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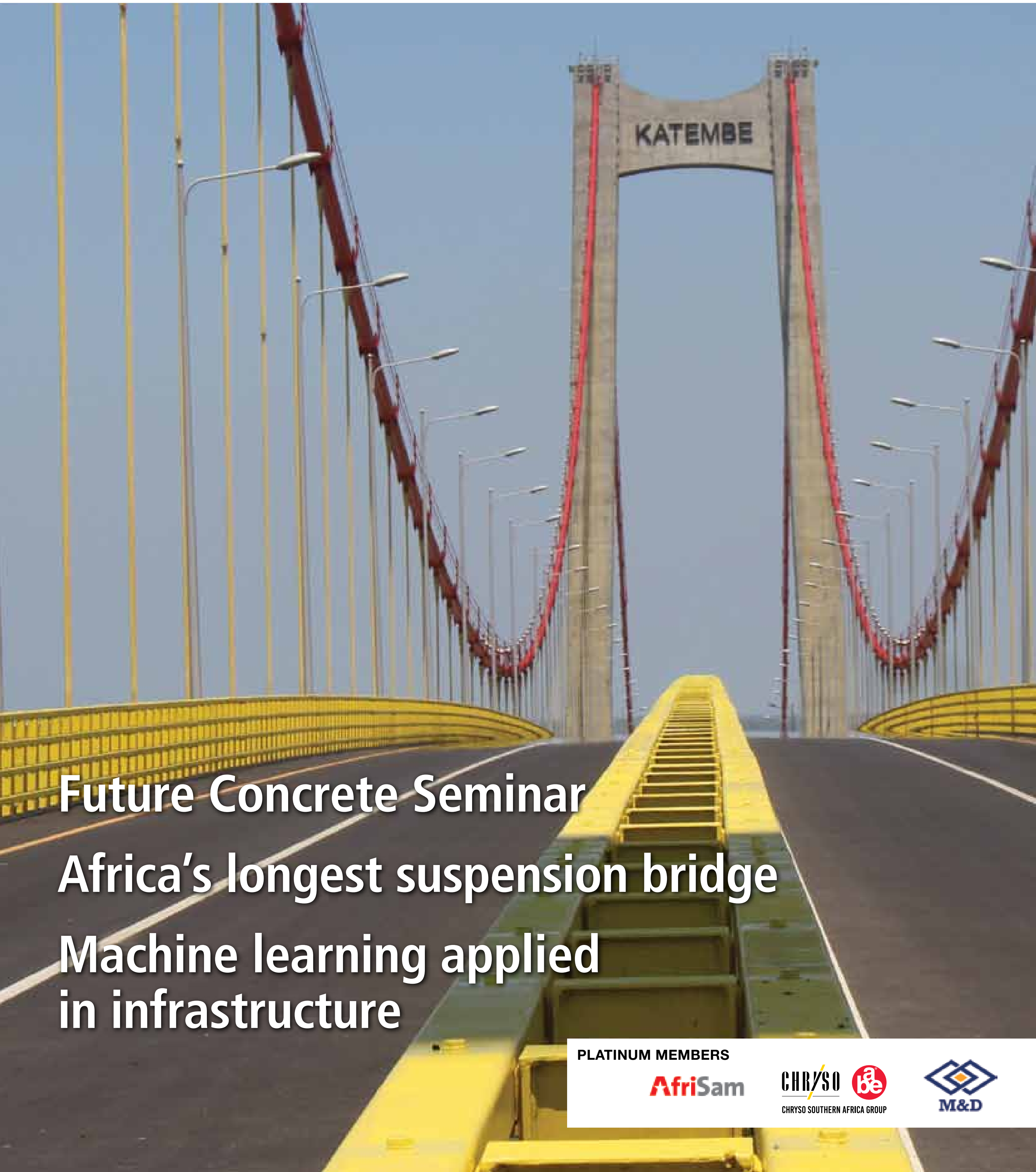

