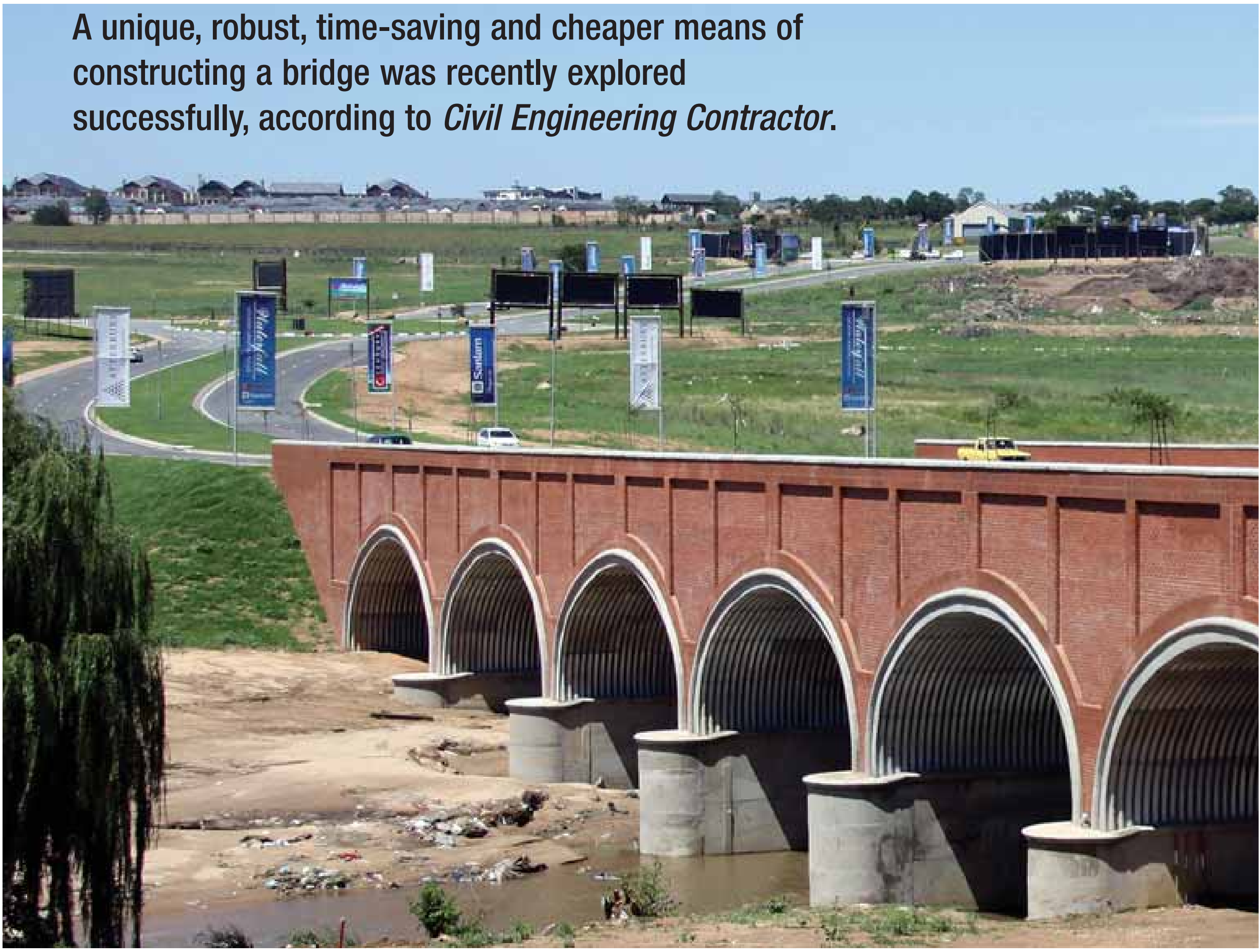
Optimise efficiency at half price

A unique, robust, time-saving and cheaper means of constructing a bridge was recently explored successfully, according to *Civil Engineering Contractor*.



Waterfall City, a new multifunctional township just 10 minutes away from Sandton, between Woodmead and Midrand, is being built.

