The Guideway System of the Monorail Kuala Lumpur – Design & Erection

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Summary

A Monorail was constructed in the city centre of Kuala Lumpur, Malaysia. The 8.6 km long dual guideway starts at the Pekeliling Bus Terminal in the ‘north’, pass through Kuala Lumpur’s ‘Golden Triangle’ before reaching KL Sentral in Brickfields.

Along the route, there are many congested roads with large intersections and only a narrow centre median to accommodate the support columns. The alignment design is using various combinations of straights, curves and spiral transitions in order to follow the existing road alignment.

The design of the Monorail Guideway structure is based upon individually (approximately 648 Nos.) precast post-tensioned beams, which are launched into the final position and stitched together with insitu concrete. In order to achieve a continuous frame system, individual spans (between 2 to 5 Nos.) are stressed together with continuity tendons. Based on the alignment information each frame is modelled three-dimensionally and analysed individually.

Keywords: Monorail, prestressing, precast beam, mould adjustment, beam launching, frame analysis

1. Introduction

Fig. 1: The first large scale Monorail system in Malaysia

The Kuala Lumpur Monorail (KLM) Project was a pioneer project in many ways with new advances in engineering, construction and management, not just by Malaysian standards, but at an international level also. Although KLM was the first large scale Monorail project in Malaysia, the Monorail technology has been used elsewhere in the world for more than forty years. However, some of the structural design concepts, critical alignment geometry, span arrangements and construction methodology used in KLM can be considered a first anywhere in the world. The following describes the steps taken making the construction of the guideway beam a success.

2. Design Concept of KLM Guideway System

2.1 General

The KL Monorail’s infrastructure includes 8.6 km of elevated dual guideway beams, eleven stations, five associated power sub-stations and one depot for maintenance and overhaul.

The Monorail guideway structure is unique in many ways since the structure also forms the running surface for the vehicle, unlike other rail or highway structures, which have additional surfacing, or track laid over the top. This fundamental constraint of the design criteria means that the beams have to be formed to suit the final alignment geometry, including both vertical and horizontal curves, gradients, transition curves and superelevation.

2.2 Substructure

The substructure consists of 900mm diameter bored piles in Kenny Hill formation or 300mm diameter micropiles in limestone formation with cast insitu pilecaps and columns. Generally the crossheads are precast and secured to the column with a prestressed bar connection.

2.3 Superstructure

The design of the superstructure is based on individually precast post-tensioned beams that are erected and stitched together with insitu concrete joints and continuity post-tensioning to form continuous frames of beams consisting of between two and five spans (Fig. 2).

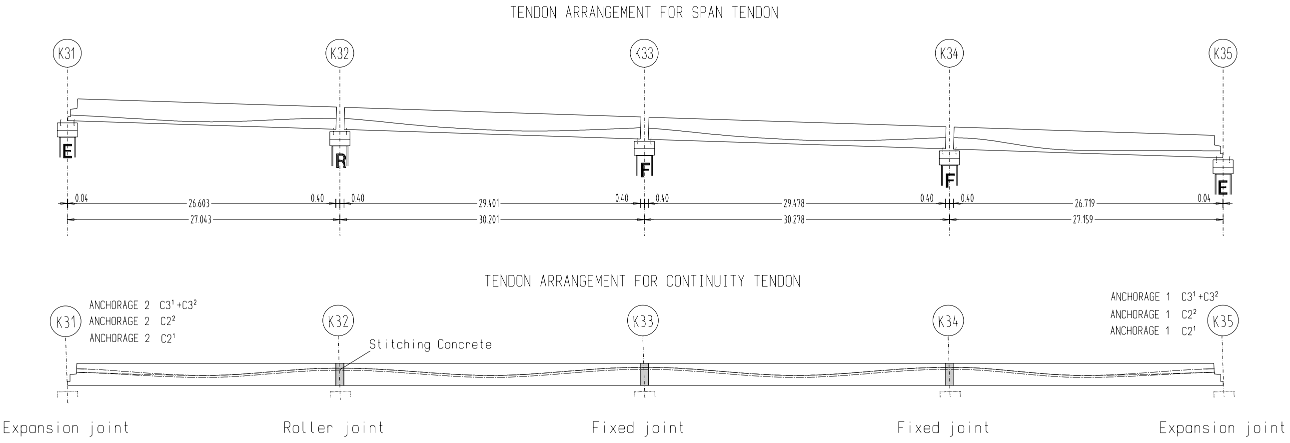

Fig. 2: Span & continuity post-tensioning arrangement

Given that the alignment of the beams is so variable with multiple span combinations each frame is considered unique, and must be modelled and analysed individually.