Future Concrete Seminar

Africa's longest suspension bridge

Machine learning applied in infrastructure

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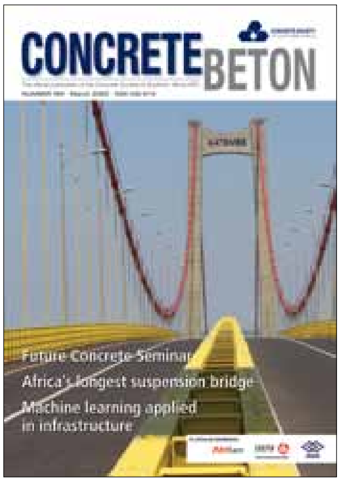
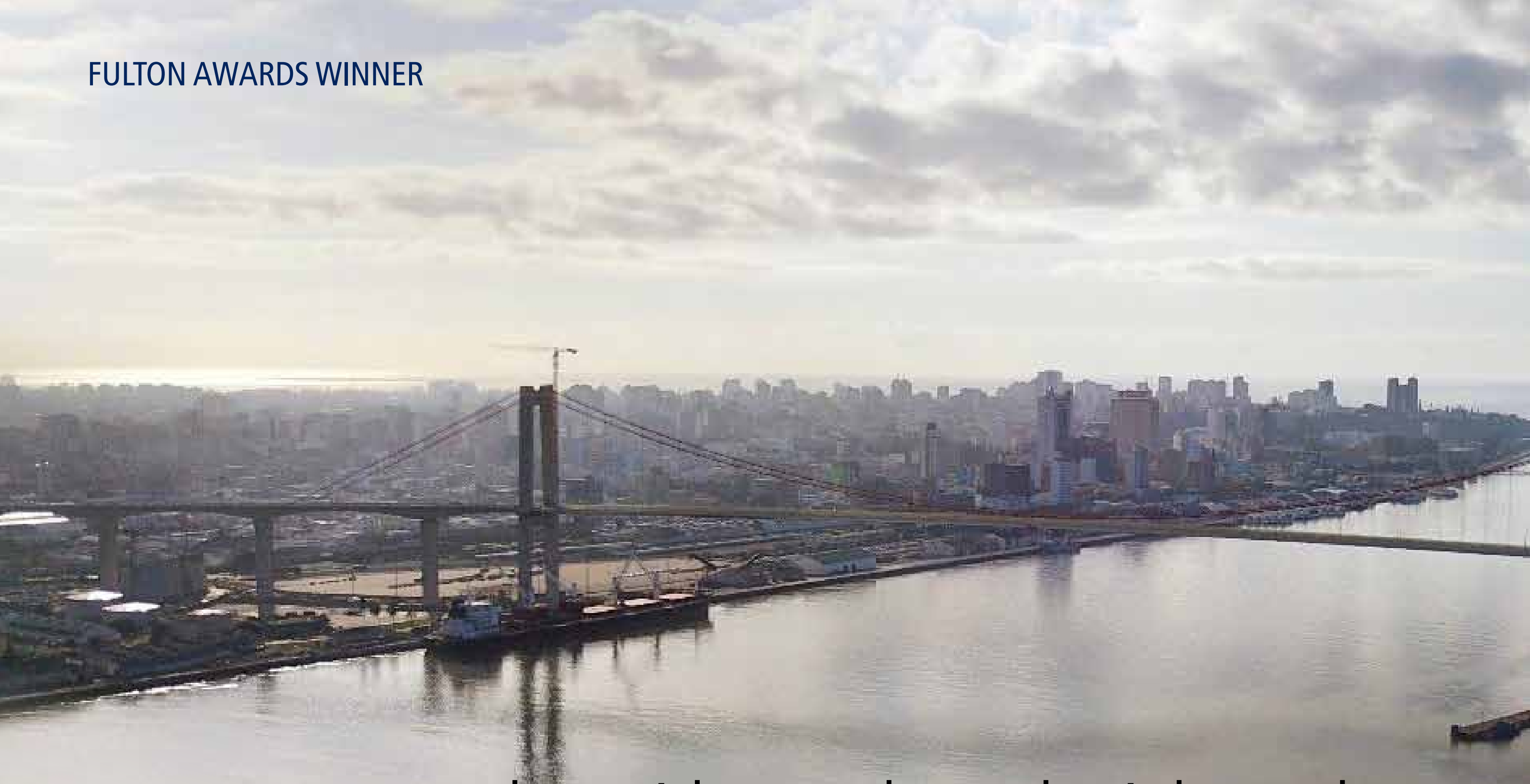


COVER: The Maputo-Katembe Bridge, Africa's longest suspension bridge. Page 8.



Maputo-Katembe Bridge and North Link roads, Mozambique

After its completion and inauguration in November 2018, the Maputo Bridge not only became the longest suspension bridge in Africa, but also one of the most durable concrete structures built in Southern Africa, with a main span of 680 m and total length of 1225 m between the anchor blocks.

Construction of the bridge started in mid-2014 with a total project value, including the southern link roads, of approx. US$750 million. Design and execution were carried out by China Road and Bridge Corporation (CRBC), based on FIDIC's Silver book EPC contract. German consultant GAUFF Engineering was responsible for quality supervision as well as design verification against Eurocode.

The main bridge consists of two reinforced concrete approach viaducts from the North and South banks respectively, which connect to the main span, a suspension bridge made up of a segmental steel box girder deck, held up by two large RC anchorage blocks where the bottom part below ground level is filled in the shaft in rectangular chambers of different levels with sand (25 % of weight) and concrete (75 % of weight).

The bridge carries four lanes of traffic, two in each direction, with a design speed of 80 km/h.

The North and South approach bridges were built utilizing two different design and construction methods based on the local conditions.

