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城市轨道交通车辆段海绵城市设施抵抗暴雨效果数值模拟

NUMERICAL STUDY ON PERFORMANCE OF THE SPONGE CITY FACILITIES FOR URBAN RAIL TRANSIT DEPOT

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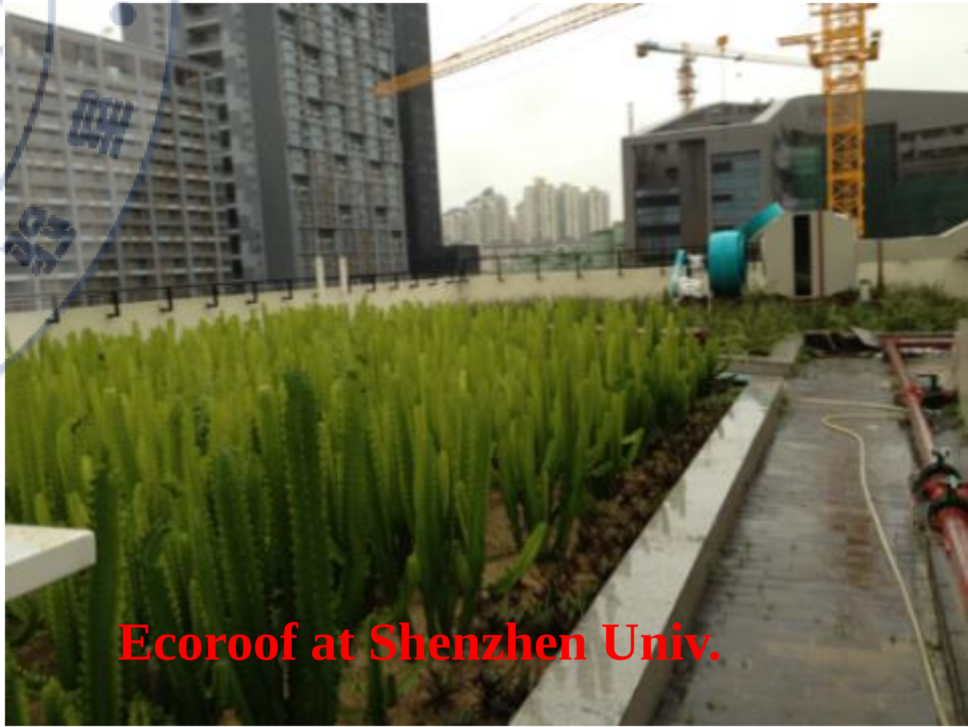
主要内容 Contents



不用浇水、不用施肥、不排放污染物的深圳大学土木结构实验楼生态屋顶

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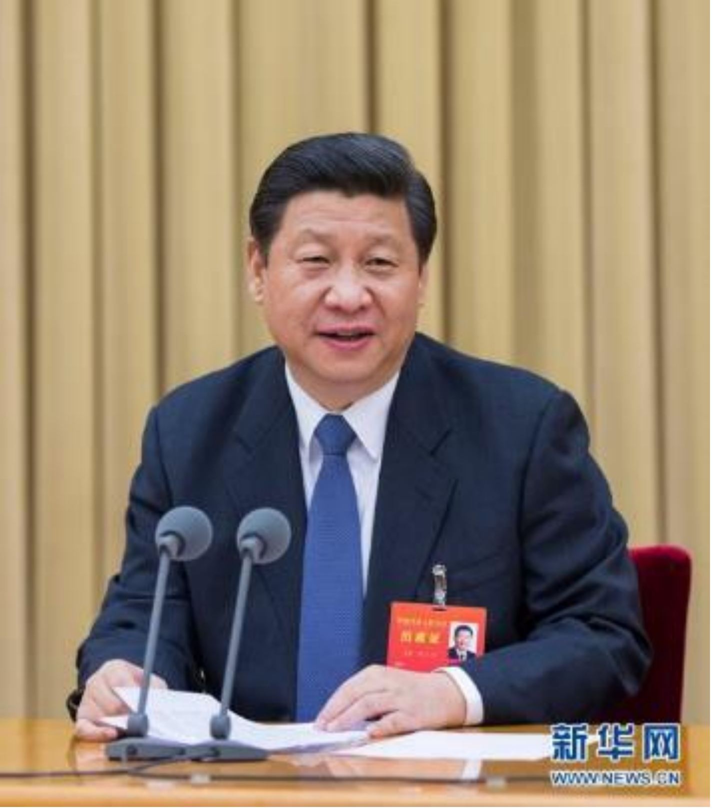


12月12日至13日，中央城镇化工作会议在北京举行。中共中央总书记、国家主席、中央军委主席习近平发表重要讲话。新华社记者王晔摄

海绵城市的由来 Origination of the Sponge City

习总书记在2013年中央城镇化工作会议上明确指出：

为什么这么多城市缺水？一个重要原因是水泥地太多，把能够涵养水源的林地、草地、湖泊、湿地给占用了，切断了自然的水循环，雨水来了，只能当作污水排走，地下水越抽越少。解决城市缺水问题，必须顺应自然。比如，在提升城市排水系统时要优先考虑把有限的雨水留下来，优先考虑更多利用自然力量排水，建设自然积存、自然渗透、自然净化的“海绵城市”。

In consideration of the urban waterlogging and water pollution problems, General Secretary of the Communist Party of China, Xi Jinping, proposed the great strategy of constructing the sponge city through natural storage, natural infiltration, natural purification and natural drainage by gravity flow in December 2013.

1.前言 Introduction

1.1 计算方法 Methods

- 海绵城市设施规模可以采用容积法、数值模拟法、合理公式法和水量平衡法确定;
- 容积法、合理公式法和水量平衡法只能给出海绵城市的规模，不能计算径流变化过程;
- 只有数值模拟法可以模拟海绵城市设施方案的径流变化。

2014年5月11日深圳宝安区107国道（左）和深圳大学（右）受淹状况

- The scale of the sponge city facilities can be determined by volumetric method, numerical simulation, rational formula and water balance method.
- Volumetric method, rational formula and water balance method can only determine the scales of sponge city facilities, but they can not calculate the process of runoff change.
- Only Numerical simulation can simulate the hydrological process of the sponge city facilities.

1.前言 Introduction

1.2 常用的数学模型 Simulation models

- EPA开发的暴雨洪水管理模型（storm water management model, **SWMM**）
- EPA开发的SUSTAIN (System for urban stormwater treatment and analysis integration)
- 英国HR Wallingford公司的InfoWorks
- 丹麦DHI公司专为中国市场的SCAD（Sponge City Aided Design）
- 澳大利亚eWater和莫纳什大学为水敏感城市设计（WSUD）开发的MUSIC（Model for urban stormwater improvement conceptualization）模型

- 这些水文模型的海绵城市模块基本上是在SWMM的LID模块上的再开发的，各种模型的计算结果也大同小异。因此，本研究采用SWMM分析长圳车辆段海绵城市设施的效果。
- These models have similar LID modules of SWMM, therefore, SWMM is used in this study.

