Planning and Design of Happy Valley Underground Stormwater Storage Scheme

W H Luk*, Anthony K L Tsang**, Harry W P Yu***

* Chief Engineer, Drainage Projects Division, Drainage Services Department, The Government of the Special Administrative Region Hong Kong
** Senior Engineer, Drainage Projects Division, Drainage Services Department, The Government of the Special Administrative Region Hong Kong
*** Engineer, Drainage Projects Division, Drainage Services Department, The Government of the Special Administrative Region Hong Kong

Abstract
Happy Valley is a well-developed low-lying urban area located in the hinterland of the Wan Chai District and is surrounded by a hilly terrain. Serious flooding had occurred in Happy Valley and areas in its vicinity including areas such as the Happy Valley Recreation Ground and Hong Kong Jockey Club racecourse. To address the flooding problem, the Drainage Services Department proposed a Happy Valley Underground Stormwater Storage Scheme at the Recreation Ground. Upon completion, the flood protection level in Happy Valley will be raised to withstand a rainstorm with a return period of 1 in 50 years, and the risk of flooding in Happy Valley and areas in its vicinity will be substantially reduced.

This paper will present the background and planning of this flood relief project in Happy Valley and how the project team developed innovative, sustainable and integrated engineering solution for the benefit of the society.

1. INTRODUCTION

Happy Valley is a low-lying urban area surrounded by a hilly terrain in Wan Chai District. Serious flooding had occurred in Happy Valley and areas in its vicinity including Happy Valley Recreation Ground (HVRG), Hong Kong Jockey Club (HKJC) racecourse, Morrison Hill Road and Wong Nai Chung Road during the heavy rainstorms on 24 August 2000, 24 April 2006 and 7 June 2008 (**Figures 1 and 2** refers).

Figure 1: Serious flooding on 7 June 2008: (a) at Happy Valley Recreation Ground and racecourse; (b) at Junction between Morrison Hill Road and Queen's Road East; and (c) at Wong Nai Chung Road.