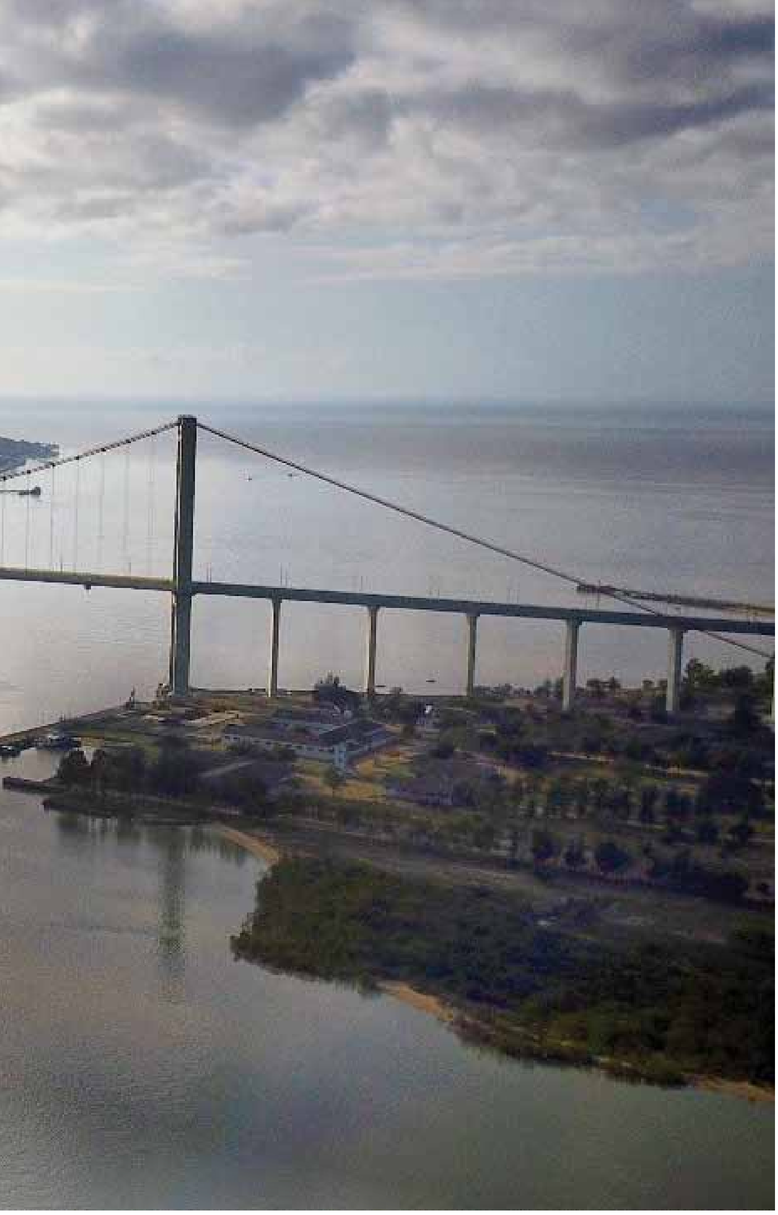
In the North, the first 240 m of the approach bridge was constructed with use of 30 m-long precast post-tensioned T-beams. The next 853 m was constructed utilizing balanced cantilever construction methods rising towards the main bridge with a gentle S-curve. The southern approach bridge was constructed using prefabricated post-tensioned T-beams of 30 m and 45 m culminating in a total length of 1234 m. The approach bridges connect on each side to a single-span double-hinged suspension bridge with a centre span of 680 m. The side spans are 260 m and 285 m long respectively. In reality, 3 different types of bridges were constructed and connected: the North Approach is a balanced cantilever bridge which was constructed via segmental launcher, connecting to the main span making up the suspension bridge, ending in the post tensioned T-beam bridge which is called the South Approach.

Moreover, three further bridges connecting the main structure to the existing Maputo infrastructure were built under the same EPC contract as cast in place pre-stressed concrete bridges. They are the A Ramp (508 m), N Ramp (230 m) and the K Ramp (240 m).

The bridge concept was designed to Chinese standards with the overall design verified against Eurocode specifications.

Geological site conditions were made up of various strata comprised of imported fill, tidal silt in the upper layers with fine sand and clay in the lower layers. The groundwater level was also extremely high due to its proximity to the bay. These adverse soil conditions required several different foundation engineering solutions; diaphragm walls for the anchorage shafts; bored piles up to a diameter of 2.2 m drilled with a slurry suspension; subsoil stabilization using cement-stabilized earth piles; high-pressure grouting below the diaphragm walls; lowering of the groundwater; pile loading tests with embedded hydraulic cylinders; driven reinforced-concrete piles and sheet piling. These foundation solutions all required a highly workable fluid concrete, so that casting at extreme depths could be achieved with self-compaction over a long period of time during these procedures.

Construction of the shafts of the anchor blocks on the North and South banks started in early 2015. Each gravity anchorage is made up of the foundation, splay-saddle buttress, and anchorage chambers,



of which some are empty, and some are filled with concrete and sand requiring a specific density, all adding to the total weight of the structure. Each shaft has an external diameter of 50 m, a wall thickness of 1.2 m and a wall panel depth up to 56 m. The anchorage structure on the south side of the crossing with the final excavation depth of 37.50 m below ground level is believed to be one of the deepest open shafts in the world at the time of construction.

