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# Deep tunnel sewerage system phase 2 – hydraulics

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## Abstract

The Deep Tunnel Sewerage System (DTSS) is aimed at providing a robust and efficient means of catering to Singapore's used-water needs. DTSS2 is the second phase of this project, comprising an approximately 30-km long South Tunnel, a 10-km long Industrial Tunnel, 60-km of Link Sewers and a new Water Reclamation Plant integrated with a NEWater facility. In contrast with tunnels designed to store overflows in combined sewer systems, the DTSS tunnels convey used-water all the time from Singapore's separated system. This paper describes hydraulic analyses that were conducted during the feasibility study and preliminary design. The topics covered include hydraulic modelling of the entire system with the main goal of ensuring system resilience, air management to avoid odours at ground level, and isolation of tunnel section using gates for potential maintenance or repair. The resilience analyses concentrated on the system functionality in case of a failure, to ensure that used-water can be safely conveyed to a treatment plant. The air management system included several odour control facilities and air jumpers to avoid escape of odorous air from the system and the isolation gates requires detailed hydraulic analyses to cater to the high heads involved.

**Key words:** deep tunnel, hydraulic modelling, resilience, tunnel air management, tunnel segment isolation, Used-water

## INTRODUCTION

Large tunnels are increasingly used around the world for wastewater conveyance or storage in separated or combined sewer systems. Examples include the Central Interceptor in Auckland, New Zealand (Grace *et al.* 2017); the Southeast Collector in Toronto, Canada; the Thames Tideway Tunnel in London, England (Crawford *et al.* 2016); the STEP Tunnel in Abu Dhabi, UAE (Lyons *et al.* 2011); the North Dorchester Bay Tunnel in Boston, USA (Heath *et al.* 1998) and many more. Each tunnel system has its unique characteristics. A significant differentiator is whether the collection system is combined or separated. In combined systems, tunnels are often used to store overflows that would occur during wet weather and convey these to a treatment plant after the rain event. A characteristic of these systems is the very large inflows that occur periodically (Vasconcelos & Wright 2017). In separated systems, as in Singapore, flows are less variable but wet weather influences are nevertheless present due to infiltration and inflow, commonly referred to as I/I.

The Singapore Deep Tunnel Sewerage System (DTSS) was conceived in the mid-1990s to serve Singapore's long-term used-water needs (Water Technology 2019). The DTSS concept uses deep tunnels to intercept the flows in existing sewers for conveyance by gravity to centralized Water

Reclamation Plants (WRPs). DTSS Phase 2 (DTSS2) completes the DTSS by connecting the North Tunnel built under Phase 1 with a new South Tunnel and a new WRP at Tuas. An emphasis of DTSS2 was resilience, as well as application of lessons learnt from DTSS1. Other planning objectives included cost optimization, energy and land-take minimization, ease of operation and maintainability. The DTSS2 comprises the following:

- a 30-km long South Tunnel, 3.0 to 6.0 m in diameter
- a 10-km long Industrial Tunnel, 3.3 to 4.0 m in diameter
- 60-km of link sewers
- 17 vortex drops into the tunnels and
- the new Tuas Water Reclamation Plant, which will also include a NEWater facility that will further treat the used-water for reuse

The paper presents hydraulic analyses that were conducted for the planning and design of these large wastewater tunnels and, in that sense, it is a ‘best practice’ paper. The paper also presents several novel elements and the analyses that were conducted to develop and size them. The novel elements include (i) use of the tunnel to equalize flows to the Tuas WRP, (ii) distributed odour control facilities and air jumpers for air management and (iii) the use of gates for tunnel segment isolation.

## METHODOLOGY

### Hydraulic modelling

Collection system modelling is commonly undertaken for large wastewater tunnelling projects, whether for storage or conveyance purposes (Lind *et al.* 2010; Plant *et al.* 2014). Collection system modelling provides quantitative estimates of parameters needed for the design, and each project has a slightly different set of questions to be addressed. For the DTSS2 project the items of interest were:

- Analysis and evaluation of a range of DTSS2 tunnel configurations, including single and dual tunnels with gravity flow (and a downstream pumping station) or siphon flow
- Validation of the 3 Water Reclamation Plants (3-WRP) concept (at Kranji, Changi and Tuas – see Figure 1).
- Analysis of system failure scenarios for identification of resilience measures
- Preliminary assessment of self-cleansing capacity and subsequent sediment transport modelling
- Assessment of an ‘attenuated’ mode of operation in which the flows pumped by the Tuas Influent Pumping Station are managed to yield as constant a flow as possible in the WRP to ensure reliable used-water treatment and NEWater production.
- Provide input to the air management analyses.

Hydraulic modelling was conducted using the MIKE URBAN collection system modelling software (DHI 2014). The model covered both the existing DTSS1 and the proposed DTSS2 systems, as shown in Figure 2. Of particular importance was the specification of the influent flows to the system. The dry weather flows were specified based on population predictions and per capita contributions. Both factors are subject to uncertainty and low, medium and high growth scenarios were developed. And, based on a thorough review of Singapore as well as international data a per capita used-water contribution of 0.345 $m^3$/capita/day was adopted, which is 15% above the 2013 rate. This number is the overall used-water flow divided by the population; it therefore includes commercial and industrial contributions, as well as visitors and wet weather infiltration and inflow. Diurnal flow variations were specified based on flow measurements in the system.