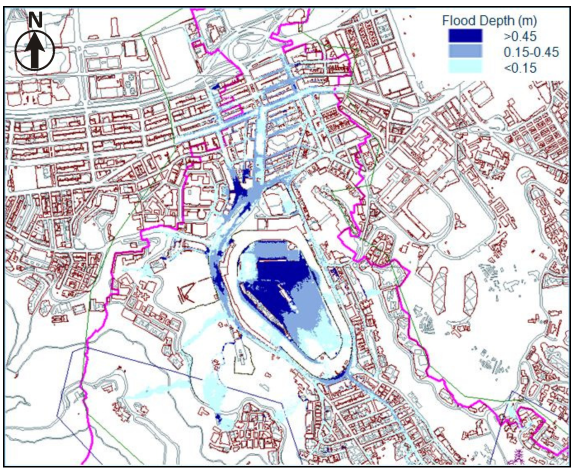

Figure 2: Flood Extent of Rainfall Event on 7 June 2008

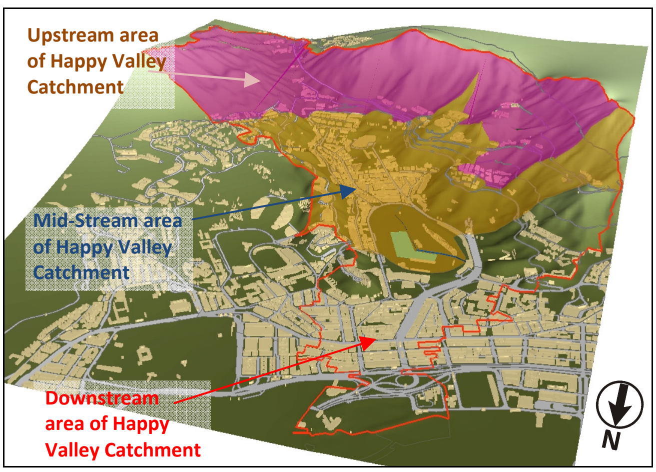

Figure 3: 3-D Terrain View of Happy Valley Catchment

The Government of Hong Kong Special Administrative Region (HKSAR) has commissioned two major flood relief projects in the northern Hong Kong Island, namely the Hong Kong West Drainage Tunnel (HKWDT) and Lower Catchment Drainage Improvement Works (LCDI), to relieve the flooding hazards of the Happy Valley catchment (**Figure 3** refers). HKWDT serves to intercept stormwater runoff from an approximate 140 ha area of upstream catchment, while LCDI at the downstream catchment involves conventional drainage improvement method to mitigate the flooding problem in the low-lying areas of Wan Chai and Causeway Bay (**Figure 4** refers). However, the flooding hazard cannot be fully addressed solely by these two projects as the existing drainage system in the mid-stream and downstream urban areas of Happy Valley Catchment is rather flat and susceptible to tidal influence. Assessment results show that under a 50-yr Return Period Rainfall Event, the infield area of the HVRG and the roads in the vicinity are still exposed to high risk of flooding, which will affect about 70,000 residents and 2,000 shops in that region (**Figure 5** refers). Therefore, further improvement works are required in the mid-stream catchment of Happy Valley to enhance the flood protection level of the stormwater drainage system to an acceptable level in order to safeguard the continuous and sustainable development of the area.

The Drainage Services Department (DSD) of the Government of HKSAR therefore decided to construct an underground storage tank beneath the existing HVRG to alleviate flood hazard. It will serve as a flood detention system to temporarily store the floodwater from a storm event during peak time to alleviate flooding in the Happy Valley catchment. The adoption of underground storage tank will also enable the maintaining of existing amenity facilities above ground in the HVRG.

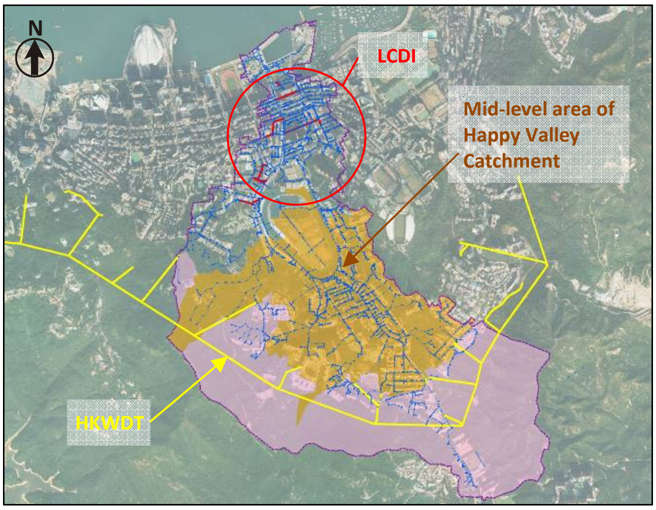

Figure 4: Happy Valley Sub-catchment Plan and Locations of HKWDT and LCDI

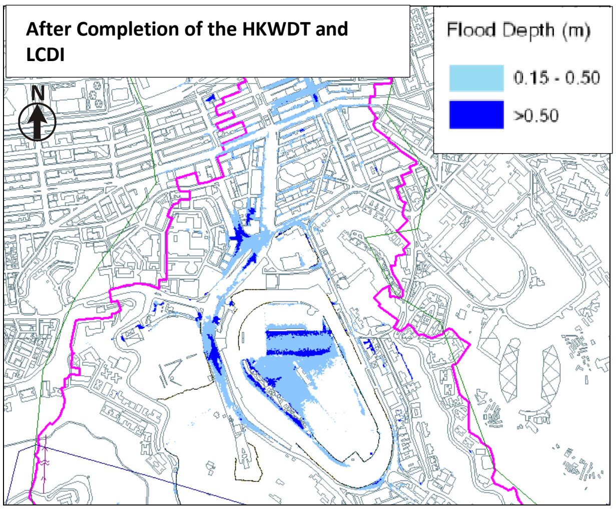

Figure 5: Flood Extent under 50-yr Return Period Rainfall Event after completion of HKWDT and LCDI

2. HAPPY VALLEY UNDERGROUND STORMWATER STORAGE SCHEME (HVUSSS)

The objective of the HVUSSS is to provide flood attenuation in the Happy Valley catchment during severe rainstorms of intensity up to that of a 1 in 50 year rainstorm event. Major components of the HVUSSS include: inlet structure, twin cells diversion box culvert, overflow weir system, underground storage tank and pump house (**Figures 6 and 7** refers).