Waterfall City has been designed specifically to maximise its spatial advantages by exploiting its location relative to the broader economic systems of Sandton, Rivonia, Sunninghill and Midrand, and to improve the economy of the township as a whole hence its mixed element design. Key to this objective was the construction of a high-order transport linkage between Sunninghill and Midrand (Maxwell Drive) which would accommodate heavy traffic flows of 30 000 vehicles per day at higher speeds with infrequent, free-flowing access spaces. And, as this linkage was to cross the Jukskei River, a commensurate bridge had to be built.

> **"A design proposal using a reinforced-concrete construction method, proved to be too expensive at R15 000/m²."**

Cheaper and effective

While the Jukskei River may be a small meandering stream in winter, it turns into a raging torrent after a typical Johannesburg summer thunderstorm with peak river swells at heights of 5 m not too unfamiliar. This required the bridge to be designed to survive a one in 50-year flood with

Project: Maxwell Drive Bridge
Location: Gauteng
Value: R18,5-million
Start: 2010
End: 2010
Client: Century Property Developments
Consulting engineer: C-Plan Civil Engineers
Main contractor: KNS Construction

Tony Stone

peak river swells of 7,5 m. C-Plan Civil Engineers, as part of its overall civils responsibility for the Waterfall Country Estate, was tasked with the design and management of the construction of the 88 m-long, 27 m-wide bridge which, with the overriding "country estate", dictated that the bridge design should complement the intended ambience and have a multiple arched look and feel.

Accordingly, in order to meet the client's aesthetic expectations and budget cap, two options were considered.

The first, a design proposal by an international company, using a reinforced-concrete construction method, proved to be too expensive at R15 000/m². The second system, as selected, was an Armco solution which cost R8 250/m². The overall cost was R18,5-million, including the design costs for the foundations.

"The Maxwell Drive Bridge has an anticipated life-span of 200 years."

The bridge-construction method of piers, fixed Armco steel low-profile arches, post-tensioned reinforced-concrete sidewalls and backfilled soil is unique, robust, time-saving and costs less, and differs quite substantially from traditional reinforced-concrete bridge construction methods. It is, however, equally efficient. The Maxwell Drive Bridge has an anticipated lifespan of 200 years.

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The trusted arch

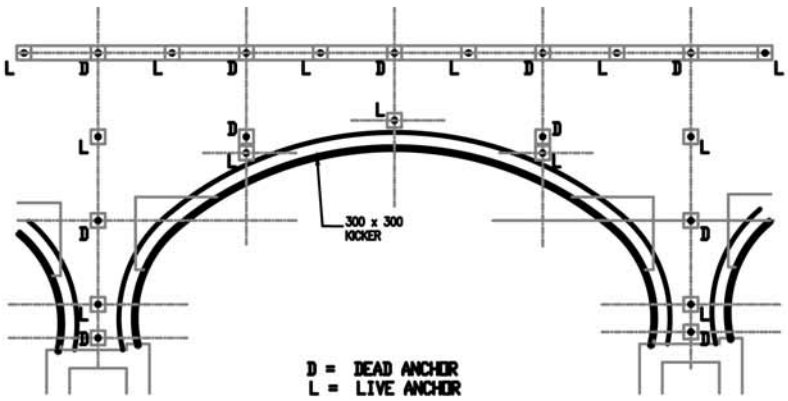
With regard to Maxwell Drive Bridge, the pitch and depth of the circumferential corrugated-steel plates are 200 mm and 55 mm respectively. It has long been known by bridge builders, ever since 1 300 BC when the Greek Mycenaeans built the Arkadiko Bridge, which still stands to this day, that the arch is a solid and robust method of bridge building. Arch bridges work by transferring the weight of the bridge and its loads partially into a horizontal thrust restrained by the abutments on either side and, in multiple arch structures, the piers. To the novice, the idea of using corrugated iron (which rusts) instead of stone, brick or concrete, to build an arch bridge, is highly questionable. However, it has long been known by engineers that zinc galvanising removes steel's propensity to rust and corrugating a material, be it cardboard, plastic or steel, strengthens the material substantially. Owing to the sinusoidal corrugated profile, the material's shear stability is enhanced. This eliminates the need for transverse stiffeners or thicker material. The corrugations increase the bending strength of the sheet in the direction perpendicular to the corrugations but not parallel to them. Normally, each sheet is manufactured longer in its strong direction. Pitch and depth also contribute to the strength of the material. Simply put, the closer the pitch, the stronger the material and the deeper the depth, the stronger the material. However, there is a close functional relationship between pitch and depth which gives the material the strength and properties required for a particular application – its weight handling.

