Underground sewage treatment plant: a summary and discussion on the current status and development prospects

Shichang Sun, Huihua Lin, Junhao Lin, Zonggang Quan, Peixin Zhang and Rui Ma

ABSTRACT

Increases in the global population and urbanization have made people's demand for rational development and utilization of urban underground space (UUS) increasingly urgent. The underground sewage treatment plant (USTP) plays an important role in sustainable urbanization as part of the UUS. Nevertheless, problems such as high operating costs and large safety hazards still restrict the development of the USTP. In this paper we intend to summarize the current application of the USTP, reflecting the specific and novel aspects of the USTP, and also some technology drawbacks and main process update problems, providing some development suggestions. To do this, essential information on USTPs globally is simply and clearly revealed under due diligence, providing a development process for the USTP and making a prediction for its future development. Furthermore, combined with the main treatment process and ecological value analysis, we give a valid view of the good application prospects of the USTP, which provides a reference for the future construction of USTPs.

Key words | investment, land occupation, process, prospect, underground sewage treatment plant

Shichang Sun
Huihua Lin
Junhao Lin
Peixin Zhang
Rui Ma
College of Chemistry and Environmental Engineering,
Shenzhen University,
Shenzhen, 518060,
China

Shichang Sun
Research Center for Water Science and Environmental Engineering,
Shenzhen University,
Shenzhen, 518055,
China

Zonggang Quan (corresponding author)
Xi'an Research and Design Institute of Wall and Roof Materials,
No. 6, Chang'an South Road, Yanta District, Xi'an 710061,
China
E-mail: *quanzg01@163.com*

INTRODUCTION

The activated sludge (AS) process has been in existence for more than 100 years since its inception. During this time, different types of wastewater treatment processes oriented by different treatment purposes have emerged one after another, such as anaerobic/anoxic/oxic (A/A/O) (Qiang *et al.* 2015), anoxic/oxic (A/O) (Peng *et al.* 2006), membrane bioreactor (MBR) (Ren *et al.* 2010), moving bed biofilm reactor (MBBR) (Gilbert *et al.* 2014), sequencing batch reactor (SBR) (Qin *et al.* 2005), oxidation ditch (OD) (Alaya *et al.* 2010), NF/RO membrane (Tang *et al.* 2011) and so on in recent years. The sewage treatment plant (STP) with these treatment processes as the main body is an important facility for solving the problem of water pollution and has been playing an important role in improving the urban ecological environment and saving water resources. Due to considerations of cost investment, process technology, energy consumption and greenhouse gas emissions, most of the existing STPs in operation have adopted the above-ground construction form. In order to minimize odor, noise and other pollution, these above-ground sewage treatment plants (ASTPs) are basically built on the outskirts of the city, away from the downtown area. Nevertheless, with the continuous advancement of global society and economy, the shortage of land resources in big cities such as New York, Beijing, Tokyo, Hong Kong, and others is becoming more and more serious (Ho *et al.* 2016). The ASTPs that used to be on the outskirts of the city are now surrounded by new residential areas and are gradually becoming the new urban centers. Correspondingly, odor and noise pollution emerge and cause negative effects for the residents nearby. As a consequence, an environmentally friendly underground sewage treatment plant (USTP) with a smaller area (only 1/3–1/2 of the area of ASTP) and no odor pollution has gradually attracted people's attention (Kämppi 1994).

doi: 10.2166/wst.2019.429

Urban underground space has been used to accommodate a variety of urban infrastructure, such as the subway, underground parking lot, underground shopping center and USTP (Makana *et al.* 2016). Reasonable development and utilization of underground space can alleviate various contradictions in modern urban development (Nishida & Uchiyama 1993; Malone 1996; Wallace & Ng 2016). The 21st century is a new era for human development and utilization of underground space. Developed countries and developing countries have progressed rapidly in the exploration and utilization of underground space. USTPs have ushered in new development opportunities. However, the technical problems in the maintenance and upgrading of USTPs cannot be ignored. When the main treatment process is designed and selected, it must comprehensively consider the project investment, total sewage treatment, effluent water quality requirements, sludge production and other aspects (Wilson 1994). A reasonable, advanced and capable main process is crucial to the sewage treatment capacity and treatment effect of the USTP, which is directly related to the future development of the USTP (Wang & Gong 2018). However, there is no article that systematically summarizes and discusses the advantages and disadvantages, main process types, existing problems and future development prospects of the USTP.

In order to make up for the gap in the review of USTPs, and to promote the application and promotion of USTPs in the field of sewage treatment, this paper makes a summary of the current application and development prospects of USTPs. To accomplish this, the author has spent years collecting data on USTPs around the world. This paper comprehensively introduces the structural characteristics and derivative forms of USTPs, and the development, changes and application status of the mainstream treatment processes of USTPs. In particular, this paper also compares and analyzes the differences in engineering construction, land occupation cost and sewage pipe network investment between USTPs and ASTPs in combination with actual engineering cases. In addition, this review provides a comprehensive analysis of the landscape design of the sewage treatment plant and the construction of the urban complex, revealing the economic value and ecological value of the USTP. Finally, in view of the problems in the operation, safety and management of USTPs, it is pointed out that the innovation and breakthrough of sewage treatment technology and the development of construction technology are the keys to the sustainable development of USTPs.

