Dubai Metro: building the world’s longest driverless metro

The 23 km Green line of the Dubai Metro opened in September 2011, exactly 2 years after the 52 km Red line, making it the world’s longest driverless metro. In a city dominated by the car but projecting heavy population growth, the metro has been designed to provide unparalleled levels of customer comfort and finishing, together with the frequency, punctuality and coverage to meet the emirate’s future strategic needs and ambitions. This paper provides an overview of the £4.8 billion project, with particular emphasis on the heavy civil engineering solutions delivered within a highly stylised and exacting architectural context, from an outline plan in 2002 to a fully operational reality in 2011.

1. Introduction

Dubai city in the United Arab Emirates has experienced rapid physical and economic growth in recent decades, resulting in severe road traffic congestion. Further population growth is expected – rising 50% in the emirate overall to reach 3 million by 2017 – along with a significant increase in tourism.

Ruler Sheikh Mohammed bin Rashid Al Maktoum has long recognised that an integrated transportation solution would be needed to support Dubai’s ambitions of becoming a world transit centre and Middle East financial hub. A strategic decision was therefore taken by the Dubai government in 1997 to develop a high-quality metro system as the backbone of an integrated mass-transport system.

Even at this early stage the government appreciated that coaxing drivers out of their cars in a desert environment would be a significant challenge. It would require the highest standards of design, comfort and safety to succeed, along with an integrated approach to rail, water, taxi and bus public transit services.

Initial studies in 2002 compared the feasibility of a variety of metro alignments to maximise coverage of the city together with principal construction methods and procurement options. In 2004 the newly formed Dubai Metro appointed Systra as lead consultant to turn initial feasibility studies into outline designs, which subsequently became the basis of design-and-build tender documentation issued later that year.

The contract was awarded in May 2005 to Dubai Rapid Link consortium – comprising Mitsubishi Heavy Industries Limited, Mitsubishi Corporation, Obayashi Corporation and Kajima Corporation of Japan and Yapi Merkezi Insaat Ve Sanayi A.S of...
Turkey. Design of civil, electrical and mechanical works was subcontracted to Atkins and design of rail systems subcontracted to Mitsubishi, supported by specialist sub-suppliers such as Thales for systems software.

An associated project management and consultancy services agreement contract was also awarded in 2005 to a joint venture of Systra–Parsons. This was to help the client manage the design-and-build contractor and serve as the client’s designated engineer.

The contracts were initially let by the Dubai Municipality but were later managed by the Dubai Roads and Transport Authority, formed in 2006 and led by chairman and executive director Mattar Al Tayer, an honorary fellow of the Institution of Civil Engineers. Figure 1 shows an overview of the £4.8 billion project’s organisational structure.

2. Architectural context

The architectural vision of the project was set to an extremely high design standard from the outset and aimed to make a major contribution on the world stage of metro architecture. The ambition was to design an iconic network which would be readily recognised by the entire population, while providing the highest level of comfort and safety to both able-bodied and handicapped passengers. All these ambitions were of intense importance to the client and remained a major focus for its rail agency management and staff.

Many of the wider design aims and themes were derived from heritage themes, such Dubai’s pearl-diving history being reflected in the light ‘clam-shell’ frames for the overground stations and entrances (Figure 2). The metro makes use of both underground and overground
stations to integrate itself into the existing fabric of Dubai, using four distinct colour themes to help passengers distinguish stations – green (air), blue (water), brown (earth) and red (fire). In the historical heart of Dubai, the client specifically developed design themes derived from the architectural heritage of the older central business district. These consist of earth tones which relate the traditional mud brick and stucco structures found in the emirate.

Further heritage enhancements at Al-Ras and Al-Ghubaiba stations on the Green line include station entrances and interiors designed to fit discreetly into the existing historical fabric by the use of form, materials and details of the local vernacular, with overground entrances of the ‘heritage’ type stations fitting inconspicuously alongside historical Arabian courtyard houses. This approach includes features such as the ‘barjeel’ or wind tower, which was traditionally used to cool the inside of dwellings by way of passive ventilation strategies. On the underground stations this is reinterpreted for lift shafts and entrance pods (Figure 3).

