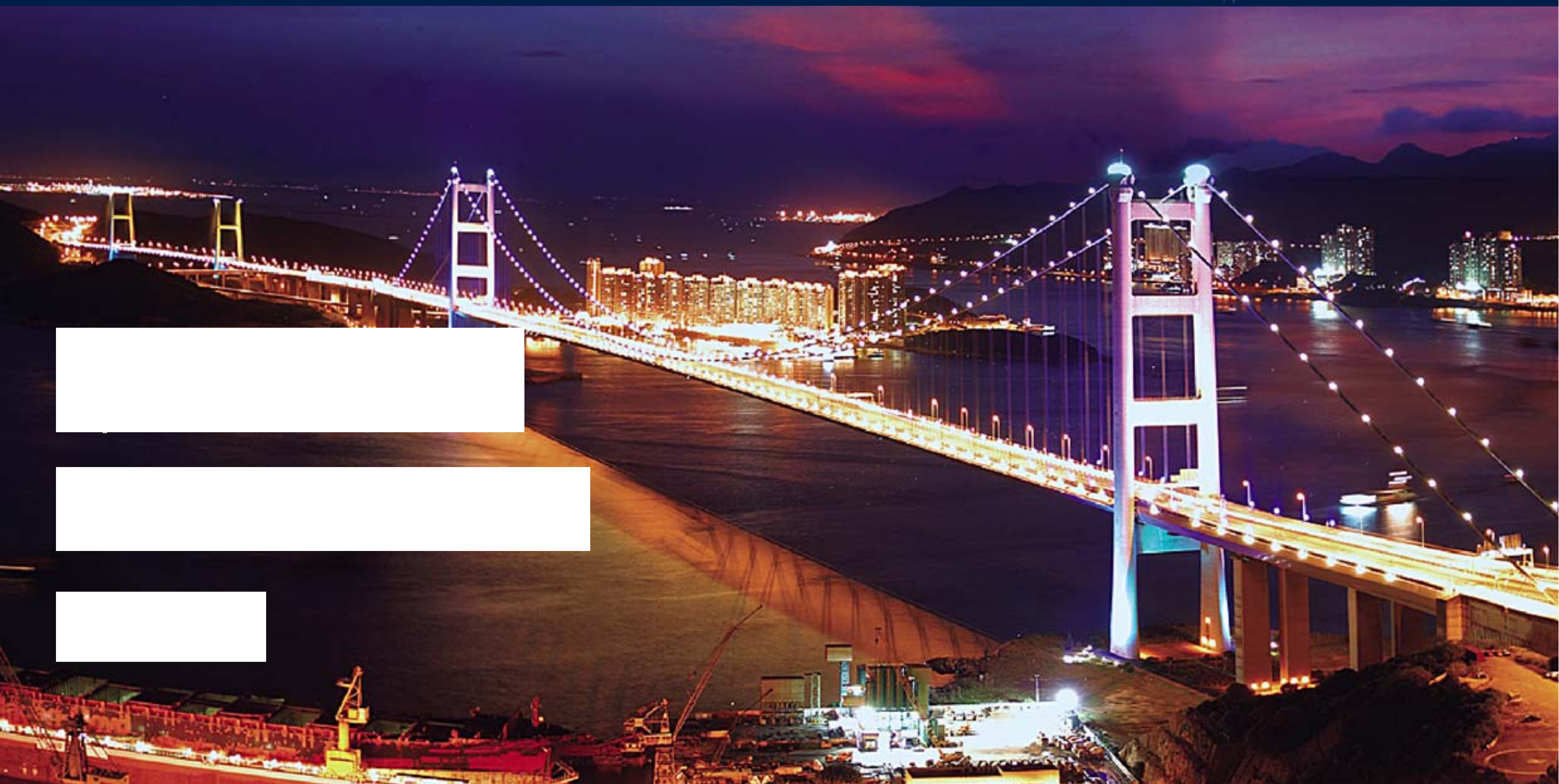
International Conference on

BRIDGE ENGINEERING

– Challenges in the 21st Century

1 - 3 November 2006, HONG KONG

Welcome Messages | Committees | Full Papers | Acknowledgements



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BACK

Oral Presentations

Session 4A
Maintenance & Management

Research and Practice of Health Monitoring For Major Bridges in The Mainland of China
OU Jin Ping

Measurement of Bridge Cable Forces and Dynamic Displacement Using Digital Camcorder
JI Yun Feng

Evaluating the Cable Forces in Cable Supported Bridges Using the Ambient Vibration Method
Andreas ANDERSSON

Experimental Investigation of Damping in Cracked Concrete Beams Usable in Bridges (Beam-Slab)
Alireza GHARIGHORAN

Geometry Control of Ching Chau (Min Jiang) Bridge Under Construction Stage
MAK Yu Man