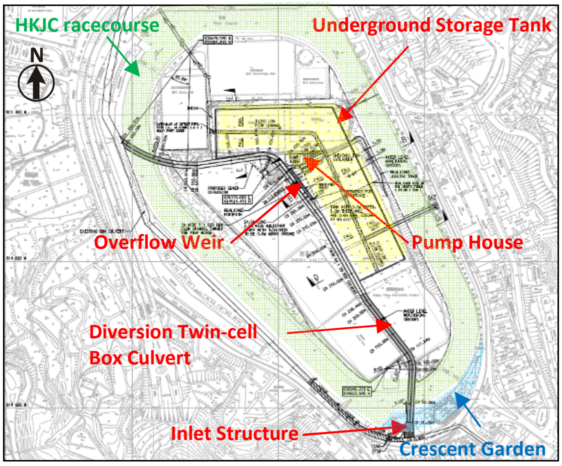

Figure 6: Major Components of the HVUSSS

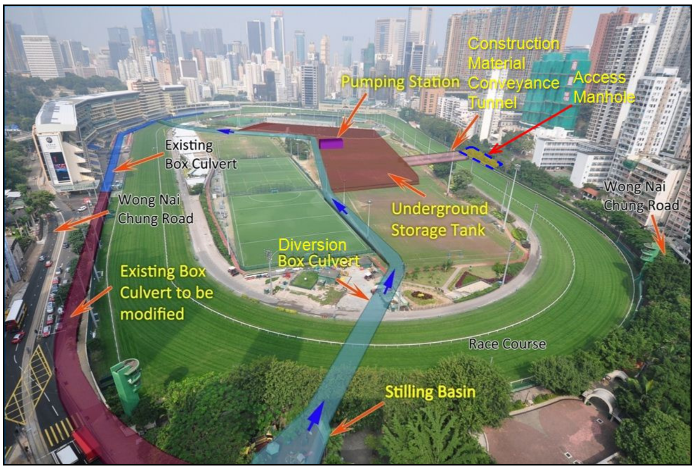

Figure 7: Photomontage of the HVUSSS

Runoff from the upstream catchment will be converged at the inlet structure at Crescent Garden before discharging further downstream. The existing box culvert will be modified and the runoff will be conveyed through the newly-constructed diversion twin-cell box culvert of about 630m long crossing underneath the HKJC racecourse and HVRG. The inlet structure will also function as a stilling basin to stabilize flow entering the diversion twin-cell box culvert. A stabilized flow is crucial for avoiding excessive runoff flowing into the storage tank via the overflow weir system.

In days of low flow, stormwater collected at the inlet structure will be conveyed along the diversion twin-cell box culvert to the downstream drainage network without entering the underground storage tank. During major rainstorm events, the excess runoff in the diversion box culvert will enter the storage tank via the "movable" overflow weir system. The crest levels will be adjusted automatically based on real-time monitoring data of flow depths in drainage network upstream and downstream of storage tank, water level in the storage tank, and tide levels in Victoria Harbour which thus allows filling of the storage tank at the most optimal time. Subsequently, emptying the tank by means of both pumping and gravity draining will be adopted to discharge the stored water from the tank after a rainstorm event.

The underground storage tank beneath HVRG will have a capacity of 60,000m^3 and plan area of 20,000m^2. The associated pumping station with design pumping rate of 1.5m^3/s will be required for draining stored water in the storage tank. After completion of the HVUSSS, it is expected the risk of flooding in Wan Chai and Happy Valley districts will be lowered and the public will be relieved from financial losses and disturbances resulted from flooding. The amenity facilities within the HVRG will be maintained for public use after completion of the HVUSSS construction.

3. ADVANCED HYDRAULIC MODELLING TECHNOLOGY

Numerical hydraulic modelling analysis has been adopted in many drainage improvement projects in recent years. The advantages of using hydraulic modelling are that it is fast, efficient and can accurately present the results taking into account the time lag due to difference in time of concentration from each contributing sub-catchment. Most of the hydraulic models are able to simulate unsteady, gradually varying flow in looped networks with flat or reverse gradients where the direction of flow may reverse.

