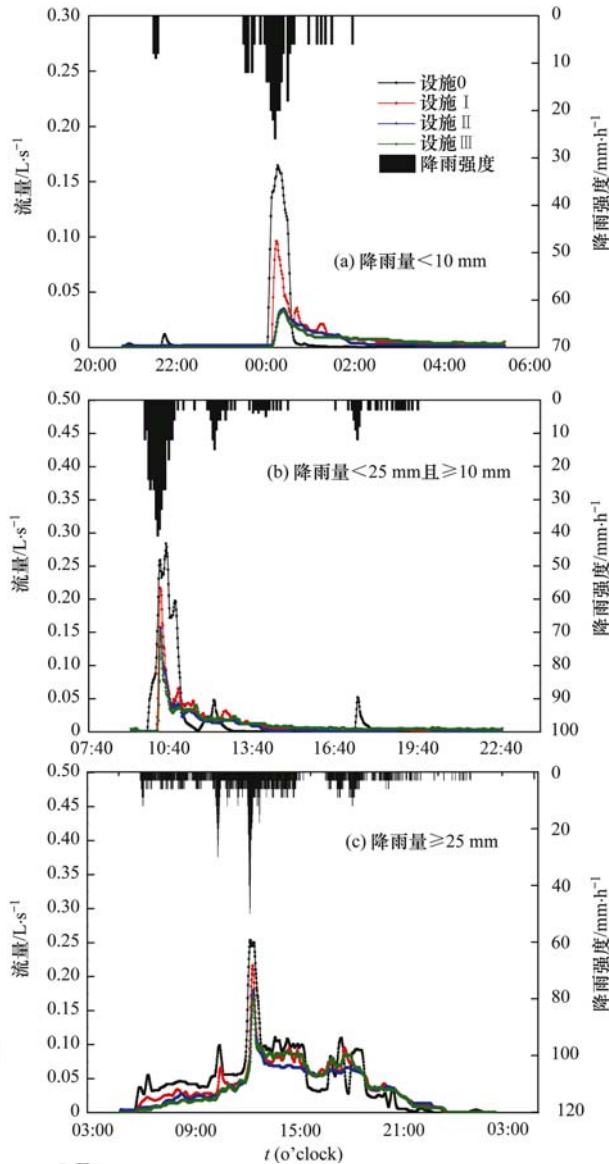


图3 不同降雨量条件下各设施的出流过程
Fig. 3 Outflow process of each facility under different rainfall conditions

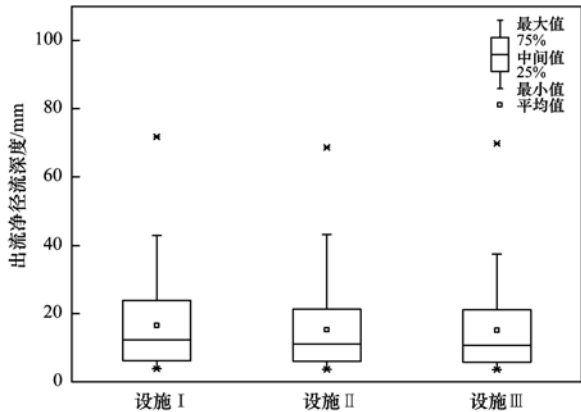


图4 不同降雨事件中各设施的出流水量的分布
Fig. 4 Distribution of outflow of each facility in different rainfall events