2. 长圳车辆段概况及海绵城市设施设计目标

Outline of Changzhen Depot and Index of sponge city construction

2.1 长圳车辆段概况Outline of Changzhen Depot

- 地铁6号线长圳车辆段位于深圳市光明区，鹅颈水东西向横穿地块中部，地块西南角有条鹅颈水南支流穿过。
- 建设场地占地面积24.94ha，总建筑面积23.38ha，其中单体建筑面积16.87ha，无单体盖体面积6.51ha，盖体投影面积为14.82ha。场地不透水面积较大，地表高程介于16.40~23.35m，变化较小。建设场地整体呈北高南低、东高西低之势。
- 在设计海绵城市设施时，应充分发挥建设场地的地形及地理优势，通过创新的设计，充分发挥海绵城市设施的功能。

- The Changzhen Depot of Shenzhen Metro Line 6 is located in Guangming District, Shenzhen. The Ejingshui River and the south tributary of the Ejingshui River flow through the area.
- The land area is 24.94ha, and surface elevations are 16.4 to 23.35m.

图1 长圳车辆段位置图
Location of Changzhen Depot

2. 长圳车辆段概况及海绵城市设施设计目标

Outline of Changzhen Depot and Index of sponge city construction

2.2 海绵城市设施设计目标 Design index of sponge city facilities

1) 控制性指标：年径流总量控制率为70%，对应深圳市设计降雨量为31.3mm；
2) 控制性指标：污染物削减率（以TSS计）大于50%；
3) 控制性指标：污水再生利用率60%；
4) 控制性指标：内涝防治标准50年一遇；
5) 指导性指标：人行道、停车场、广场透水铺装比例90%；
6) 指导性指标：绿地下沉比例60%；
7) 指导性指标：不透水下垫面径流控制比例70%；
8) 指导性指标：因地制宜地布置海绵城市设施，鼓励创新。

1) Control index: 70% volume capture ratio of annual rainfall, corresponding to the design rainfall in Shenzhen of 31.3mm;
2) Control index: Pollutant reduction rate (TSS) is greater than 50%;
3) Control index: Sewage reuse rate is 60%;
4) Control index: waterlogging prevention standard of 50 years return storm;
5) Guiding indicator: Permeable pavement ratio of sidewalk, parking lot and square is 90%;
6) Guiding indicator: Green space depression ratio is 60%;
7) Guiding indicator: Ratio of runoff control to impervious underlying surface is 70%;
8) Guiding indicator: The sponge city facilities should be arranged according to local conditions and innovative facilities should be employed.

3. 海绵城市设施布置方案Layout of the sponge city facilities

3.1 汇水区域划分及方案布置Dividing catchment and scheme of the sponge city facility layout

- 根据长圳车辆段（研究区域）地表高程、建筑形态特点以及车辆段排水规划，将研究区域划分为六个汇水子区域。
- 车辆段出入段线为S1汇水分区，生产仓储区为S2汇水分区，车辆段运行库依据屋面虹吸排水系统划分S3、S4和S5三个汇水子区域，宿舍办公区为S6汇水分区。
  - The catchment is divided into 6 subbasins for laying out the sponge city facilities.

现状下垫面航拍图(从北向南看)

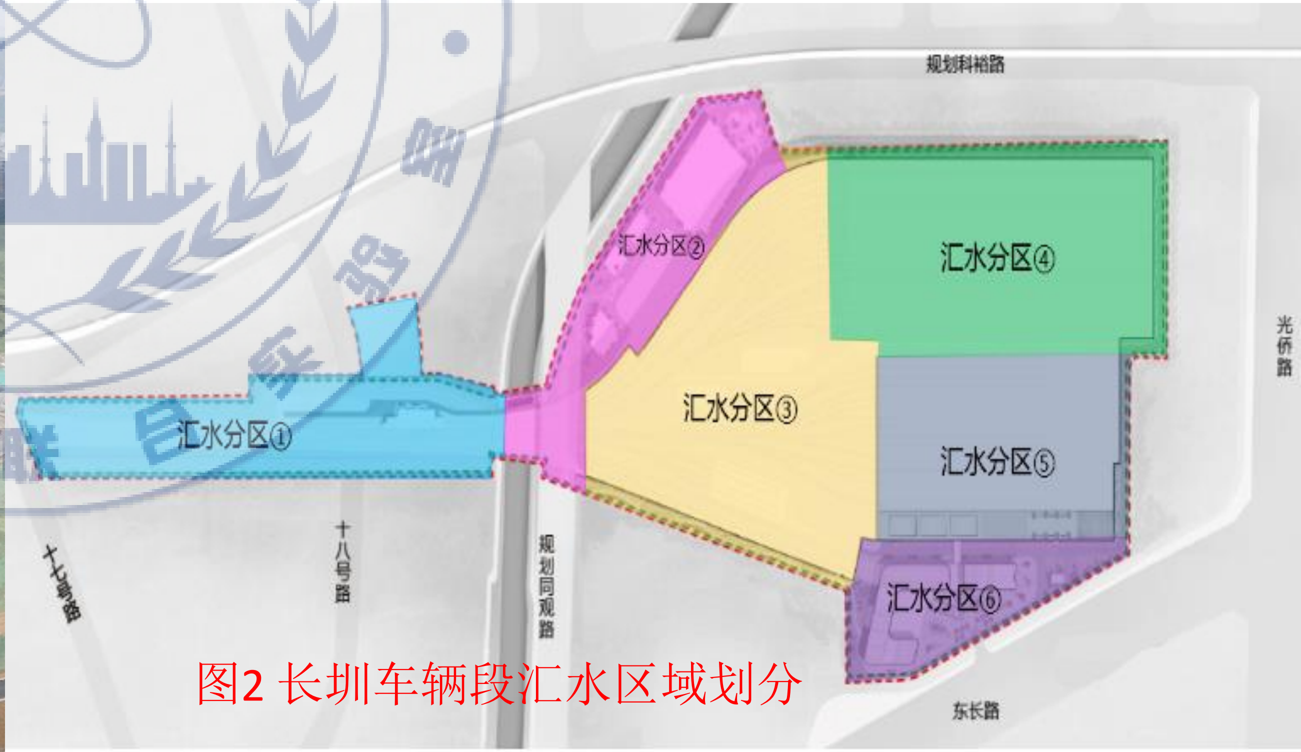


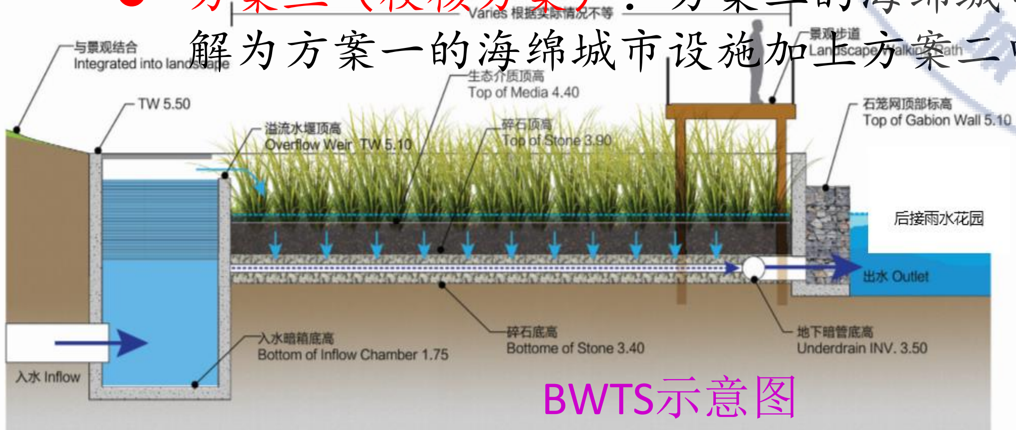
图2 长圳车辆段汇水区域划分

3. 海绵城市设施布置方案Layout of the sponge city facilities

3.1 汇水区域划分及方案布置Dividing catchment and scheme of the sponge city facility layout

制定了以下三种海绵城市设施布置方案：Three schemes were arranged according to the characteristic of the Changzhen Depot.