Static and Dynamic Load Testing of the New Svinesund Arch Bridge
Raid KAROUMI

Session 4B
Design

Twin Off-Set Pylons Cable-Stayed Bridge in Ningbo
James PENNY

The Design and Analysis of Twin Skewed Arch Bridges for Castle Peak Road, Hong Kong
Anthony M R PEARSON

An Analytical Study on the Mechanical Characteristic of Joint System in Prestressed Composite Truss Bridge
Natsuko KUDO

Confining Steel Design of Bridge Columns based on Ductility Demand for Earthquake Load
LEE Jae Hoon

Comparative Study on Ultimate Strength of Super Long-Span Self-Anchored and Partially Earth-Anchored Cable-Stayed Bridges
Masatsugu NAGAI

Recent Developments and Some Technical Issues about Precast Segmental Construction in China
XU Dong

BACK

BACK

THE DESIGN AND ANALYSIS OF TWIN SKEWED ARCH BRIDGES FOR CASTLE PEAK ROAD, HONG KONG

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Summary

Castle Peak Road is a major distributor road in Hong Kong currently undergoing a major upgrade to a dual 2 lane road with improved alignment. The improvement design included many viaduct structures to enable the improved alignment to cross the numerous gullies and defiles along the route. One of these crossings was originally proposed as a twin two span, 55 m long structures crossing a steep sided gulley. A value engineering exercise identified that the substitution of these bridges with a reinforced earth structure, with imbedded arch bridges to span approximately 28 m across the gulley at low level, would provide benefits to the construction programme as well as cost savings.

Due to the terrain and founding conditions, the arch bridge foundations were required to be on a skew of approximately 45 degrees. Because of the skew, and to suit the terrain in the gulley, the bridge was split into two separate structures (for north and south bound carriageways) similar to the conforming design, and each structure was designed with stepped foundations. The stepped foundations also suited the complex founding conditions. Each arch structure was designed as a curved concrete slab.

The paper describes the design and analysis of the bridges, including the two computer model analyses of the arches which were carried out. Initially, a grillage analysis was used to model each arch (with a Wood Armer transformation of the bending moments and torsions carried out). The grillage model showed large torsion effects at the arch slab internal corners formed by the stepped foundations. To verify the results of the grillage a further finite element analysis of the critical arch was carried out. Some analysis results and comparisons are presented. Generally, acceptable correlation was obtained between the load effects from each model, with some differences at the arch discontinuities; which are considered to be a result of the grillage discretisation and hence concentration of load effects.

The arches and the RE Wall embankment are now in service and performing well.

Keywords
Arch, Bridge, Skew, Reinforced Concrete, Alternative

1. Introduction

Castle Peak Road is one of the longest roads in Hong Kong and a main distributor carrying traffic from the Kowloon peninsular to the North-West New Territories. From Tsuen Wan to Tuen Mun a further arterial road, the Tuen Mun Road, carries main through traffic but the Castle Peak Road serves both as a distributor for local traffic and as an overflow route for the extremely busy and often congested Tuen Mun Road.

The section of Castle Peak Road from Tsuen Wan to Siu Lam was an undivided two lane (two way) road with a poor alignment dictated by the historic alignment and the topography of the route; very close to the sea, with rocky outcrops interspersed by sandy beaches, and crossed by a large number of stream courses. Due to the increase in traffic demand this section of the road was required to be improved and the Highways Department, Hong Kong awarded a number of phased upgrading works contracts.

Phase 3 of the upgrading works, between Ting Kau and Sham Tseng was awarded to China State Construction Engineering (Hong Kong) Ltd {China State}. The design of the upgrading included the construction of a dual (four lane) carriageway on a much improved alignment with a number of improved junctions and pedestrian facilities. Because of the terrain crossed by the road, the improved alignment required the construction of a number bridges and viaducts and extensive retaining walls and earthworks. Due to the difficulties of transporting materials, and construction over the topography, most of the bridges were designed as precast prestressed concrete beams with concrete slab decks.

See Figures 1 and 2 below for a general layout of the conforming contract design.

On award, the Contractor held a number of Value Management and Value Engineering sessions to identify possible solutions to project risk areas. A number of opportunities were identified and one of these was the replacement of the twin beam and slab bridges, EO1B, at Ting Kau with smaller arch bridges supporting reinforced earth embankments to form the road. The originally proposed bridges had an overall length of approximately 55 metres, whereas the arches span approximately 28 metres.

This paper describes the design and analysis of these arch bridges, and the embankment above them.