THE ENGINEERING DESIGN OF USTP

Structural features of USTP

The USTP refers to the whole or part of the sewage treatment structures and auxiliary buildings set in the underground space naturally formed or manually excavated below the ground to form a plant that can meet the needs of sewage sludge treatment. Daily inspections, operations, and maintenance activities can be completed in the space below the ground. In general, USTPs usually adopt a double-layer underground design. The second floor underground (-2F) is usually used as the pool layer of sewage and sludge treatment structures, and the first floor underground (-1F) serves as the operation management layer and the production auxiliary building layer (Qiu 2011). The ground floor above the underground structures can be used to construct natural buildings such as comprehensive office buildings, parking lots, sports fields and other functional buildings or green park spaces. At present, most of the USTPs in the world adopt this double-layer underground design. This design has significant advantages in saving land cover, controlling noise pollution and odor pollution, and beautifying the natural landscaping, compared with the traditional arrangement in the ASTPs.

Derivative forms of USTP

Semi-USTP

Semi-USTPs refer to sewage treatment plants built partly underground and partly above-ground, where there is a certain height difference between the aboveground structure and the underground structure. In the semi-USTP, workers generally conduct inspections, operations, and maintenance on the above-ground space. For such a semi-USTP, the number of floors on the top of the above-ground structure of the semi-USTP continues to increase, forming a building with a basement and a ground floor, and then, a building-type USTP is formed (Qiu 2017). Sewage treatment ponds or auxiliary buildings can be installed in the underground and above-ground floors of a building-type USTP. The semi-USTP or the building-type USTP own the advantages of lower construction and operation cost, mainly due to the smaller excavation works in the underground space, compared with the double-layer underground USTP.

Tunnel/rock-cave-type USTP

The tunnel/rock-cave-type USTP is built in a tunnel or a rock cave. It generally does not change the original mountain structure and surface landscape, and has good adaptability for mountainous cities, such as Hong Kong (Wallace & Ng 2016). In tunnels or rock caves, sewage treatment structures are either divided into upper and lower floors above the ground or spread out on one floor. The staff operates and maintains directly the treatment structures, and there are long roads and passages nearby. It is convenient for vehicle operation and personnel passage. There are a large number of ventilation and vents inside the tunnel/cave, which are connected to the shaft for ventilation and deodorization. The tunnel/rock cave USTP needs engineering survey and cavern support planning work to be carried out for the geotechnical soil in the selected area before construction. The key guarantee for the good operation of a tunnel/rock cave USTP is advanced design concepts and mature construction technology experience. In the 1980s, Hong Kong constructed an 80,000-metre-deep underground cavern to house a sewage treatment plant after a careful inspection, planning, and design process. This has greatly alleviated the problem of Hong Kong's dense population and tight land resources.

Buried sewage treatment plant (BSTP)

When the elevation of the pool body in the USTP is lower than or equal to the elevation of the flat surface, this form of the sewage treatment plant is called the buried sewage treatment plant (BSTP) (Qiu 2017). The main difference between the BSTP and the USTP is whether production activities such as daily inspection, operation, and maintenance by operators enter the underground space. The daily inspection operation and maintenance by workers in the BSTP are carried out in the above-ground space, while the inspection space of the USTP is mainly completed in the ground. The structure of the BSTP is provided with opening facilities such as observation holes and manholes on the ground above the pool surface. Another significant difference between the BSTP and the USTP lies in the scale of sewage treatment. The treatment scale of the BSTP is very small, generally ranging from 100 m^3/d to 10,000 m^3/d. The sewage treatment process of the BSTP generally adopts the MBR process, which has a better water discharge effect and low investment cost and is an intensive and efficient sewage treatment system. The above-ground space is generally designed as a simple green park space, and the other floor space is almost zero.

GLOBAL APPLICATION OF USTPS

Statistical analysis

The world's first USTP originated in Finland, and the USTP has been slowly developed since then. The first USTP in Sweden was built in the 1950s, but the USTP failed to develop further due to geological conditions and technical conditions. In the 1980s and 1990s, with the advancement of science and technology, and the consideration of environmental protection, land resources and economic benefits, USTPs gradually attracted people's attention (Bartel & Janssen 2016). Many countries were actively and intensively developing USTPs. The first USTP in Pec pod Sněžkou was selected owing both to environmental concerns and the promising geology of the proposed site (Uher 1987). In recent years, with the rapid development of the social economy and underground excavation technology, the USTP has undergone significant development and application. In China, from 2010 to 2019, more than 30 USTPs were put into operation, and some USTPs are under construction. In Finland, Sweden, Norway, Japan, and other countries, with superior geological conditions and advanced excavation technologies, a certain number of USTPs have been built. In addition, in some big cities in the Netherlands, South Korea, England, Singapore, Malaysia, etc., a number of USTPs have also been established, which have alleviated the problems of urban land occupation and environmental pollution (Maejima *et al.* 2003). According to extensive on-site and data investigations, the derivative forms, name, location, scale, commissioning time, treatment process and water use of nearly 50 USTPs have been summarized. The relevant information is shown in Table 1.