Opportunities

Not quite a city yet, Waterfall City will be by the year 2020. This sprawling, walled-in, high-security 1 800 ha, R220-billion property development with its own CBD, retail hub, "smart" village, equally smart country estate, equestrian estate and retirement village, is the biggest of its kind in South Africa, and promises to keep the building and civil-construction sectors ticking over for more years to come. The project is valued at about R21-billion.

Building

The project comprises a shopping centre, two retirement villages, industrial and business parks, a private hospital, a five-star hotel, petrol stations, horse-riding and cyclist trails, and houses. More prospects will emerge over time as it is a mixed-use development providing retail space, industrial and business parks, as well as homes ranging in price from low-income properties costing just R200 000 to luxury mansions in an equestrian estate selling for many millions. Mark Corbett, chief executive of Century Property Developments, says that the project is the biggest development of its kind in Africa and one of the largest in the world. The equestrian estate won the CNBC International Property Award for the best residential estate in Africa. There are already 80 completed homes in the estate which offers stables, bridle paths, paddocks, training tracks, veterinary and tack rooms, a jumping and dressage arena and lunging ring. He says that one house within the estate has already been sold for R70-million.

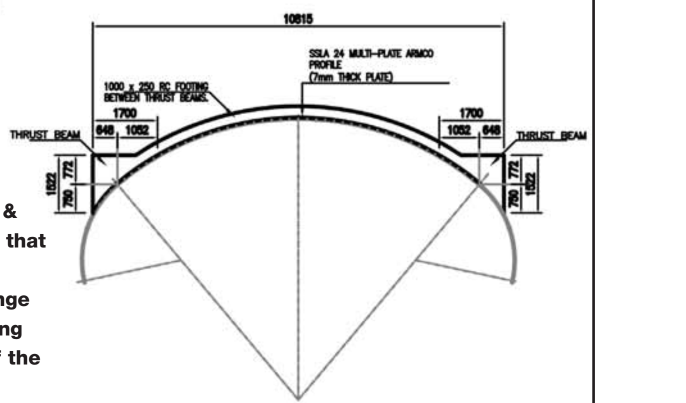


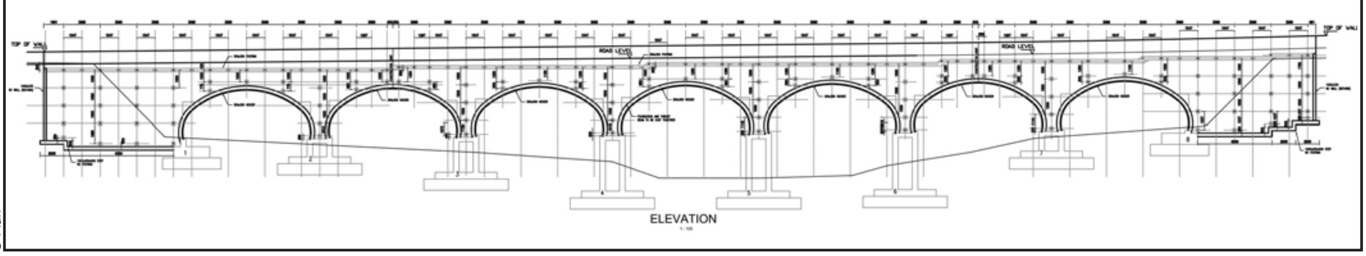
R8 250/m² vs R15 000/m²

The steel arches brought construction down to R8 250/m². This is opposed to the initial reinforced-concrete suggestion amounting to R15 000/m². The section properties of the arc-and-tangent type of corrugation are derived mathematically using a design thickness which is a little different to the measured or specified thickness.

The properties include:
- **area (A);**
- **moment of inertia (I);**
- **section modulus (S); and**
- **radius of gyration (R).**

Research by the American Iron & Steel Institute (AISI) has shown that failure loads in bending and deflection within the elastic range can be closely predicted by using computed section properties of the corrugated sheet.





