6 INNOVATIVE DESIGN AND CONSTRUCTION METHODOLOGIES FOR THE CONSTRUCTION OF THE CAPE FLATS 3 BULK SEWER ENSURING SUSTAINABLE CONVEYANCE OF SEWERAGE EFFLUENT FOR THE NEXT 100 YEARS AND MORE

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ABSTRACT

The challenges facing the City of Cape Town's implementation of the Sewer Master Plan are the provision of sustainable Bulk Sewer systems which will ensure not only basic services, but a sustainable long term bulk sewer service allowing for the growth and densification of the various catchments. The sustainability of the bulk infrastructure is not only a function of basic service delivery, but a balance between operational maintenance and efficiency of the bulk sewer system.

With the flat natural gradients of the Cape Flats, constructing a gravity system will exceed the design parameters for a Bulk sewer system, resulting in siltation and reduction in capacity. The route options through narrow and densely populated corridors did increase the complexity of gravity sewer design and construction, where a more basic approach was used to determine the final route option.

The upgrading of the existing pump station was key to the decision to consider a rising main instead of a gravity main. The cost advantages of having upgraded electrical motors ensures the best efficiency on the system curve of existing pumps as well as enabling the design team to deliberate on a rising main for the total length of 4800 meters.

The flow velocity and corrosion protection were important factors in the design to ensure effective operation and to reduce the impact of pressure transients in case of pipe or power failure. The highly congested but best route could only be traversed by implementing continuous shoring system in these areas to mitigate the dangers of deep construction depth and the loose Cape Flats sandy soils. This open trench system would cause substantial interruptions to a large part of the City and would require the rerouting of traffic for extended periods during construction. The City of Cape Town's project team subsequently decided to consider the tunnelling option for 1200 meters of pipeline on the most congested parts of the route. With the recent introduction of the Ductile Iron jacking pipes, the benefit of having one homogenous material for the total length of the pipeline was favorable and hence selected as the preferred pipe material. The tunnelling was successfully installed across eight sections with a high degree of precision, ahead of schedule and within budget. This paper will demonstrate the challenges faced with the installation of a new Bulk Sewer pipeline with the innovative approaches to Bulk Sewer design and the implementation thereof.

INTRODUCTION

"To cope with this continued urban growth we will need to invent new ways to manage cities and make them more effective…the way for a new ecosystem of services which will enable both a better quality of life and reduced energy consumption."1

1 R. Provoost, 'Smart cities: innovation in energy will drive sustainable cities', https://www.theguardian.com/sustainable-business/smart-cities-innovation-energy-sustainable, 13 November 2013. Accessed 28 May 2017.

This paper highlights the relationship between the civil engineering project (Project: Cape Flats Bulks Sewer 3 Phase 2) and the challenges posed by urbanisation, population growth and the broader limitations of bulk sewerage within the City Cape Town. The three Cape Flats sewers forming the Cape Flats system, is currently serving a population of 880 000 across a catchment area of 18 200 hectares, representing a significant portion of the City of Cape Town's metropolitan area. It is estimated that the population served by the Cape Flats system will increase to 1.58 million in the next 50 years. The City of Cape Town's population growth combined with an aging sewer infrastructure system resulted in a situation where the older pipeline systems were insufficient to address the growing capacity. The Cape Times reported in the mid-2000s that the City of Cape Town was sitting on a sewer time bomb. Where the current project, Cape Flats 3 Bulks Sewer - Phase 2(CF 3) aims to address this concern, the construction and refurbishment of a bulk sewer system poses considerable environmental, social and engineering challenges.

In combination with the environmental, social and technical challenges facing the City of Cape Town's Sewer Master Plan implementation, is the further consideration of the sustainable long term bulk sewer service provision as opposed to the provision of a short term basic service. The sustainability of the bulk infrastructure is not only a function of basic service delivery, but a balance between operational maintenance and efficiency of the bulk sewer system.