Generally, spans are around 30m, however due to various obstructions such as junctions, buried utilities and drainage, as well as other structures such as stations and switches, the spans vary between 12m and 44m.

3. Alternative Design Concept

The design of the KL Monorail Guideway Beams was carried out based upon an Alternative Design.

Different contractors submitted their bid for the construction of KL Monorail Guideway Beams. Genesis Structural Systems Sdn Bhd (GSS) teamed up with Köhler & Seitz Engineering Services S/B to submit a proposal and establish an estimated construction cost. All existing information, which had been produced by earlier parties, was evaluated/checked and then K+S provided GSS with a guaranteed Bill of Quantities to price. As a result, the bid by GSS was the lowest and GSS was awarded with the Design & Construct package for KL Monorail Guideway Beam. The early creation of a close working relationship between contractor and consultant prior to contract award enabled a competitive proposal to be made.

4. Detail Design of KLM Guideway System

4.1 Establish Design Criteria

The KLM is very different from many civil engineering projects since there are so many influencing factors on the design. Therefore it is fundamental to establish a full set of design criteria and then document them prior to commencing design activities. These factors include:

a) vehicle loading;

b) vehicle rideability;
c) other system requirements such as E&M inserts for signalling, communications and traction power;
d) local authority requirements;
e) codes of practices and standards; and
f) construction methods and operational requirements such as casting cycle times, transport, lifting and erection systems, prestressing systems and other material specifications.

The preparation of such a design criteria document requires the input from many parties including, client, end users, system supplier, various construction teams as well as perhaps those with previous experience through research and further study.

4.2 Detailed Analysis and Design

The difficult aspect of Monorail design is that the whole structure is completely three dimensional with loadings applied in more than one direction or plane. As well as the vertical axle loads there are lateral centrifugal forces, hunting forces, wind loads on train and structure, longitudinal braking and traction forces, as well as the typical thermal, creep and shrinkage forces associated with prestressed concrete design.

With such an array of loadings to apply to more than eighty unique frames, the selection of a software package(s) which could model all of these criteria together with the soil interaction from the fixed piers within the portal frame type structure, was crucial. The software “Sofistik” was used which allowed all of the forces to be applied to each three dimensional frame model, including an auto loader to simulate the moving train.

The software also provided all the necessary details for the prestressing design including post-tensioning forces, losses and expected tendon extensions. The design required a time dependent analysis for the creep and shrinkage effects since the construction method required several stages of prestressing at different phases of the construction, as well as different support conditions during lifting, storage, transportation and placement. The software was able to provide all this and allowed the input for each frame to be entered using various template formats to make the whole analysis process more efficient.

4.3 Preparation of Detailed Construction Drawings

Shop-drawings should be prepared by the Consultant/Designer since they are in the best position and understanding of critical construction details.

Ambiguities, misunderstandings and confusion during the construction execution are eliminated via fully descriptive shop drawings to enhance to overall construction quality. More important, detailed shop-drawings help to avoid cost overruns. Any design related problems encountered during the construction process are extremely costly and delay the project completion.

5. Construction of KLM Guideway System

5.1 Methodology and Buildability

It is paramount that the construction methodology be thought out at the onset of any project and continuously throughout the duration of the project particularly as new and different situations and locations present themselves. With a wide variety of span combinations and alignment geometry shared with differing topography on site, the methods of construction were required to be flexible enough to suit the stringent requirements of the permanent works design. However, it was also necessary for the permanent works to be tailored to suit the methodology in some cases.

5.2 Special requirements for precasting

5.2.1 Concrete Technology

The design of the guideway beams called for grade 60MPa concrete. The immediate focus was on developing a concrete mix having minimum cement content in order to reduce the hydration temperature during curing. Based upon experience in Germany, a target cement content of 420kg/m3 Ordinary Portland Cement was envisaged. Extensive testing, including more than fifty trial mixes, were undertaken to develop a concrete mix design capable of meeting the necessary durability, workability and strength requirements.

