Incheon Bridge Project–The role of the Contractor's Checking Engineer

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Summary

A 12.3 km long sea crossing is currently under construction at Incheon in South Korea. At a cost of US$1.4 billion, the crossing will link the new Incheon International Airport on Yeongjong island to Songdo (New City) and the new International Free Enterprise Zone (IFEZ) which are both currently under construction. A cable stayed bridge will cross the 625.5m wide by 74m high navigation channel leading to the Port of Incheon. With an 800m long main span, this will be the longest spanning bridge in South Korea and will form part of one of the longest sea crossings in the world. A joint venture team comprising Halcrow, Arup and local consultant Dasan was appointed by design and construct contractor Samsung Construction JV (SCJV) as the Contractor's Checking Engineer (CCE) in March 2005.

Keywords: independent design check; cable-stayed bridge; sea crossing; ship impact

1. Introduction

The Incheon Bridge, illustrated in Fig. 1, will carry six lanes of traffic across the straits between Yeongjong island and the Korean peninsula. The project is being procured by the Korea Highway Corporation (KHC) on a BOT basis. KODA Development Ltd, the AMEC led Concessionaire, in joint venture with the City of Incheon, will finance and manage the toll-bridge for 30 years before returning the project to the Korean government.

Construction of the bridge was let on a Design & Build basis and construction works began in June 2005. SCJV, a group of seven Korean construction companies are carrying out the works with design services provided by consultants Seoyeong Engineering (Korea), Chodai (Japan) and others.

Fig. 1 *Incheon Bridge*

The majority of the length of the bridge is constructed as low level viaduct structures with pretensioned precast 50m long concrete box girder spans. Where the alignment rises to cross the navigation channel, precast segmental balanced cantilever approach bridges with 145m spans link the viaducts to the cable stayed bridge which provides the 800m long navigation span itself.

The bridge is constructed over tidal flats and in up to 20m depth of water. Marine deposits overly rock strata. All of the foundations are large diameter cast in place concrete piles socketed in the weathered or soft rock strata.

Korea is in a region of moderate seismicity and the bridge is designed for a 1,000 year return period event which governs the design of the substructures. In addition the bridge can be subject to typhoon wind loading which is significant for the high level structures. In particular wind buffeting loads and aerodynamic stability has been important to the design of the cable stayed bridge.

Crossing the main navigation route into Incheon port the bridge is designed to withstand ship impacts of up to 100,000 DWT. Protection is provided in the form of sacrificial dolphin structures which are configured around the piers close to the navigation channel.

2. The role of the Contractor's Checking Engineer

The CCE's role was to perform an independent check of the permanent works (see Sections 4 to 6) to confirm that they were in accordance with the basis of design and carry out an independent review of the Temporary Works (see Section 7) as well as review a number of technical reports (see Section 8). The independent checks were deemed to be a higher order check than the independent review as only the drawings were received for the permanent works requiring a complete re-analysis of the structure with corresponding stress checks and calculations. Both drawings and calculations were received for the independent review of the temporary works which did not necessarily require any further analysis. The CCE's deliverable was to provide SCJV with two different types of check certificates required to cover the Independent Design Checks and the Independent Design Reviews. These were a Design Check Certificate (DCC) and a Design Review Certificate (DRC) accordingly.

The project organisation chart is shown in Fig. 2 below. SCJV appointed Seoyong (Korea) to design the concrete viaduct structures and Chodai (Japan) to design the cable stayed bridge with the CCE checking all permanent and temporary works. A number of other parties were also involved in the checking and approvals process after certification by the CCE. These are identified as highlighted boxes in Fig. 2 and were required as part of the normal Korean process for designing and checking infrastructure works. Feed back from these parties often resulted in changes to the drawings in order to incorporate local detailing practice or satisfy local statutory requirements. As a result, a further round of checks were normally required by the CCE before issuing SCJV with a Final Check Certificate (FCC) covering the amended drawings.