- 方案一（初始方案）：考虑后期车辆段上盖平台修建生态屋顶（即考虑蓄水功能的绿色屋顶。主要海绵城市设施包括：1）生态屋顶（具有蓄水功能的绿色屋顶）：设置在宿舍楼及主基地上盖部分；2）雨水花园：设置在场地东北角S2汇水分区和西南角的S6汇水分区，用于收集这两个汇水分区的雨水；3）多功能蓄水池（景观湖）：设置在雨水花园末端，用于收集雨水花园渗透后雨水及周边雨水径流；4）地下蓄水池：设置在景观湖末端，用于调蓄雨水；5）高位雨水花坛（Bioretention parterre）：设置在上盖建筑边缘，收集屋面雨水。这种花坛是充分考虑虹吸式排水管而特别设计的；6）透水铺装：主要为场地内停车场及人行步道；7）生态污水处理系统（Biological wastewater treatment system, BWTS）：设置在雨水花园的前端，暴雨时处理雨水，平时处理中水。
- 方案二（优化方案）：鉴于上盖建筑物与目前的车辆段工程建设不同步，对混凝土结构周边的绿地功能进行优化，取消方案一中设置在S4的生态屋顶，将其承担雨水消纳分散到地表S3、S4和S5汇水分区的地表绿地中的生态滞留带（植草沟）承担。
- 方案三（校核方案）：方案二的海绵城市设施加上方案一中被取消的S4汇水分区中的生态屋顶，也可以理解为方案一的海绵城市设施加上方案二中的生态滞留带。本方案主要用于校核海绵城市设施的削减效果。



BWTS示意图

3. 海绵城市设施布置方案Layout of the sponge city facilities

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3.1 汇水区域划分及方案布置 Dividing catchment and scheme of the sponge city facility layout

- Scheme 1 (Initial Scheme): The ecoroof (green roof with water storage function) is built on the platform of the depot after 2022. The main sponge city facilities include: 1) ecoroof : set up on the dormitory building and the depot platform; 2) raingarden: Set up in S2 on the northeast corner and S6 on southwest corner for collection of rainwater in two subbasins; 3) multi-purpose pond (landscape lake): set in near the raingarden to collect runoff from the raingarden in S2; 4) underground pond: set near the landscape lake; 5) Bioretention parterre: set in S3 to collect platform roof rainwater. It is a specially designed planter with full consideration of siphon drains; 6) pervious pavement: mainly for parking lots and sidewalks; 7) Biological wastewater treatment system (BWTS): set in the front of raingarden, which is used to treat rainwater during rainstorm, usually treat the reclaimed water from the sewer treatment plant.

- Scheme 2 (Optimized Scheme): In view of the fact that the superstructure is not synchronized with the current vehicle depot construction, the green space function around the concrete structure is optimized, and the ecoroof set in S4 of Scheme 1 is replaced by the bioretention zone in S3, S4 and S5.

- Scheme 3 (Checking Scheme): The sponge city facility in Scheme 2 plus the ecoroof in S4 of Scheme 1. This scheme is mainly used to check the reduction effect of sponge city facilities.

汇水分区	需求容积（m³）	设计容积（m³）
2	386	1085
3	1709	2134
4	1371	1588
5	1050	996
6	340	312
合计	4856	6115

图例	海绵设施
	汇水分区范围
	建筑边线
	景观湖
	生态停车场
	高位花坛
	水景喷泉
	生态屋顶
	生态护坡
	雨水花园
	生态排水系统
	生态雨水箱
	排水沟
	地下蓄水池

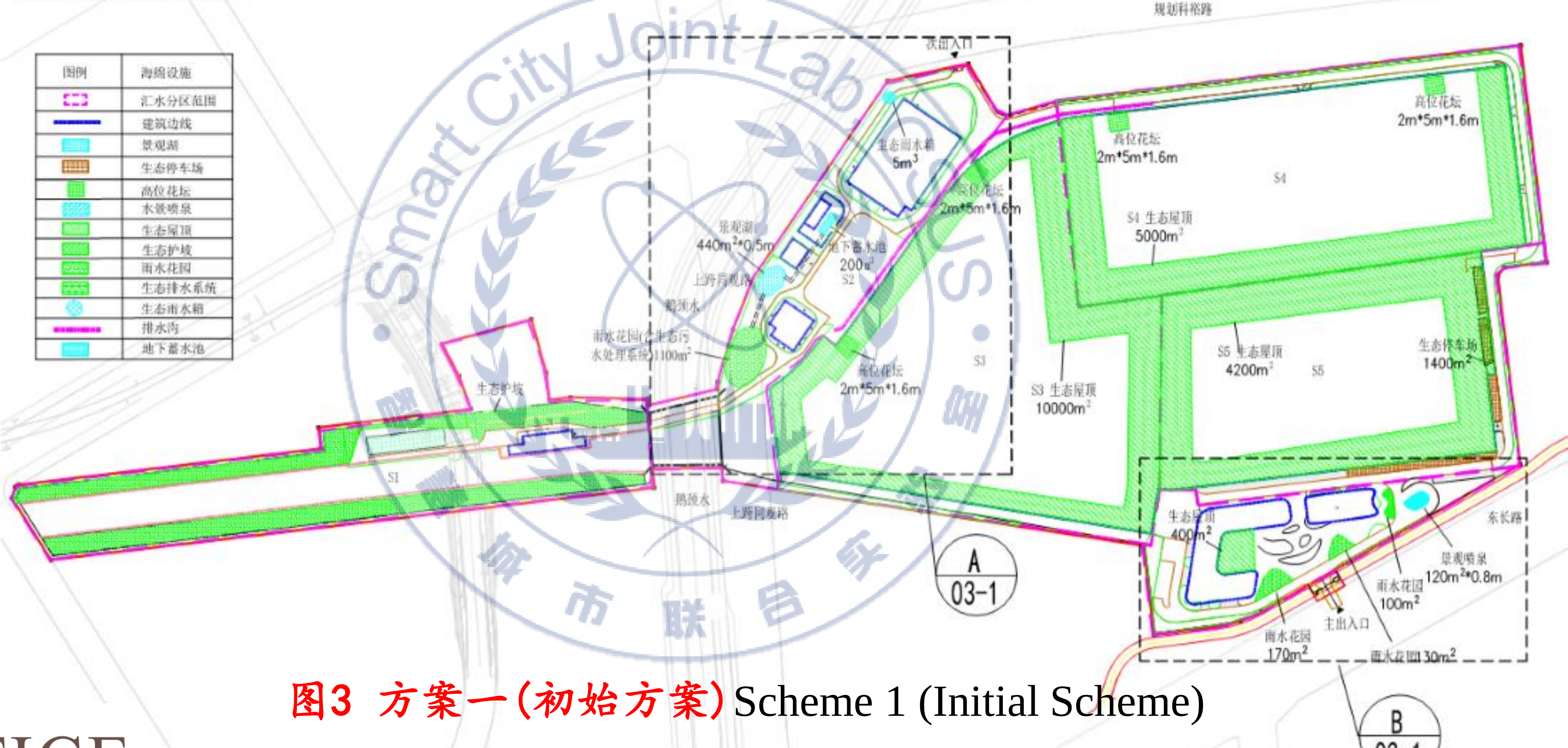


图3 方案一(初始方案) Scheme 1 (Initial Scheme)

