Abu Dhabi’s strategic tunnel enhancement programme: odour extraction system approaches
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ABSTRACT
The Emirate of Abu Dhabi has experienced tremendous growth since the mid-1970s resulting in significant overloading of its existing sewerage system. Master planning determined that the best long-term wastewater collection and conveyance solution was construction of a deep tunnel sewer system. Implementation of this massive project faced numerous challenges, including the goal of no odours and limited odour control facilities. To accomplish this, the consultant team examined a unique approach of a single odour control system installed at the proposed downstream tunnel pumping station. Rigorous analysis utilising computer-based models confirmed the viability of this approach. However, other approaches including multiple satellite (localised or regional) odour extraction systems were considered. To better understand entrained air forces at vortex drops, and to confirm the preferred odour extraction approach, physical modelling of drop structures and overall tunnel system was implemented. Results and findings concluded that a regional odour extraction system approach was preferred over a single (centralised) extraction approach. This paper focuses on the process of selecting the preferred odour extraction approach and preliminary capacity sizing of regional systems.

Key words | odour control, tunnel, vortex drop shafts

INTRODUCTION
The Emirate of Abu Dhabi has experienced tremendous growth since the mid-1970s when its current sewerage system was designed. The Abu Dhabi Sewerage Services Company (ADSSC) is the service provider for sewerage services throughout the Emirate. Many of its existing sewerage infrastructure assets are overloaded and reaching the end of their intended life and can no longer accommodate the projected extensive growth. Consequently, ADSSC has embarked on a major capital improvement program (CIP). One of the key components of the CIP is the Strategic Tunnel Enhancement Programme (STEP). The following components are included in the scope of STEP:

• Approximately 40 km of deep tunnel sewer, with internal diameters of 4.0, 5.0 and 5.5 m.
• Over 50 km of micro-tunnelled link sewers.
• New main tunnel pumping station at the downstream end of the deep tunnel sewer.
• Decommissioning of 35 existing sewerage pumping stations.

An overview of this programme is presented in Figure 1. When completed, STEP and ADSSC’s associated Tactic Investment Program scheme will constitute arguably the largest tunnelled sewerage system in the world.

ODOUR CHALLENGE
One of the key challenges faced by STEP is related to odour control. With the proposed tunnel route passing through some of the premier planned developments, the directive from higher authorities was clear; no odours and limited odour control facilities would be permitted.

To accomplish the stated goal, the consultant team examined a unique approach of a single odour control system installed at the proposed downstream tunnel pumping station. Several modelling tools including INTERCEPTOR...
(a computer-based model developed in-house to predict the generation, transport, and fate of \( \text{H}_2\text{S} \) in wastewater collection systems) and AFT FATHOM 7.0 were utilised for estimating the generation and fate of dissolved sulphides in the deep tunnel sewer portion of STEP and connecting link sewers as well as natural ventilation rates. Modelling and actual odour sampling confirmed that predicted odour levels will be extremely high with predicted levels thousands of times greater than odour threshold limits. It was further determined that for the preferred centralised odour control extraction approach, the vortex drop structures should be provided with the following features in order to increase natural ventilation and reduce corrosion potential:

- De-aeration chambers and associated drop shaft venting would not be incorporated into the drop shaft design to maximise air movement from the link sewers into the deep tunnel sewer.
- Drop shafts would be connected to the deep tunnel sewer using crown-to-crown connections to allow flows from the drop shaft to spill over into the deep tunnel sewer (i.e., minimal backpressure) which will result in higher natural air flows entering the tunnel.

While the centralised extraction approach was preferred given the stated goals, other approaches exist for odour extraction, including multiple satellite (localised or regional) odour extractions systems. Regional systems are generally located at drop structures or other potential ‘hot spot’ locations. Both these options were examined by the consultant team.

Key findings and conclusions showed that the preferred approach included installing vacuum relief valves (set at \(-500\) Pa) at drop structures and pressure type manhole covers throughout the link sewer system. This approach is expected to keep link sewers relatively air tight which will limit short-circuiting potential, help ensure that headspace negative pressures are maintained at a minimum of \(-50\) Pa, and push this containment zone out beyond the sewer collection system connection points.

Based on these earlier evaluations and computer modelling, the preferred approach for STEP was the centralised odour extraction system. The primary benefits of such a centralised approach for STEP are:

- Reduced aesthetic, noise, and odour concerns at the Al Wathba odour facility since it is located several...
kilometres from any identified sensitive receivers or significant populations.

- Lower first (capital) and operating costs compared with the regional odour extraction systems approach.
- Higher availability of land to locate odour control facilities compared with heavily populated areas of Abu Dhabi island and mainland.

However, there is risk associated with a centralised system since it has not been implemented for a deep tunnel sewer system of this size and complexity. To mitigate some risk associated with implementing the centralised odour extraction system, and to better understand entrained air forces at vortex drops, physical modelling of drop structures and overall STEP system was recommended.