The available sewage treatment technology of the USTP is very extensive. With the development of science and technology, some typical processes used in ASTPs such as A/A/O, MBR, multiple A/O, MBBR, SBR, etc. are gradually being used in the USTPs. The treatment scale of a single USTP has increased from a minimum of $1*10^4$ m^3/d to a maximum of $60*10^4$ m^3/d, and the total sewage treatment scale of all the USTPs has increased from $10*10^4$ m^3/d to more than $300*10^4$ m^3/d. The effluent quality of USTPs has also continuously improved, and the use of effluent has changed from the initial emission to the current

Table 1 | A summary of 50 USTPs in chronological order

Item	City	Country	Scale (*10^4 m^3/d)	Completion (year)	Process
ReDokhaven	Rotterdam	The Netherlands	34.0	1987	AS
Kashima	Shimane	Japan	0.2	1992	AS
Viikinmäki	Helsinki	Finland	27	1994	AS
Stanley	Hong Kong	China	1.2	1995	AS
Hayama	Kanagawa	Japan	0.7	1999	AS
Bromma	Stockholm	Sweden	14.0	1999	AS
Noval	Eastburn	England	21.6	2000	AS
Bekkelaget	Oslo	Norway	16	2000	AS
Neihu	Taipei	China	15	2002	AS
Daegu	Daegu	Korea	4.5	2002	A/A/O
Toulon	Toulon	France	10	2002	A/A/O
Ukima	Tokyo	Japan	10	2003	A/A/O
Yongin	Yongin	Korea	11	2005	AS
Incheon	Incheon	Korea	13.0	2005	A/A/O
Dihua	Taipei	China	50	2007	Multiple A/O
Geolide	Marseille	France	30	2008	BAF
Jingxi	Guangzhou	China	10	2010	MBR
Biological island	Guangzhou	China	1	2010	SBR
Buji	Shenzhen	China	20	2011	A/A/O
Kunming No.10	Kunming	China	15	2012	MBR
Jingang District	Zhangjiagang	China	2.5	2012	A/A/O + MBR
Kunming No.9	Kunming	China	10	2013	MBR
Guxian	Yantai	China	6	2013	A/A/O
Industrial park	Suzhou	China	3.6	2013	MBR
Qingshan	Guiyang	China	5	2014	A/A/O
Madi River	Guiyang	China	3	2014	A/A/O
South 3rd Ring	Zhengzhou	China	10	2014	A/A/O
Anning	Kunming	China	6	2014	A/A/O
Taiping	Kunming	China	2.5	2014	A/A/O
High-tech District	Tsingtao	China	9	2014	MBBR
Shiwuli River	Hefei	China	5	2014	A/A/O
Kunming No.11	Kunming	China	6	2015	A/A/O
Kunming No.12	Kunming	China	5	2015	SBR
Zhengding	Shijiazhuang	China	10	2015	MBR
Binhu District	Hefei	China	3	2015	MBR
Busan	Busan	Korea	10	2015	A/A/O + MBR
Henriksdal	Stockholm	Sweden	86.4	2015	MBR
Taozi Bay	Yantai	China	15	2016	MBR
Tiantang River	Beijing	China	8	2016	A/A/O + MBR
Daoxianghu	Beijing	China	8	2016	MBR
Jinyang	Taiyuan	China	32	2016	A/A/O + MBR

(*continued*)

Table 1 | continued

Item	City	Country	Scale (*10^4 m^3/d)	Completion (year)	Process
Xiaojia River	Beijing	China	8	2016	A/A/O + MBR
Gunagan	Guangan	China	5	2016	A/A/O
Bishui	Beijing	China	18	2017	Multiple A/O
Nanxiang	Shanghai	China	15	2017	A/A/O
Kuige	Guangan	China	2	2018	A/A/O
Sanqiao	Guiyang	China	4	2018	A/A/O
Huaifang	Beijing	China	60	2019[a]	MBR
Pantai No.2	Kuala Lumpur	Malaysia	32	2020[a]	A/A/O
Changi No.2	Changi	Singapore	22.8	2020[a]	A/A/O + Anammox

[a]Scheduled time. There may be some errors or omissions in this table, we welcome readers to modify and improve it.

recycling. Hence we arrive at the conclusion that the USTP has a very broad development prospect worldwide.

Development trend of USTP

The total number of USTPs with different sewage treatment processes and their respective annual trends are shown in Figure 1. Since 1990, the 'not-in-my-backyard' problem of urban STPs has been of more and more concern (Wang & Gong 2018). From the current statistics on the total number of USTPs and their annual changes, before 2000, the total number of all USTPs was no more than ten, and all adopted the AS process. In the 10 years from 2001 to 2010, although the total number of new USTPs (ten) changed little compared with that before 2000 (eight), the main treatment process used by these USTPs has changed significantly. In general, after 2000, the types of sewage treatment processes have tended to diversify, and many new wastewater treatment processes, such as biological aerated filter (BAF), SBR and MBR processes, have also been used in USTPs. We know that the development of wastewater treatment processes is closely related to the state of social development, changes in people's needs, and advances in science and technology. It can be seen that before 2000, the pollutants in urban sewage were relatively simple, mainly for the purpose of removing chemical oxygen demand (COD), nitrogen and some suspended substances. The discharge standard of effluent was relatively low, and the AS method was the most mature technology at that time. Therefore, the USTP is the most secure using the AS process. Since 2000, with the development of society, the composition of urban domestic sewage has become complicated, the refractory organic matter has increased, phosphorus pollution is serious, and even some new pollutants have appeared. It is impossible to meet people's requirements for water quality treatment by relying only on the AS process. At the same time, people have accumulated enough experience in the planning and design of USTPs, and in the development of technology there has been great progress. Some new sewage treatment technologies that are mature in the application of ASTPs are gradually being applied to USTPs. Since 2011, the total number of USTPs has increased significantly, reaching 31, of which 13 are in the A/A/O process, nine in the MBR process and four in the A/A/O + MBR process. This indicates that with the intensification of urbanization, the development of USTPs is getting better and better, and the sewage treatment process used in USTPs is also tending to become diversified and efficient. Moreover, the Anammox process with low energy consumption, less residual sludge, and no need for any carbon source has been first applied