汇水分区	需求容积（m³）	设计容积（m³）
2	386	1085
3	1709	2134
4	1371	688
5	1053	996
6	340	312
合计	4856	5215

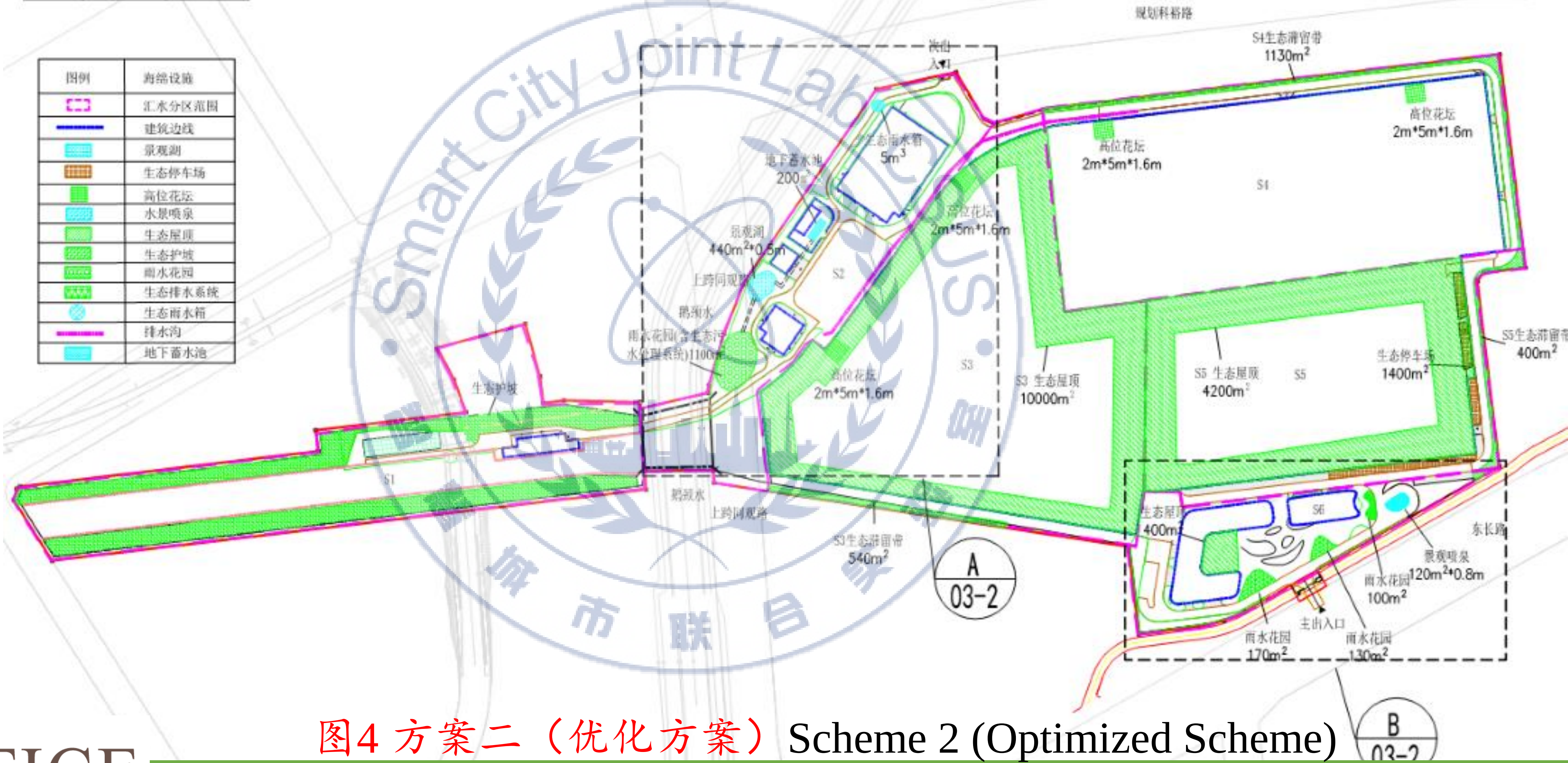
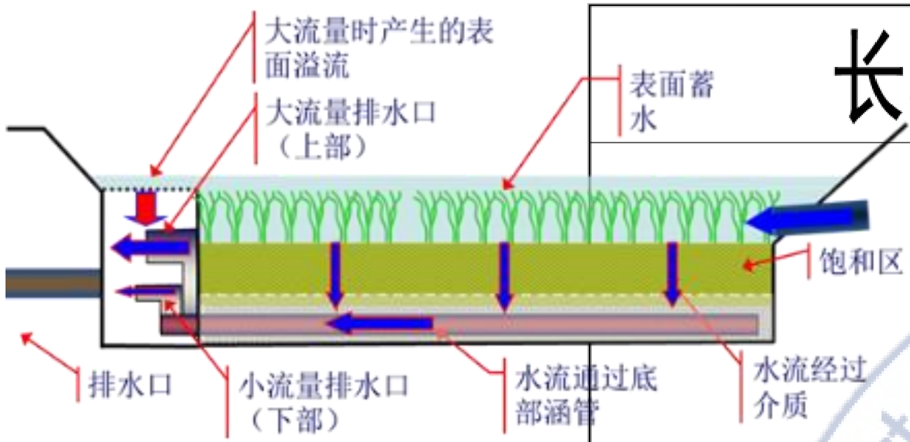


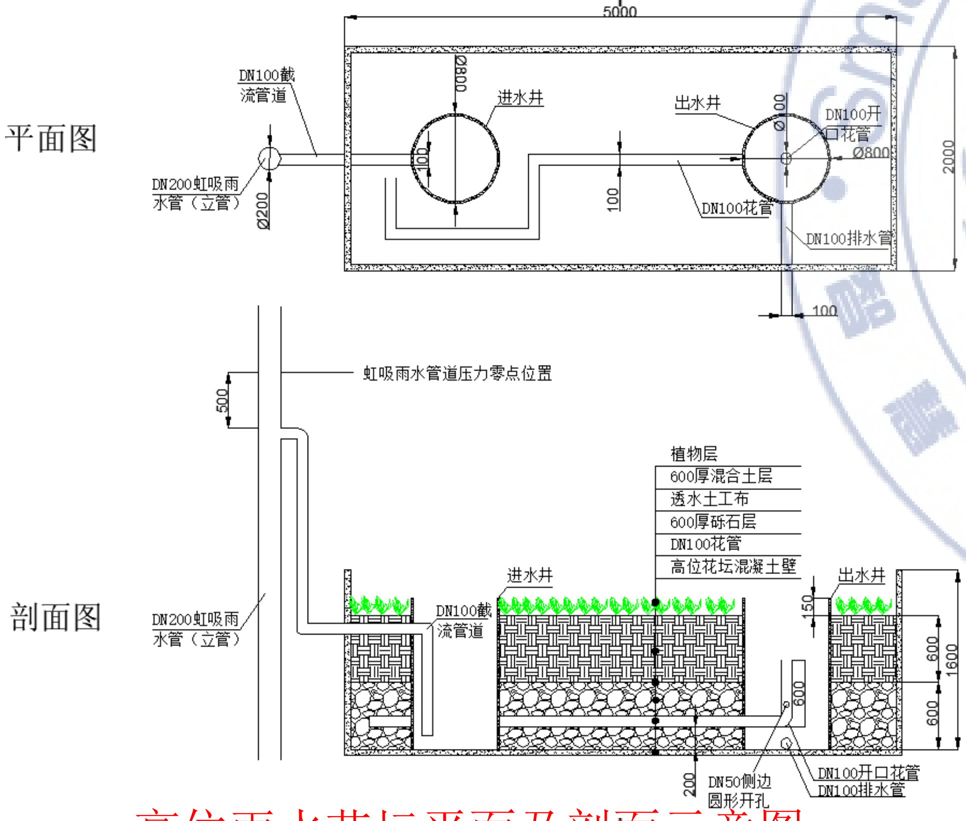
图4 方案二（优化方案）Scheme 2 (Optimized Scheme)