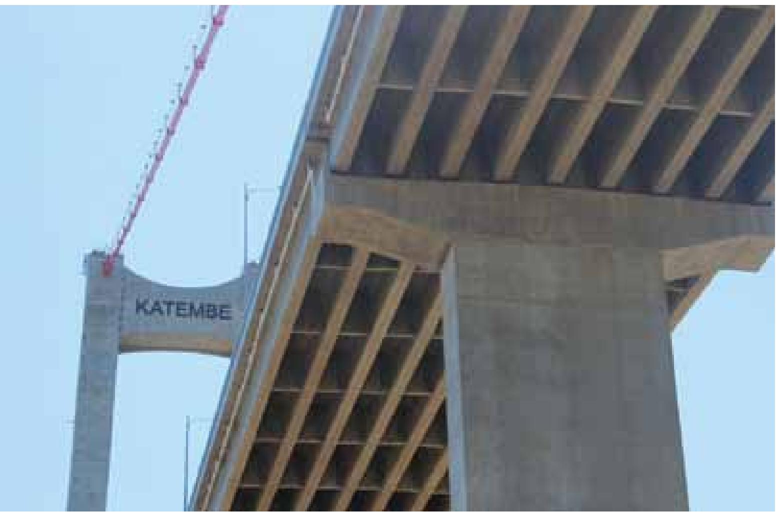
In addition to the excavation profile, the verticality of the diaphragm wall panels was permanently monitored using special Koden measuring devices. Steel pipes were installed into the reinforcement cages to facilitate cross-hole sonic logging tests to detect any abnormalities in the self-compacting concrete. Gradually as the excavation works inside of the shafts progressed, the diaphragm wall was reinforced by an internal cast-in-situ concrete lining ring, which was extended up to a thickness of 2.5 m towards the bottom. The foundation level at the shaft bottom itself has to carry a tremendous load. The south anchorage block weighs an impressive 170000 t with approx. 75% of concrete and 25 % of sand filling.

Extensive soil and bearing capacity investigations and studies showed that additional soil improvement measures were necessary at the bottom of the 37.50 m deep excavation. One third of the bottom in-situ surface bearing capacity met the required design bearing capacity; an additional 1.5 m depth was excavated from the other third and replaced with C20 concrete and the remaining third was strengthened by installation of 28 unreinforced concrete piles 12 m long and with a diameter of 1.5 m.

As there was no comparable project in Mozambique for the design of the bridge foundation piles, the design was based on the findings of a geotechnical investigation which started two years ahead of the actual construction work. Pile construction for the towers and foreshore bridge piers began simultaneously with the anchorage excavation, and before pile production could begin, their bearing capacity was verified using static test loads. Based on the findings all piles were optimized in both diameter and length. These tests were performed by the University of Nanjing.

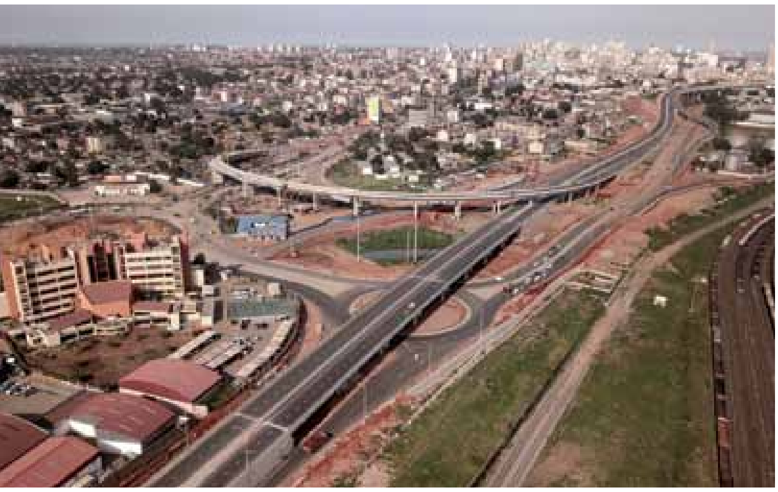
The production of the piles followed the international reverse-circulation-drilling method. A total of 283 piles was constructed for the approach bridges, each with a diameter of 1.5 m and an average depth of 50 m, and 48 piles were installed for the towers, 24 at each tower, and each with a diameter of 2.2 m and length of 105 m at the South tower and 95 m at the North tower and a further 91 piles for the bridges of the ramps. The quality and integrity of the concrete in all piles was verified by a third party from South Africa making use of CSL after more than 28 days. Concrete cubes were manufactured for 7, 28, 90 and even 365-day compressive strength tests and slump testing was done on every truck to confirm workability.

The towers of the bridge are a frame-shaped structure composed of two vertical legs connected by an upper transverse girder at the top and a lower transverse girder approximately 45 m from the north tower base and 42 m from the south tower base. To increase lateral stability both tower legs were inclined at 2° towards the bridge's centreline.