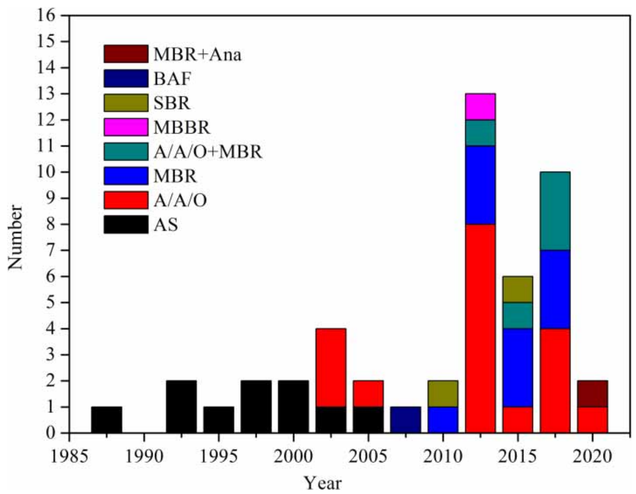

Figure 1 | Annual variation of the number of USTPs with different processes.

to the Changi No.2 USTP. It indicates that achieving energy saving and consumption reduction while ensuring high water quality will become the main goal of future underground sewage treatment (Hao *et al.* 2014).

Before 2010, the annual change in the total scale of sewage treatment in USTPs showed a similar trend as the total number of water plants (Figure 2). After 2010, there was a continuous growth of the treatment scale, increasing from $97.6*10^4\ m^3/d$ to $175*10^4\ m^3/d$. This growth showed a different trend from the change in the number of USTPs. This is because, in 2015, although the number of newly built USTPs had decreased, the treatment scale of single USTPs had increased significantly. For example, in the Henriksdal USTP in Stockholm, after an upgrade, the MBR treatment process was adopted, and the treatment scale reached $86.4*10^4\ m^3/d$, becoming the largest USTP in the world. It can be predicted, with the innovation of sewage treatment technology and the continuous progress of underground excavation technology, that the treatment scale of USTPs will gradually increase.

Comparative analysis of different sewage treatment processes

The USTP has higher requirements for the selection of the optimal sewage treatment process due to the limitation of geological and environmental risks compared with the ASTP. At the same time, USTPs need to solve more technical problems and spend higher costs in the planning, construction and environmental assessment process. Therefore, it is especially important to reduce operating and maintenance costs through a combination of process innovation and process optimization. Accordingly, the sewage treatment processes with the advantages of shorter process flow, fewer processing units and more convenient design have become increasingly popular. Therefore, since 2000, some sewage treatment processes with small land occupation, large volumetric load, high treatment efficiency and low residual sludge generation have been widely used in the USTP, such as MBR, MBBR, SBR, BAF, etc. The comparison of the total number and total treatment capacity of USTPs with different treatment processes worldwide is shown in Figure 3. The number distribution of USTPs in different treatment processes is: A/A/O (18) > AS (10) = MBR (10) > A/A/O + MBR (5) > SBR (2) > BAF (1) = MBBR (1) = MBR + Anammox (1). The total processing scale of USTP for different treatment processes is quite different. The processing scale from large to small is: MBR ($221.0*10^4\ m^3$) > A/A/O ($159.0*10^4\ m^3$) > AS ($140.7*10^4\ m^3$) > A/A/O + MBR ($60.5*10^4\ m^3$) > BAF ($30.0*10^4\ m^3$) > MBR + Anammox ($22.8*10^4\ m^3$) > MBR ($9.0*10^4\ m^3$) > SBR ($6.0*10^4\ m^3$). It can be found that A/A/O and MBR have an absolute advantage over other processes, both in terms of quantity and total sewage treatment scale. In addition, compared with the A/A/O process, the MBR process has more advantages in upgrading the treatment scale of the USTPs.

In order to better analyze the advantages of each sewage treatment process applied to USTPs, the advantages and disadvantages of each sewage treatment process and the treatment scale were compared (Table 2). It can be seen from Table 2 that the MBR process has the advantages of low land occupation, high nitrogen and phosphorus removal efficiency, stable operation, little residual sludge generation, and can realize fully automatic control, etc. The MBR

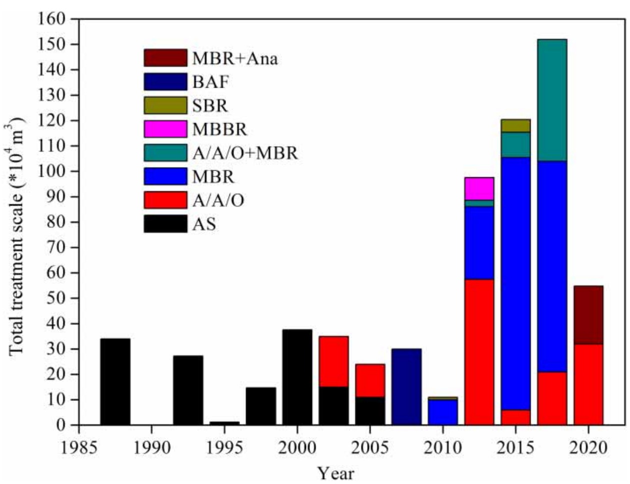

Figure 2 | Annual variation of the treatment scale of USTPs with different processes.