长圳车辆段海绵城市建设试点工程

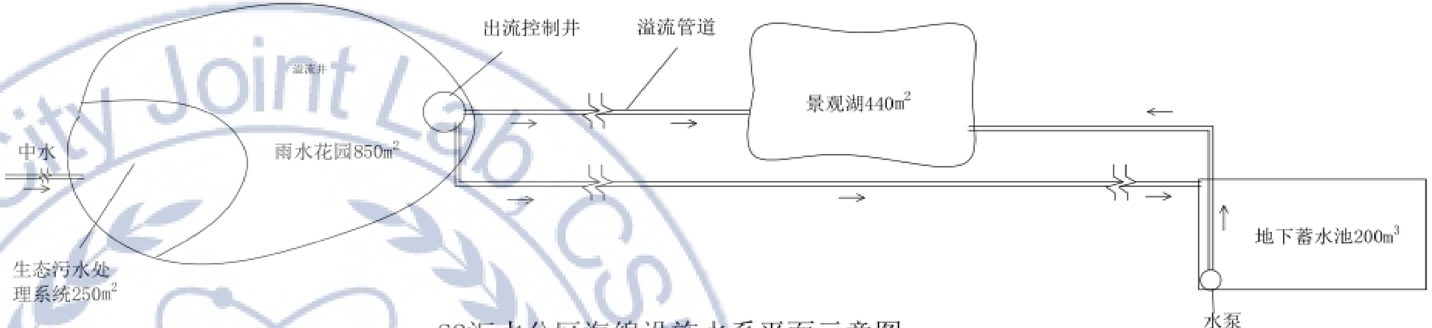
海绵城市设施组合图



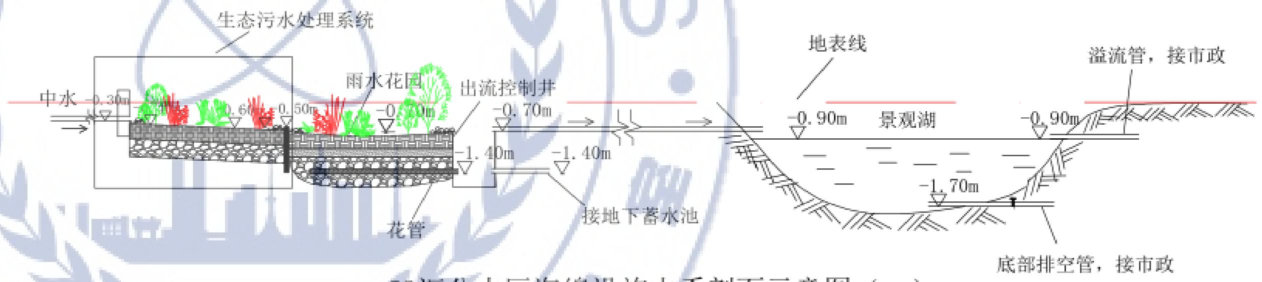
BWTS出口控制装置示意图



高位雨水花坛平面及剖面示意图



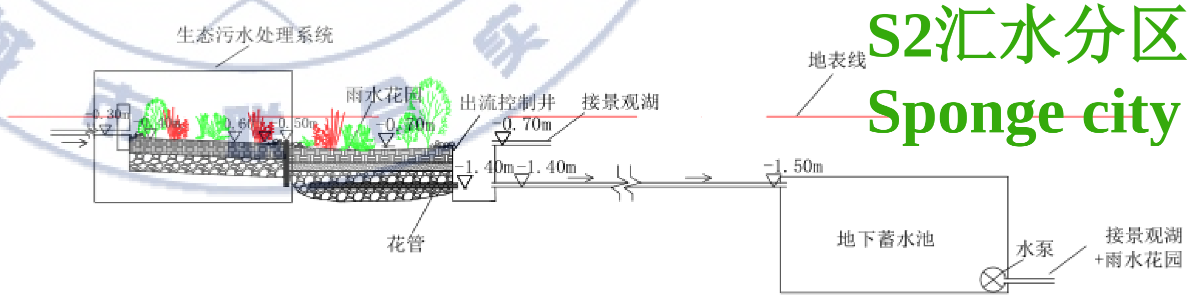
S2汇水分区海绵设施水系平面示意图



S2汇水分区海绵设施水系剖面示意图（一）

S2汇水分区海绵城市设

Sponge city facilities in S



S2汇水分区海绵设施水系剖面示意图（二）

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3.海绵城市设施布置方案Layout of the sponge city facilities

3.2 海绵城市设施规模的确定Determination of the scales of the sponge city facilities

- 各个方案所需海绵城市设施规模根据容积法确定。为消纳70%年径流总量控制率对应的设计降雨量产生的径流量，应设置不小于4856m³的调蓄容积（不计S1）.
- 经过反复试算，方案一、方案二和方案三的海绵城市设施调蓄能力分别为4873m3，5215m3，6115m3；对应的年径流总量控制率分别为70.8%，72.1%，77.2%。
- 方案一、方案二和方案三工程造价分别为1301.6万元、1175.8万元和1425.8万元。可以看出，方案二的远期造价低于其它两个方案。

雨水花园实景图（新加坡嘉佩乐酒店）

- The scales of the sponge city facilities for each scheme is determined by the volumetric method. In order to absorb the runoff generated by the design rainfall corresponding to the 70% volume capture ratio of annual rainfall, the storage volume should not be less than 4856m^3 (excluding S1).
- After repeated trial calculation, the storage capacities of the sponge city facilities of Scheme 1, Scheme 2 and Scheme 3 are 4873 m^3, 5215 m^3 and 6115 m^3, respectively, and the corresponding volume capture ratios of annual rainfall are 70.8%, 72.1% and 77.2%, respectively.
- The project costs of Schemes 1, 2 and 3 are 13.016 million Yuan, 11.758 million Yuan and 14.258 million Yuan, respectively. It can be seen that the project cost of Scheme 2 is lower than those of the other two schemes.

4. 数值模拟 Simulation

4.1 SWMM模型简介 Outline of SWMM

SWMM于1971年由美国环境保护署（EPA）开发，主要用于动态降雨情景下径流水量与水质的模拟分析。该模型经过多次完善升级，在2015年4月发布最新版本EPA.SWMM5.1。模型中包括水文、水利、水质三大模块。目前，SWMM模型广泛应用在城市排水系统规划设计、降雨径流模拟评估、生态雨水管理设施的设计与评价等。

LID模块主要针对下列7种LID设施开发：1）透水铺装、2）雨水花园、3)绿色屋顶、4)街道花坛、5）雨水桶、6)渗渠、7)植草沟。

- SWMM is a dynamic precipitation-runoff model that is used to simulate a single precipitation event or a long-term runoff and water quality. The runoff module comprehensively deals with the precipitation, runoff and pollution load in each sub-basin.
- SWMM for the hydrological calculation of the LID facilities is its LID control module, which can simulate the hydrological process of the following 7 LID facilities:
- 1) Permeable pavement, 2)Raingardens, 3) Green roofs, 4) Street planters, 5) Rainbarrel, 6) Infiltration trench and 7) Vegetative swales.