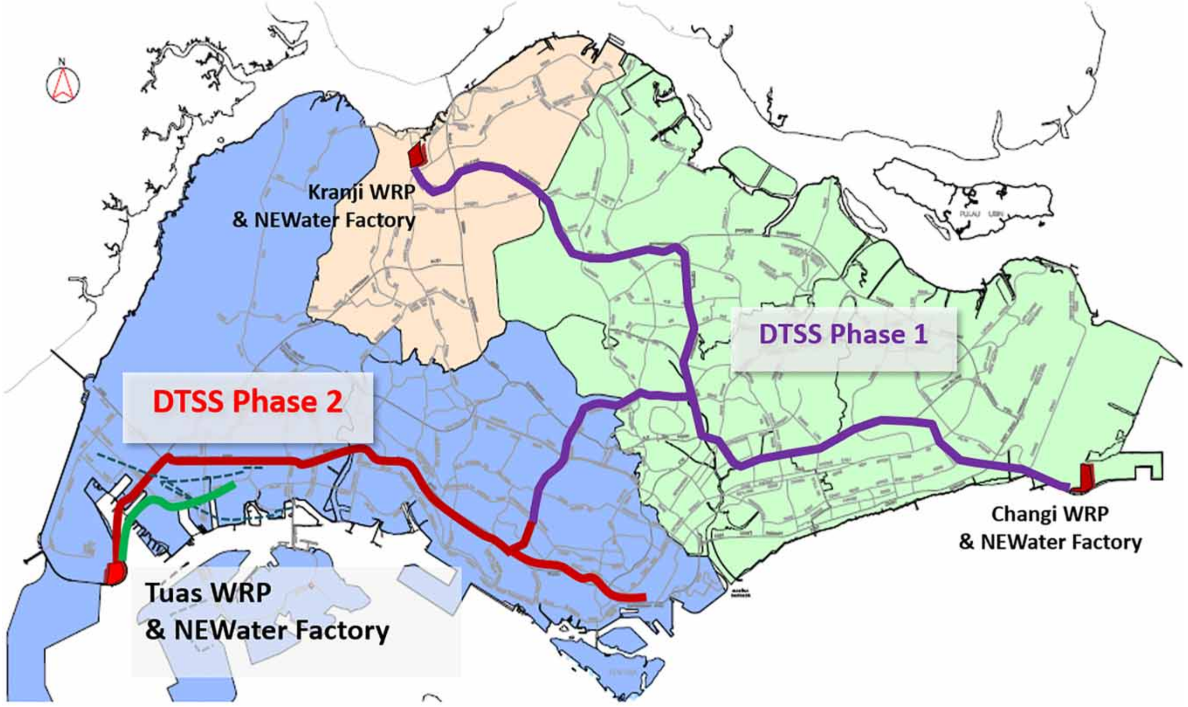

**Figure 1** | DTSS concept.

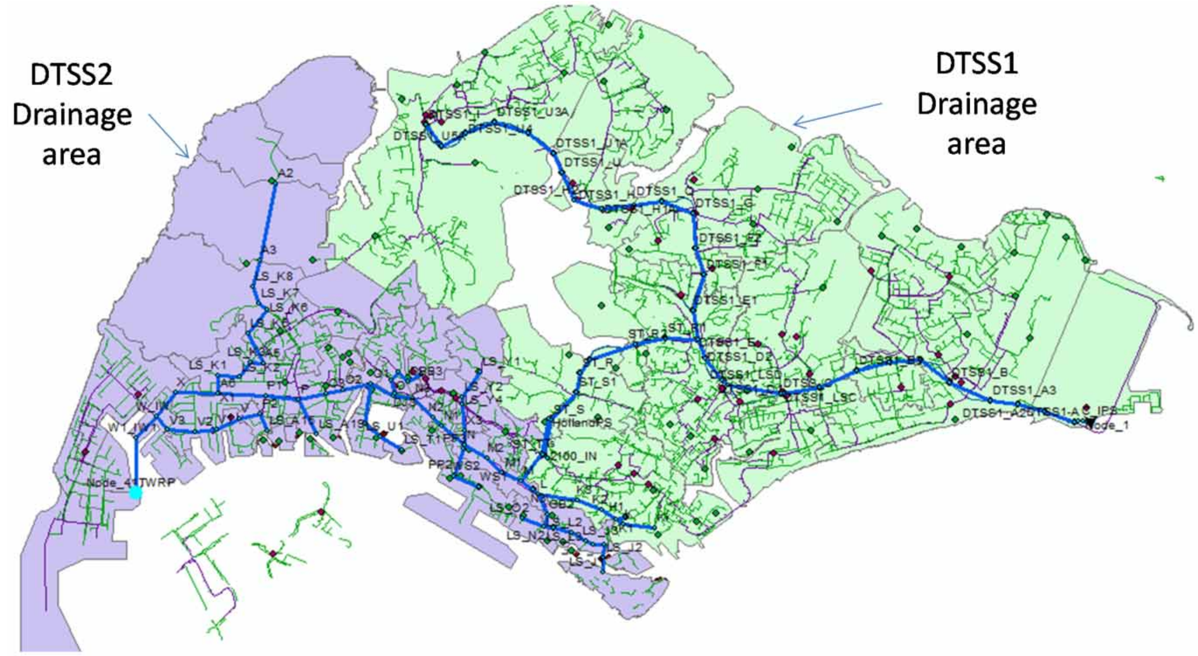

**Figure 2** | Hydraulic model coverage.

To assess the wet weather contributions to tunnel flows, flow records at 11 pumping stations were analysed over a number of events. An example analysis is presented in Table 1, which resulted in an average rainfall contribution of 5.1% (volume of wet weather flow in excess of dry weather flow divided by the rainfall volume over the catchment). Another characteristic that was identified (based on reviews of the hydrographs) is whether the particular catchment exhibited a fast or slow response to the rain. The wet weather flows were subsequently increased to account for global climate

**Table 1** | Wet weather flow analysis at sample pumping station

| Event/Period | Total flow ($m^3$) | ADWF[a] ($m^3$) | Rain (mm) | Wet weather I/I (%) |
|---|---|---|---|---|
| Event 1 – 15–20 June 2010 | 269,200 | 137,000 | 154 | 4.4% |
| Event 2 – 16–21 July 2010 | 287,300 | 137,000 | 152 | 5.0% |
| Event 3 – 9–11 June 2010 | 89,800 | 68,500 | 24 | 4.5% |
| January (low rainfall) | 764,100 | 708,100 | 55 | 5.2% |
| June 2010 | 998,900 | 685,300 | 340 | 4.7% |
| July 2010 | 1,236,90 | 708,100 | 484 | 5.5% |
| Event 4 – 25–28 Sept 2013 | 148,000 | 91,400 | 55 | 5.3% |

[a] Average Dry Weather Flow.

change, which may results in an increase of storm intensities and I/I. Wet weather flows were simulated using MIKE URBAN's I/I flow simulation capabilities such that transient simulations of storms with various return periods could be conducted, as well as long-term simulations.

The model was calibrated by comparison of calculated hydrographs and water levels at a limited number of flow monitors in the existing system. Because much of the system is not built yet, the calibration was limited. To be conservative a Manning's coefficient of 0.013, representative of aged conditions, was used for the tunnels.