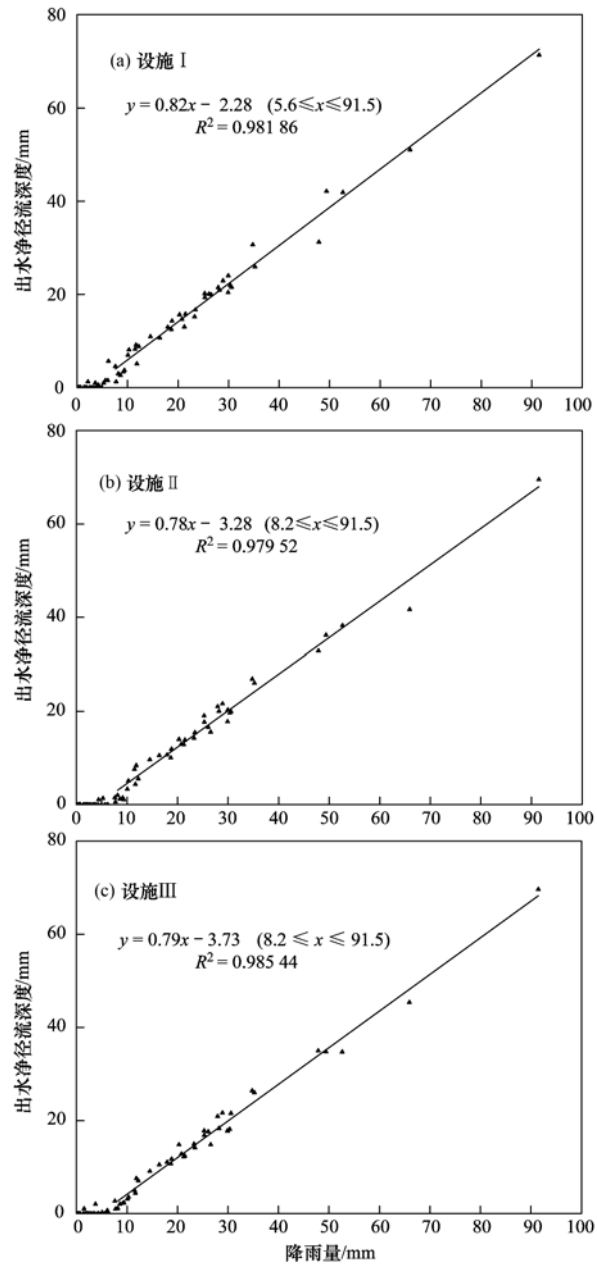


图5 各设施降雨量-出流量关系

Fig. 5 Relationship between rainfall and outflow of each facility

总量控制率关系得到图6。从中可知：在平水年降雨条件下，各设施的径流总量控制率可较实测值高约5%。

2.4 峰值削减与峰现延迟效果

根据产生出流的60场降雨事件的设施出流流量以及空白对照流量评价不同设施的峰值削减与峰现延迟效果，结果见图7。设施Ⅱ与设施Ⅲ的峰值削减率与峰现延迟时间无显著性差异($P>0.05$)；而设施Ⅰ的峰值削减率与峰现延迟时间低于设施Ⅱ、设施Ⅲ，且存在显著差异($P<0.05$)，表明透水混凝土的削峰及峰现延迟能力较差。Collins等^[30]于北

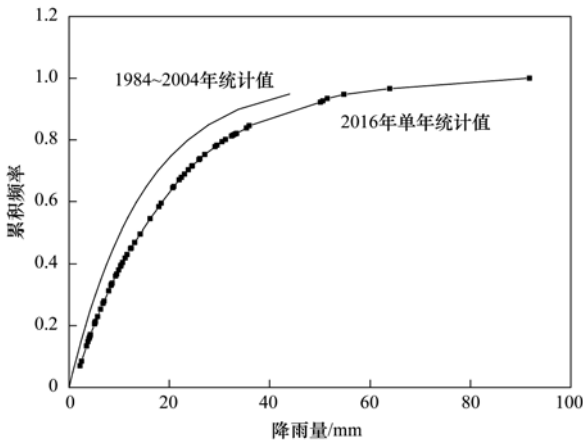


图 6 上海 1985 ~ 2004 年与 2016 年的降雨量概率累积曲线
Fig. 6 Cumulative probability curve of rainfall in Shanghai during 1985-2004 and 2016