PHYSICAL MODEL STUDY

Given the size and complexity of the STEP investment, ADSSC elected to proceed with the development of the recommended physical model study. The modelling study aimed to validate and refine certain design concepts associated with the drop shaft structures for STEP with an emphasis on the proposed centralised odour control approach. Tests were conducted for both the centralised and regional extraction concepts with the physical model study completed in November 2010. A schematic of the model is presented in Figure 2.

Due to scale issues, the shorter model tunnel could not accurately represent the prototype 40 km tunnel from a pressure drop standpoint. However, the following conclusions were developed as a result of the study:

- Under high liquid flow conditions coupled with tunnel negative pressures of ~0.10 kPa it is expected that high natural air flow rates would occur at drops exceeding previously selected 7.6 m³/s pumping station odour extraction capacity. Limited prior work (Lorenzo & Ghanem 2008; Sorensen et al. 2008) has been done related to air movement in and extraction from deep tunnel systems. Earlier predicted values were estimated from a study conducted in 1983 for the city of Milwaukee, Wisconsin (Jain & Kennedy 1985). This study included physical modelling of various drop configurations including vortex drop structures. However, the vortex drop structures were all modelled with de-aeration chambers which function to reduce the amount of air entering the tunnel. Therefore, these data under predicted air entrainment values for vortex drop without de-aeration chambers characteristic of STEP. Additional data research was not successful in finding vortex drops without de-aeration chambers.
- When tunnel natural air flow rates exceed pumping station odour treatment capacity a pressure bubble can form within the tunnel causing out-gassing at adjacent drops.

As a result of these new findings, providing a regional odour extraction approach is beneficial for several reasons:

- It provides redundancy in case the pumping station odour extraction system is compromised.
- It provides the necessary additional capacity to maintain a negative pressure within the tunnel under flow conditions exceeding current pumping station odour extraction system capacity.

Because of pressure bubble concerns and the length of the tunnel, it was recommended that a regional odour treatment system be installed. This approach would include two or more regional systems designed to extract air directly out of the tunnel. This approach would also retain the concept of allowing drop structures to naturally ventilate link...
sewers while the regional systems would extract the air collected within the tunnel for treatment.

**REGIONAL EXTRACTION CONCEPT**

Using the results from the physical model testing, a concept for extraction of odour at yet to be defined locations along the route of the deep tunnel sewer was developed. This regional system would be connected so as to extract foul air directly from the tunnel headspace.

**Regional system capacity sizing**

Physical modelling results were carefully analysed and evaluated for determining the amount of air expected to be generated at drop structures under all normal operating conditions.

Natural airflow at drops is influenced by many conditions. These include:

- **Liquid flow rate:** Lower liquid flows tend to pull less air while higher liquid flows pull more air. This is observed in Figure 4 (Lyons et al. 2010) herein. Similarly, lower liquid flows do not have the ability to generate significant negative pressures upstream while high liquid flows can generate greater than −500 Pa. This is an important fact that was confirmed via physical modelling.

- **Link sewer tightness:** A relatively air-tight link sewer will tend to reduce natural air flow rates. This fact was observed during the physical model testing. A representative vortex drop was tested under various upstream negative pressure conditions to correlate air flow to link sewer vacuum. A graph illustrating this phenomenon is provided in Figure 3 (Lyons et al. 2010) herein. Note that for low liquid flows a small increase in upstream vacuum causes a significant decrease in air flows. Conversely, for high liquid flows a small increase in upstream vacuum has a lesser impact on air flows.

- **Link sewer headspace cross-section:** As liquid flows increase and associated air demands increase, link sewer size can have an appreciable impact on air flows. If air demands are great and link sewer size is small, the cross-sectional area of the link sewer headspace can cause high air velocities and subsequent high pressure drop.

Air flows were further corrected based on expected system leakage. A matrix was produced to assign leakage rankings to individual link sewers. A leakage opening size based on percentage of link sewer line size was assigned to each link sewer according to their respective leakage ranking. The assigned opening was treated like a sharp edged orifice and a pressure drop was calculated across the opening based on the high flow. The calculated pressure drop was used to ‘correct’ the air flow rate based on the correlation between air flow and link sewer pressure found in Figure 4. In addition, pressure drop within link sewer headspace was calculated based on high flows and the sewer pipe running at 50% full. Similar to leakage openings, the calculated pressure drop was used to ‘correct’ the air flow rate based on Figure 4 data.

Air flows for all vortex drops were extracted from Figure 4. Note that for an expected tunnel negative pressure of −50 Pa, Qa:Ql ratios are 1.0 for low liquid flow and 1.2 for high liquid flow. Based on the physical modelling findings, all measured Froude scaled air flows must be multiplied by a correction factor of 1.94. Therefore, all values extracted from Figure 4 have been multiplied by this correction factor.

A summary of predicted air flow characteristics for each drop structure is provided in Table 1. The following are key findings from Table 1.