## Resilience

Resilience has been a goal of sewer system developers for a long time, resulting in systems that have operated satisfactorily for over a century in cities such as London and Paris. The main objective then was the ability to cater to population growth. Recently, global climate change has been another concern (Crawford *et al.* 2016). For the DTSS project, population growth was taken into account by using population predictions for the year 2100, with sufficient flexibility to account for different possible geographical growth patterns. But a major resilience concern was to ensure that used-water could be safely conveyed to a WRP in case of a failure in the system.

For the hydraulic analysis, a set of 11 tunnel failure scenarios was developed – see Figure 3, as well as extreme wet weather events. The different failure scenarios were simulated in the hydraulic model individually and in combination to identify the optimum suite of resilience measures. The following options were considered and optimized:

- Option 0: Single tunnel, with spur tunnel connection to the North Tunnel
- Option 1: Single tunnel + section isolation
- Option 2: Single tunnel + section isolation + link sewer cross-connections
- Option 3: Dual tunnel

## Air management

Air management is a significant issue for large wastewater tunnels. For combined system storage tunnels, the main issue is the occasionally very large water inflows, which require the equal air outflow to be accommodated safely and without causing odours (Geogaki *et al.* 2017). For conveyance tunnels the main issue is generally odours (Locke *et al.* 2018) and this was the case for DTSS.

Air flow in sewers has been the subject of a number of studies including field measurements (Pescod & Price 1982; Witherspoon *et al.* 2009), physical modelling (Lyons *et al.* 2011), momentum-based modelling (Ward *et al.* 2011), head-based modelling (Brocard *et al.* 2012; Eftekharzadeh *et al.* 2013) and CFD modelling (Edwini-Bonsu & Steffler 2004). The different modelling approaches

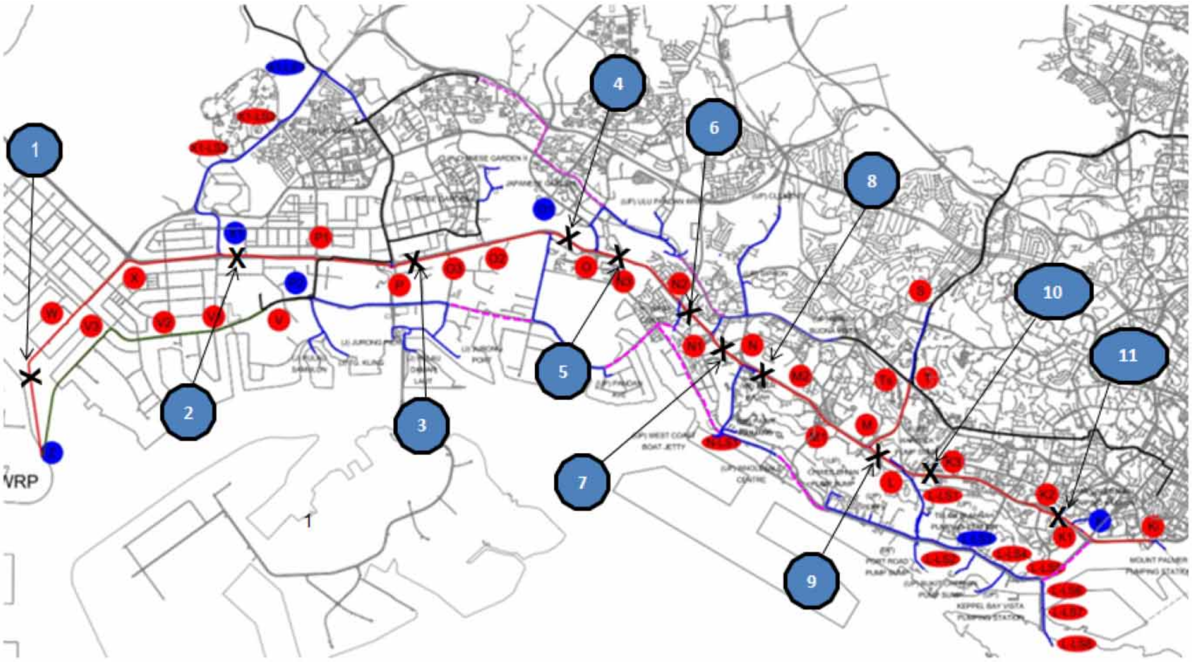

**Figure 3** | Postulated failure locations.

show deviations from measured data that can be explained by several factors. One factor is that air flow in sewers is affected by a number of mechanisms including friction, atmospheric pressure variations, air density, and water level changes due to flow variations (Lowe 2016). The latter is most important in storage tunnels.

Another important factor is the degree of communication between the sewer and the atmosphere. In most near-surface sewers, the degree of communication is high, with many openings, particularly in combined systems. This is a condition that can be called 'well ventilated sewer' and a formulation (briefly summarized below) was developed to assess this air flow (Brocard *et al.* 2012). In deep tunnels, however, the number of communication points with the atmosphere is reduced and attempts are frequently made at sealing the tunnel. This can be seen as the opposite of the well ventilated sewer. In this case, the air flow is constant with distance.

For DTSS2, the head-based modelling approach was used (Brocard *et al.* 2012), assuming that the air flow is mainly controlled by the shear stresses between the air and the tunnel wall and between the air and the flowing water surface, as shown schematically in Figure 4.

The governing equation for the air flow is:

$$\frac{\Delta H}{\Delta x} = -\frac{f_C\, P_C}{4A}\,\frac{V_A\,|V_A|}{2g} + \frac{f_W\, W}{4A}\,\frac{(V_W - V_A)\,|V_W - V_A|}{2g}$$

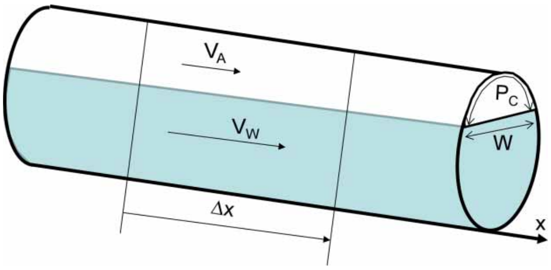

**Figure 4** | Air co-flow in sewer.

where H = head, measured in height of air (m), x = distance, positive in the wastewater flow direction (m), $V_A$ = air velocity (m/s), $V_W$ = water velocity (m/s), $P_C$ = air contact perimeter with conduit (m), A = air cross section area ($m^2$), W = water surface width (m), g = acceleration of gravity ($m/s^2$), $f_C$ = air-conduit friction factor, $f_W$ = air-water friction factor. In this equation, the head loss is assumed positive in the positive x direction (i.e. decreasing head in the x direction).