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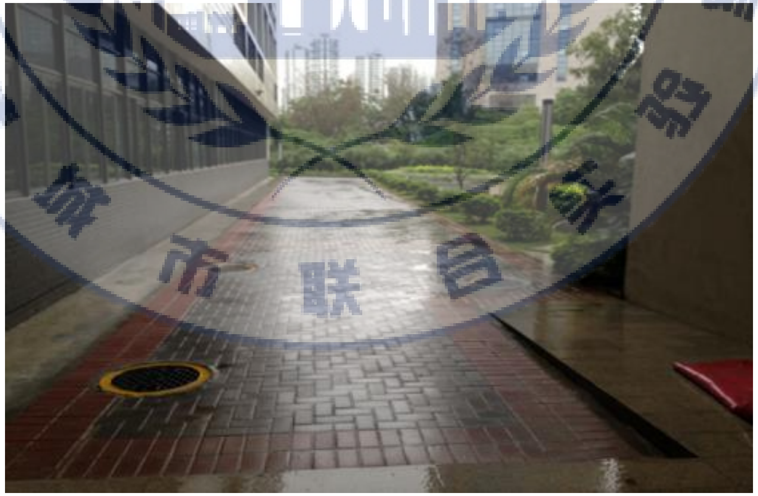
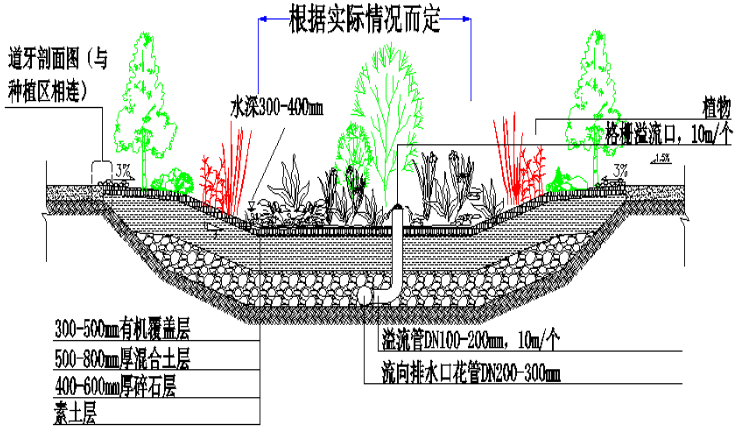


深圳大学透水铺装



雨水花园结构剖面图

4. 数值模拟 Simulation

4.1 SWMM模型简介 Outline of SWMM

- EPA开发的暴雨洪水管理模型（storm water management model, **SWMM**）
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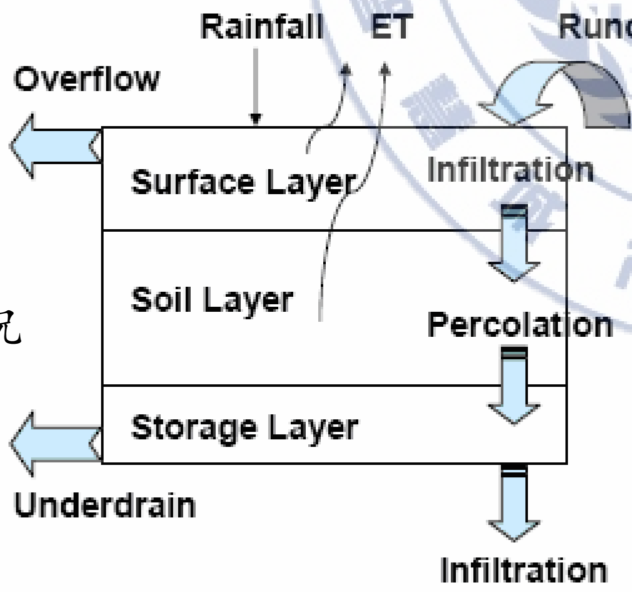
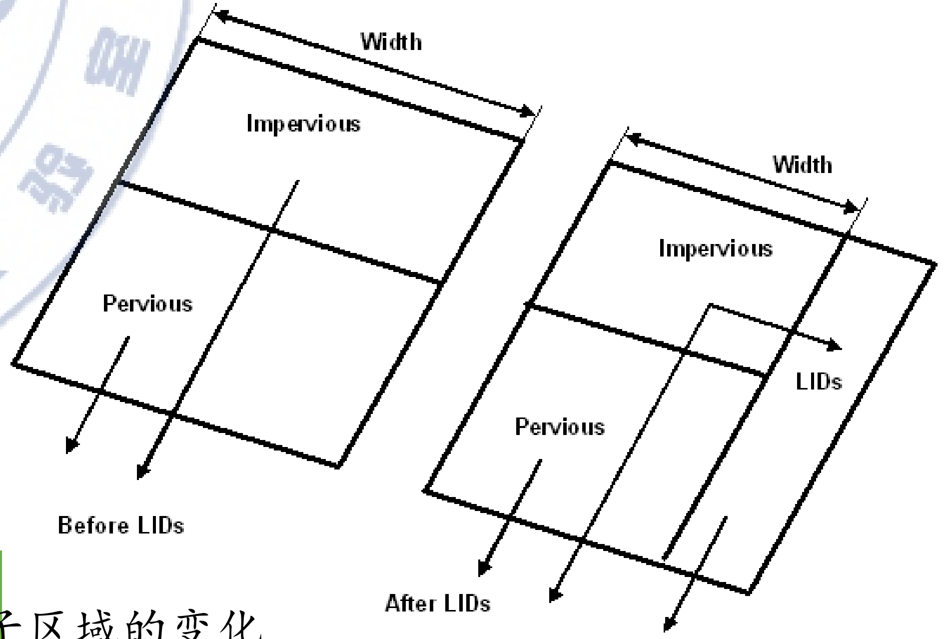


LID设施水流动状况



加入LID模块后子区域的变化

4. 数值模拟 Simulation

4.2 计算条件 Calculated conditions

- 表1给出了深圳市不同重现期对应的24小时历时的降雨量。为了分析不同海绵城市设施布置方案抵抗暴雨的效果，利用SWMM对表2所示的降雨事件进行了模拟分析。同时，为了校核容积法确定的海绵城市规模是否合理，对70%年径流总量控制率对应的设计降雨量，也进行了计算。
- SWMM模型参数根据长圳车辆段的气象、工程地质和水文地质条件、排水管网、海绵城市设施的类型、构造和介质配合比等确定。