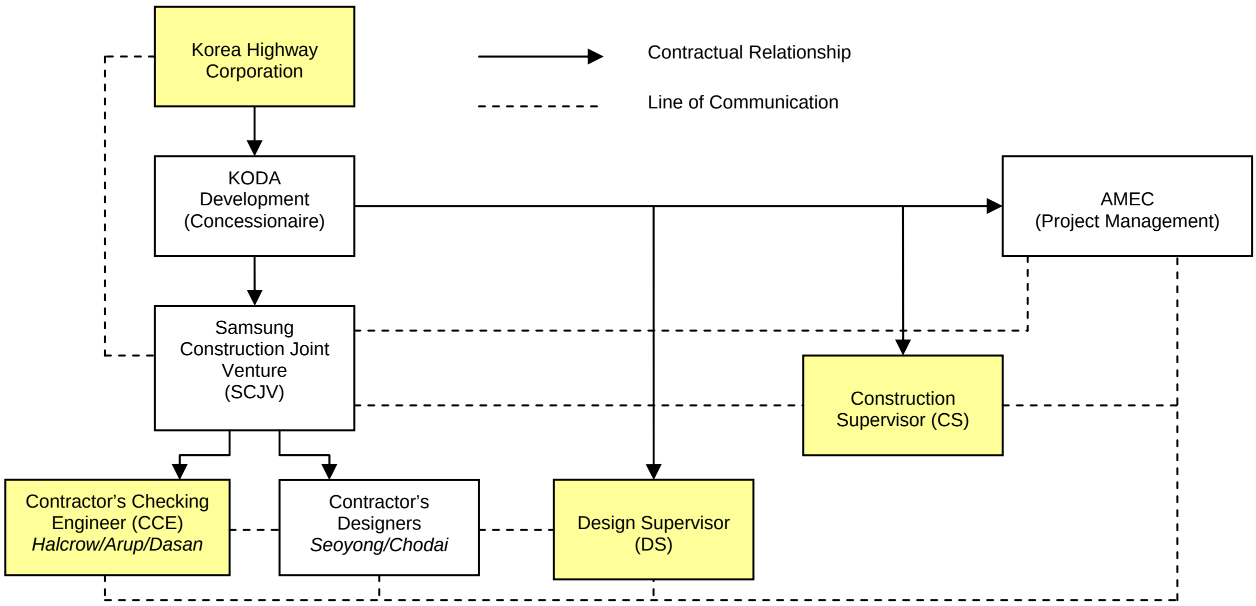

Fig. 2 *Organisation Chart*

As a fast track project, the design was prepared as a sequence of packages in accordance with the demands of the construction schedule. Managing and organising the CCE's joint venture team required communicating and coordinating with the checking teams, which were located in different offices worldwide, as and when the design packages became available. Working closely with the design team in the Incheon site office was essential for the effective delivery of design packages to the checkers and dealing with the day to day issues arising from during the procurement of the design. Halcrow, using staff based in offices in Hong Kong, Shanghai and UK, Arup, with staff based in Hong Kong and UK and Dasan having their main design office in Korea provided the CCE with an integrated design checking team with both local and international experience.

Site offices were provided by SCJV and senior representatives from Halcrow, Arup and Dasan maintained a full time presence there during the design phase of the project. A project specific management plan and quality procedures were developed to help manage the coordination of inputs from all parties and keep track of the checkers comments and the certification process.

The contract duration for the CCE's checking role was initially 2 years but this was extended in March 2007 to keep a CCE presence on site further into the construction period.

3. Basis of design

3.1 Design Standards

The design basis for the Incheon Bridge was originally set out in two key documents, the Project Performance Requirements (PPR) written by the Ministry of Construction and Transportation and the Concessionaire's Supplementary Requirements (CSR) introduced by KODA.

The PPR references the AASHTO LRFD Bridge Design Specifications as the key standard for structural design. However, in order to ensure a consistent performance with other Korean bridges the PPR also wrote out a full set of loads and load combinations which were extracted from the Korea Bridge Design Standards. The bridge had to be designed to cover both the LRFD and the PPR loading conditions although in both cases analysis, verification and detailing requirements were in accordance with LRFD. In almost all cases the PPR loads proved to be the governing design condition.