The following hydraulic models are commonly adopted in the urban drainage system planning:

i) *One Dimensional (1-D) Model* – Traditional modelling technique adopted in many older drainage master plans. It considers only the performance of drainage network under rainstorm events. However, the topography of the concerned area and the possible gravity discharge of overland flow flooded from one manhole to another could not be simulated in this 1-D modelling.

ii) *One Dimensional (1-D) with One Dimensional (1-D) Overland Flow Path Model* - The One Dimensional (1-D) with One Dimensional (1-D) Overland Flow Path Model is adopted in many recent drainage improvement projects trying to tackle the shortcoming of the traditional 1-D Model. Considering the flood water would overflow to the carriageway and flow to the topographical low spot once the drainage system is surcharged, overland flow paths are adopted as open channels in the model to simulate this situation. The maximum flood depth of the overland flow path is used for the flood risk analysis.

iii) *One Dimensional (1-D) with Two Dimensional (2-D) Ground Model* – This latest modelling technique has been adopted in the HVUSSS project. The 1-D module is used to examine the performance and adequacy of the existing stormwater drainage system, whereas the flow pattern of flooding water/surface flow is assessed by the 2-D module. The 2-D ground surface acts as the overland flow surface. The results would indicate the behaviour of the overland flow under complex geometries with different flow directions based on the topography of the catchment area. The overland flow, which generates from a flooded manhole, would be able to return to the drainage system, thus providing a more realistic simulation of the flooding situation during a storm event. The flow direction, maximum flow velocity and flood depth of the ground model provide a good reference for the flood risk analysis.

The 1-D model used in this HVUSSS project was based on records of the drainage networks constructed within the catchments. For the 2-D ground surface for modelling of the surface flow, a detailed three dimensional data was required for creating a triangular mesh grid of the ground surface for incorporation into the 1-D with 2-D Ground model. In order to utilize most recent topography for the whole Happy Valley Catchment, data from a territory wide topographical survey using the airborne Light Detection And Ranging (LiDAR) was adopted (**Figure 8** refers). The topographical data was then integrated with the below-ground stormwater for forming the hydraulic model of Happy Valley region.

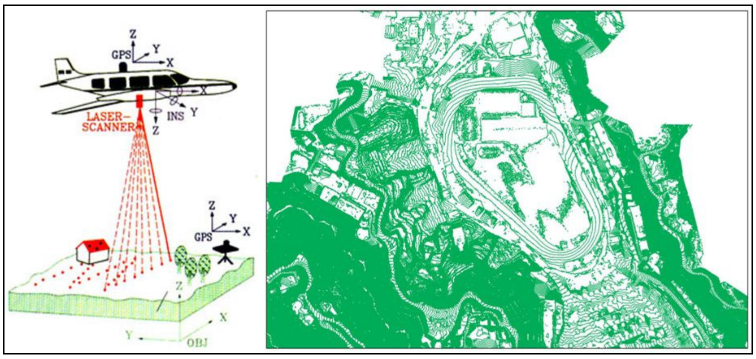

Figure 8: Topographical Survey using LiDAR and Sample of LiDAR Scan of Happy Valley area

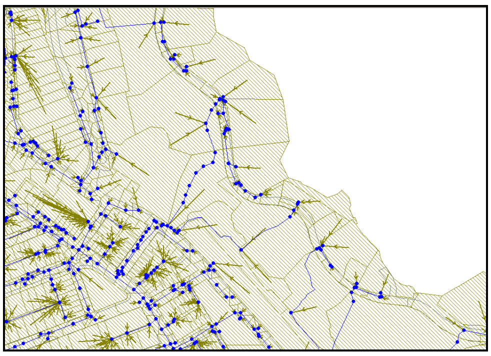

Figure 9: Sub-catchment Plan of Happy Valley Catchment - InfoWorks CS Model

The Happy Valley Catchment area covers approximately 3.6 km^2. Upon review of the collected data, detailed site investigation and flow surveys have been carried out to assess the existing condition of the stormwater drainage system, extent of utility crossings and flow data for model verification and calibration. Types of site investigation are listed as follows:

i) *CCTV Survey* - Assess the structural and service condition of storm drains and confirm the interconnections inside the stormwater drainage systems;

ii) *Manhole Survey* - Obtain additional data on existing site condition to supplement hydraulic model;

iii) *Topographical Survey* - Obtain level information for runoff drainage pattern/ natural streams and verify accuracy of the LiDAR data;

iv) *Man-entry Survey* - Check existence of utility crossings and other intrusions; and

v) *Flow Monitor Survey* - Record the Flow data during rainfall events for hydraulic model verification and calibration.

Based on the LiDAR Data and discharge manhole nodes, preliminary sub-catchment polygons were produced. However, manual editing was still required since not all conditions could be modelled in the GIS scripting, such as the presence of impermeable boundary walls and buildings with designated storm drain discharge points. **Figure 9** shows part of the sub-catchment plan of Happy Valley catchment in the computer model after manual corrections.