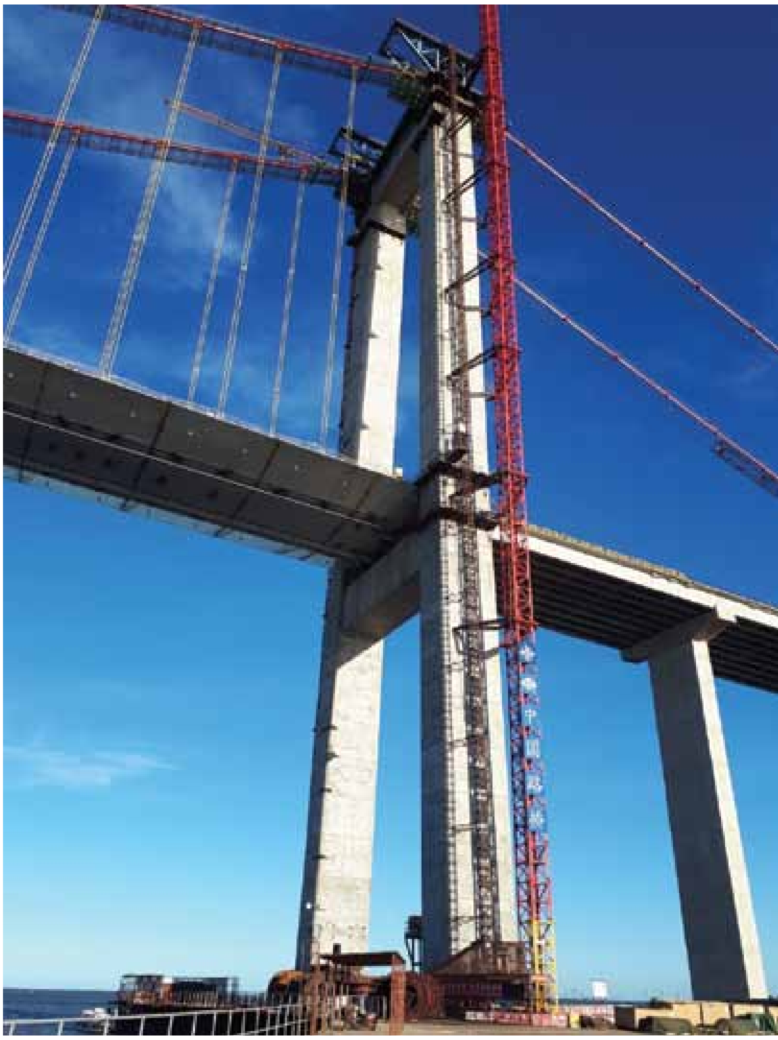
Post-tensioned 45 m-long T-beams connect to Pylon M2.

Free cantilever bridge (spans < 119 m) and the northern anchor block.

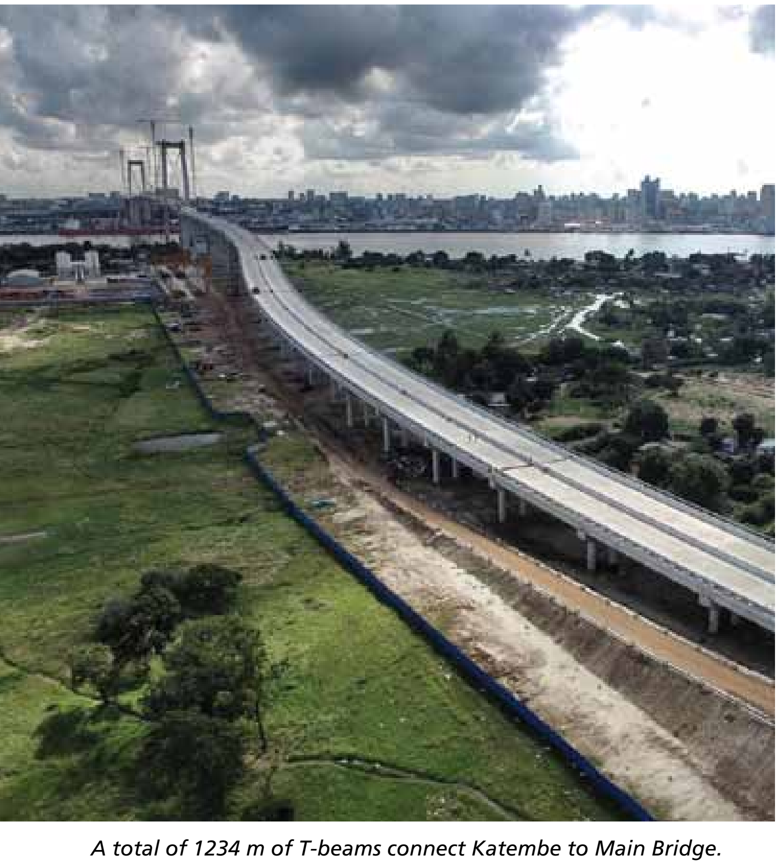


K-Ramp and K-Line going from National Road EN1.