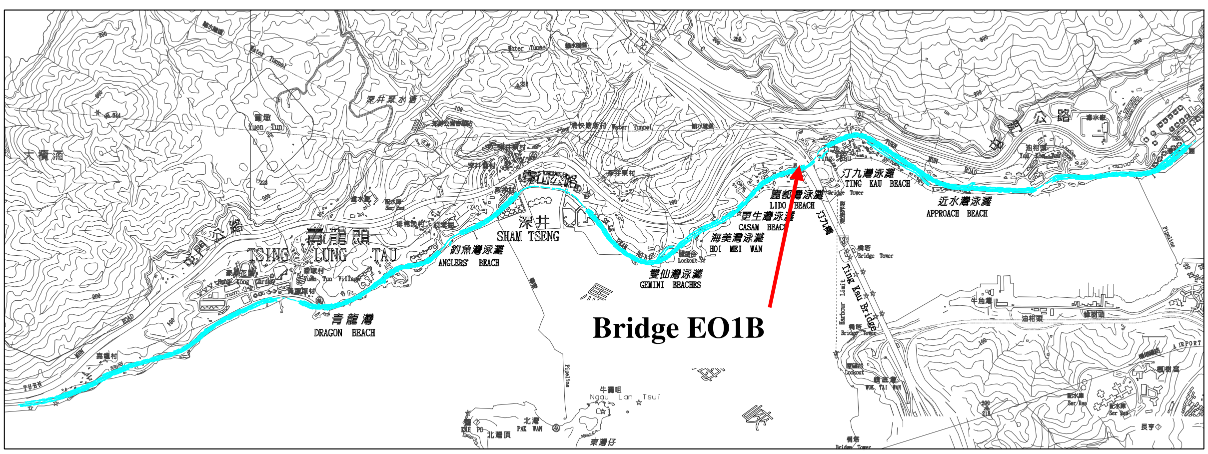


Figure 1: Castle Peak Road Improvement

2. Arch Bridge Design and Analysis

2.1 The Value Engineering Proposition

The conforming design bridges were twin two span precast beam and slab bridges with central supporting piers and cross heads. They are skew as shown in Figure 3. Each bridge carries two lanes of vehicular traffic and a footpath and has a width of approximately 10.8 metres. The bridges cross a steep sided gully which carries a high surface water runoff during the rainy season. The alignment of the road is also constrained by the piers of the Ting Kau Bridge approach viaduct, which crosses Castle Peak road at this location. A further constraint to construction was the requirement that Castle Peak Road be kept open at all times with only limited lane closures with contra-flow controlled by flagmen or traffic lights. As may be seen from Figure 2, the new bridges abut very closely to the existing old alignment of the road and an existing access road, making access to the bridge construction work site, and space for material storage etc, extremely limited and hence imposing severe constraints to the construction.