The use of ‘mashrabiya’ or ornate latticework once used for shading and as privacy screening has been reinterpreted as architectural ornament both within the elevations and interiors of the structures. Other underground stations in the area, such as Khalid Bin Al Waleed and Union, present historic images baked into robust vitreous enamel panels, offering passengers a glimpse into Bedouin traditions and Dubai’s desert past.

3. Summary scope of works

The metro consists of 75 km of new-build metro lines with 47 stations and three depots in the current formation (Figure 4). The overarching plan was to connect existing densely populated neighbourhoods with newer financial and business districts, commercial hubs and mixed-use districts to maximise ridership and coherence of travel.

The infrastructure was delivered in two distinct phases, both adopting a fast-track approach to achieve the client’s strategic aims (Khaja, 2007): the Red line, comprising a route of 52 km served by 29 stations, and the Green line, providing a further 23 km and 20 stations. Both lines share two underground interchange stations each side of Dubai Creek: Union and Khalid Bin Al Waleed.

The 52 km Red line runs northeast to southwest from Rashidiya station to Jebel Ali station, with 5·7 km of the railway underground in one bored tunnel, 42·8 km operating on an elevated viaduct and 3·5 km at grade. The Red line’s two large car park facilities (park and ride), 25 elevated stations and four underground stations provide convenient access and multimodal connections for all passengers. In addition, there are two maintenance depots at either end of the line.

The 23 km Green line runs from Etisalat station to Creek station with 8·3 km of the line operating in a single tunnel and the remaining 14·7 km operating on an elevated viaduct. The route has 12 elevated stations, eight underground stations, one car park and a dedicated maintenance depot at the northern end.

4. Tunnelling

The Red and Green line tunnel sections and underground stations are in the older and more densely populated sections of Dubai. As a result the ‘as-built’ information on the foundations of adjacent properties was generally not available and the contractor had to...
undertake its own investigations to ensure it did not impact these structures (Beau and Maghazy, 2008).

All tunnels were constructed using three earth-pressure-balance tunnel-boring machines with 9·56 m diameter. The total length of bored tunnels was 4·2 km for the Red line and 7·1 km for the Green line. The type of tunnelling machine chosen by the contractor was based on its expertise on other projects worldwide and was suited to the conditions in Dubai, where the ground was generally calcareous sandstone overlain by cemented sands and marine sand. Average progress rate for the tunnelling works was ten tunnel rings a day, equivalent to 15 m.

The segmental tunnel lining is 8·5 m inner diameter and 9·3 m outer diameter. It was constructed using G50 concrete to achieve the 4 h fire rating required and was designed to take both permanent and temporary construction loads. To supply the tunnel segments the contractor constructed a precast yard outside the city. At peak production this facility was producing in excess of 60 segments per day.

In total there are ten underground stations, four on the Red line and eight on the Green line, with two serving as interchanges. Khalid Bin Al Waleed station is on the south side of Dubai Creek and employs a cruciform platform configuration that allows passengers to change lines by moving up or down a level, while Union station is on the north side of the creek and employs a parallel transfer strategy, allowing passengers to change lines on shared platforms. A number of the underground stations were located in the middle of major interchanges such that significant traffic-management arrangements were required to provide suitable working site areas.

In addition to being substantial structures in their own right, the underground stations were constrained by the programme as they also served as launching and receiving shafts for the tunnelling machines, requiring significant real-time monitoring to ensure successful breakthroughs (Figure 5) (Beau et al., 2008). All stations were constructed using diaphragm walls and traditional top-down construction techniques. The diaphragm wall panels were all typically 2·8 m × 1·2 m in width and up to 50 m deep for the main station boxes and 0·8 m width and 20 m depth for the entrances. Construction of the diaphragm walls was typically undertaken under bentonite using Liebherr 855 or equivalent crawler cranes and associated clam-shell mechanical grabs.