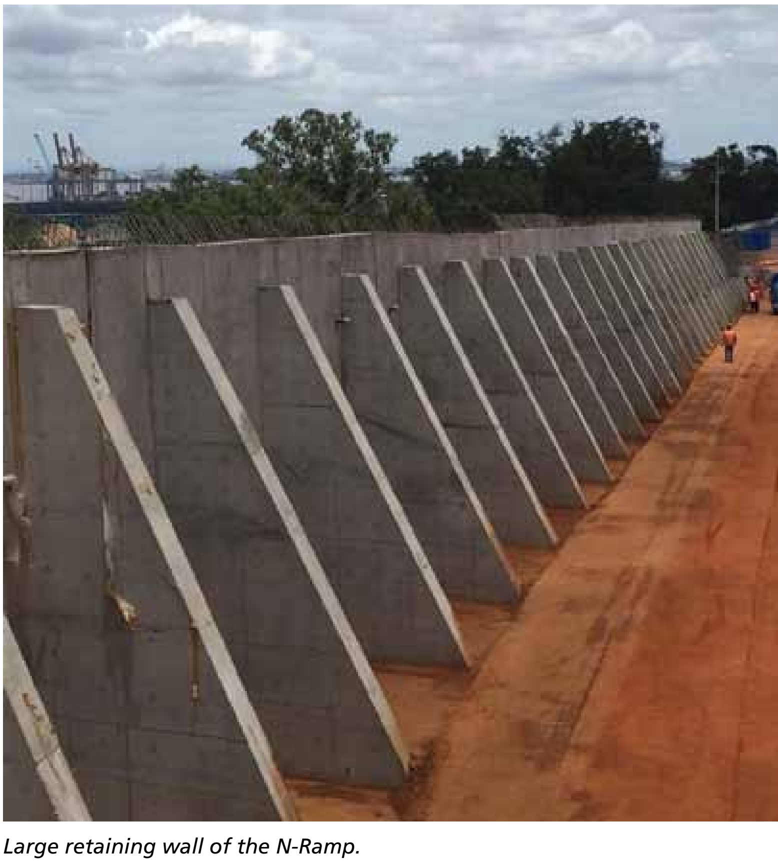
Bridge and ramps of 978 m to North Approach Bridge.



South Pylon - the tallest structure in Maputo (138 m).



A total of 1234 m of T-beams connect Katembe to Main Bridge.



Large retaining wall of the N-Ramp.

The main structure of the tower is comprised of rectangular hollow box sections, each with a height of 7 m and a width of 5 m. The wall thickness of the upper part of the tower is 1 m, and this increases to 1.2 m towards the bottom, resulting in a total thickness of 1.8 m at the base. The final height of the tower on the North side (Maputo) above the pile cap is 137.1 m and on the South side (Katembe) is 138.1 m.

The superstructure for the North Approach Bridge was designed as full pre-stressed concrete with 3-dimensional prestressing. The cross sections of the cast-insitu box girder of this 853 m long balanced cantilever bridge is a double cell box on the relevant piers N08 to N15. For the prestressing of the 3 vertical webs, for each 50 cm two rows of thread bars with an outer diameter of 32 mm are used. Their yield strength is f_{pk} = 785 MPa, elastic modulus E = 2.0 x 105 MPa with a control stress for the prestressing procedures at 0.9 x f_{pk} = 706.5 MPa.

The superstructure is continuously joined to the substructure of the Pier N09 to N12. For that procedure vertical bars with a length of up to 20 m are also used to complete the required anchoring during the construction stages only. At the Piers N13, N14 and N15 the cast-insitu box girder is supported by pot bearings. As a temporary anchoring, four solid reinforced concrete blocks ensured the required anchoring during the construction. After the completion of the superstructure, the temporary connections were removed, and the previously installed bearings took over the complete loading.

Strands with a nominal diameter of 15.2 mm for the prestressing for the longitudinal webs and transversal top slab, the diaphragms of the first segment of the box girder, the T-beams, pier caps and the lower and upper cross beam of the pylons are built in. The characteristic of the strand with a high strength and low relaxation steel material follows a yield strength of f_{pk}=1860 MPa, an elastic modulus Ep = 1.95 x 105 MPa and a relaxation rate less than 0.035. The designed control stress was 0.75 f_{pk} = 1390 MPa during the prestressing actions.