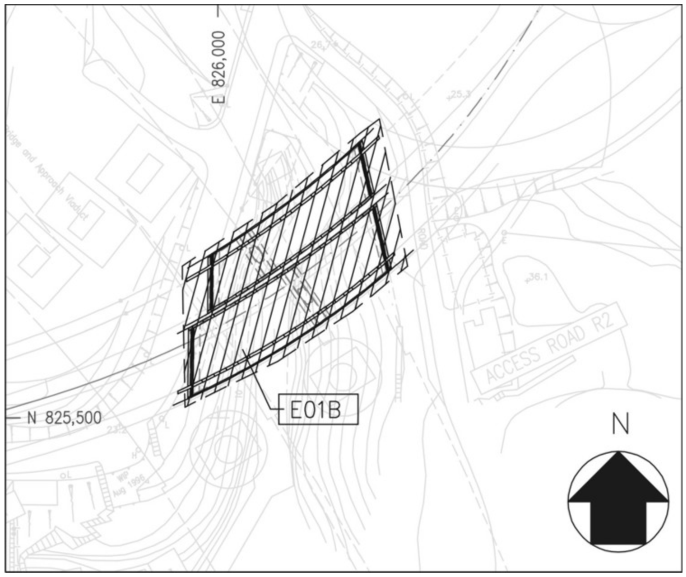


Figure 2: Bridge E01B Location

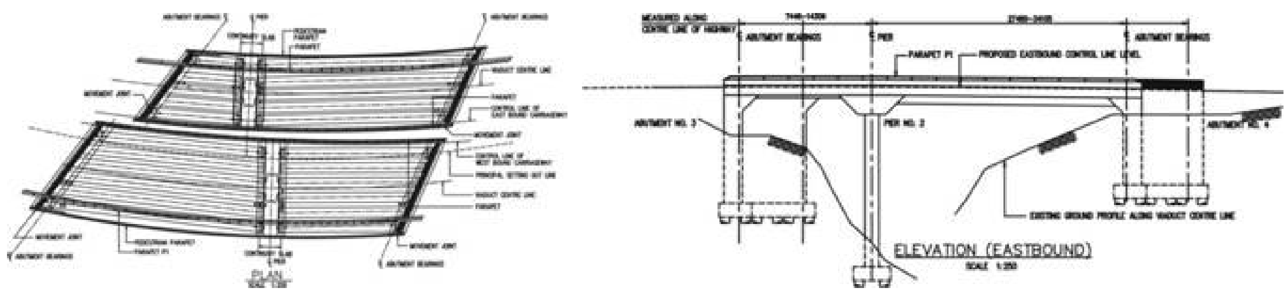


Figure 3: Conforming Bridge Design

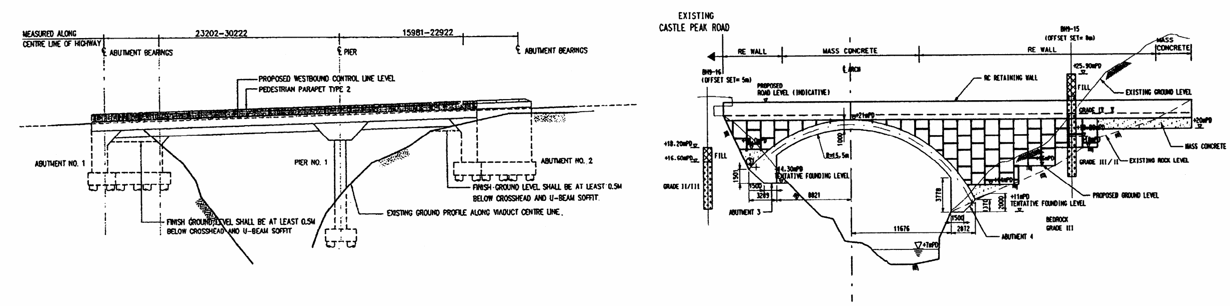
Due to the above constraints, and especially the traffic considerations, it was considered that a non-bridge solution for the gulley crossing would provide advantages in programme risk mitigation. However, as the gulley carries a high stream flow in the wet season some form of bridging was required. Hence the requirement for the arches spanning the gully, at a lower level than the road carriageway but at a level which is able to pass the maximum probable stream flow in the gulley.

The advantages of this scheme were assessed as follows:

- limited disruption to Castle Peak Road traffic during the construction of the arch bridges, as they are completely "off line" and require only limited material delivery, laydown and storage areas as compared to the conforming design,
- limited disruption to Castle Peak Road traffic during construction of the reinforced earth embankment as the materials could be delivered in batches to suit the construction progress,

- improved programme certainty, due to the “off line” construction being little affected by the road conditions on Castle peak Road,
- An overall cost saving to the contract.

A comparison of the conforming design and the alternative is shown in Figure 4 below.



Conforming Design Alternative Design

Figure 4 Comparison of Designs

The alternative bridge concept, together with other value engineering designs, was presented to the Highways Department and the Engineer for their review and agreement at the early stages of the contract. After discussion and minor amendments the concept was accepted by all parties and, together with other value engineering designs, formed part of a Supplemental Agreement to the Works Contract.

2.2 Preliminary Arch and Embankment Design

At the initial stages of the alternative bridge preliminary design it was decided to adopt the conforming road alignment and the conforming road cross section. This decision avoided complications with tie-ins to other sections of the road widening. Whilst simplifying the design of the road this caused some complications for the design of the bridges as the line of the gully is at a skew to the road alignment. Hence the alternative bridges either had to be skew or of a much larger span. The topography of the gully indicated that two structures (one for each carriageway, similar to the conforming design) and also skew structures would be preferable.

Site investigations were based on the limited site investigation carried out for the conforming contract design, additional bore holes, trial pits and trenches, rock mapping and a visual inspection of the site. These investigations indicated that sound rock would be available at shallow depth. The bedrock generally comprises moderately strong to strong, moderately to slightly decomposed granite and rhyolite. Arch structures founded on rock on the sides of the gully were therefore confirmed as being viable and cost effective. Some colluvium was encountered further up the gully slope, and the preliminary design allowed for this to be removed so that the reinforced earth wall embankment could sit on uniformly hard bearing; being either the underlying rock or the arch bridges.

To minimise the arch spans and maximise the cheaper embankment fill, the arches should be as close to the bottom of the gully as possible. But the arches, and embankment above, should also not form an obstruction to the storm water flow in the gully. Hence calculations determined the maximum probable height of storm water flow in the gully. These calculations took into account the afflux from the existing Ting Kau Bridge piers adjacent to the proposed arch bridges. Detailed computer simulation was carried out using the HEC-RAS computer program. The arch foundation levels were set above the estimated maximum water levels.

Environmental impact was another consideration of the designs; and a study determined that the effect of the alternative arch and embankment construction would impose no greater effect than the conforming contract design.

The skew nature of the arches posed a problem to the structural design, with possible large torsion moments at the skew corners, similar to a flat skew slab but complicated by the compression action of the arch. The skew could also cause a diagonal line of thrust in the arch and uplift at the acute corners. Any uplift would be unacceptable, as would any over-concentration of arch compression into a small area of the springings rather than along the whole width of the arch. These potential problems were avoided by designing the skew to be made up, conceptually, of a number of parallel arch strips of different lengths and different springing points. These strips are coincident in elevation with the springing for each strip stepping up the side of the gully to follow the gully topography. The skew is then made in discrete steps. The stepped nature of the arches is illustrated by the plan and sections shown in Figures 5, 6 and 7 below, and also in the structural model shown in Figure 9.