After completion of the diaphragm and successful outcome of the dewatering pumping tests to ensure adequate cut-off, the contractor proceeded with the station excavation works. For this to progress, substantial temporary propping systems were used until the permanent slabs were completed and were sufficiently cured to take the loads. Temporary openings were provided in the slabs to service the ongoing civil works underneath (Figure 6).

The contractor was conscious of the criticality of the stations to meet the tunnelling schedule and, during the progress of the works, was able to optimise the unexpectedly favourable ground conditions. This made it possible to increase the propping spans and reduce the number of propping layers in excavations, helping to maintain progress rates in established urban areas (Yamashita et al., 2010).

5. Viaducts

The viaducts for the Red line were approximately 44·1 m long and those for the Green line were 14·7 km in length (Smith et al., 2009). The overall strategy for constructing the viaducts and overground stations was dictated by the movement of the launching girders. A total
of ten launching girders were utilised for the construction of the Red line and eight of these were then relocated to the Green line (Figure 7). The movement of the launching girders was planned to minimise the number of assembly and disassembly operations. There was also a programme constraint that they must pass through the station before the station roof steelwork could proceed above the viaduct parapet level.

The movement of the launching girders therefore had a significant impact on the production of the viaduct deck elements, which were manufactured at a purpose-built precast yard near Jebel Ali (Figure 8). The yard achieved an average daily production of 40 viaduct units per day for both lines, as well as manufacturing all superstructure pier-cap units and three-span bridge elements.

As the viaduct crossed a number of existing and future road interchanges, some of the required spans were too great to be constructed using a launching girder. The contractor opted to construct these three-span sections using a balanced-cantilever method. The average weight of each segment in these spans was approximately 55 t, with the heaviest almost 90 t. In total, 48 spans on the Red line and 24 spans on the Green line were constructed using this method.

6. Piling works

The ground conditions in Dubai are quite good for piling works, with pile depths ranging from 20 m to approximately 50 m in areas adjacent to Dubai Creek. The total numbers of piles and piers for the Red and Green lines were 2627 and 1945 respectively.

The majority of the piers for the viaduct were typically 1·75 m or 2 m diameter and were supported on monopiles of either 2·2 m or 2·4 m diameter respectively. The piles were designed as friction piles as end-bearing was ignored due to potential risks of weak substrates, and the design was optimised by the contractor to eliminate the need for pile caps. Concrete for the piles was C50/20, while C40/20 was used in the piers. Due to the aggressive ground conditions, cover to the pile reinforcement was 120 mm and the top 2 m of the pile had additional waterproofing applied (Smith and Hendy, 2009).

Piling works were undertaken using a number of rigs, the most typical being the Bauer BG 22/28 rotary rig, with average pile construction times of 30 h from commencement of boring to completion of concreting. Generally, water or polymer was used as a supporting fluid and the use of bentonite minimised due to concerns over potential skin friction loss. In some locations, however, bentonite was approved for use subject to implementation of strict quality control procedures.

7. Overground stations

The streamlined overground stations have been carefully designed to provide spectacular views over the Arabian Sea, the distant desert...
Figure 9. Overground type 1 stations have the concourse at ground level

and the city’s remarkable skyscrapers between the two – including the 828 m Burj Khalifa, currently the world’s tallest building (Aldred, 2010). The appropriately glazed and carefully detailed envelope allows natural lighting to be used for illumination and passenger orientation. There are three types of overground stations.

- Type 1 – concourse at ground level, platform above ground (Figure 9).
- Type 2 – concourse and platforms 5 m above ground, accessed by entrance pods and footbridges, with free flow of vehicles and pedestrians beneath (Figure 10).
- Type 3 – similar to type 1 with concourse at ground level but with expanded train operations. Additional platform allows for an additional ‘pocket track’ for future line extensions as well as special operational functions for rolling stock.

All stations were constructed on piled foundations and, in the case of type 2, a reinforced concrete spine beam runs the full length of each station to support the concourse steelwork and roof.