The above equation can be used to simulate the conditions of full ventilation (no head gradient along the sewer) by setting $\Delta H/\Delta X = 0$. The result can be expressed as:

$$\frac{V_A}{V_W} = \frac{-1+\sqrt{a}}{a-1} \text{ with } a = f_C P_C / f_W W$$

Air/water velocity ratios calculated using the above equation for several different relative water depths and otherwise typical parameter values for wastewater applications are summarized in Table 2. The resulting ratios vary from 0.36 to 0.44. These values are consistent with the measurements of Pescod & Price (1982), but somewhat higher than those of WERF (Witherspoon *et al.* 2009).

**Table 2** | Air/water velocity ratios for ventilated sewers

| | | | | | | |
|---|---|---|---|---|---|---|
| Relative water depth | Y/D | 0.3 | 0.5 | 0.6 | 0.7 | 0.8 |
| Relative friction factor | $f_W/f_C$ | 0.7 | 0.7 | 0.7 | 0.7 | 0.7 |
| Inscribed angle | $\sigma = 2$ Acos $(1 - 2Y/D)$ | 2.32 | 3.14 | 3.54 | 3.96 | 4.43 |
| Relative surface width | $W/D = \sin(\sigma/2)$ | 0.92 | 1.00 | 0.98 | 0.92 | 0.80 |
| Relative air perimeter | $P_C/D = \pi - \sigma/2$ | 1.98 | 1.57 | 1.37 | 1.16 | 0.93 |
| Dimensionless parameter | $a = f_C P_C / F_W W$ | 3.09 | 2.24 | 2.00 | 1.81 | 1.66 |
| Air/Water velocity ratio | $V_A/V_W =$ | 0.36 | 0.40 | 0.41 | 0.43 | 0.44 |

### Tunnel sections isolation

Unlike rail or road tunnels, which can be easily accessed for inspection and maintenance, it is relatively difficult to access a sewer tunnel that is constantly conveying used-water. The design of DTSS2 has taken the unique step of including the ability to insert large drop-in roller gates (estimated weight approximately 30 tons) to isolate sections of the tunnel and allow interventions for inspection and any necessary repairs. The incoming used-water flow will be conveyed around the isolated section through near surface sewers built for this purpose – see Figures 5 and 6.

A significant hydraulic issue associated with the isolation gates is their removal. As the gates are lifted, used-water will rush under the gate at high speed. With a head of up to 43 m upstream, the velocity of the flow under the gate will be in the order of 30 m/s and this requires special attention to ensure that damage to the tunnel liner will not occur. To assess the situation, including the length of tunnel affected by high velocities, Computational Fluid Dynamics (CFD) modelling was conducted, as well as a physical model.

The CFD modelling was conducted using the FLOW3D code with the RNG k-epsilon turbulence model. A section of the 6.0 m diameter tunnel was simulated including most of the shaft containing the isolation gate as well as 300 m of downstream tunnel. The simulation domain was discretized in a mesh of 2.3 million box-like cells 0.1 m on the side near the gate to 0.5 m farther in the tunnel. Model simulations were conducted with and without water in the tunnel section downstream of the gate. Water downstream of the gate could be used to slow down velocities and this could be achieved by