This paper demonstrates the challenges faced with the installation of a new Bulk Sewer pipeline while employing innovative approaches to Bulk Sewer design and the implementation thereof. The research finds its existence at the nexus of the basic principles of engineering and science and the technological innovation which strives for sustainable development. The basic principles were incorporated through route design which relied on traditional evaluation parameters, flow assessments and vertical alignments. Once the horizontal alignment was established, the size of the pipe and type was determined through flow analysis. Furthermore, various treatments of the pipe were determined in order to mitigate environmental and corrosive effects for the long term. The vertical alignment in turn navigates the existing services, road crossing and other infrastructure in order to maintain maximum efficiency of the design flow. From these basics principles modern technology and new innovations were implemented to ensure sustainable engineering outputs.

The project has made use of innovative methodologies to promote efficiency in operations. These innovations include tunnelling, sheet piling and a vortex drop structure. The project's greatest engineering initiative was the successful use and implementation of tunnelling. The use

TABLE 1: Route evaluation scores

Route No.	Route description	Score out of 100						Weighted score	Rank
		Technical factors			Social Factors (Private property)		Economic factors		
		Length (m)	Working width	Total bends	Direct access	Indirect access	Estimated cost		
Weighting		0.00	0.25	0.10	0.25	0.10	0.30	1.00	
0A	Petunia - Hazel - Pooke	100	84	100	38	6	100	71	6
0B	Vanguard - Turfhall	86	100	81	100	97	82	92	1
1	Voorspoed - Welby - Turfhall	81	95	0	0	68	74	53	10
2	Shaanti - Angela - Vanguard - Turfhall	81	97	11	25	75	75	61	7
3	Shaanti - Angela - Reen - David - Turfhall	84	93	10	21	73	79	60	8
4	Yusuf Gool - Open Space - Pooke	90	97	45	75	77	85	81	2
5	Yusuf Gool - Open Space - Khalfe - Pooke	88	95	17	55	76	82	71	5
6	Yusuf Gool - Open Space - Pooke - Jeram - Bodau - Pooke	87	98	5	84	78	81	78	4
7	Yusuf Gool - Gatesville Flats - Pooke	90	92	52	75	73	85	79	3
8	Appledene - Blossom - Carnie - Johnston	76	72	35	58	0	71	57	9
9	Bosduif - Klipfontein - Carnie - Johnston	69	75	48	37	18	61	53	11
10	Klipfontein - Duinefontein	0	0	92	100	100	0	44	12

of tunnelling was a ground-breaking initiative, which offsets potential negative social and environmental impacts and promoted sustainable engineering within the City of Cape Town. Sheet piling allows for a more ergonomically structured workspace which ultimately reduces the area required for construction work and also limits the dewatering requirements. Lastly, the project included the installation of a vortex drop structure, which limits odorous gas emissions, increases efficiency of the system by mitigating energy dissipation and reduces toxicity of the sewage and its negative corrosive effects by adding oxygen to the wastewater.

The aim of this paper is to discuss and elaborate on the challenges which arise from design approaches required for a Bulk Sewer system and the concomitant installation thereof within an urban area, through the lens of the project: CF 3. This paper comprises sections on design and construction which will discuss the various aspects included in this project.

DESIGN

Route Engineering

Determining a route for the construction of a large-diameter pipeline through a densely built-up area was extremely challenging. CF 3 traverses through populated suburbs for a length of 5,2 kilometres starting at the Bridgetown sewer pump station in Athlone and terminating in Springfield road in Phillipi. The completion of CF3 essentially provides capacity to enable the severely dilapidated existing bulk sewers to be decommissioned periodically for much needed rehabilitation.

Detailed investigations ensued, giving light to twelve route options which were assessed in terms of their technical viability, costs, as well as the potential impact the construction may have on the adjacent communities. All the various criteria for the efficient operation of a bulk sewer was tabulated and indicated in Table 1 with the factors considered and their various weighting.

Table 1 illustrates the highest scoring pipeline route, Route 0B, but after reviewing the detailed plans of the area, it was discovered that newly installed high voltage electrical cables along the route deemed this option non-feasible. The second highest scoring route, Route 4, was therefore the preferred route in terms of the technical, social and economic considerations.