Addition of fly-ash was one of the options studied to reduce the hydration temperature. However, fly-ash proved not suitable as a high early strength of 28Mpa at 18 hours or sooner is required in order to apply first stage prestressing which then facilitates the lifting and removal of the beam from the mould within 24 hours from pouring concrete, subsequently reducing cycle times.

A mix with 420kg/m3 Ordinary Portland Cement provided the required strength characteristics yet was unable to provide the required workability of around 160mm slump. Various different mix designs with different aggregate sources, particularly sand, as well as different superplasticising additives from different suppliers were tested.

Finally, a concrete mix using 460kg/m3 Ordinary Portland Cement with a new type of superplasticiser called "Kao Mighty", proved to be the best solution to the strength and workability needs.

In regards to curing, the concrete beams were wrapped in plastic to contain the humidity and were shaded from sunlight to reduce external heating. Curing by water was not advised as it creates a high differential temperature between outer surface and beam core, which might cause micro-cracks at a later stage.

5.2.2 Mould Setting Data

Developing a mould system and a method of converting the alignment design into a series of mould setting information was one of the major technical challenges of KLM.

The first step by K+S was to model three-dimensionally different shapes of guideway beams to get a better understanding about the beam geometry and to be able to check mathematical calculations later on.

The alignment design uses various combinations of straights, curves and spiral transitions. Similar to the design of highways and railways the following parameters are used:

- Gradients (max. 5%)
- Vertical & horizontal curves (min. RV = 1500m & min. RH = 67m)
- Spiral transitions (min. length = 15m)
- Superelevation (max. 12%)

This results in warped concrete surfaces, which need to be properly represented by the formwork skin.

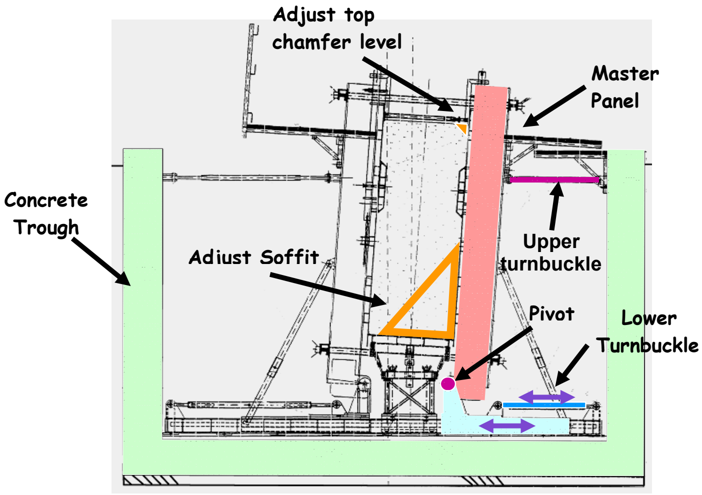

Fig. 3: Configuration of Beam Formwork System

The formwork used to cast the beams facilitates the following major functions as shown in Figure 3. After understanding the mechanics of the formwork, it became necessary to find the most practical and simple way in adjusting the formwork to produce the required beam geometry. By adjusting upper and lower turnbuckles - jacks 1 & 2 respectively - the required beam geometry could be achieved.

The warped beam surface is produced by tilting of the cross-section in accordance to the required superelevation each jack position. The angles at each corner shall always be 90° as required by the train manufacturer's system specifications (Fig. 4).

K+S provided mould setting data for each and every jack to achieve the beam geometry in a most accurate manner. It needs to be noted that the beams are cast in an “optimized” position which may differ substantially from the final position on site to minimize mould adjustment work and to facilitate the concreting process.

The flexible moulds are surveyed using the latest precise total station instruments and then adjusted to the high degree of accuracy required to achieve the stringent surface tolerance requirements for the final ride comfort.

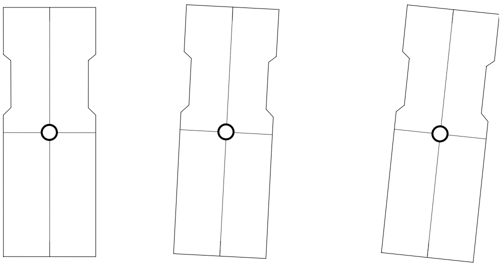

Fig. 4: Tilting of cross-sections at different jack positions

5.3 Specialist Equipment

The beam transport, lifting, stabilising and adjustment methods for this project are probably what make the KLM stand apart from other Monorail projects. The longer spans, tighter radii (68m on mainline) and continuous span arrangements required extensive design and development of the temporary works equipment necessary.