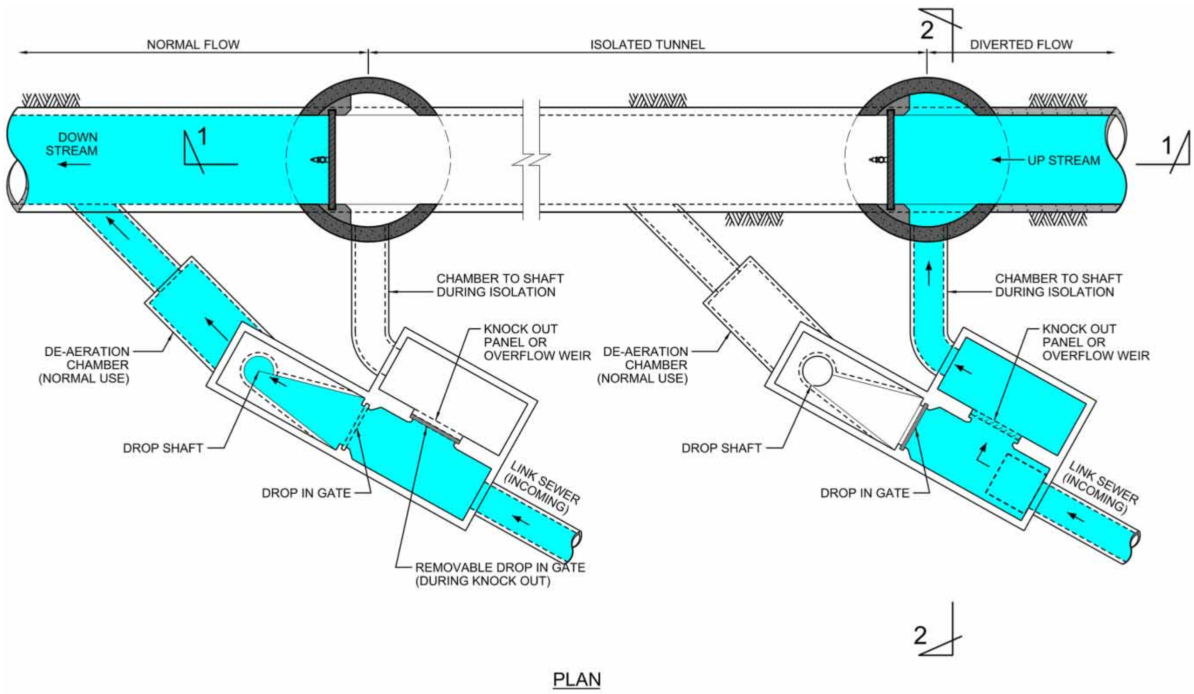

**Figure 5** | Flow re-routing during segment isolation.

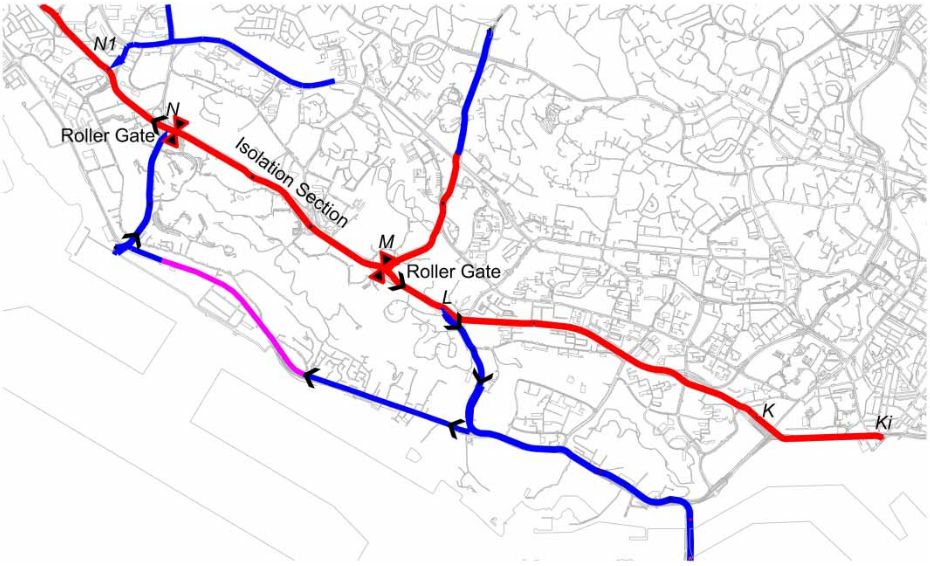

**Figure 6** | Tunnel isolation using roller gates and link sewer bypass loop.

shutting down or throttling the Tuas WRP influent pumps for a period of time until water rises to the desired level in the tunnel.

A physical model of the gate opening was also conducted at Nanyang Technological University. The physical model covered the gate shaft and approximately 300 m of the downstream tunnel at a scale of 1 to 31.5. As appropriate for open channel flow, the model was operated according to Froude scaling law. Velocity measurements were made using Particle Image Velocimetry (PIV), a laser-based system. Pressure measurements were also conducted as there was a concern that the high velocities might be associated with low pressures that could pull the liner off the tunnel wall.

## RESULTS AND DISCUSSION

### Hydraulic modeling

Operating the Tuas WRP Influent Pumping Station at a constant flow during dry weather was simulated. In this attenuated mode of operation, the South Tunnel would be used for storage, with its water level rising during the day and declining at night, as shown in Figure 7. The hydraulic model was used to evaluate the self-cleaning characteristics of the South Tunnel under this mode of operation and to optimize the operation of the Tuas WRP Influent Pumping Station during wet weather.

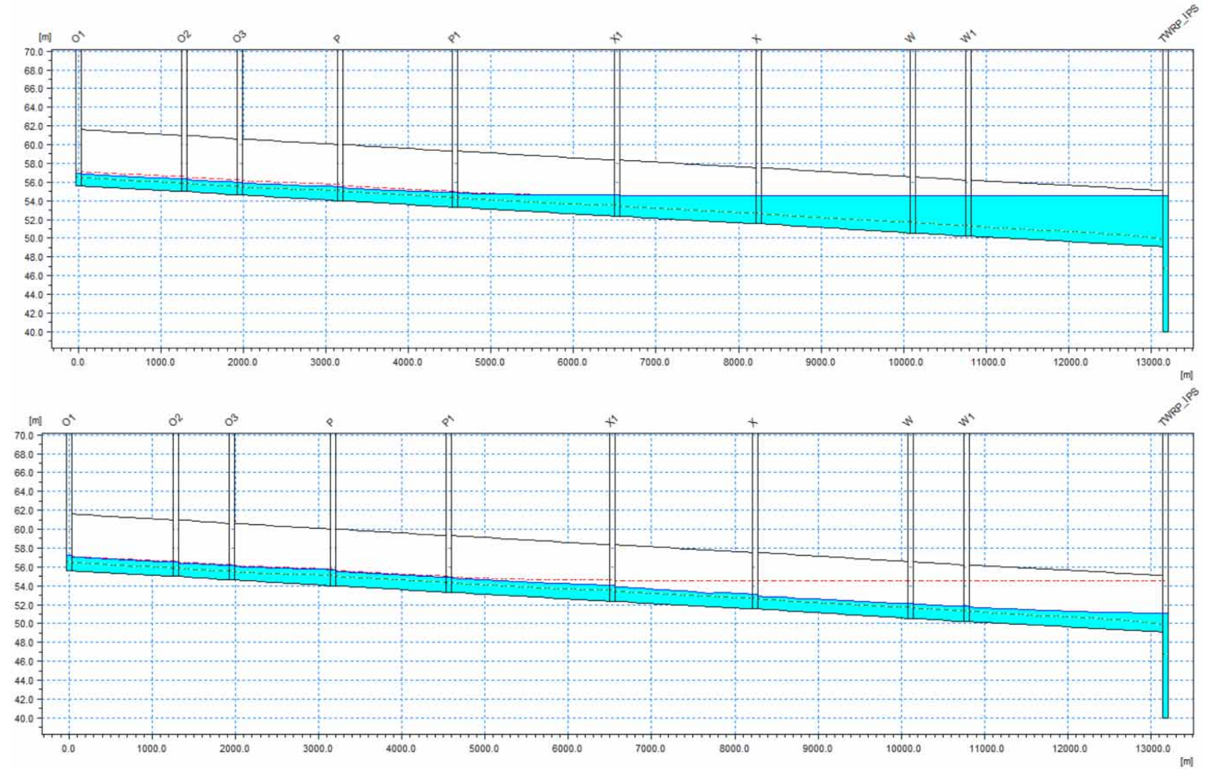

**Figure 7** | Year 2060 dry weather flow maximum and minimum levels.

Relative to self-cleaning, achieving a velocity of 1 m/s at least once a day was used as a preliminary criterion because of its ease of application, although it was recognized that several other factors are also relevant (CIRIA 1996; ASCE 2007). With the attenuated mode of operation, the modelling showed that this criterion was not met in the downstream section of the tunnel and a more thorough analysis involving sediment transport modelling was recommended.