For particular structures of the drainage network in Happy Valley catchment with hydraulic complexity, a state-of-the-art three-dimensional computational fluid dynamics (CFD) has been adopted to simulate the flow and hydraulic performance of these structures. CFD is a computer modelling method which simulates 3-D fluid flow. The method involves setting up a mesh which splits the water into a large number of small elements. The software then calculates the predicted flow by solving iteratively a series of equations for conservation of mass, momentum and energy.

The advantage of using CFD is that the time required for setting up the CFD model and the subsequent changes to the CFD model is less than that using the traditional physical model.The CFD model can be set up quickly via the computer, and the simulation results at any part of the CFD model can be viewed in detail and be presented in any desirable way.

The reliability of the CFD model has also been improved through calibration and verification of the computer programs. Latest CFD modelling software can now produce reliable simulation results. An example of two side weirs modelled in CFD is shown in **Figure 10**.

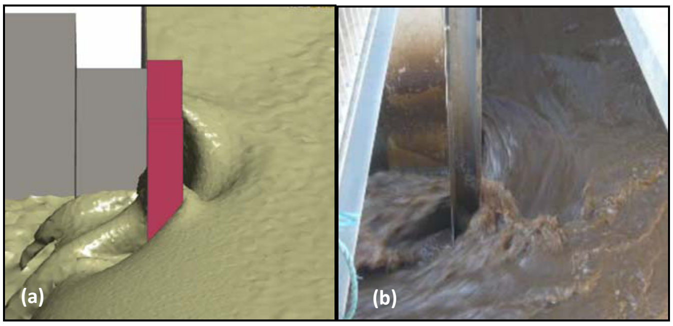

Figure 10: Example of two side weirs (a) modelled using CFD; (b) using physical model

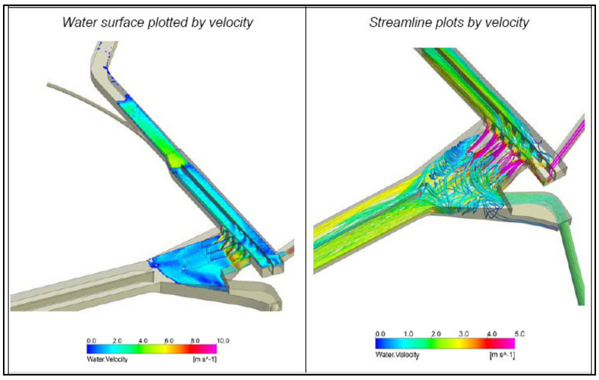

Figure 11: CFD results of Inlet Structure

In this HVUSSS project, the CFD models have been established to optimise the flow convergence design of the inlet structure, flow pattern along the diversion box culvert, and the flow characteristic of the side overflow weir. It was also used for determining the hydraulic parameters of the existing utility crossings and other intrusions inside the decked nullah along Canal Road. In addition, after CFD simulation, the properties of these hydraulic structures with hydraulic complexity would be converted into equivalent design parameters and entered back into the 1-D model to provide more accurate analytical results.

Figure 11 demonstrates the CFD simulation results showing the predicted water surface and flow velocities of the stormwater entering the inlet structure. By simply modifying the CFD model, an optimized design of the inlet structure producing stabilized steady flow entering the diversion box culvert could be obtained for better hydraulic performance. HVUSSS project is the pioneer project to use CFD models for determining hydraulic performance of the design without using any physical model for verification.

This is the first time intergrated 1-D, 2-D and 3-D hydraulic modelling techniques were used to design a new drainage system in Hong Kong. In order to verify the accuracy of the whole hydraulic model, rainfall data collected from historical rainstorm events including 7 June 2008 had been input into the model and the simulation results were then compared with the actual flooding conditions observed on site. It was found that the simulation results matched closely with the observations (**Figure 12** refers).