- Low air flows are approximately three times smaller than high air flows.
- There is a possibility that, due to excessive air demand under high liquid flow conditions, vacuum relief valves will be activated for link sewers MPS1, MPS13, and MPS17 as liquid flows approach high flow conditions. Vacuum relief valves will limit link sewer headspace vacuum levels to −500 Pa. This high vacuum will tend to reduce air flows by as much as 50% below the
uncorrected high air flow values as represented by the corrected high air flow values.

- The estimated pressure drop within link sewer headspace under all flow conditions is low and therefore inconsequential to impacting air flows.

The total predicted maximum required extraction air flow capacity for the STEP tunnel and link sewers is 35.41 m³/s. The pumping station is currently designed to draw 7.6 m³/s from the tunnel. The remaining shortfall is 28.0 m³/s. Any regional system(s) sized to meet the 28.0 m³/s capacity will ensure that tunnel and link sewers are maintained at a negative pressure and pressure bubbles are avoided under all normal flow conditions.

**Recommendation**

A two regional extraction systems option was recommended. This option includes the pumping station odour extraction system at the far downstream end of the tunnel acting as regional system number one (7.6 m³/s) and another large regional extraction system (28 m³/s) located at the approximate mid-point of the tunnel. This option would also include a provision for adding another

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**Table 1 | Drop structure characteristics**

<table>
<thead>
<tr>
<th>Link sewer connection point</th>
<th>Type</th>
<th>Leakage ranking</th>
<th>Low flow Qa (m³/s)</th>
<th>High flow Qa (uncorrected) (m³/s)</th>
<th>Pressure drop through leakage openings (Pa)</th>
<th>Pressure drop through link sewer headspace (Pa)</th>
<th>High flow Qa (corrected) (m³/s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>MPS 2&amp;3 Inflow @ WS1</td>
<td>Simple b</td>
<td></td>
<td>0.94</td>
<td>4.47</td>
<td>39</td>
<td>&lt;100</td>
<td>3.35</td>
</tr>
<tr>
<td>NWLS Inflow @ MH N03</td>
<td>Simple b</td>
<td></td>
<td>0.21</td>
<td>1.02</td>
<td>12</td>
<td>&lt;100</td>
<td>0.92</td>
</tr>
<tr>
<td>MILS Inflow @ AS1</td>
<td>Vortex a</td>
<td></td>
<td>0.02</td>
<td>0.1</td>
<td>3</td>
<td>&lt;100</td>
<td>0.092</td>
</tr>
<tr>
<td>MPS1 Inflow @ MH P03</td>
<td>Vortex a</td>
<td></td>
<td>0.49</td>
<td>2.8</td>
<td>699</td>
<td>&lt;100</td>
<td>1.40</td>
</tr>
<tr>
<td>SILS Inflow @ WS3</td>
<td>Vortex a</td>
<td></td>
<td>0.04</td>
<td>0.21</td>
<td>120</td>
<td>125</td>
<td>0.19</td>
</tr>
<tr>
<td>OCLS Inflow @ AS3</td>
<td>Vortex b</td>
<td></td>
<td>0.15</td>
<td>0.89</td>
<td>190</td>
<td>&lt;100</td>
<td>0.72</td>
</tr>
<tr>
<td>MPS13 Inflow @ WS4</td>
<td>Vortex a</td>
<td></td>
<td>4.47</td>
<td>26.82</td>
<td>2,670</td>
<td>&lt;100</td>
<td>13.4</td>
</tr>
<tr>
<td>MPS17 Inflow @ WS6</td>
<td>Vortex a</td>
<td></td>
<td>2.98</td>
<td>17.87</td>
<td>2,400</td>
<td>&lt;100</td>
<td>8.94</td>
</tr>
<tr>
<td>MPS8 Inflow @ AS6</td>
<td>Vortex b</td>
<td></td>
<td>1.64</td>
<td>9.84</td>
<td>285</td>
<td>&lt;100</td>
<td>6.40</td>
</tr>
<tr>
<td>Total</td>
<td></td>
<td></td>
<td>10.94</td>
<td>64.02</td>
<td></td>
<td></td>
<td>35.41</td>
</tr>
</tbody>
</table>

a: Ranking of 1 – Medium leakage (opening size of 20% of link sewer size).
b: Ranking of 2 – High leakage (opening size of 30% of link sewer size).

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**Figure 4 | Qa versus Ql for vortex drop structure.**
regional system in the future if necessary. The additional regional system would provide additional redundancy and improve zone of influence.

CONCLUSIONS

Air dynamics within deep tunnels are complex and difficult to quantify. Limited technical research has been done related to air movement in, and extraction from, deep tunnel systems. Physical modelling is a useful tool to better understand and predict air entrainment and air movement within vortex drops and tunnel systems. For the STEP system, a two regional extraction systems approach proved to be most favourable. Proper sizing, appropriate treatment technology, careful siting, and effective operation will ensure the deep tunnel, drop structures, and link sewers are well ventilated and maintained at a negative pressure under all normal operating conditions. By so doing, odours will be contained and removed, helping assure ADSSC’s goal of no odours can be achieved.

REFERENCES


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