During rain events, when the water level in the Tuas Influent Pumping Station screen shaft exceeds the normal dry weather range, the pumping station will switch mode to wet weather operation. The ramping up of pumps should lag behind the flow increase to allow some attenuation of small wet weather events and smoothing of the impact to the WRP processes. For larger events a gradual flow ramping up was tested in the hydraulic model and found to be satisfactory.

Surge modelling and sediment transport modelling were also conducted, but these are not covered in in this paper.

### Resilience

The reliance modelling showed that the connectivity between DTSS Phases 1 and 2 via the extension of the Spur Tunnel (Option 0) provides an enhanced level of resilience, by allowing some flow transfer from the North Tunnel to the South Tunnel. However, additional measures were found necessary to meet the system containment criteria set forth by Singapore National Water Agency, Public Utilities Board (PUB).

The preferred system was determined based on an assessment of hydraulic performance and levels of service, resilience, cost and benefits including minimising disruption to NEWater production. The dual tunnel option (Option 3), although it obtained higher benefits score in the cost-benefit analysis, was eliminated because of its highest risk-weighted costs. Option 1 was ascertained to be most cost-effective, but tunnel isolation alone would not prevent system spillage and therefore, cross connections were added to the isolation capability (Option 2).

## Air management

The calculation methodology described earlier was used to develop an air management sytem for DTSS2. The access manholes along the deep tunnels will largely be sealed but, over time, escape pathways may develop; and the link sewers upstream will offer more opportunities for air escape if pressure build-up occurs. Therefore, the objective was to maintain a slight negative pressure in the tunnels.

The approach that was selected involves odour control facilities (OCFs) to extract and treat odorous air, and air jumpers (AJs) to convey air from the incoming link sewer to the deep tunnel and to push it along the tunnel to next available OCF. The OCFs will treat the air extracted from the deep tunnel at that particular shaft including air from the incoming link sewers, as shown in Figure 8. The AJs, shown in Figure 9, will be located at sites where OCFs would not be feasible due to existing land use, for example built-up areas.

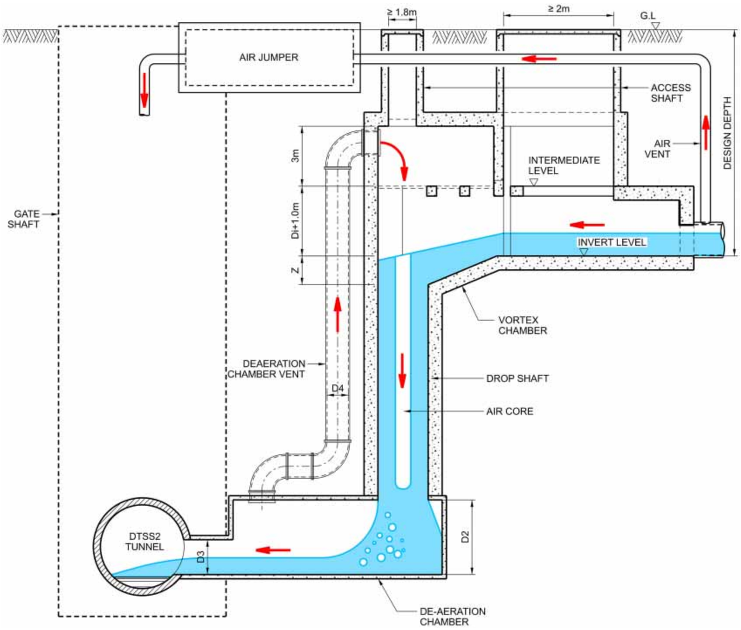

**Figure 8** | Odour control facility schematic.

In total, 13 AJs and four OCFs were identified for the DTSS2 tunnel and link sewer network.

The ability of the vortex drop to replace the air jumpers was investigated. Vortex drops naturally pull air and, if the air flow driven by the vortex is equal to or greater than the incoming air flow in the link sewers, air jumpers may not be necessary. This would also require connecting the bottom of the vortex drop to the tunnel crown, to allow air passage at all times. The air pulling capacity of vortex drops has

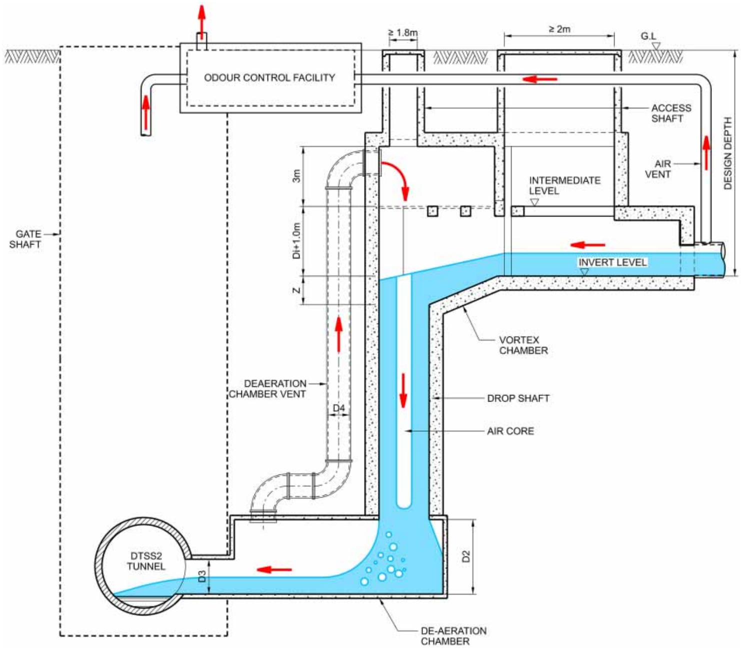

**Figure 9** | Air jumper schematic.

been studied in scale models conducted for other projects, from which an air to water flow ratio on the order of 1.5 was derived (Lyons & Odgaard 2010). All link sewers at the hydraulic drop structures just upstream of the tunnels have air to water flow ratios exceeding this number, suggesting that fan-enabled air jumpers were needed. Air jumpers also have the benefit of providing flexibility relative to a fully passive approach relying on the air pulling capacity of the vortex.