C-Plan

Critical path pursued

The eight pier foundations, to differing depths, were taken down to rock level. The two abutment piers, 1 and 8, were constructed off 30,3 m x 5,2 m x 1 m beds of G6 foundation fill compacted to 95% MOD AASHTO density. Piers 2, 3 and 7 were constructed off equally long and deep but 7 m-wide beds of identical foundation fill and density. Over the beds, a 50 mm blinding layer, of class 15/19, was set. Pier 4 was constructed off a bed of 15 MPa concrete blinding while piers 5 and 6 were founded on rock with Pier 6 requiring a levelling triangular bed of 15 MPa concrete blinding.

1

2

3

Photographs by Tony Stone

1 Preparation under way
Preparing the reinforcing for a reinforced-concrete pier base.

2 Concrete poured
Pouring concrete into the prepared pier base.

3 Another round
The process continues.

4 Base support
Preparing the pier base support for two of the steel arches.

5 Reinforcement under way
Workers preparing the reinforcing bars for the pier cap.

6 Casting tackled
Casting the indented Armco unbalanced channel.

The footings construct for each pier was particularly important – being the bases to which the low-profile steel arches are anchored. Footings 1 and 8 comprise reinforced-concrete bases 27 m x 3,2 m x 1 m with each topped by a single, 500 mm-wide low wall upon which the indented Armco unbalanced channel (UBC) is affixed to serve as the anchor point for one end of a low-profile steel arch. Similarly, footings 2 to 7 were constructed, equally long, but with reinforced-concrete bases 5,5 m wide and 600 mm deep. Off these bases, variable-height, box-like structures with 500 mm-thick side walls were constructed – each with twin, oppositely angled and indented UBCs affixed. In the vertical plane, the sidewalls are interspaced with 50 mm-diameter weep holes. AfriSam supplied the rapid hardening concrete, to a minimum specification of 30 MPa, for the pier construction.

4

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From colluvium to granite

Soil layer: Colluvium		
Measurements		**Description**
Average thickness	0,44	Consists mainly of clayish silt-like sand material with varying percentages of clay and gravel. It generally has a low to moderate plasticity, low potential expansiveness, low linear shrinkage and a moderate grading modulus. Colluvium is a good sub-grade, a poor sub-base and is not suitable for use in base course on roads but will have good workability as construction material. It has a slight to medium compressibility when compacted and has fair to poor drainage characteristic. It is a reasonably stable embankment material.
Variation	0,05 – 1,92	
Soil layer: Pebble marker		
Measurements		**Description**
Average thickness	0,35	Is a silt-like sandy gravel with low plasticity, low potential expansiveness, low linear shrinkage and a moderate grading modulus. It is a good sub-grade, poor to good sub-base, not suitable for use in base course on roads but will have a good workability as construction material. It has a low to very low compressibility when compacted and has a good to fair drainage characteristic. It is a reasonably stable embankment material.
Variation	0,0 – 0,97	
Soil layer: Reworked residual granite and residual granite		
Measurements		**Description**
Average depth	0,63	Consists mainly of clayish silt-like, gravel-like sand material with varying percentages of clay. The material generally has a low to moderate plasticity, low potential expansiveness, low linear shrinkage and a moderate grading modulus. It has a medium- to high-potential expansiveness. Reworked and residual granite is a good sub-grade, a poor sub-base, is not suitable for use in base course on roads but has good workability as construction material. It has a slight to medium compressibility when compacted and has fair to poor drainage characteristics. It is a reasonably stable embankment material.
Variation	0,0 – 1,85	

Notes to table

Ferricrete

This hardpan formation was encountered in test pits GPS247 and GPS253. Refusal was reached on the highly ferruginised material at 1,00 m and 0,70 m respectively.

Granite

As exposed, the entire site is underlain by granitic rocks of the Basement Complex (Johannesburg-Pretoria Dome).

Water

An important factor in bedrock and soil composition, through which the water moves, is that granite virtually has no effect on pH or, at worst, may raise it slightly. However, the soils in the area are mildly corrosive for steel pipes.

7 mm-thick steel

The seven steel arches of the Maxwell Drive Bridge are each made up of 99 hot-rolled, zinc-galvanised, 300 WA corrugated-steel plates which are 7 mm thick.

1 **Placed in position**
An Armco galvanised, corrugated-steel plate was placed into position. Mobile cranes were used to lift the plates in place, considering the heaviest weighed in at 400 kg.