The arches are designed as fixed at the springings. This then requires them to be reinforced rather than plain concrete. It was considered that reinforcement would be required for the discontinuities at the springing steps in any case, and hence a relatively more complicated concrete pin (which would also have had a potentially greater maintenance burden) was avoided.

The curve of the arch was designed to provide a reasonable span to rise but the span-to-rise varies greatly within each structure due to the skew arrangement - see Figure 5, 6 and 7 below. In all cases the arch slab was arranged so that the depth of fill over the arch crown is greater than 2.0 metres. This minimum depth allowed the arch slabs to be designed as buried concrete structures in accordance with BD 31/01 [Highways Agency, 2001]. It also allowed the parapet structure of the road embankment to pass over the slab without obstruction.

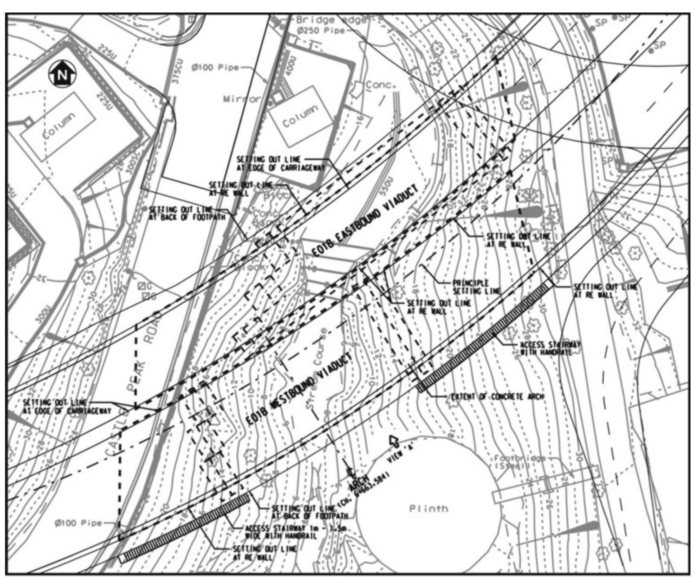


Figure 5 - Bridge EO1B Alternative Design, Plan

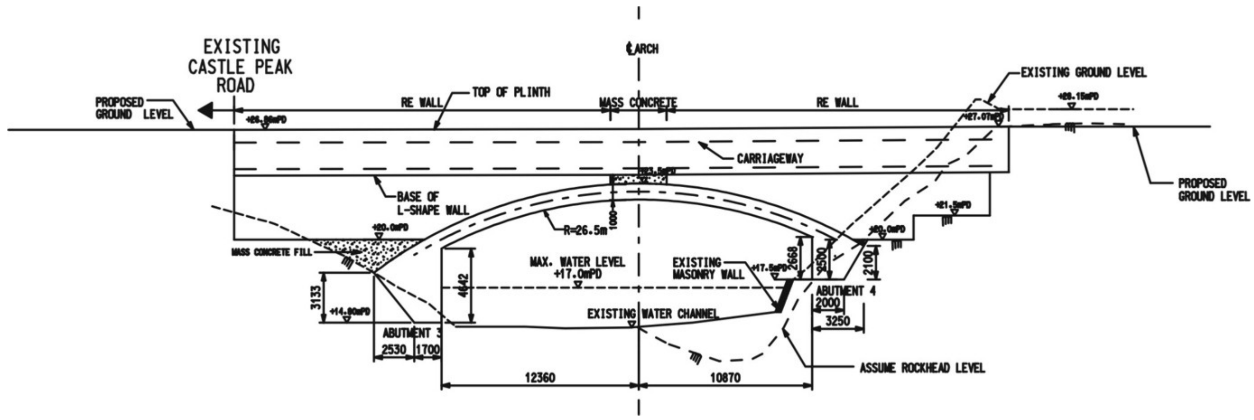


Figure 6 - Bridge EO1B Eastbound – Longitudinal section at the north kerb.