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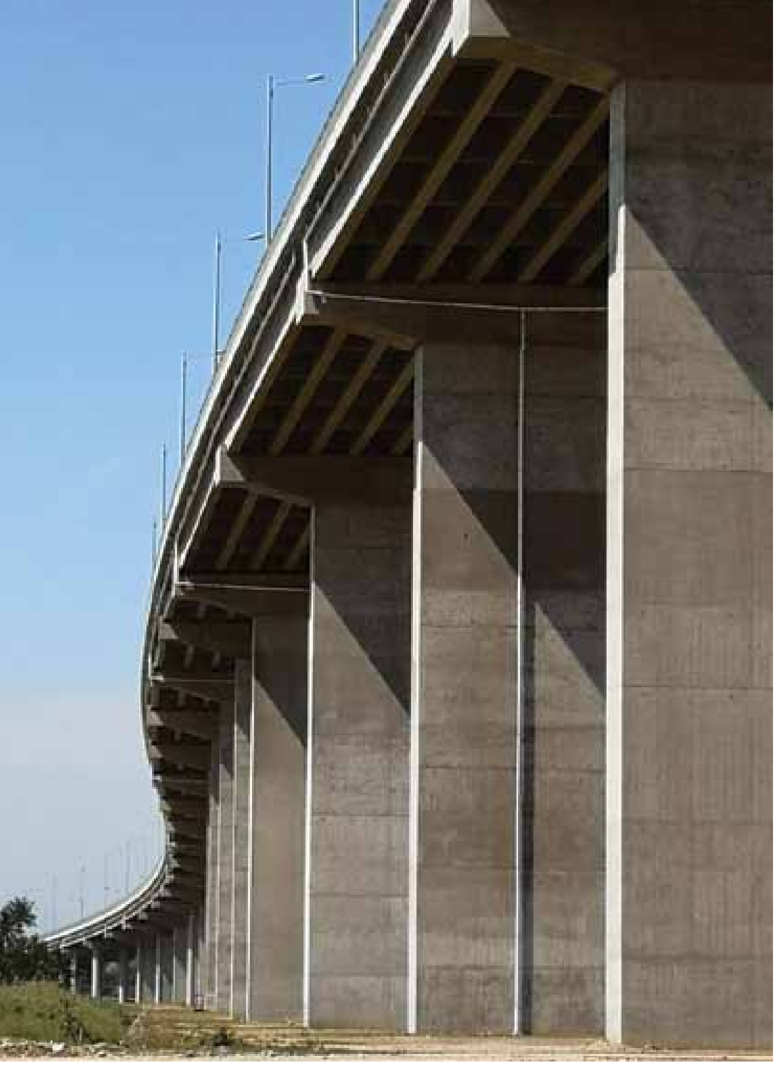
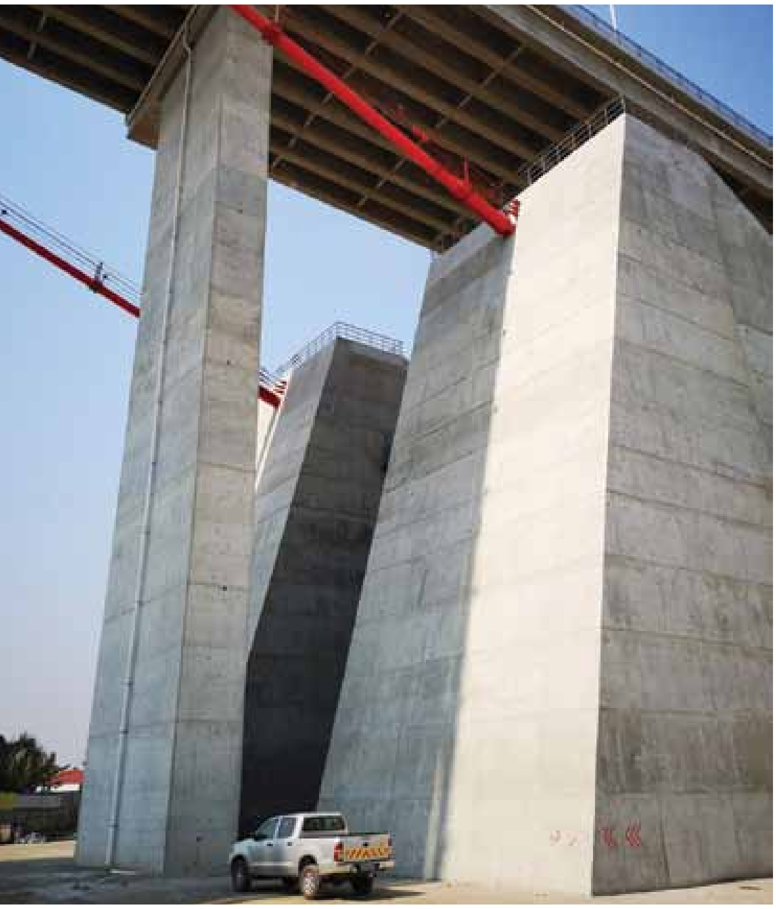
After the strands were installed in the embedded plastic corrugated pipes and the concrete reached 85 % of the required strength, the prestressing procedure could be performed. During tensioning procedure, the tension force and elongation were controlled, and the theoretical elongation compared to the measured elongation. The latter had to be in an allowed range of ±6%.