A sensitivity analysis was conducted to determine whether or not the ranking of routes changed significantly when the weightings scheme was varied. Three alternative weighting schemes were applied for this purpose, each favouring either the technical, social, or economic factors, respectively. These iterations confirmed that ranking of the preferred route, i.e. Route 4, did not change with the varied weighting schemes and remained consistently higher that the third ranked route.

With the pipelines horizontal route determined, as shown in figure 1, the next challenge in the design, was the vertical alignment of the pipeline in the flat topography of the Cape Flats.

Vertical alignment

The vertical alignment of the CF3 was largely determined by the natural flat topography and the significant number of existing services crossing along the final horizontal alignment. This inevitably resulted in the sewer consisting of a longer portion of rising main and shorter portion of gravity main. With the pipeline navigating the existing services along the horizontal alignment, various high points were created requiring a number of air valves. Positive pressure over the air valves needed to be maintained creating a Barometric loop at the transition from pressure to gravity flow.

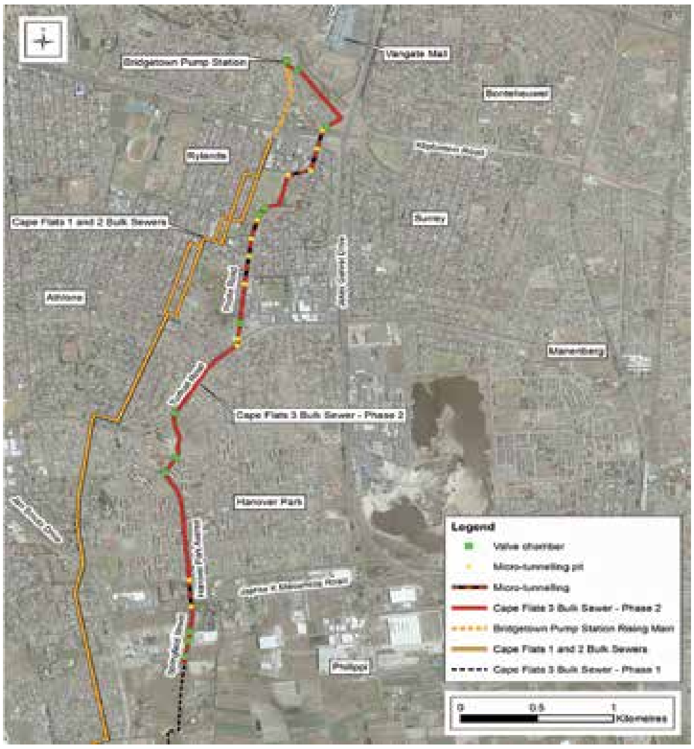


FIGURE 1: **Construction of the Cape Flats 3 Bulk Sewer – Phase 2 Locality Plan**

Barometric Loop and Vortex Drop Structure

The vertical alignment and air-valve configuration required a customised barometric loop design for the rising main discharge chamber. The barometric loop would comprise of an elevated outlet discharging into the downstream gravity sewer through a drop structure.

The outlet of the rising main was provided with a barometric loop for two reasons:

- It should maintain a positive pressure over the air valves as they required 10 KPa in order to seal.
- A high end point will ensure that the pipe does not drain when the pumps switch off and allow air into the pipeline.