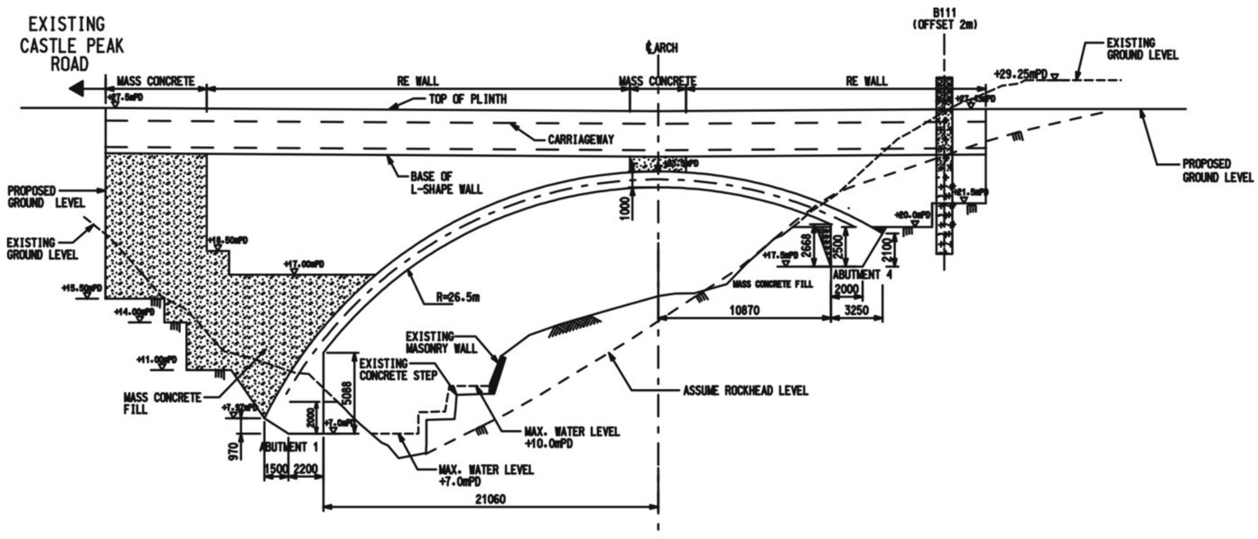


Figure 7 – Bridge EO1B Eastbound -Longitudinal Section at the south kerb

Preliminary analysis determined that an arch slab depth of 1 metre would be suitable. A circular shape was adopted for the arch profile. A preliminary study determined that the difference in load effects in the circular arch were insignificant when compared to the structurally preferred parabolic shape, but the Contractor preferred a circular shape to simplify the erection of centring for the arch soffit.

The arch structure foundations were thickened to provide adequate load spread to the founding rock and to accommodate the off-centre thrust of the arch load, caused by the foundation fixity, so that all parts of the foundation remained in positive compressive contact with the founding strata.

To minimise the amount of concrete to be cast in the forming of each arch slab, and to minimise the volume of reinforced earth embankment, the widths of the arches were restricted to the roadway width only; with the footpaths on each carriageway cantilevering off embedded parapet structural walls located at the top of the embankment (or on top of the arch slab at the arch crown).

The upper two metres of the embankment was not designed as a reinforced earth structure but constrained by an “L” shaped parapet wall. This portion of the embankment consisted of the road pavement and a zone for minor utilities if required. See Figure 8 below.

The reinforced earth embankment was designed in the usual manner with reinforcement strips overlapping at the carriageway centreline. The extent of the embankment mirrors closely the extent of the conforming design bridge structures.