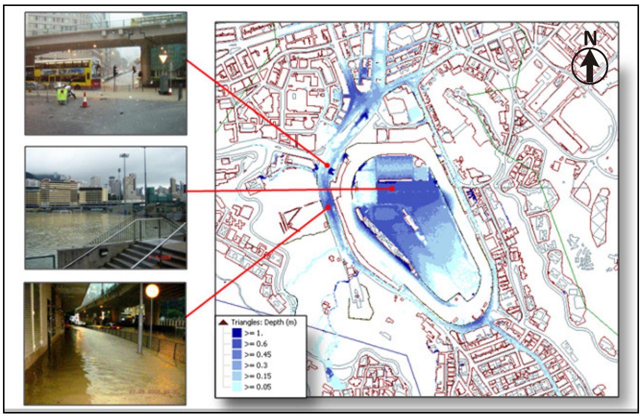

Figure 12: Simulation Result on 7 June 2008

4. ENVIRONMENTAL AND SUSTAINABLE DESIGN CONSIDERATIONS

DSD was striving for a sustainable solution for the flooding problem in Happy Valley. Below are the key design considerations that have been taken into account in the planning and design of the HVUSSS to enhance sustainability and environmental protection.

4.1 Automatic Movable Crest Weir as Overflow Weir System

As mentioned before, the design of HVUSSS has adopted an off-line flood detention method. The excess stormwater would overflow into the storage tank via the overflow weir system when the water level in the box culvert is higher than the top level of the crest weir. Traditionally, fixed weirs were used for the overflow weir system for its simplicity in operation and maintenance. However, the shortcoming of using fixed weir is that the crest level cannot be altered during operation and in order to limit the maximum flow depth in the box culvert the level of crest weir has to be pre-set at a level where pre-mature spilling of stormwater from box culvert to the storage tank would likely occur. This pre-mature spilling would take up part of the storage capacity of the tank and hence additional design storage capacity had to be allowed to withstand the design rainstorm.

Hence, in the design of HVUSSS, 13 nos. of automatic "movable" crest weir penstocks were adopted as the overflow side weir system which allow variable weir heights during operation. With the aid of real-time monitoring of runoff and tidal levels by level sensors installed upstream and downstream of the HVUSSS as well as in the storage tank, the crest weirs would only be lowered as necessary to divert the stormwater from the box culvert to the storage tank via the crest weirs and hence attenuate peak flow conveyed by the existing downstream drainage systems. This real-time controlled movable weir would ensure the filling of the storage tank at the most optimal time to prevent pre-mature or late overspill of stormwater into the storage tank. This design element optimizes the total storage capacity and reduces the design capacity of the storage tank by about

30% and thus reduced the amount of excavation required during construction and be more environmental friendly for less construction and demolition materials would be generated. Moreover, the prevention of pre-mature or late overspill of stormwater would minimize the pumping required and thus enhance sustainability during operation. The “movable” crest weir would also allow closure of the opening during normal days to prevent any possible unpleasant odour from entering the storage tank from box culvert.

The stepped approach of the overflow weir system operation is demonstrated in **Figure 13**.