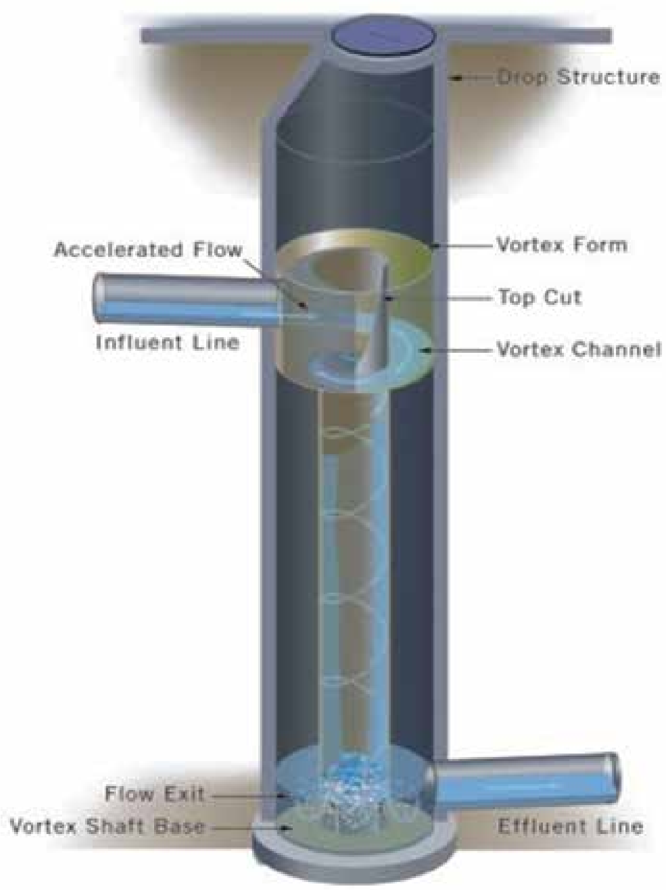
With this requirement, a high point of 3.3 meters above normal ground level is required resulting in a discharge height to the gravity section of the project of 6.8 meters. A number of options were considered with this high drop, taking into account the risk of odour problems, and the highly corrosive and toxic conditions associated with turbulent flow. Internationally a vortex drop structure is used in this situation, which was never used before in the City of Cape Town. It was researched and found to be the best possible application in this condition.

This specialised drop structure causes the effluent to flow in a spiral, down a vertical shaft in a way that creates a downdraft that traps airborne gases, and forces air into the sewage flow to oxidise the hydrogen sulphide (H_2S) gas, thereby minimising odours and the release of toxic gases from the drop.(See figure 2)

Geotechnical investigation

A geotechnical investigation was conducted along the selected route, which included 44 Dynamic Penetrometer Super Heavy (DSPH) tests, 12 geotechnical boreholes and 14 trail holes. These tests indicated the soil conditions to be relatively uniform, consisting of medium dense fine sands

FIGURE 2: Vortex drop structure



underlain by dense to very dense slightly ferruginised sands. No evidence of rock or ferricrete hardpan was encountered.

Furthermore, the water table was 1.5 to 3.0 meters below surface level which meant the pipe would be constructed below the water table. The in-situ soil density is generally medium dense in consistency and provided a good stable trench bottom, in particular in a de-watered conditions and also suited tunnelling. The ground water chemistry is not markedly aggressive, however iron concentrations in some areas may be potentially corrosive to some pipe materials.

Flow Assessment

Current flows

The scope of the flow assessment was extended to not only include an investigation into current and future flow volumes associated with the bulk wastewater conveyance system in the sewerage catchment area of the Cape Flats Waste water treatment works, but to include Athlone wastewater treatment works. The purpose of the assessment is firstly to assist with the medium to long-term high-level planning for the bulk wastewater system as well as providing the basis for the design of the proposed CF 3. The data for the sub-catchments and various pump stations were collected and disseminated into a workable model of the catchment with current and future flows with a consideration of densification and fully developed state condition.

Future flows

For the determination of the future flow rates for the project year 2062, the Spatial Growth Model was used with the most conservative long

FIGURE 3: Schematic diagram of bulk wastewater conveyance system illustrates the ultimate flows estimated for 2062.