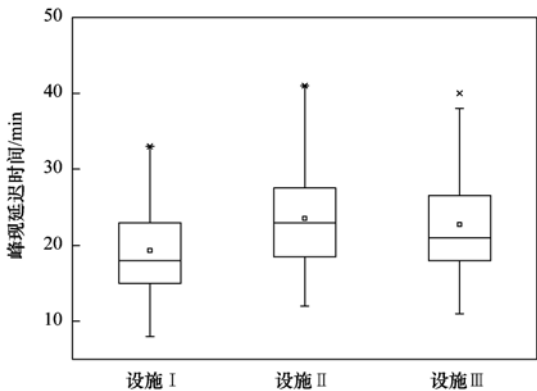
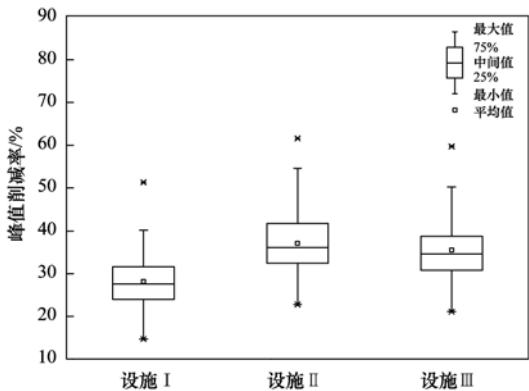


图 7 各设施峰值削减率与峰现延迟时间
Fig. 7 Peak reduction rate and time to the peak rate for each facility

表 4 降雨情况与设施水文效果相关性¹⁾

Table 4 Correlation between rainfall characteristics and hydrological effects of facilities

设施	降雨强度与峰值削减率	降雨强度与峰现延迟时间	前期晴天数与峰值削减率	前期晴天数与峰现延迟时间
I	-0.749	-0.667	0.143	0.172
II	-0.726	-0.645	0.102	0.226
III	-0.722	-0.618	0.122	0.261

1) 黑体字表示数据在 0.05 水平上具有显著性

在大雨期间峰值削减率与峰现时间的影响不明显.

3 结论

(1) 缝隙透水砖面层的稳定渗透速率小于透水混凝土面层. 使用 1 a 后, 2 种面层表面稳定渗透率均明显下降, 实际降雨条件下有径流产生. 透水混凝土铺装、两种缝隙透水砖铺装以及无防渗层的缝隙透水砖铺装的表面产流量之间无显著差异.

(2) 2016 年的实际降雨条件下底部不透型透水混凝土铺装、底部不透型缝隙透水砖铺装的年径流总量控制率分别为 24.2%、28.5%, 平水年各设施的径流总量控制率估算较实测值高约 5%. 加入

卡罗来纳州的半透型透水铺装实验所得的峰值削减率与峰现延迟时间均大于本文的结果, 这可能由于半透型透水铺装底部可以存储、下渗部分水量, 导致出流量较小, 相应峰值削减率与峰现延迟时间较大. 本文的实测结果表明, 不透型透水铺装即使径流总量控制效果较差, 由于出水相对普通不透水铺面径流存在削峰、缓排作用, 对未能就地消纳的径流量仍具有改善场地水文性能的效果.

降雨强度和前期晴天数与各设施峰值削减率和峰现延迟时间的 Pearson 相关系数见表 4. 各设施出流的峰值削减率和峰现延迟时间与降雨强度存在显著负相关性, 而与前期晴天数不存在相关性. 随着降雨强度的增大, 设施峰值削减率与峰现延迟时间呈现对应减小趋势; 而前期晴天数的长短对各设施

5% 水泥的水泥稳定碎石基层强度大于碎石基层且对设施的径流削减能力没有影响, 透水混凝土面层设施的水文控制效果弱于缝隙透水砖面层的设施.

(3) 在实际降雨条件下, 3 种透水铺装设施底部出流量与进流量的关系可以用直线方程表示, 其中透水混凝土设施的拟合方程为 $V_{出水} = 0.82V_{降雨量} - 2.28$ ($5.6 \leq V_{降雨量} \leq 91.5$, 单位 mm), 缝隙透水砖设施的拟合方程为 $V_{出水} = 0.78V_{降雨量} - 3.38$ ($8.2 \leq V_{降雨量} \leq 91.5$, 单位 mm).

(4) 透水混凝土面层设施的峰值削减率与峰现延迟时间小于缝隙透水砖面层设施, 水泥稳定碎石结构层在削峰能力与峰现延迟时间上均与碎石结构

层相近。设施对未能直接消纳的水量仍具有改善场地水文性能的效果。

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