The curvature of the beams presents the obvious problem of managing a displaced centre of gravity at every stage of construction, from lifting the beams from the mould to storage in the casting yard, to maintaining their stability during transport and subsequent placement on the crosshead supports. This can only be done by studying the location and conditions of the supports, which vary for all these situations and are further complicated by the different curvatures and superelevations that occur on transition beams.

5.3.1 Lifting Beams from Mould

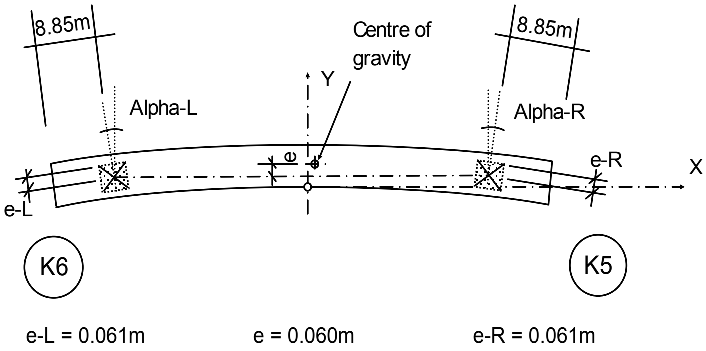

Fig. 5: The centres of gravity, lifting positions and estimated eccentricities are calculated and supplied

Special lifting brackets were utilised in the casting yard that could be preset to counter balance the offset centre of gravity. The amount of adjustment and subsequent torsional forces in bracket and beam were reduced by moving the lifting positions in from either end. These positions were shown on the detailed shop drawings, having previously been calculated (Fig. 5). This also had the effect of reducing the sagging moments during early stage lifting. These identified positions were also used for supporting the beams during storage and transport.

5.3.2 Beam Transport

With beams typically weighing anything from 35 tonnes to 185 tonnes and up to 44m in length the selection of the equipment to be used and its configuration must also be worked out with specialist consultants and equipment suppliers. Multi-axle hydraulic platform transporters were used.

5.3.3 Beam Lifting

The heavy lifting operations played a significant role in shaping the success of the KLM. The logistical constraints of working in the city with the many tight roads, sidewalks, trees and street furniture as well as the buried utilities was a fundamental part of the equipment selection and lift planning. Generally, two telescopic mobile cranes were used in tandem lifting to place the beams. A combination of 160 tonnes and 300 tonnes capacity were used with some other cranes used from time to time including a massive 350t Manitowoc 4100 Ringer crane to place beams over the River Klang.

Fig. 6:Lifting bracket

As with the transportation, the interface between crane and beam was another vital element to the success and safety of the operation. This lifting bracket had to cope with the offset centre of gravity at a lifting position that will be accessible from the crosshead such that it could be removed after placing. The bracket was also designed to adjust for the centre of gravity and tilt the beam to the correct superelevation whilst still hanging from the crane hook. A basic operational requirement was that the bracket must be quick and easy to install and remove to enable two beams to be erected within the 11.00pm to 6.00am road closure time window.

In order to satisfy these criteria the bracket incorporated hydraulics to adjust the lifting sling position on the bracket whilst still maintaining full load (Figure 6). Sufficient range of adjustment had to be provided for all variations of beam. The specialist designer worked closely with the fabricator to detail available materials and practical welding details, together with the hydraulics supplier and operations team for this safety critical piece of equipment.

5.3.4 Beam Stability and adjustment

After lifting the beam into position the beam must be stabilised and made secure until final adjustment. A unique stability system was developed to clamp the beams firmly in position yet act as a guide during placing and facilitate precise adjustment to the final alignment position within tolerances of a few millimetres (Fig. 7).

Fig 7: Beam Stability System

6. Conclusion

Some of the achievements made on the Kuala Lumpur Monorail Guideway Beam construction were only made possible through teamwork and determination to develop new systems and methods of construction not previously used before.

Many of the systems including precasting moulds, transport, lifting and stability temporary works equipment were developed specifically for KLM and many aspects are unique. The study and advancement in the temporary works technology for this project has been at the heart of the success of the KLM guideway construction.