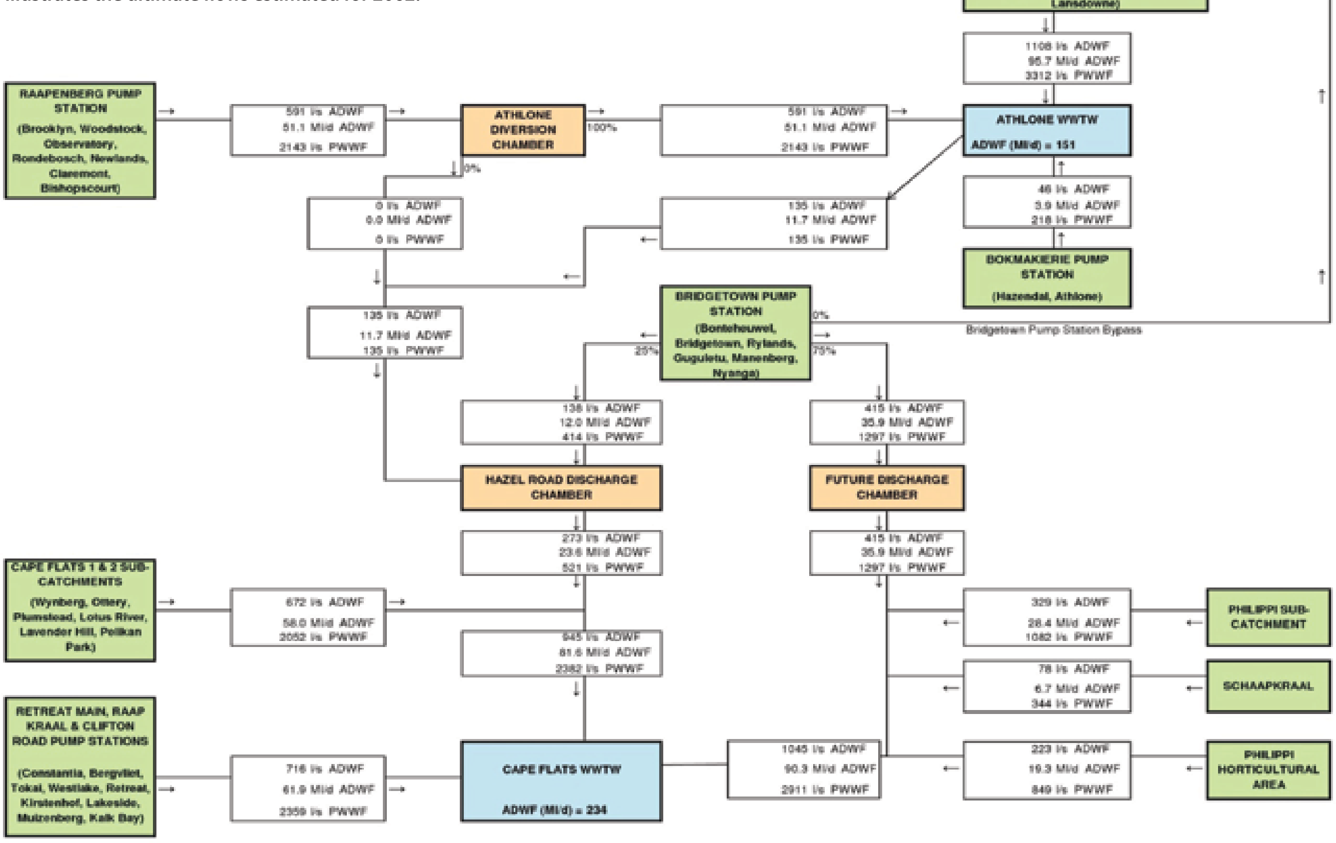


TABLE 5: Assessment of various pipe sizes in terms of flow velocity

Year	Flow condition	Flow rate (l/s)	Flow velocity (m/s)				
			Existing 750 mm ND	900 mm ND	1 000 mm ND	1 100 mm ND	1 200 mm ND
2012	ADWF	408	0.991	0.617	0.503	0.415	0.348
	PDWF	802	1.948	1.212	0.988	0.816	0.683
	PWWF	1 283	3.116	1.939	1.581	1.305	1.093
2062	ADWF	554	1.346	0.837	0.683	0.564	0.472
	PDWF	1 034	2.512	1.563	1.274	1.052	0.881
	PWWF (25% split)	414	1.006	-	-	-	-
	PWWF (75% split)	1 241	-	1.876	1.529	1.262	1.057
-	Minimum design flow	150	0.364	0.227	0.185	0.153	0.128
-	Maximum design flow	1 300	-	1.965	1.602	1.322	1.108

term predictions assumed. This generally predicts development with higher than average densities. The Spatial Growth Model does not take into account densification of existing developed areas and unplanned informal settlement's, therefore 2010 population figures were inflated by 0.6% per annum over and above additional population resulting from new developments.