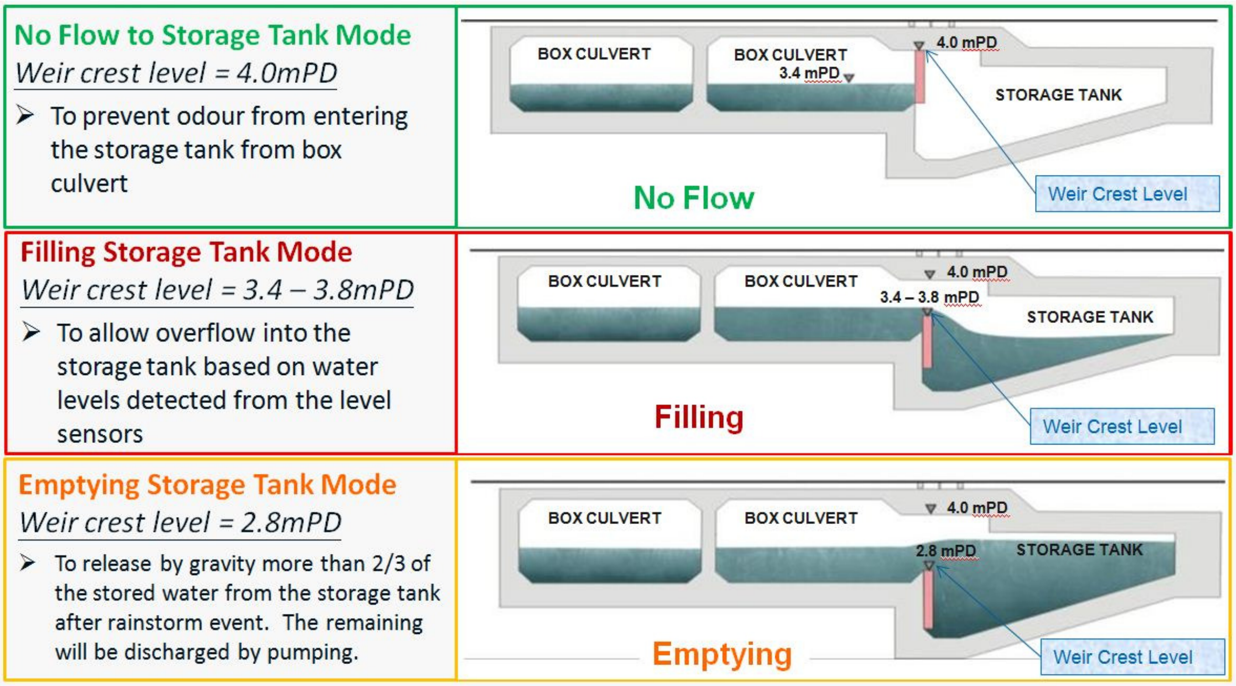

Figure 13: Stepped Approach for the Operation of Automatic “Movable” Overflow Weir System

4.2 Shallow Tank Design

For the tank design, another consideration was the dimensions of the tank to provide the required design storage volume. Traditional thinking was that a deeper tank with smaller plan area would be more favourable since it would occupy a smaller site area and cause fewer disturbances to the public during construction. In this project, however, greater emphases on the sustainability of the HVUSSS have been placed in determining the sizing of the tank.

Since automatic “movable” crest weirs were adopted for the overflow weir system, the crest weirs could be lowered after rainstorm events to facilitate gravity draining of stored water in the filled storage tank to the box culvert. This arrangement would further enhance sustainability by saving energy consumption and thus recurrent cost for discharging water from the storage tank by pumping. Since the design invert level of the box culvert was controlled by the existing invert levels and design tidal sea levels at the downstream, a shallower tank would allow a higher portion of the stored water to be discharged by gravity via the automatic movable crest weirs. Under the latest design configurations, more than two-thirds of the stored stormwater could be discharged by gravity and the remaining would be emptied by pumping. Depth of the storage tank was also minimized to facilitate adoption of pumps with lower pump head and capacity for further saving energy consumption.

4.3 Climate Change

Climate change has recently become one of the key issues in design consideration. Climate change creates a higher variability in the occurrence of extreme events, which increases uncertainty towards many traditional probabilistic-based flood protection guidelines, thus augmenting the vulnerabilities of urban areas. Under such circumstances, it is necessary to introduce innovative paradigm to deliver sustainable and cost-effective design components as a long term solution to adapt to the uncertainties.

In view of the rising sea water level attributed to climate change, the HVUSSS has, for the first time in drainage design in Hong Kong, taken into account a rise in water level of 3mm per year for the next 20 year as the downstream boundary condition.

Apart from design, the adoption of automatic "movable" crest weir system could also be used for responding to climate change considerations. The use of movable crest weir would eliminate the need for civil work modification in the future due to a higher variability in the change of sea level after the HVUSSS has been commissioned. The operation of the weir penstock could be programmed to adjust the weir crest to a slightly higher level in order to avoid pre-mature spill into the storage tank due to the annual increase in tidal level.

5. PUBLIC INTERESTS

It is a huge challenge to balance both the need for adequate flood protection as well as public interests on environmental protection and greening during construction and after the completion of the HVUSSS project. During the planning and design stage of the project, several public consultation sessions have been conducted to collect comments and opinions from the nearby residents and other concerned parties. These consultations ensure the needs and concerns from the public would be properly addressed.

The footprint of underground storage tank, pump house and other associated drainage works will occupy 6 out of 11 existing sports pitches in the HVRG, the closure of sports pitches is therefore inevitable and may cause inconvenience to the public when using the amenity facilities in HVRG. The project team therefore liaised with the Leisure and Cultural Services Department (LCSD), the managing authority of the HVRG, and other sports associations at a very early stage of planning for the pitch closure arrangements. The two-phase construction works arrangement was then planned so that no more than 3 nos. of sports pitches would be closed at any one time and hence minimize disturbance to the users of the HVRG. As the whole storage tank would be constructed underground, and the pump house and other associated utilities were designed to be buried as far as possible, the area for amenity use by the public would not be reduced after completion of the project. Also the sightline from the HKJC's grand stand would not be affected through strict imposition of height restrictions to the proposed superstructures.