The purpose of the upper and lower beams is to brace the tower legs, and these are made up of rectangular hollow box type sections. The upper beam is 5.5 m deep and 6 m wide, with a wall thickness of 800 mm, and the lower 6 m deep and 6 m wide, with a wall thickness of 1.0 m.

The main cable consists of 91 bundles containing 91 wires of 5 mm-diameter, which are draped over the main cable saddles of the towers and connected to the anchor blocks on each side of the river. The total length of the wires in both cables are a staggering 21878 km. The cables are bound with fixed strapping tape and hot-cast sockets are provided on both ends. Each hot-cast socket is composed



The beauty of concrete in geometry in construction.



Heat of hydration had to be controlled during the casting of anchor blocks and other elements.

of an anchor cup, cover plate, wire divider plate and a zinc copper alloy which is cast inside the anchor cup. These cables are one of only 27 dehumidified suspension cables in the world!

For the hangers, galvanised high strength steel wires will be used. The transverse distance between the main cables and hangers is 21.88 m and the standard distance between the hangers along the bridges main span orientation is 12 m, with the length of hangers ranging from 73 m at the towers to 3 m at midspan.

Each hanger consists of 61 parallel steel wires, 5 mm in diameter, with a strength grade of 1770 MPa. In total there are 55 hangers attached each side to the 57 steel box segments which make up the main span.

For the construction of the adjoining concrete bridges to the longest conventional suspension bridge in Africa, cement type CEM II 42.5 A-LN is supplied by Cimentos de Mozambique (CM). This is a Portland Limestone Cement comprising between 80-94 % clinker and between 6-20% limestone. It has the ability to produce cement strengths between 42.5 MPa and 62.5 MPa. Two different manufacturers from South Africa were used to supply the project with Fly Ash (FA) to induce Pozzolanic activity within the cement. All the fly ash supplied conformed to SANS 50450-1:2011 requirements for concrete.

The advantage of the addition of FA in the range of up to 40% of the total cementitious materials for the fresh concrete lies in improving workability and reduces water requirement for a given slump and slightly retards the setting time. Concrete had to be pumped up to a height of 140 m to the top of the saddle house.

For the hardened concrete the main advantages were a massive decrease in the CO_{2e} emissions, strength development with age and a reduction in production costs. Other improvements were the reinforcement's resistance to chloride attack, improvement to sulphates resistance, refinement of pore structure, reduction of permeability, prevention and retardation of the alkali-silica reaction, reduction of heat generation caused by hydration and also significantly reducing the risk of thermal cracking that could possibly have taken place during the casting of the 3 x 4000 m³ anchorage bases. Internal cooling systems were extensively used throughout the project.

Two of the unique aspects of the concrete on this project was the addition of up to 40% fly ash and a specially formulated superplasticizer.

This not only offers immediate cost savings (<10 %) but also long-term benefits. The PFA, sourced from South Africa, allows the concrete to achieve much higher long-term strength gains, and the fineness of the PFA contributes to the concrete being less permeable resulting in a much more durable concrete, as the river sand lacked fines. An additional benefit of the PFA is also a 20% reduction in the heat produced due to the exothermic reaction that is hydration, highly important in mass concrete.

The water-reducing superplastizer was highly important due to the extreme depths and heights casting occurs at, which needed a highly workable (200 – 230 mm slump) concrete with cohesive flow characteristics without segregation and a delayed setting time, the water reducing and ion exchange effect of the superplasticizer also greatly contributed to the durability and strength of the concrete.

The Durability was in fact confirmed by the University of Cape Town's Concrete Materials & Structural Integrity Unit (CoMSIRU) which tested samples that were cored 9 months after casting from the bottom slab of the anchorage, the report stated that the result of the cores tested was the best ever obtained from site manufactured concrete tested at their facility.

In total 21 different concrete mix designs ranging from C20 to C50 were designed and tested. Supply of aggregate came from 4 different suppliers as there was concrete manufactured 7 days a week as it was not possible to have a continuous supply from only one supplier. The North and South bank operated independently and thus each had their own concrete mix designs.

Further durability testing was performed at Concrete Testing Services in Johannesburg on the concrete cover that varied between 50 mm and up to 150 mm thick.

Even though the durability indexes did not form part of the Employers Requirements and the cost was borne by the contractor, it was bilaterally decided to do the indexes test on concrete of varying ages, to confirm that substituting cement with Fly Ash, did indeed improve not only the strength with age factor, but also played a major contribution in increasing the durability of the structure to guard against the harsh marine environment.

Suggested ranges for the durability classification using index values "Research monograph no. 2, MG Alexander, JR Mackechnie, Y Ballim" indicated the results as being excellent. ▲

Editor's Note: This project was the winner in the 'Infrastructure > R100 million value' category.

PROJECT TEAM
Client: Empresa de Desenvolvimento de Maputo Sul, E.P. (EDMS)
Principal Agent: China Road and Bridge Corporation (CRBC)
Consultants: Gauff GmbH & Co.
Specialist suppliers:CM Cimentos de Moçambique; Ulula Ash