The future effluent flows were estimated based on the following approaches:

- The average annual daily demand (AADD) for water was determined based on the Guidelines for Human Settlements and Design,
- It was assumed that 80% of the AADD would return to the sewer reticulation resulting in the average dry weather flow (ADWF)
- The peak dry weather flow (PDWF) and peak wet weather flow (PWWF) were estimated by applying a daily peak factor to the ADWF, determined using the Harmon Formula, and then applying a storm water infiltration factor of 1.6.

Figure 3 indicates a schematic layout of the results of the estimated designs flows at the year 2062. Due to the uncertainty in the future sewage effluent volumes to be conveyed in the existing section of the CF 3 project, it was accepted that the CF 3 should have a design capacity of at least equivalent to the peak flow at the Bridgetown Pump Station, 1297 l/s.

The rising main pipe size is primarily a function of the range of flow rates to be accommodated in the rising main and the corresponding range of velocities. The size of pipe must also satisfy the system curve of the existing Bridgetown pump station. Table 5 below indicates the flow rates together with the corresponding flow velocities in the various pipe sizes in question for the optimal pipe size to be considered.

The flow velocities will at least rise daily to 0.988 m/s in dry weather conditions, ensuring no permanent sedimentation. Table 6 shows that the 900 mm pipe would result in velocities considered too high in the PWWF and the 1100 mm pipe with very low flows in ADWF conditions which would ultimately cause sedimentation. The 1 000 mm pipe was the best suited diameter for this purpose.

The wide selection of available pipe materials was evaluated in terms of properties, ease of handling in small work spaces, corrosion resistance, availability and costs. Depending on the material selected, the availability of fittings and hydraulic characteristics were taken into account. For the pipe size required, ductile iron was the preferred material when evaluating against the above criteria.

Corrosion protection

The corrosion protection for the ductile iron pipe selected was required to have a 2 000 micron dry film thickness (DFT) polyurethane internal corrosion coating with the spigot and socket ends 300 microns DFT epoxy coated and will have 900 microns DFT polyurethane external corrosion coating. For protection on more aggressive soils, 250 micron polyurethane sheeting was used to prevent contact between pipeline and soil as well as stray currents, where special fittings were protected by 1 500 microns DFT polyglass.

Crossing main roads was normally undertaken by means of pipe jacking and done using concrete pipes, which cannot be subjected to high pressures. However, with the introduction of ductile iron jacking pipes, manufacturers could supply ductile iron pipes that can be installed and operated as pressure pipelines. These jacking pipes meet the criteria of the Class K9, required for the design and result in a similar pipe material for the full length of the project. The selected jacking ductile iron pipe corrosion protection was specified as 400 g/m^2 zinalium coated with epoxy pore sealer externally and a concrete protective jacket ensuring a constant outside diameter.

In order to ensure that corrosion protection measures were implemented to a high standard an independent coating inspector was appointed to carry out random checks and tests at different stages of the application and issue a Certificate of Conformance upon completion.

Surge Analysis

The surge analysis depicted in Figure 4 confirms the maximum surge pressure at the pump station to be typically between 500 to 600 KPa. This relative low pressure indicates that the air valves provide sufficient surge protection in terms of the design.

Gravity Sewer Section

The gravity section of the pipeline was designed for the same flow condition which showed that a 1200 mm ND pipeline at a slope between 1:380 and 1:900 would yield the best flow condition in the pipeline based on:

- Minimum flow between 150 l/s and 1 300 l/s
- Flows to be sub critical with Froude number of less than 0.8.