The OCFs and AJs were sized to handle dry weather as well as wet weather conditions from the estimated system commissioning in 2027 up to year 2100. The incoming air flows in the link sewers were estimated by assuming well-ventilated conditions, i.e. zero head gradient in the link sewers. The variations of air pressure in the deep tunnel were calculated for a range of conditions, including dry and wet weather, and air flows of the odour control facilities were adjusted to ensure a small negative pressure would be maintained in the deep tunnel. The required negative pressure was determined to be –2.4 mm of water, based on Singapore weather conditions of fairly constant year round temperature and humidity.

The air flow governing equation was solved using used-water flow characteristics (velocity and depth) determined by the MIKE URBAN model. The resulting OCF and AJ capacities are summarized in Table 3. These capacities are provided here to provide an indication of the air flows involved, and they may change

**Table 3** | Air management facilities capacities

| | | **Shaft** | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | K1 | L | M | N | N1 | N2 | N3 | O1 | P | X1 | Tuas |
| | Fan speed | AJ | Aj | OCF | OCF | AJ | AJ | OCF | AJ | AJ | OCF | OCF |
| | | **Flows ($m^3$/s)** | | | | | | | | | | |
| From link sewer | Sp 1 | 0.2 | 2.4 | 0.9 | 3.4 | 1.5 | 0.4 | 2.3 | 0.8 | 2.8 | 5.0 | |
| | Sp 2 | 0.4 | 4.2 | 1.4 | 6.3 | 2.5 | 0.7 | 4.1 | 1.4 | 2.6 | 5.0 | |
| From tunnel | Sp 1 | | | 0.0 | 0.0 | | | 2.0 | | | 0.0 | 3.0 |
| | Sp 2 | | | 2.0 | 4.0 | | | 4.0 | | | 8.0 | 6.3 |
| OCF capacity | | | | 3.4 | 10.3 | | | 8.1 | | | 13.0 | 6.3 |

during final design. The observation can be made that these air flows are relatively high. This is in part because of the large size of the tunnels and link sewers, which will result in large air spaces. The large tunnel and sewer sizes were selected to ensure sufficient used-water flow capacity in the future, this being an overriding requirement for the system. Because of the variations in air flow requirements, two-speed fans are proposed, controlled by pressure measurements in the tunnels and link sewers.

Emergency vents were included to cater to large wet weather events. The MIKE URBAN model was used to simulate the 100-year storm to identify the potential trapping of air pockets in the tunnel as the flow increases and two emergency vents were added to the South Tunnel design to safely convey the air to ground level. Without such vents, trapped air pockets can create geysers (violent eruptions of air and water) at shaft locations (Vasconcelos & Wright 2017; Brocard *et al.* 2015).

### Tunnel sections isolation

The isolation gates will be required to withstand an unbalanced load of up to 43 m of hydraulic head. To provide the required structural strength and facilitate deployment, stainless steel gates with guide wheels will be lowered into tracked guide channels. This roller gate system will ensure proper gate alignment to minimise frictional forces when lowering or raising the gates.

Due to weight and logistical requirements, the gates will be fabricated in modular form and stored offsite. When a section of tunnel requires isolation, the roller gates modules will be transported to the site and assembled within the shaft using a mobile crane and support beams, as shown in Figure 10. The first gate module will be lowered onto the support beams. The second module will then be placed above and bolted to the first module. The connected gate modules will then be lifted and the support beams slid out. The gate modules will be subsequently lowered and the support beams slid in to the second gate module. The process will be repeated for the last gate module.

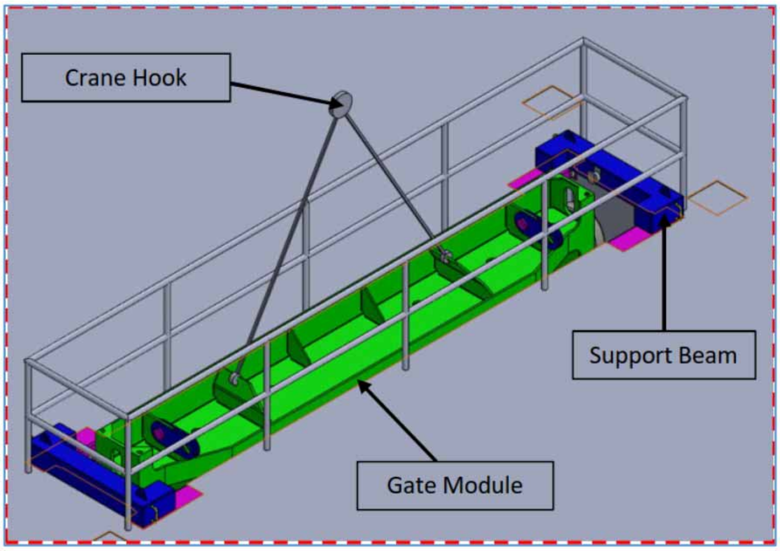

**Figure 10** | Gate assembly at ground level via support beams.

Once all the gate modules are assembled, the mobile crane will be used to place a drum hoist on top of the shaft. The drum hoist will first lift the gate to allow removal of the support beams. Then the drum hoist will lower the gate to the bottom of the shaft. The hoist cables will remain attached to the gate even after the gate has been lowered into position. When isolation is no longer required, the drum hoist will be used to raise the gate. Once the gate is secured at the assembly position, a mobile crane will be used to remove the drum hoist and the gate modules. The gate modules will then be cleaned, inspected, and stored for future re-use.

The CFD model developed to address the gate removal hydraulics was run in steady state mode with fixed gate openings and in transient mode with rising gates. The simulations assumed an upstream head of 43 m based on the hydraulic analyses. A sample of the CFD model result is shown in Figure 11. Velocities exceeding 28 m/s are found downstream of the gate and because of the transition between the flat floor at the gate to the circular tunnel, significant splashing was observed.