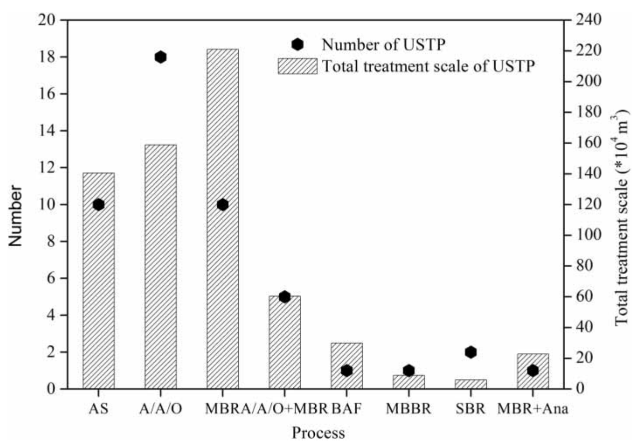

Figure 3 | Comparison of the number and the total treatment scale of USTPs with different processes.

Table 2 | Comparisons of different sewage treatment processes in USTPs

Process	Treatment scale (10^4 m^3/d)	Advantages in USTPs	Disadvantages in USTPs
MBR	3.0–86.4	Low land occupation, high nitrogen and phosphorus removal efficiency, stable operation, little residual sludge generation, suitable for secondary and advanced treatment.	High construction investment, high operation and maintenance costs.
A/A/O (& multiple A/O)	2.0–32.0	Low construction investment, low operation and maintenance cost, high removal efficiency, stable effluent quality, can be combined with other processes.	Large land occupation, high residual sludge generation, low carbon source consumption, needs other units for advanced treatment.
MBBR	9.0	High treatment load, low construction investment and operating costs, low sludge yield, less land occupation.	Low removal efficiency, low stability.
SBR	1.0–5.0	Simple process flow, convenient management, low land occupation, low construction investment, good treatment efficiency, low sludge yield.	High requirements for automation, high operation and maintenance cost.
BAF	30.0	Low land occupation, high removal efficiency, low operation cost, strong impulsion load resistance.	High requirements for automation, easy blockage, difficult backwashing.
AS	0.2–34.0	Low construction investment, low operation and maintenance costs.	Low removal efficiency, large land occupation, high sludge yield.

process is one of the most advanced wastewater recycling processes in the world, especially suitable for USTPs with limited land space and high automation requirements. It can not only be used for secondary treatment of nitrogen and phosphorus removal but also be combined with the A/A/O process for advanced treatment (Wang *et al.* 2012). The effluent quality of this process is high, reaching the standard of landscape water or recycled water. According to the statistical results in Table 1, at present, the number of USTPs adopting the MBR process and MBR + A/A/O combination process has reached 23, the total treatment scale has reached $281.5*10^4$ m^3/d, and the scope of application is very wide. It seems that the MBR process is the most suitable treatment process for USTPs, while defects such as high construction investment and high operation and maintenance costs have seriously affected the extensive use of the MBR process. As we all know, the cost of USTPs in planning, construction, and bed evaluation is high. Therefore, to expand the application of MBR technology in USTPs, we still need to find ways to reduce the cost of the MBR process.

From the perspective of saving construction investment and operation and maintenance costs, the A/A/O process has obvious advantages. In addition, compared with the traditional AS process, the A/A/O process is more effective in denitrifying and dephosphorizing, and inhibiting the expansion of filamentous bacteria (Qiang *et al.* 2015). Although the A/A/O process is relatively complex and the single processing equipment occupies a large area, the development and application of integrated common-wall technology effectively alleviate these defects of the A/A/O process. Therefore, the A/A/O process can be widely used in USTPs. In order to obtain more stable and higher effluent quality, the A/A/O process is often combined with other treatment units, such as final clarifier or MBR. The MBR unit is used to replace the final clarifier in the A/A/O process for advanced treatment, which can improve the sludge concentration in the biochemical pool and the removal efficiency while saving land occupation. As a special variant of the A/A/O process, the multiple AO process, moreover, has obvious advantages in carbon source saving, and high nitrogen and phosphorus removal efficiency (Peng *et al.* 2018). It has been applied in the Daoxianghu Reclaimed Water Plant in Beijing, China.

ECONOMIC VALUE AND ECOLOGICAL VALUE OF USTP

Economic value

We determine the economic value of the STP as the total of the land occupation cost, the construction investment, the operation and maintenance cost, and the pipeline network investment. A comparison of the economic value between the ASTP and USTP is given in Table 3. The planning land of the ASTP includes not only the construction land

Table 3 | A comparison of the economic value between USTP and ASTP

Item	USTP	ASTP
Main process	A/A/O, MBR	A/A/O, A/O, OD
Total treatment scale (*10^4 m^3)	8.00–20.00	20.00–100.00
Area covered for STP (ha)	2.00–4.66	15.00–49.10
Area covered for isolation strip (ha)	0.00	1.50–7.50
Total area covered (ha)	2.00–4.66	16.50–56.60
Land used for sewage treatment (m^2/m^3)	0.23–0.29	0.57–0.83
Construction investment for STP ($/$m^3$)	564–848	282–424
Pipeline network investment for STP ($/$m^3$)	≈0	42–71
Land acquisition cost for STP ($/$m^3$)	141–330	706–1,130
Total investment for sewage treatment ($/$m^3$)	706–1,177	1,031–1,625
Operation/maintenance cost ($/$m^3$)	0.20–0.24	0.15–0.17

Note: the land price was determined as 14.12 million $/ha, 1 ha = 10,000 m^2.