The traffic arrangement during construction, including the transportation in-and-out the HVRG and the traffic impact to the surrounding Wong Nai Chung Road, was also of great concern to the public. In order to preserve the capacity of the existing only vehicular access underneath the HKJC racecourse, a new underground construction material conveyance tunnel connecting the site to a fully enclosed access point at Wong Nai Chung Road outside the HVRG would be built for material transportation during construction (**Figure 14** refers). The use of this conveyance tunnel and the fully enclosed access point would also minimize the noise, dust and other nuisance to the public. Furthermore, although the traffic impact assessment concluded that the traffic impact arising from construction works would be minimal, additional strict restrictions on the use of Wong Nai Chung Road by construction vehicles during peak hours would also be imposed to further reduce the possible traffic impact to the public.

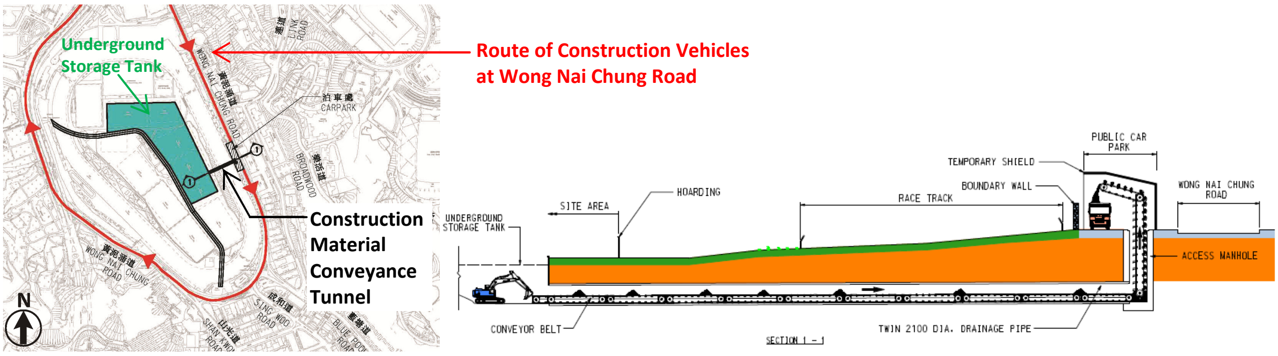

Figure 14: Plan View and Section of New Construction Material Conveyance Tunnel

6. CONCLUSION

The challenge of the HVUSSS is to alleviate the flooding problems in this high-density and well-developed low lying area of Happy Valley when major excavations is inevitable. By the use of latest hydraulic modelling techniques in the industry and other innovative engineering applications, a sustainable stormwater storage scheme with minimal nuisance to the public was proposed. The implementation of the HVUSSS would ensure the social-economic growth and the safety of the public by bringing the flood protection level up to stipulated standard to cater for a rainstorm event of 1 in 50 year in the Happy Valley Catchment.

Reference

1. Ackers, J. C. (2008). *Flood Detention Reservoirs – Hydrological and Hydraulic Design*, British Dam Society Seminar, London.

2. Ackers, J. C. and Bartlett, J. M. (2009). *Flood Storage Works, Chapter 10 of Fluvial Design Guide*, Environment Agency, London.

3. Black & Veatch (2011). *Final Report - Review of Drainage System Planning for Happy Valley Catchment - Feasibility Study,* Black & Veatch, Hong Kong.

4. Black & Veatch (2011). *Working Paper No. 9 Computational Fluid Dynamics on Happy Valley Underground Stormwater Storage Scheme (HVUSSS) - Review of Drainage System Planning for Happy Valley Catchment - Feasibility Study,* Black & Veatch, Hong Kong

5. Drainage Services Department (2000). *Stormwater Drainage Manual – Planning, Design, and Management*. Drainage Services Department, The Government of Hong Kong Special Administrative Region.

6. MWH Soft (2010). *InfoWorks v11 User Manual*, MWH Soft, Colorado.

7. Walter T.W. Poon *et al* (2011). *Computational Hydraulics Aspects of the Happy Valley Flood Storage Scheme, Hong Kong*, The 4th IWA-Aspire Conference & Exhibition, Japan