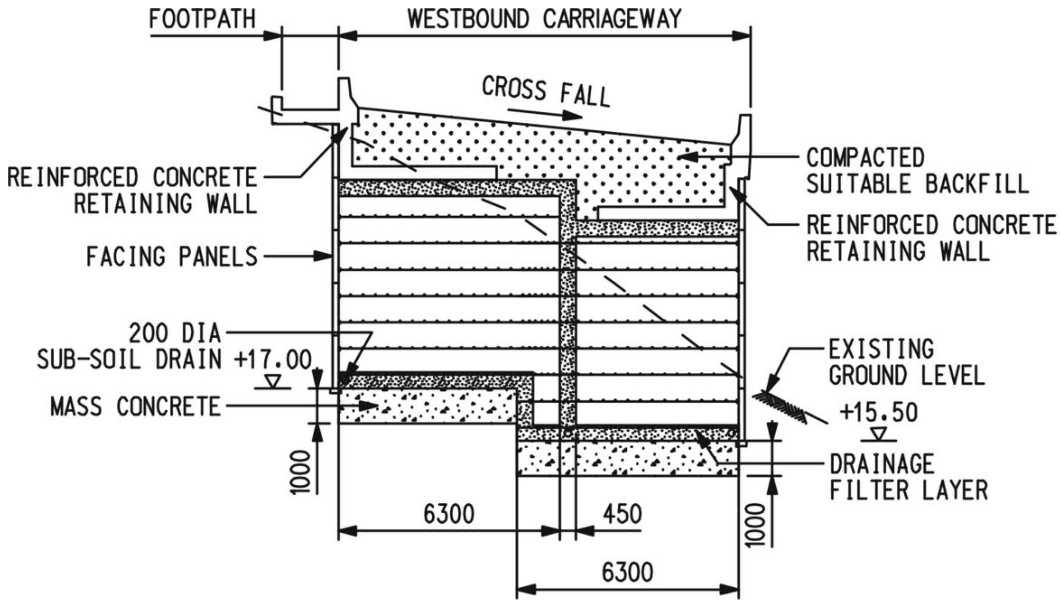


Figure 8 – Typical section of Embankment

2.3 Detailed Arch Design and Analysis

The detailed analysis of the arch structures was carried out with the aid of the SuperSTRESS computer program. This is a general stiffness matrix structural analysis program. Because of the curvature of the arch, grillage members could not be used and three dimensional beams were used to model the arch slabs using a three dimensional frame (3D frame) model. However the basic principles for the determination of the member properties were similar to those for a grillage model as explained, for instance, by Hambley [HAMBLEY, 1991].

The applied loading design for the arch structures was generally to the Structures Design Manual [Hong Kong Highways Dept, 1997] which also refers to BD 37/88 [HIGHWAYS AGENCY, 1988]. However, one difference from the usual bridge design in Hong Kong was the use of BD 31/01 [op cit]. This design standard, for the design of buried concrete box type structures, was used to apply the soil load, including surcharge horizontal loads, to the arch. The use of this standard had two main effects. The first was to allow that the structure was not subject to significant temperature loads because it was effectively buried. The second was the arrangement and combinations of load. Vertical loads and their horizontal effects are effective and act on the structure within a distance determined from the depth of overburden and the overburden soil parameters. The standard gives guidance for the distribution of traffic loads, through the embankment, to the structure. Also combinations with maximum load and load factors on one side of the arch and minimum load and load factors on the other were considered. Also the horizontal earth pressures to be applied vary from active (Ka) to at rest (Ko) pressures.

The effects of the footpath cantilever were considered by application of triangularly distributed loads transversely across the arch slab structure. Similarly, loads on individual traffic lanes were considered, and appropriately distributed through the soil embankment to determine maximum torsion in the slab.

Creep and shrinkage of the concrete of the arch was considered by use of long term Young's modulus values and the application of an equivalent temperature drop. Live load effects using short term Young's modulus values were considered in combination with both long term and short term effects of permanent loads to achieve an envelope of critical effects. The critical effects are in the long term.

Because of the skew, and to a lesser extent because of the traffic lane load distribution, the arch structures are subject to torsion. Similarly to flat slabs this torsion may be combined, with the coexistent moments in the orthogonal slab directions, following Wood and Armer [WOOD, 1968 and ARMER, 1968] to achieve a reasonable design moment. Normally the computer program will combine the tri-moments easily to output the Wood Armer design moments. However, due to the curvature of the arch structures, and because of the sharp discontinuities at the foundations steps forming the skew, the SuperSTRESS program gave somewhat spurious results at the corners of the slab. Hence the Wood Armer transformations to design moments were done manually, with reasonable assumptions being made at the boundaries.

Due to the large effects at the slab discontinuities shown in the model, increased quantities of transverse reinforcement were used in these areas to distribute the possibly localised peak values.

Shear effects were taken directly from the 3D frame model in the usual manner.

Foundation effects were taken directly from the 3D computer model and distributed to the spread footing foundations to determine bearing pressures and foundation thickening reinforcement.

A summary of critical effects is shown in Table 1, below.

Load Case	Location	Torsion (Mxy) kNm/m	Wood Armer Moment * (Mx) kNm/m	Maximum Compression (Nx) kN/m
Critical ULS Combination	Springing A	1130	6770	9010
	Crown	60	1370	5740
	Springing B	10	2500	6000

* Transformed Wood Armer Moment

Table 1 – Summary of Critical Effects

2.4 Arch Finite Element Analysis

Because of the high torsions and moments in members at the discontinuities in the arch slabs, and the inability of the SuperSTRESS program to automatically calculate Wood Armer moment transformations, an independent check of the grillage results, using a finite element (FE) computer model was also prepared for the east bound arch. The arch was modelled with shell elements. The computer program used, LUSAS, allowed the reasonably accurate modelling of the curvature of the arch and modelled accurately the stepped foundations and arch slab discontinuities forming the skew. See Figure 9 below.