(15.00–49.10 ha), i.e., the land used for the sewage treatment structures, and the road inside, but also the greenbelt land (1.50–7.50 ha) which usually covers the surrounding area 200–300 metres away from the STP. The USTP needs much less land for construction. On the one hand, all the sewage treatment structures are arranged compactly based on integration and common-wall technology. On the other hand, no greenbelt (0.00 ha) is needed because all the noise and odor-producing units are covered and the gaseous pollutants are collected and treated underground. Taking the sewage treatment scale of the STPs into consideration, it can be found that the area covered for the treatment of per m^3 sewage ranges from 0.57 m^2/m^3 to 0.83 m^2/m^3 in the ASTP, which is more than two times that of the USTP, changing between 0.23 m^2/m^3 and 0.29 m^2/m^3. What cannot be ignored is that, except for less land occupation for the construction of the USTP, another apparent advantage is the use of the above-ground space. Related data show that 98% of the total above-ground space of the USTP can be used for green land or the arrangement of communal facilities, and no more than 2% is needed to be used for the functional units such as vents, central control rooms, and laboratories. Thus, it can be confirmed that the USTP will cover almost no land one day with the further development of the above-ground space.

The construction investment of the USTP is usually as high as 564–848 $/$m^3$, two to three times higher than that of the ASTP with the same treatment scale, for the need of deep excavation and underground layout. Additionally, for the limitation of underground space, a sewage treatment process with compact structure, high efficiency, and high operation and maintenance requirement is usually required, leading to the higher equipment investment of the USTP than that of the ASTP. For the noise, odor and visual pollutions generated during sewage treatment, the location of the ASTP is usually chosen in the suburb far away from residential and business areas, which leads to a great increase of the length of the pipeline network for the transportation of sewage (Tee *et al.* 2014), while the USTP can be built near the residential area of the city center, where sewage is collected, treated and reused. Therefore, the investment in a pipeline network is almost zero (Younis & Knight 2010). Taking the land cost into consideration, the USTP (706–1,177 $/$m^3$) has certain advantages over the ASTP (1,031–1,625 $/$m^3$) in total construction investment. For the addition of deodorization in the USTP, the ventilation and lighting equipment's power consumption occupies nearly 30–50% of the total cost. It will lead to a significant increase of operation cost in the USTP (0.20–0.24 $/$m^3$), which is a little higher than that (0.15–0.17 $/$m^3$) of the ASTP. Hence, how to reduce the operation cost of the USTP is an urgent problem to be solved.

Ecological value

As mentioned above in 'Comparative analysis of different sewage treatment processes', reducing the construction and operating costs of USTPs is important for the widespread application of USTPs. Except for the technological innovation in the field of sewage treatment, the landscape design on the above-ground space is the important method to offset some part of the total investment. The ecological value of the STP includes the implicit ecological value and the explicit ecological value generated by the landscape design on the above-ground space. The landscape must involve people's participation and experience, which is also one of the most important features of landscape design in the USTP. Referring to the existing reports on USTPs, the author believes that the ecological value of USTPs lies mainly in the above-ground landscape. The above-ground construction of the USTP reflects the concept of sustainable development. While controlling pollution, it maximally extends its functions and strives to integrate with the surrounding environment. This enhances the ecological environment while increasing the comfort of the surrounding residents. It may also inevitably increase the value of the surrounding land price, unexpectedly. For example, the ground landscape can be used for community gardens, urban parks, and the ground can be used for leisure gymnasiums, parking lots, etc.

Landscape design should integrate water culture, water ecology and water landscape. For example, in the wetland water ecological purification area, it is necessary to design a hydrophilic facility so that people can really touch the water body and see the fish and aquatic plants inside. Since the USTP can be built in urban areas, where the population is relatively dense and the land area is limited, the landscape design also needs to pay attention to the combination of urban functional areas, make full use of public landscape space, and promote harmonious coexistence between man and nature. Taking the Pantai USTP in Malaysia as an example, its landscape design is clear, reasonable and compact. The sewage treatment plant can provide nearly 140,000 m^2 of leisure parks on the basis of meeting the production and living demand, bringing spiritual satisfaction and enjoyment to the surrounding residents (Shao *et al.* 2014). In 1942, the capital of Sweden, Stockholm, built the first modern USTP using local superior geological conditions and advanced excavation techniques. They arranged the entire factory floor into a park. The entrance of the USTP, using clever architectural art, greatly enhanced the city's appearance, and at the same time increased the green area for the city, which attracted worldwide attention (Jansson 1989). In China's Shenzhen Buji Sewage Treatment Plant, the sewage treatment plant is located in the central urban area, less than 50 metres away from residential buildings. The ground space of the USTP has a leisure park for the residents to entertain and rest, to meet the needs of the surrounding residents, and to attract people to the surrounding residential areas, thus increasing the price of the land around. As shown in Table 4, the price of the commercial housing nearby the Buji USTP is higher than that far away, which may be closely related to the request of people for a better recreational and healthy living environment. This is also a good example of the ecological value of the ground landscape of USTPs.