The roofs to the overground stations were a primary focus for the client. Their shape and detailing was required to make a legacy statement for Dubai and also reflect the city’s heritage. The contractor proposed an elegant clam-shell shape to encompass the station and provide sufficient space for passenger circulation and sufficient back-of-house area for operational staff and necessary plant and equipment rooms.

Construction of the roof sections involved detailed sequencing of the works to ensure no adverse temporary loading conditions were experienced. The contractor adopted a method of working from the centre of the stations and systematically progressed towards the ends. When the central section of the roof and the intermediate ribs and cross-bracing were completed, they were de-propped and allowed to stand freely. The contractor then proceeded to assemble the cantilevered end-sections in a systematic manner until both end-sections could be simultaneously released from their temporary supports.

Figure 10. The concourse for overground type 2 stations is 5 m above ground level to free circulation beneath
8. Entrances and footbridges

The station entrances, known as entrance pods, follow similar design principles to those of the stations’ main bodies. The iconic gold curvilinear roofs of the stations are echoed in the form of the entrance pods and offer aesthetic continuity between the different structures. The entrance pods have been designed to allow comfortable access to both the underground and overground stations and have been positioned to engage existing neighbourhoods and future developments. Structural and architectural provisions have been provided to allow for additional entrance pods to plug directly into the entrances at footbridge level. Bus and taxi laybys have been positioned in close proximity to the entrances to allow for the most comfortable modal shift.

The metro alignment was constructed to one side of major roads on both the Red and Green line and, accordingly, entrances and footbridges were constructed to facilitate passenger access (Figure 11). The extensive network of footbridges (Smith et al., 2011) thus also stitches large areas of the urban fabric together over major highways, which were previously impassable by pedestrians. In addition, on some of the longer elements, travelators are provided to encourage the public to travel to the stations on foot. The total length of all the elevated footbridges for the Red and Green lines is 3.8 km and 0.6 km respectively.

In general, the footbridges could be erected by arranging for a temporary closure of the traffic lane for a few weeks followed by the erection and completion of all structural and external cladding works. This was not the case in some areas, especially over Sheikh Zayed Road which is the main artery through Dubai. To overcome this obstacle, the contractor designed the footbridges so that they could span the entire five-lane width of the highway. It also used two self-propelled modular transporters, specially imported from Japan (Figure 12), to erect these 200 t sections during a 5 h contra-flow after they had been fully fabricated on the side of the highway. In total, 26 spans were erected this way during weekend closures over a period of 10 months.

9. Maintenance depots

Three maintenance depots are provided on the Dubai Metro. Two of these serve the Red line and are located on either end of the line at Rashidiya (174 000 m²) and Jebel Ali (107 000 m²). The remaining depot serves the Green line and is located at Al Qusais (268 000 m²). The depots have been designed to handle a total storage capacity of 104 trains on the Red line and 60 trains on the Green line.

Construction of the depots involved some site clearance and utility diversion works before bulk earthworks could be undertaken to lower
the ground level to the required grade. All buildings were also designed
to continue with the architectural theme developed for the stations and
accordingly the specification for the finishes was very high.

All depots contain covered and air-conditioned siding and cleaning
buildings along with a number of ancillary buildings. Each depot also
contains its own dedicated control centre, with the network operation
control centre being located at Rashidiya and a backup control centre
in Jebel Ali.

10. Electrical and mechanical

The electrical and mechanical systems within the stations and
depots were a significant element of the works and required
major planning and detailing. During the design development
phase, a detailed assessment of cooling load and associated space
requirements was undertaken. This took into account expected
loads in key areas such as solar loads, occupancy loads, lighting and
equipment loads from the individual systems along with the general
requirements for traction power, communications, fire suppression
systems and air conditioning.

The entire power distribution system for the metro is provided
from three dedicated main power stations, each of which receives 132
ekV power from the Dubai Electricity and Water Authority grid. This
distributes the power by way of a 33 kV ring main system to substations
located at each station, car park and independent building. From here
power is then transformed and distributed to the 750 V direct-current
traction power system and to the building low-voltage system.