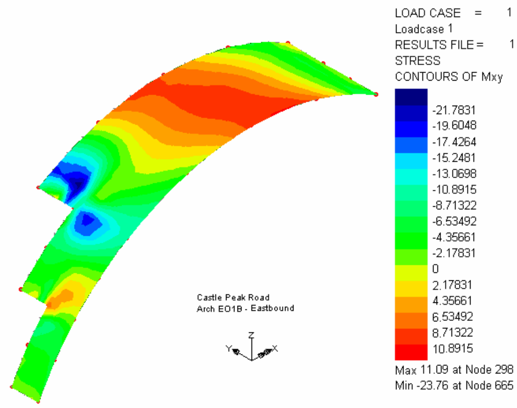


Figure 9 – Finite element Results Contours – Self Weight Torsion

Location	Model	Moment (Mx) kNm/m	Torsion (Mxy) kNm/m	Compression (Nx) kN/m
At Springing A (shortest strip)	3D Frame	650	28	1040
	Finite Element	120	25	1000
At Springing A (longest strip)	3D Frame	10	0	630
	Finite Element	50	0	300
At arch Crown (shortest strip)	3d Frame	-200	1	520
	Finite Element	-60	-10	650
At arch Crown (longest strip)	3d Frame	-100	1	754
	Finite Element	-60	-10	650
At Springing B (shortest strip)	3D Frame	430	0	550
	Finite Element	100	5	500
At Springing B (longest strip)	3D Frame	194	0	950
	Finite Element	70	0	900

Note – Moments not transformed

Table 2 – Comparison of Computer Analysis Model Results

A comparison of results, for the self weight of the arch, is given in Table 2. Note that Springing A is the discontinuous support.

The load effects from the 3D grillage frame were used to design the reinforcement in the arch slabs as they are generally more conservative.

2.5 Discussion of Comparison of Models and Results

A review of the results indicates that the 3D Frame (grillage) model appears to correlate the compression in the arch reasonably well in most areas of the structure. There is, however, a tendency for the FE model to distribute the compression, transversely, into the closest support more than the grillage model. This is to be expected given the nature of the models. The correlation of transverse moments is reasonable and both models indicate larger transverse moments at the re-entrant corners at the arch discontinuities. The torsions are the best correlated effects.

The moments in the shortest arch strip - and especially at the re-entrant corner near the join with the adjacent strip – are not particularly well correlated. It is considered that the 3D grillage frame has not modelled this area as well due to the discontinuity and that the load effects have been concentrated largely into a single grillage member. These concentrated effects have then carried over to the crown of the arch. The correlation of moments is better in the longer arch strip away from the discontinuities.

As with all FE models, care must also be taken to arrange the elements in a manner suitable to the structure being modelled. Similarly the arrangement of a 3D grillage type model and the calculation of the associated the member properties must also be carefully considered in order to accurately represent the discontinuities of structures such as these bridges.

Both the 3D grillage and the FE model highlighted the larger torsion and transverse moment effects at the discontinuities in the arch slabs. Based on the results, it is considered that either the 3D frame model or the FE model is acceptable for modelling structures such as these – provided that care is taken with the modelling of the discontinuities and with the transformation of the moments and torsions to design moments. Grillage type models should be constructed so that arrangement and spacing of the members can represent the transverse flow of load from continuing strips to discontinued strips reasonably accurately.

For simple structures such as these arches, an FE model is easy to set up and reasonably easy to use. However load application and combinations take a similar effort to a 3D grillage frame model. The results of the FE model, for this simple structure were relatively easy to interpret. The 3D frame model required a lot of calculation of member properties and, subsequent to analysis, calculation of the Wood Armer transformations. The 3D model required interpretation at the discontinuities and adjacent supports. Therefore it is recommended that an FE model be considered for the analysis of similar structures.

3.0 Construction and Use

Both the arch bridges have now been constructed and the carriageways are open to traffic.

During construction some small modifications were made to the designs to amend the foundation locations – and hence the arch steps. Also it was found more cost and programme effective to cast low grade concrete in the lower portions of the embankment, rather than have relatively short areas of reinforced earth embankment. The bridges were constructed with very little disruption to the existing traffic on Castle Peak Road and hence one of the major benefits of the alternative design was achieved.

Both bridges, and their associated embankments etc, appear to be performing very well in service. Figure 10 shows an elevation of the westbound arch with the eastbound arch partly visible behind. The piers in the foreground, on the right of the picture, and to the rear of the arches are supports for the Ting Kau Bridge approach viaduct.

4.0 Conclusions

Both the 3D frame model and the FE models appeared to model the stepped, skewed arches effectively and give results which are applicable for the designs. The output of the 3D grillage frame model required manual manipulation to calculate the required design moments from the bi-polar moments and torsions. The correlation between the 3D frame model and the FE model was generally acceptable and suggests that FE models may be useful tools for analysis of similar structures.

Both 3D frame and FE models highlighted the large moment and torsion effects at the arch slab discontinuities which form the skew.

The step foundations combined with the discontinuous arch strips appears to be a suitable design arrangement to achieve a skewed arch. The alternative design provided positive benefits to the contract in terms of programme and cost.

5.0 Acknowledgements

The author wishes to acknowledge the Hong Kong Government Highways Department, Major Works Project Management Office, and China State Construction Engineering (Hong Kong) Ltd for their kind permission to publish this paper. Thanks are also due to all the staff at Jacobs Babtie, especially Mr. Andrew Ip, who were involved in the project.

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Figure 10 - View of completed arch.

BACK