2 **Bolted in**
The position steel plate is bolted in. The span of each arch measured 11,27 m from UBC bolt hole to UBC bolt hole.

3 **Near completion**
The first row of plates for one arch nears completion. Each bolt was tightened to a torque of 300 Nm.

4 **The next row**
Fitting the next row of plates. A total of 4 799 bolts per arch were placed and tightened.

5 **Scaffolding in place**
With the scaffolding jig in place, production hots up. The steel used conforms to SANS 1431.

6 **Closing in**
Closing in on the crown. The job is almost complete and ready for the next phase in the construction process.

1

2

3

Photographs by Tony Stone


4


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6

Steel arches dominate

The plates differ in size and are bolted together in a very specific order – 10 are half plates used to stagger the order of placement to maximise the strength of the arch – similar to the principle of brick-laying. In order to achieve the fit, the low-profile arch shape plates are sized into different lengths and widths – the heaviest weighs in at 400 kg. This necessitated the use of mobile cranes to lift the plates into place. KNS Construction was quite clever in making up a jig, from scaffolding, to facilitate the plate laying and bolting process – understandable when considering that the span of each arch measured 11,27 m from UBC bolt hole to UBC bolt hole with a rise of 4,27 m. It was important that this was done so that the exact design shape could be maintained during erection, and that the component bolting would be carefully aligned. Each bolt was placed manually and tightened loosely until all the plates were in place, progressively and uniformly, from one end of the structure to the other. Each bolt was then tightened to a torque of 300 Nm. In all, 4 799 bolts per arch were placed and tightened. This task was given to a dedicated team of four who, after placing and manually tightening 33 593 bolts, probably don't want to see another bolt – at least for a while.

In terms of durability of the steel used, 300 WA conforms to SANS 1431. Also, due to its application, its durability has been increased two-fold. Firstly, in its galvanising and, secondly, its durability was extended by the application of an *in-situ* bitumen coating.

Chemical composition (%) (ladle analysis) as specified in SABS 1431 1987

Grade	C	Mn	Si	P	S	Nb
300 WA	0,22	1,60	0,50	0,040	0,050	0,03

V	Nb+V	Al	Cu[1]	Ni[2]	Cr[2]	Mo[2]
0,03	0,04	0,10	0,35	0,30	0,30	0,10

Mechanical properties as specified in SABS 1431 1987

Grade	Tensile strength (MPa)	Minimum yield strength (MPa) for thickness t (mm)				Elongation % (min) on gauge length of		
		3<t<16	16<t<40	40<t<63	63<t<80	50 mm	200 mm	5,65 So
300 WA	450/620	300	300	290	280	24	20	22

Note 1

The environmental range factors used in determining the durability requirements are:

- Normal conditions with pH = 5,8 – 8,0 for R > 2 000 ohm-cm to mildly corrosive conditions with a pH = 5,0 – 5,8 for R > 1 500 ohm-cm.
- Metallic coated ranges, zinc (galvanized), with pH = 5,8 – 10,0 for R = 2 000 – 10 000 ohm-cm and pH = 5,0 – 12,0 for R > 10 000 ohm-cm.
- A low abrasion level (Level 2) with minor bed loads of sand and gravel having velocities of 1,5 m/second or less.

Note 2

Zinc-coated (galvanized) steel (AASHTO M36, ASTM A929) is produced with a coating weight of 610 g/m^2 of surface (total both sides) to provide zinc coating thickness of 43 mm on each surface.

Note 3

A bituminous coating (AASHTO M190, ASTM A849) applied to the exterior surface of the pipe with a minimum thickness of 1,3 mm extends durability by up to 20 years.

The last steps

Structural backfill

Thrust beams, constructed on opposite sides of an arch, are critical structural components in long-span structural plate structures – in this instance, 27 m wide. These beams function as part of the structural backfill zone and are not sized as a conventional structural beam which is subjected to bending and shear. Thrust beams are used in the following ways:

- **Backfill:** Thrust beams provide a perfect backfill material in the zone just above the spring line at a tangential radius change. In this zone, it is normally difficult to place and compact granular materials to specified density. The vertical face of the thrust beam provides substantial surface area to develop backfill support.
- **Fixity:** Thrust beams provide a degree of fixity (rotation resistance) which is critical to allow the large top radius arc to develop ring compression.
- **Load distribution:** Thrust beams function as a spreader or reaction block to distribute construction loads along the structure as backfill is placed over the large-radius top arc.