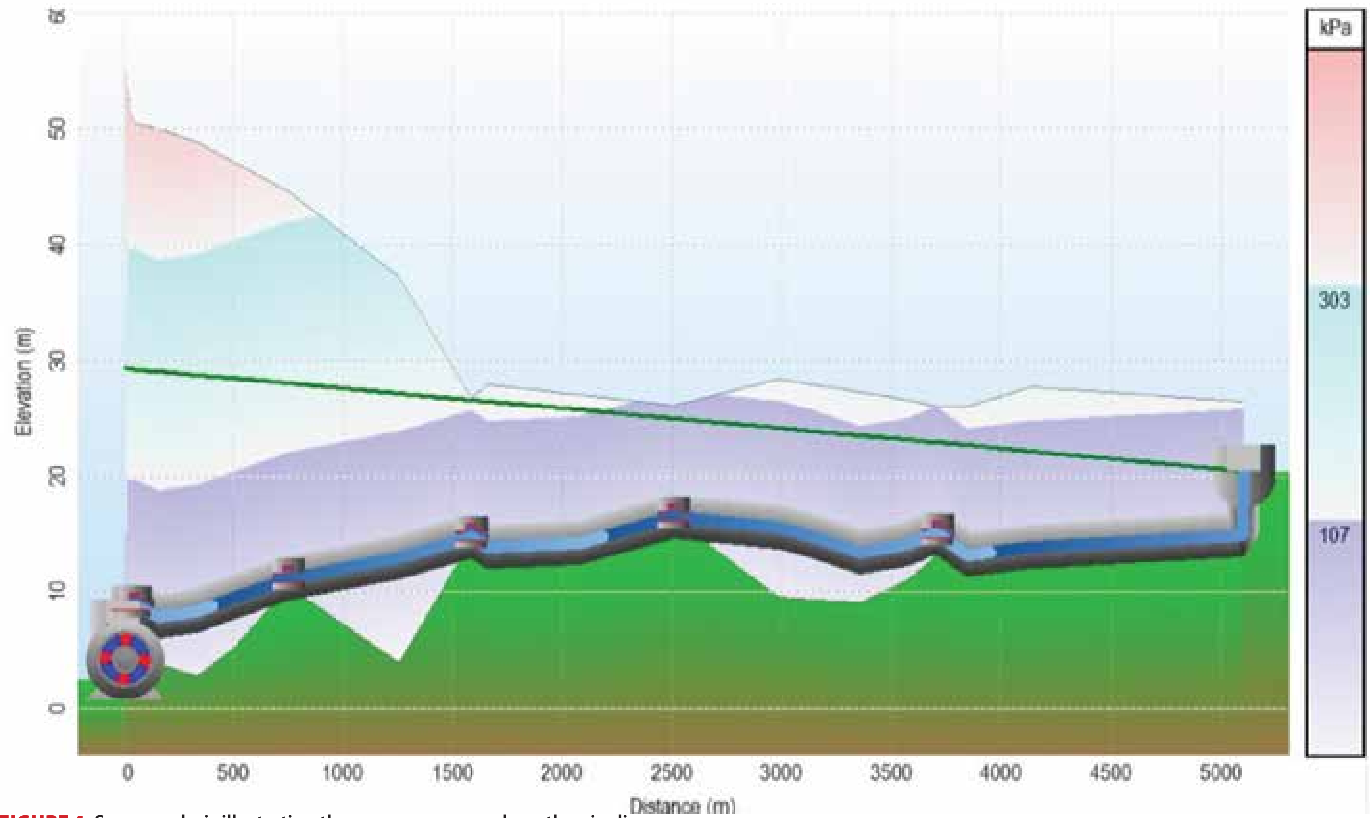


FIGURE 4: Surge analysis illustrating the surge pressures along the pipeline

The Life Factor Method was used to determine the sacrificial layer requirement. Due to the high level of corrosion potential shows that the sacrificial layer in Calcium Aluminate cement with dolomitic aggregate would need to be thicker than what would have been feasible in terms of pipe manufacturing. Due to the potentially high corrosion potential, the gravity section of the CF 3 has been designed with a 1 200 mm nominal diameter concrete pipe and a 3 mm high density polyethylene (HDPE) liner along its full length.