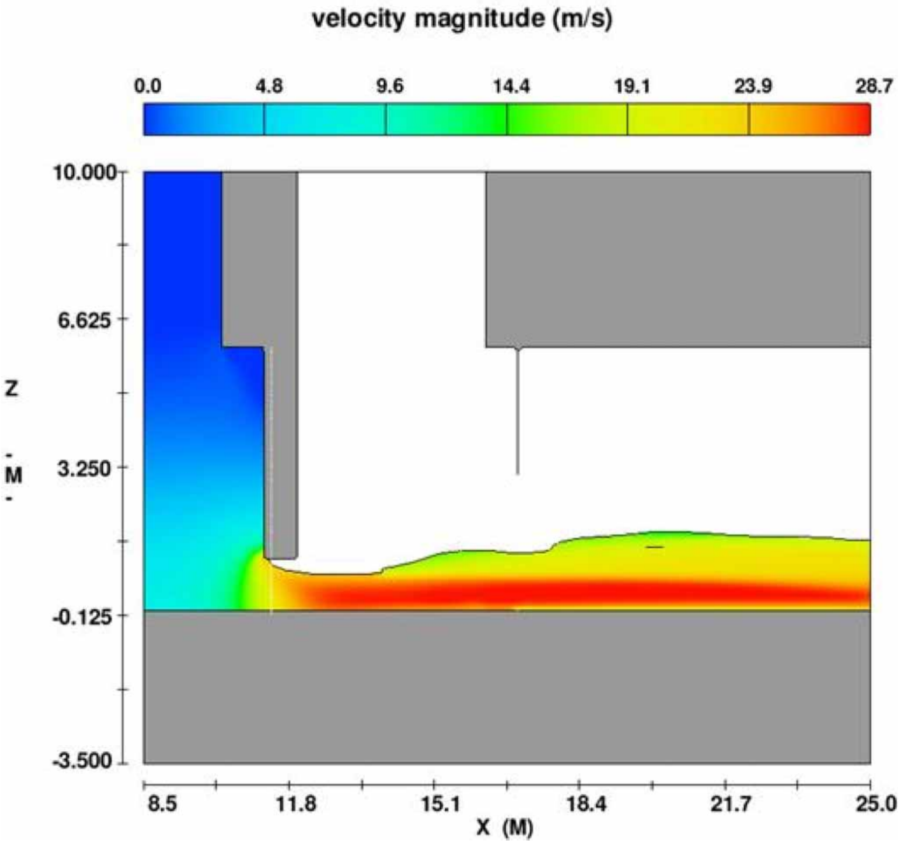

**Figure 11** | Long profile of water level and velocities four minutes after the start of gate opening.

The same conditions as modelled with the CFD were simulated in the physical model and the results were close. Examples of measured flow velocities are shown in Figure 12. The measurements also identified a pressure drop downstream of the gate, but not to the point of having negative pressures. These results were used to develop tunnel liner protection against the high velocities. Immediately downstream of the gate stainless steel cladding will be used. As no negative pressure was seen in the CFD analyses or measured in the physical model, the tunnel section after the steel lining will be lined with HDPE liner since the risk of HDPE delamination due to cavitation is small. Nevertheless, for approximately 40 m from the steel lined section, full round HDPE lining was specified rather than the 330-degree coverage with open invert.

## CONCLUSIONS

The hydraulic analyses undertaken during the feasibility study and preliminary design, assisted by the MIKE URBAN model of the entire system, provided critical inputs to decision-making for the

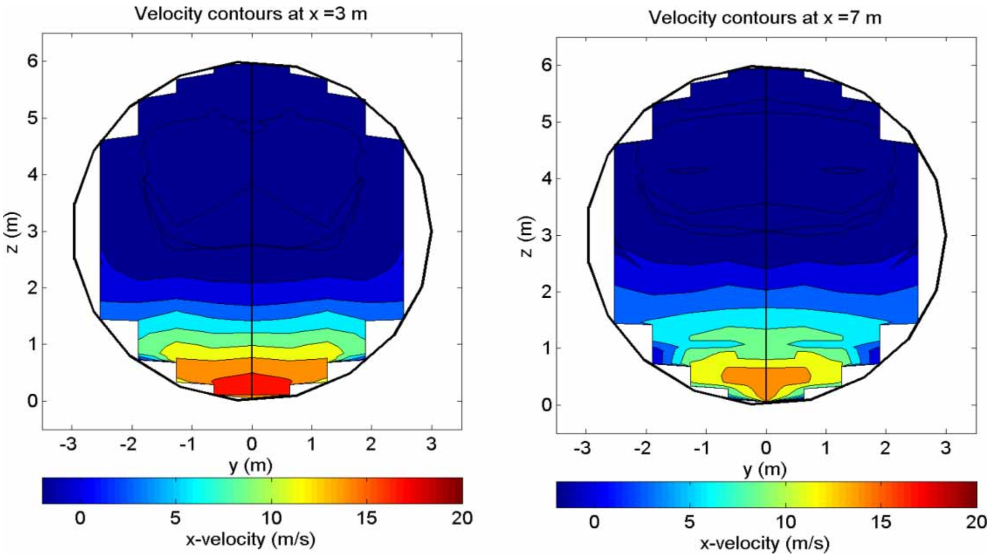

**Figure 12** | Measured velocity profiles in the physical model.

development of an efficient and reliable DTSS2 design, which adds significant resilience to the overall DTSS. Key findings and conclusions from the hydraulic analyses included:

- The 3-WRP system is significantly more resilient than the original 2-WRP scheme.
- A single gravity tunnel with isolation gates and additional tunnel and link sewer cross-connections optimizes system reliability and resilience from an operations perspective; and is the preferred system.
- Together with isolation roller gates, cross-connecting the DTSS 2 link sewers allows for flow bypass to perform tunnel maintenance or repairs, if ever needed, thereby preventing the potential discharge of untreated used-water, as well as the potential disruption to NEWater production.
- Hydraulic modelling results provided key inputs for air flow modelling, to identify the capacity of the required air management facilities, and for surge analyses, to identify potential surge issues and the need for emergency vents.
- Hydraulic modelling enabled the development of feasible system operational regimes, in regards to the Tuas WRP Influent Pumping Station operation, flow controls and air flow management.
- The air management system developed for DTSS2 using air jumpers and odour control facilities to minimize potential odour problem at ground level, provide sufficient ventilation in the tunnel and prevent excessive pressurization or depressurization of the air above the water in the tunnel
- CFD and physical modeling of isolation gate removal provided information to assist in the design of the tunnel liner downstream of the gates to avoid damage due to the high flow velocities under the gates.

Comparable hydraulic analyses are typically conducted for the design of large wastewater tunnels. This paper presented the analyses undertaken for the DTSS2 tunnels to point out specifics and approaches that could be included in future similar undertakings, with the understanding that all systems are different and subject to different constraints and goals. The inclusion of isolation gates is unique and prompted by the mandate to increase resilience relative to system failures in a setting where the consequences of failures could be devastating.

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