Table 4 | Commercial housing price around the Buji USTP

Distance (m)	Main price ($/m²)
0–100	7,077 ± 354
100–200	6,907 ± 311
200–500	6,723 ± 212
500–1,000	6,369 ± 354
>1,000	6,086 ± 424

PERSPECTIVE

In general, USTPs are the product of social urbanization, increased population density, and shortage of land resources. They require more resources and costs from planning, construction, environmental assessment, operation, and maintenance than the ASTP, and moreover, higher technical requirements. From these perspectives, USTPs do not seem to be ideal for urban sewage treatment. The development of new things is a gradual process. These problems can be improved and solved with the accumulation of experience, technological innovation, and continuous technological advancement. More importantly, when the cost of land occupation, investment in the network, and the ecological environment are taken into consideration, the USTP is a new 'low-cost' sewage treatment model, an environmentally friendly, resource-intensive, and sustainable wastewater treatment. Therefore, with the increasingly scarcity of urban land resources, the development prospects of USTPs are considerable.

In addition, the high operating costs (Zheng *et al.* 2011), the large safety risks, and technical breakthroughs are still inevitable problems in the development of USTPs. Different sewage treatment processes correspond to different USTP designs and planning layouts. The choice of different wastewater treatment processes is not only related to the quality of the effluent, but also related to the design and construction costs, operation and maintenance costs, and safety of the USTP (Wang *et al.* 2014). Therefore, the selection of a reasonable, mature, and promising wastewater treatment process is critical to the long-term development of USTPs. Moreover, the development and utilization of urban underground space is an interdisciplinary subject involving geology, structure, environment (Kuokkanen *et al.* 2017), municipal administration, and safety. It has extremely high technical requirements. Therefore, improving the technical level, reducing the cost and improving safety are important means for the sustainable development of USTPs.

More importantly, with the complexity of urban sewage pollution components, the sewage treatment process needs to continue to develop and innovate in future research and application to meet the needs of future urban sewage treatment. The aerobic granular sludge (AGS) process (Wang *et al.* 2017) and anaerobic ammonium oxidation (Anammox) process (Castro-Barros *et al.* 2017) are determined as the most promising wastewater treatment processes in the 21st century. They have the advantages of high treatment efficiency, high nutrient load, low operation cost, small land occupation and high resource recycling efficiency, and deserve to be widely applied in USTPs. It is worth noting that the data on the characteristics of underground space in USTPs are not uniform, and even in some cases it is lacking (Bartel & Janszsen 2016). Therefore, it is necessary to establish a basic database of USTPs, develop data analysis tools, conduct feasibility analysis, and establish a good design concept to regulate the development of USTPs.

CONCLUSION

According to what has been discussed above, we can draw the following conclusions:

(1) USTPs are an inevitable outcome of urban development. Therefore, as a developing field, USTP system planning will inevitably experience 'trial and error', from immature to mature development processes.
(2) Problems such as high operating costs and large safety hazards still restrict the development of USTPs. Reasonable planning of spatial layout, improvement of EIA quality, timely processing of processes, core technology research and development and innovation are the keys to solving these problems, and are also the core of the long-term development of USTPs.
(3) There is currently no basic database for USTPs, and it is necessary to develop tools for data analysis and decision-making tailored to the development of USTPs.

Moreover, due to the different national conditions and water quality of different countries, we should design and build USTPs in accordance with local conditions, an appropriate reference to excellent experience.

ACKNOWLEDGEMENTS

This paper was supported by the National Natural Science Foundation of China (Grant No. 51708357), the Shenzhen Science and Technology Planning Project (Grant No. JCYJ20170818093116044), the National Natural Science Foundation of China (Grant No. 51878410), and the Environmental Protection Industry Development Special Fund of Shenzhen.

REFERENCES

Alaya, S. B., Haouech, L., Cherif, H. & Shayeb, H. 2010 Aeration management in an oxidation ditch. *Desalination* **252**, 172–178.

Bartel, S. & Janssen, G. 2016 Underground spatial planning – perspectives and current research in Germany. *Tunnelling Underground Space Technol.* **55**, 112–117.

Castro-Barros, C. M., Jia, M. S., van Loosdrecht, M. C. M., Volcke, E. I. P. & Winkler, M. K. H. 2017 Evaluating the potential for dissimilatory nitrate reduction by anammox bacteria for municipal wastewater treatment. *Bioresour. Technol.* **233**, 363–372.

Gilbert, E. M., Agrawal, S., Karst, S. M., Horn, H., Nielsen, P. H. & Lackner, S. 2014 Low temperature partial nitritation/anammox in a moving bed biofilm reactor treating low strength wastewater. *Environ. Sci. Technol.* **48** (15), 8784–8792.

Hao, X. D., Meng, X. T. & Fu, K. M. 2014 Targeted energy consumption and associated technologies developed in water reclamation plants in Singapore. *China Water Wastewater* **30** (24), 7–11.

Ho, Y. K., Shum, K. W. & Wong, J. C. F. 2016 Strategic use of rock caverns and underground space for sustainable urban development of Hong Kong. *Procedia Eng.* **165**, 705–716.

Jansson, B. 1989 Water and sewage in caverns and tunnels: thirty years' experience in Sweden. *Tunnelling Underground Space Technol.* **4** (1), 47–51.