高位雨水花坛平面及剖面示意图

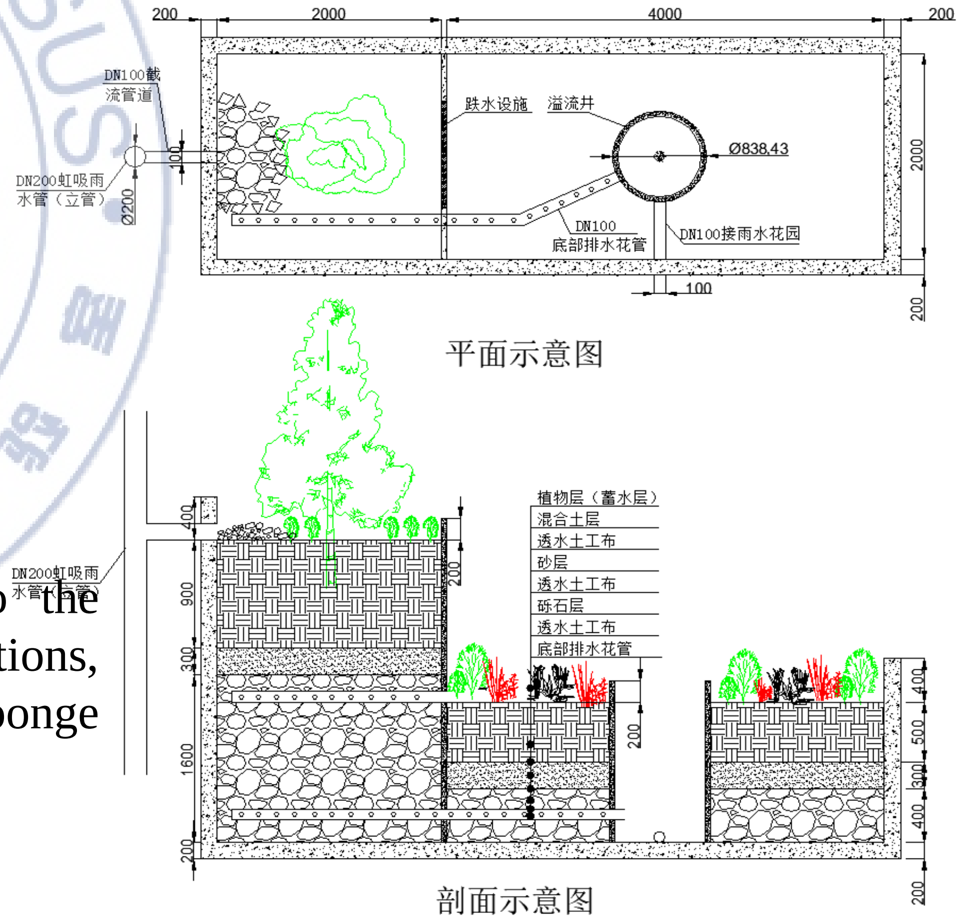


表1 降雨量—重现期对应的关系表

Daily rainfalls with different recurrence interval

重现期（年） Recurrence interval	5	10	25	50	100
降雨量 Rainfall（mm）	217.6	286	386.3	471.4	565.8

- Table 1 lists the rainfalls with different recurrence interval.
- The parameters of SWMM model are determined according to the meteorological, engineering geological and hydrogeological conditions, drainage pipe network, type , structure and media mix ratio of of sponge city facilities in Changzhen depot.

4. 数值模拟 Simulation

4.3.1 设计降雨径流分析 Analysis for design rainfall of 31.3mm

- 表2给出了31.3mm设计降雨量条件下三种海绵城市布置方案的径流量和海绵城市设施的蓄水量。可以看出，三种布置方案的径流量+蓄水量小于容积法确定的海绵城市设施的蓄水能力，这验证了利用容积法确定的海绵城市设施规模和蓄水能力是合理的。
- 需要说明的是，理论上这三种布置方案均可以实现径流不外排，也就是径流量等于零。但是，由于海绵城市设施的排水花管一般布置在地下1.5m处和排水管网也布置在地下1-2m的位置，只要径流渗透至排水花管和排水管网，如果在计算模型中不加虚拟的控制流量流出设施，SWMM模型不能给出径流量等于零的计算结果。

- The 10 minutes distribution of the design rainfall of 31.3mm was obtained by the 10 minutes distribution measured at the Shuiyuan Building on August 19-20, 2005.
- It can be found that sums of the runoff and actual storage water volume for each scheme are smaller than their storage capacities, it means that the sponge city facilities determined by the volumetric method can meet the design goal of 70% annual runoff control rate.

表2 31.3mm降雨量情况下的径流量与蓄水量对比表

Runoff and storage volume of each scheme for 31.3mm design rainfall

方案 Scheme	蓄水容积 Storage capacity（m^3）	实际蓄水量 Actual storage water（m^3）	径流量 Runoff（m^3）
无海绵城市设施 Traditional scheme	0	0	3800
方案一Scheme 1	4873	3517	1025
方案二Scheme 2	5215	3726	1009
方案三Scheme 3	6115	4219	851

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4.3.2 海绵城市设施效果分析 Calculation and Analysis

- 表3给出了不同重现期降雨情况下三种方案径流量对比分析结果。
- 可以看出，海绵城市设施可有效减少研究区域的径流量。
- 径流量的消减效果随着海绵城市设施规模增大而增大。
- 随着降雨重现期的增大，各个海绵城市设施的削减效果逐渐降低。
- Table 3 gives the calculated runoff of traditional pipeline development scheme and sponge city facility development scheme for the rainfalls with different recurrence interval.
- As compared with the traditional development, the cut rate of the runoff decrease with the increase of the recurrence interval of rainfall.
- This indicates that sponge city facilities are more effective for small probability rainfall events.

表3 不同方案径流量（万m³）对比分析
Runoffs for the rainfalls with different recurrence periods

径流量Runoff	5y24h	10y24h	25y24h	50y24h	100y24h
无海绵城市设施 Traditional scheme	3.9	5.25	7.31	9.06	11.04
方案一Scheme 1	3.72	5.03	7.01	8.75	10.7
方案二Scheme 2	3.49	4.82	6.76	8.57	10.53
方案三Scheme 3	3.43	4.74	6.74	8.49	10.44
削减率	4.62%	4.19%	4.11%	3.42%	3.07%
Reduction rate	10.51%	8.19%	7.52%	5.40%	4.61%
	12.05%	9.71%	7.79%	6.29%	5.43%

4. 数值模拟 Simulation

4.3.2 海绵城市设施效果分析 Calculation and Analysis

表4给出了不同重现期降雨情况下三种方案流量峰值的对比分析结果。可以看出，海绵城市设施可有效减少研究区域的流量峰值。流量峰值的消减效果随着海绵城市设施规模增大而增大。随着降雨重现期的增大，各个海绵城市设施方案的削峰效果逐渐降低。当暴雨重现期大于等于50年一遇时，海绵城市设施几乎没有消峰作用。

- Table 4 gives the calculated peak discharges of traditional pipeline development scheme and sponge city facility development scheme for the rainfalls with different recurrence interval.
- As compared with the traditional development, the reduction rates of peak discharges decrease with the increase of the recurrence interval of rainfall.
- This indicates that sponge city facilities are more effective for small probability rainfall events.

表4 不同方案流量峰值（m³/s）对比分析

Peak discharges for the rainfalls with different recurrence interval

峰值 Peak Discharge	5y24h	10y24h	25y24h	50y24h	100y24h
无海绵城市设施 Traditional scheme	3.3	4.47	6.34	7.68	9.43
方案一Scheme 1	3.04	4.15	5.99	7.38	9.42
方案二Scheme 2	3.04	4.15	5.91	7.36	9.31
方案三Scheme 3	2.95	4.1	5.84	7.34	9.31
	7.89%	7.16%	5.52%	3.90%	1.06%
消减率 Reduction rate	7.89%	7.16%	6.78%	4.17%	1.27%
	10.60%	8.28%	7.88%	4.43%	1.27%

4. 数值模拟 Simulation

4.3.2 海绵城市设施效果分析 Calculation and Analysis

- 表5给出了不同重现期降雨情况下三种海绵城市设施布置方案径流系数的对比分析结果。可以看出，海绵城市设施可以一定程度上减少研究区域的径流系数。
- 对于小重现期降雨，随着海绵城市设施规模的增大，径流系数有所减小；但对于大的重现期降雨，径流系数的变化不是十分明显

- Table 5 shows the calculated runoff coefficient of traditional pipeline development scheme and sponge city facility development scheme for the rainfalls with different recurrence interval.
- As compared with the traditional development, the reduction rates of runoff coefficient decrease with the increase of the recurrence interval of rainfall.
- This indicates that sponge city facilities are more effective for small probability rainfall events.