CONSTRUCTION

Open-Trench Installation with Sheet Piling

Due to the limited work space available along much of the route, and depths ranging between 2.5 meters and 4.5 meters in sandy ground conditions with a high water table, the design and contract specifications took into account that a large portion of the pipe trench excavation would need to be undertaken using a suitable shoring system. There are a number of shoring methods used locally and internationally, including timber boards, struts and walings, sheet piling and shoring boxes. Each was considered with regard to the ground conditions and required programme.

FIGURE 5: Construction of gravity sewer pipeline using the interlocking steel sheet piles

The preferred method used was the interlocking continuous steel sheet piles, as this system also acts as a coffer dam, limiting the dewatering requirements during construction. This system can also be installed and shifted along the construction route relatively quickly. Because some methods of installing sheet piles are disruptive to the public, the design and specification therefore specified 'silent' non-vibratory shoring methods to be implemented when closer than 30 meters to existing buildings.

Tunnelling

The CF 3 project traverses for 5.3 kilometres through a densely-populated area of Cape Town, where significant sections of the pipeline would need to be installed beneath busy roadways. This brought the option of tunnelling to be investigated in terms of technical and financial feasibility, with the ultimate goal of reducing the social and environmental impact during construction.

Tunnelling is a specialised pipe-jacking operation, preceded immediately by a Tunnel Boring Machine (TBM) that removes soil mechanically from the jacking face using a slurry process. The TBM can be operated remotely from a control centre on the ground surface. Following extensive technical and financial evaluation, it was found that tunnelling some sections of the project would not only mitigate social and environmental impacts, but would reduce public safety risk with a higher end-product quality. The decision was made to change the construction method to tunnelling a portion of 1 200 meters of the project.

TABLE 7: Cost implication of tunnelling construction method

Description	Amount (Rand) (excl. VAT)
Total additional costs associated with tunnelling construction method at exchange rate at the time taking our forward cover: EURO 1.00 = R15.5562 and EURO 1.00 = R15.1681	36 174 938.05
LESS savings/omissions under the scheduled items in the BoQs	25 752 282.14
Shortfall sub-total A	10 422 655.91
LESS further savings/omissions under the scheduled items in the BoQs	3 154 558.64
Shortfall sub-total B	7 268 097.27
LESS potential saving under scheduled dayworks items in BoQs based on expenditure on similar projects	2 500 000.00
Nett Shortfall	4 768 097.27

The cost comparison in Table 7 is based on an exchange rate of Euro 1.00: R15.5562, which resulted in an additional cost to the project of R4 768 097.27 or R3 900 per meter of tunnelled pipe. It must be understood that the positive social, traffic and safety impacts cannot easily be quantified and is excluded from the cost saving realised. This additional cost was absorbed by the contingencies and was completed within budget.

A contributing factor favouring tunnelling was the recent introduction of ductile iron jacking pipes to the market, which is a pressure pipe that can be jacked directly into the ground behind a TBM. Therefore this offered a more efficient and operationally-sustainable system, compared to the conventional method of installing the pressure pipe through a pipe jacked concrete 'sleeve'. During 2016, a total of 1 200 meters of pipeline was installed successfully with a high degree of precision, ahead of programme and within budget, using tunnelling.

The tunnelling component of CF3 has been presented an award of excellence, by the South African Society of Trenchless Technologies, in recognition of exceptional and excellent contributions to the active promotion, development and implementation of trenchless technology in Southern Africa for 2016.

CONCLUSION

This paper discussed the relationship between the CF 3 project and the challenges posed by urbanisation. The forecasted population growth projects a considerable strain on sewer infrastructure. The paper thus highlighted the sustainable design of the Bulk Sewer project with the view of long term efficiency.

Through analysis and discussion this paper addressed the complimentary aspects of basic principles, innovation and sustainable development. The basic principles incorporated and discussed in this paper included the route design, flow assessments and the vertical alignment of CF 3. The paper then eluded to the innovative technologies implemented. These engineering innovations include tunnelling, sheet piling and the vortex drop structure. The two main themes of this paper, basic principles of design and technological innovations, were addressed in the sections: Design and Construction.

FIGURE 6: Tunnelling the first section of pipe on CF3

The paper achieves its aim which is to address the challenges which arise from design approaches required for a Bulk Sewer system and the installation thereof.

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