Kämppi, A. 1994 Viikinmäki: Helsinki's new central wastewater treatment plant. *Tunnelling Underground Space Technol.* **9** (3), 373–377.

Kuokkanen, A., Mikola, A. & Heinonen, M. 2017 Seasonal and diurnal variations of GHG emissions measured continuously at the Viikinmäki underground WWTP. In: *Frontiers in Wastewater Treatment and Modelling, FICWTM 2017* (G. Mannina, ed.), Springer, Cham, Switzerland, pp. 464–469.

Maejima, T., Morioka, H., Mori, T. & Aoki, K. 2003 Evaluation of loosened zones on excavation of a large underground rock cavern and application of observational construction techniques. *Tunnelling Underground Space Technol.* **18**, 223–232.

Makana, L. O., Jefferson, I., Hunt, D. V. L. & Rogers, C. D. F. 2016 Assessment of the future resilience of sustainable urban subsurface environments. *Tunnelling Underground Space Technol.* **55**, 21–31.

Malone, A. W. 1996 The use of underground space in Hong Kong. *Tunnelling Underground Space Technol.* **11**, 57–64.

Nishida, Y. & Uchiyama, N. 1993 Japan's use of underground space in urban development and redevelopment. *Tunnelling Underground Space Technol.* **8**, 41–45.

Peng, Y. Z., Ma, Y. & Wang, S. Y. 2006 Improving nitrogen removal using on-line sensors in the A/O process. *Biochem. Eng. J.* **31**, 48–55.

Peng, Y., Zhang, J. & Li, D. 2018 Underground structure pattern and multi AO reaction with step feed concept for upgrading a large wastewater treatment plant. *IOP Conference Series: Earth and Environmental Science* **128**, 012056.

Qiang, Z. M., Wang, L., Dong, H. Y. & Qu, J. H. 2015 Operation performance of an A/A/O process coupled with excess sludge ozonation and phosphorus recovery: a pilot-scale study. *Chem. Eng. J.* **268**, 162–169.

Qin, L., Liu, Y. & Tay, J. H. 2005 Denitrification on poly-β-hydroxybutyrate in microbial granular sludge sequencing batch reactor. *Water Res.* **39**, 1503–1510.

Qiu, W. 2011 Design experience of Guangzhou Jingxi underground wastewater treatment plant. *China Water Wastewater* **27** (24), 47–49.

Qiu, W. 2017 The current status and prospect of underground wastewater treatment plant in China. *China Water Wastewater* **33** (6), 18–26.

Ren, X., Shon, H. K., Jang, N., Lee, Y. G., Bae, M., Lee, J., Cho, K. & Kim, I. S. 2010 Novel membrane bioreactor (MBR) coupled with a nonwoven fabric filter for household wastewater treatment. *Water Res.* **44**, 751–760.

Shao, Y. Q., Hou, F., Xue, X. F., Li, Y. P., Pang, H. T. & Mu, Y. J. 2014 Characteristics of the design of the Pantai underground wastewater treatment plant in Malaysia. *Water Wastewater Eng.* **40** (9), 24–27.

Tang, C. Y., Chong, T. H. & Fane, A. G. 2011 Colloidal interactions and fouling of NF and RO membranes: a review. *Adv. Colloid Interface* **164** (1–2), 126–143.

Tee, K. F., Khan, L. R., Chen, H. P. & Alani, A. M. 2014 Reliability based life cycle cost optimization for underground pipeline networks. *Tunnelling Underground Space Technol.* **43**, 32–40.

Uher, P. 1987 Czechoslovakia's first underground sewage treatment plant. *Tunnelling Underground Space Technol.* **2** (3), 275–278.

Wallace, M. I. & Ng, K. C. 2016 Development and application of underground space use in Hong Kong. *Tunnelling Underground Space Technol.* **55**, 257–279.

Wang, M. S. & Gong, H. 2018 Not-in-my-backyard: legislation requirements and economic analysis for developing underground wastewater treatment plant in China. *Int. J. Environ. Res. Public Health* **15**, 2339.

Wang, Z. X., Xu, X. C., Gong, Z. & Yang, F. L. 2012 Removal of COD, phenols and ammonium from Lurgi coal gasification wastewater using A^2O-MBR system. *J. Hazard. Mater.* **235–236**, 78–84.

Wang, W. X., Zhao, W. C. & Yao, M. X. 2014 Application of UCT-MBR/RO process in expansion project of Taoziwan wastewater treatment plant. *China Water Wastewater* **30** (6), 65–69.

Wang, Z. W., van Loosdrecht, M. C. M. & Saikaly, P. E. 2017 Gradual adaptation to salt and dissolved oxygen: strategies to minimize adverse effect of salinity on aerobic granular sludge. *Water Res.* **124**, 702–712.

Wilson, D. 1994 Underground solution for wastewater treatment plant. *Tunnels Tunnel.* **26** (11), 24–26.

Younis, R. & Knight, M. A. 2010 Continuation ratio model for the performance behavior of wastewater collection networks. *Tunnelling Underground Space Technol.* **25** (6), 660–669.

Zheng, L. S., Chen, Z. P., Wang, W., Li, F. & Zhang, X. 2011 Discussion on existing problems in design of bio-deodorization system in sewage treatment plants. *China Water Wastewater* **27** (12), 14–17.

First received 5 June 2019; accepted in revised form 2 December 2019. Available online 26 December 2019