Building and station air conditioning contributes quite significantly
in the overall consideration of the mechanical systems, so the client
decided to use a district-cooling supplier to provide large quantities
of chilled water. As part of a separate contract, the district-cooling
supplier constructed a number of chiller plants along with the
necessary distribution systems to meet the temperature delivery
requirement of 4·8°C as well as the high volumes.

In addition to the normal range of electrical and mechanical
systems, of particular note is the tunnel ventilation system. Due
to the stringent fire safety and evacuation requirements and
the environmental conditions, this was a particularly complex
arrangement. The entire system consists of air-handling units, tunnel
ventilation fans, pressurisation fans and dampers located at strategic
points within the tunnel sections. There are various operating modes
depending upon the location of any possible fire or emergency in the
tunnel, all of which are managed by way of the local control system
either at the point of operation or in the station master’s office in
each station. In addition, further control is provided at the operation
control centre in the depot.

The entire electrical and mechanical systems are controlled using
an environmental control system, which is fully integrated with the
operation control system. This gives real-time performance feedback
to the station master and the operation controller for all systems
by way of a multi-server network, which is provided as part of the
rail systems configuration. Integration of these two systems itself
presented a major challenge.

11. Rail systems

The provision of the supporting rail systems for the Dubai Metro
network has seen the delivery of complex inter-related systems and
sub-systems across every aspect and asset of the project (Figure 13).
These range from the world’s largest internet protocol camera
network, supported by an extensive and fully integrated network-
wide operation control system integrating communications and
facilitating advanced operational management, to the provision of
some of the most advanced maintenance systems available.

Such systems include automated wheel monitoring to an
integrated maintenance management system. This is used for
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all planned and corrective maintenance activities to maximise operational and maintenance efficiency, as well as providing an essential data bank to support future whole-life costing and business planning activities. Further key systems include the intruder alarm system integrated to every facility and the electronic links to the Dubai Civil Defence and Dubai Police provided for fire safety and incident management respectively, providing real-time transparency to key Dubai authorities to support safe and reliable operations.

With respect to train operations, both the Red line and the Green line rely on fully automated (driverless) trains, and, with the opening of the Green line on 9 September 2011, the network became the longest fully automated rail system in the world. This achievement was made possible by the leading-edge signalling and communications equipment that allows the operator to manage and control the trains from a remote operation control centre. Similarly, state-of-the-art systems automatically collect fares and passenger information, providing operational efficiency and key data for future planning. Each line operates with a fleet of five-car trains which, when operating at peak headways, are designed ultimately to carry in excess of 25 700 passengers per hour in each direction, subject to the supporting fleet size.

Current ridership has seen considerable growth, further increasing with the opening of the Green line, and with the current fleet operations can still easily support in excess of 14 000 passengers an hour in each direction (Figure 14). This capacity has been tested to the full at numerous major events and now forms a key input to the planning of all major public events within Dubai. One unique aspect of the rolling stock has been the inclusion of both a ‘women and children only’ car and a ‘gold class’ car offering an even higher level of comfort than the standard class (referred to as silver class). Both these designated areas have seen high take-up rates, reflecting the nuances of the region.

Figure 14. The current fleet of five-car, fully automated driverless trains can carry up to 14 000 passengers per hour in each direction

12. Further works

While the two principal lines of the Dubai Metro are now in full operation, the client continues to look for future transport developments and innovation. Currently, the Al Sufouh tram project is underway, providing further intra-connectivity between the coastal areas in and around the Dubai marina, as well as providing further inter-connectivity with the metro.

Further projects either in development or under investigation include an extension to the current Green line, with a possible lengthened route beyond the creek to serve the dense population centres of international and academic cities, and a possible Purple line, serving as a designated airport link between the existing airport infrastructure based within central Dubai and the huge infrastructure being developed at Jebel Ali for future air travel growth.

Whether these particular projects make the transition from planning and feasibility to reality remains to be seen but what appears clear is the continuing determination and commitment of Dubai to remain a world transit centre and Middle East financial hub. To achieve this aim it seems highly likely to continue its significant investment in world-class infrastructure to stay ahead of the regional and global competition.

References


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