表5 不同方案径流系数对比分析
Runoff coeffeicient for the rainfalls with different recurrence interval

径流系数 Runoff Coefficient	5y24h	10y24h	25y24h	50y24h	100y24h
无海绵城市设施 Traditional scheme	0.84	0.86	0.88	0.89	0.91
方案一Scheme 1	0.79	0.82	0.85	0.87	0.9
方案二Scheme 2	0.75	0.78	0.82	0.85	0.67
方案三Scheme 3	0.73	0.77	0.81	0.84	0.86
消减率	5.95%	4.65%	3.41%	2.24%	1.09%
Reduction rate	10.71%	9.30%	6.82%	4.50%	2.64%
	13.09%	10.47%	7.95%	5.62%	5.49%

4. 数值模拟 Simulation

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- 图5给出了50年一遇24h降雨下三种海绵城市设施方案的流量过程线。
- 可以看出，对于50年一遇24h降雨，海绵城市设施几乎没有削峰作用，对径流量的削减量也很小。这说明海绵城市设施对大的暴雨影响有限。

- Fig. 5 shows the hydrographs of different development modes in the case of rainfall with 50-year return period.
- The sponge city facilities have fewer effects on runoff and peak discharge for 50 years rainfall.

Figure 5 Hydrographs for different development modes for 50 years rainfall

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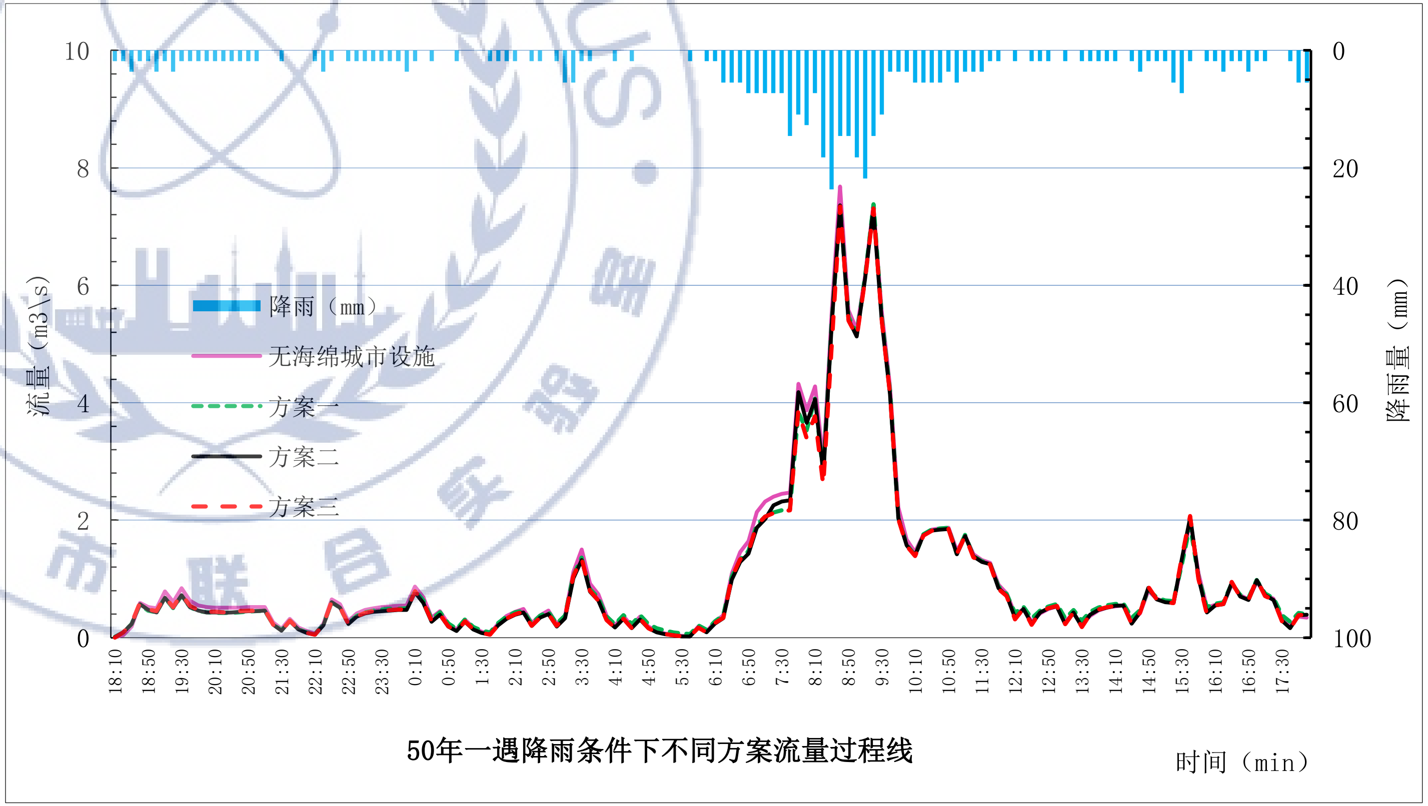

五、结论Conclusions

- 根据长圳车辆段的实际情况和深圳市海绵城市建设要求，确定了包括70%年径流总量控制率、50%面源污染控制率在内的长圳车辆段海绵城市设施建设指标，为轨道交通项目利用海绵城市设施提供了案例。
- 利用容积法制定了三种海绵城市设施布置方案，根据技术经济分析，推荐了造价最低且技术可行的方案二作为长圳车辆段海绵城市建设方案。
- 利用SWMM模型，对三种海绵城市设施布置方案的抵抗暴雨效果进行了分析。结果表明，海绵城市设施可以有效地调节暴雨径流量和流量峰值，随着降雨量的增大，海绵城市设施调节效果逐渐减少。海绵城市设施一般对重现期小于等于25年一遇24h的暴雨有效，对于大于等于50年一遇24h降雨，海绵城市设施几乎没有消峰作用。

- This study analyzes the construction index of the sponge city facilities suitable for urban rail transit depot, and arranges the sponge city facilities by volumetric method, which meet the requirement of the volume capture ratio of annual rainfall of 70% and Nonpoint source pollution control rate of 50%; and puts forward the innovative sponge city facilities such as ecolroof, bioretention parterre and ecological wastewater treatment systems.
- SWMM is used to simulate the runoff process and reduction efficiency of three schemes of the sponge city facilities in Changzhen Depot for the rainfalls with different recurrence interval from 5 years to 100 years.
- The volumetric method is only able to determine the scales of the sponge city facilities; however, it cannot simulate the dynamic runoff process of the sponge city facilities.
- SWMM can be used to determine the scales of the sponge city facilities, and it effectively simulate the hydrological process for different layout schemes.
- The results calculated by SWMM show that the sponge city facilities have obvious effects of peak discharge and runoff reduction for the storms less than 25 years return, and have fewer effects for the rainfalls with more than 50 years return.

城市轨道交通海绵城市抵抗暴雨效果数值模拟

Numerical study on performance of the sponge city facilities for urban rail transit depot

Thank you very much!

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