Stability vital

A properly bedded, accurately assembled and carefully backfilled galvanized steel arch bridge will function properly and efficiently over its entire design life. However, for the bridge to support the road pavement adequately and uniformly, and the anticipated traffic volumes, a stable composite structure is vital. Stability in the concrete-soil-steel structure interaction system requires not only adequate design of the bridge's retaining wall "box" but also a well-engineered backfill. Structural integrity depends on the selection, placement and compaction of the envelope of earth, the fill material, between and over the arches, which distributes its pressures to the abutting soil masses. To achieve this, fill material between and over the arches was placed and compacted in layers of 150 mm. Fill was placed on both sides of the arch at the same time and compacted to keep a balance in the elevation. This ensured that the shape of the arch was maintained and not skewed to left or right from a soil weight bias. Granular-type soils conforming to AASHTO specification M-145 f for heights of cover less than 3,4 m (A-1, A-3, A-2-4 and A-2-5) and for heights of cover of 3,4 m or more (A-1 and A-3) were used as structural backfill to a backfill soil density of 20,5 kN/m^3 and a surcharge load of 10 kN/m^3.

Weaknesses offset

To house the backfill over the arches and maintain stability of compaction, a 107,612 m x 26,4 m reinforced-concrete box was constructed with 230 mm-thick walls to a concrete density of 25 kN/m^3. And, to accommodate the height differential between the north and south banks, an adjustment for slope was achieved through five specifically positioned level drops. A key challenge in the construction of the bridge was to offset two potential structural weaknesses. The first being the points along the arch curve at which the arch and the reinforced-concrete sidewall met. With the weight of the compacted backfill, and the pressures brought to bear, this moment would have been a little too much and it would have compromised the integrity of the structure. This was offset by integrating a reinforced-concrete saddle, with the sidewall, over the arch at the same time as the thrust beam was built. The second was the weight of the compacted backfill and the pressures brought to bear on the sidewalls which would also have compromised the integrity of the structure. This was offset by post tensioning a total of 164 tendons which were positioned in 71 vertical planes along the entire length of the bridge, and stressed to 8% of breaking force to an accuracy of approximately 2%. The horizontal and vertical alignment of all dead and live anchors (tensioning) was alternated. With the bridge complete to the point at which the only remaining task was to lay the pavement, the 2,4 km dual carriageway through Waterfall City, from Witkoppen Road in Sunninghill to Allandale Road in Midrand, including Maxwell Drive Bridge, was constructed. Using the typical layered approach, beginning with an *in-situ* layer as the base followed by a sub-grade layer, then a C4 sub-base layer and a C3 sub-base layer, it was brought to a head with a 150 mm G1 base course topped by 40 mm of premix. Keeping the aesthetics of the bridge "country", the bridge was clad with bricks from the base of the arches to the balustrades at a cost of R1,5-million. The net effect, with its indentations to create depth, shadows and to complement the bridge's character, the client received exactly what was specified.

To sum up, the construction and commissioning of the Maxwell Drive Bridge proved three facts: the technology is sound, tried, tested and not found wanting; the bridge was built in just five months; and it amounted to almost half of the cost of building a conventional bridge.

In anybody's books, this has to be a winning solution and a definite consideration for South Africa's much-needed road-infrastructure upgrading and development. ■

Compaction zones and type of equipment

Zone	Type and size of compaction equipment	Density MOD AASHTO
1	Dynapac/Ingersoll-Rand vibratory steel wheeled roller or sheepsfoot static type	90%
2	Bomag 90 or similar double-steel wheel vibratory roller	90%
3	Hand-operated type Bomag 35 or similar with mass not exceeding 500 kg	85%
4	Sheepsfoot static type – tractor-drawn or similar approved	90%

Editor's comment

This project was selected for coverage simply because of its ability to reduce construction costs significantly. The traditional construction mindset has been challenged. This project is similar to our coverage of the construction of the Crocodile Rover Bridge on page 30 of the January 2011 edition of *Civil Engineering Contractor*. This time round, precast technology came to the rescue; challenging conventional cast *in-situ* thinking. I believe that the prevailing economic climate in which we operate will continue forcing project teams to devise novel solutions which not only reduce construction costs but accelerate production and improve overall quality.