3.2 Interpretation of the Design Basis

Before award of the contract, SCJV entered into negotiations with KODA and KHC concerning interpretation of the design basis. Issues involved clarification of the design basis, interpretation of ambiguous or conflicting requirements and requests for relaxation of certain requirements which were perceived as unnecessarily onerous. The CCE took an active role in assisting with these negotiations and wrote a number of Technical Reports providing an independent opinion making reference to projects and standards from around the world.

The use of LRFD did cause some difficulties since, although the standard was already in its 3rd Edition at the time when the design basis for Incheon Bridge was being developed, the code had not, by then, been used for the detailed design of a significant number of projects. This meant that there was limited practical knowledge regarding the application and use of the code. The most difficult sections to interpret centred around the reinforcement detailing requirements for piles since these were particularly open to interpretation and considering the number of piles required could lead to significant cost implications.

A key issue was whether the piles could reasonably be designed to behave elastically during the design seismic event which would allow a reduction in the highly congested transverse reinforcement albeit at the expense of additional longitudinal reinforcement. The CCE carried out a thorough review of the implications making reference to a seismic hazard assessment independently carried out for the Seoul metropolitan area and concluded that there was sufficient conservatism in the design event and sufficient ductility in the piles with ordinary reinforcement detailing that the structures would be able to withstand a 1 in 2,500 year event without collapse if designed elastically for the nominal 1 in 1,000 year design event.

3.3 Development of the Design Manual

SCJV produced a Design Manual for the project which consolidated the requirements of the PPR and CSR and introduced further clauses as a result of their negotiations with KODA and KHC. The CCE was required to review and certify that the Design Manual complied with the PPR and CSR and that it was appropriate for the Incheon Bridge project. The review resulted in various comments being raised which were passed on to SCJV for information and action where necessary.

A number of key changes proposed by the CCE had to be introduced before the early design packages could be certified. In order to avoid delay whilst the revised Design Manual was being approved, SCJV produced a number of Design Manual Addenda as separate documents which were referenced by the check certificates. This allowed KHC approval of the relevant Design Manual Addendum and the certified drawings to be carried out in parallel. Eventually the various Addenda were incorporated into a new revision of the Design Manual.

4. Cable stayed bridge

The cable stayed bridge (Fig. 3) is a 1,480 m long structure with an 800m main span. Two planes of PPWS stay cables support a 33.4 m wide orthotropic steel box girder. The pylon is a reinforced concrete hollow section in a diamond configuration which provides torsional stability to the main span and minimises the size of foundation which must be protected from ship impacts.

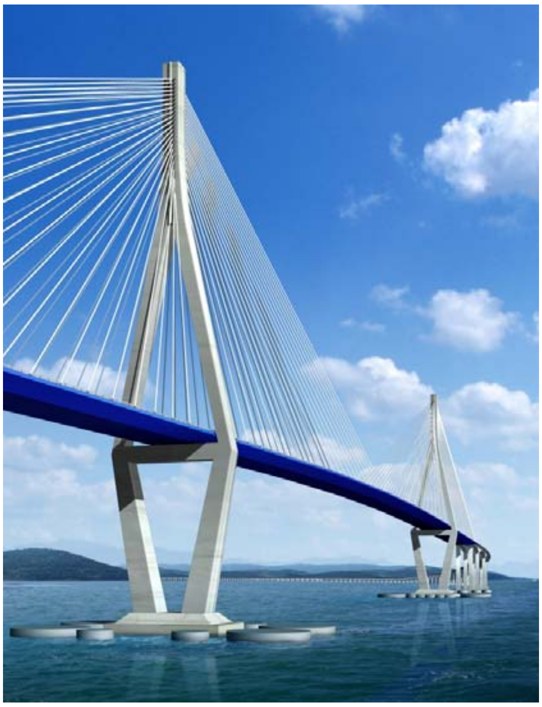

Fig. 3 *Cable Stayed Bridge*

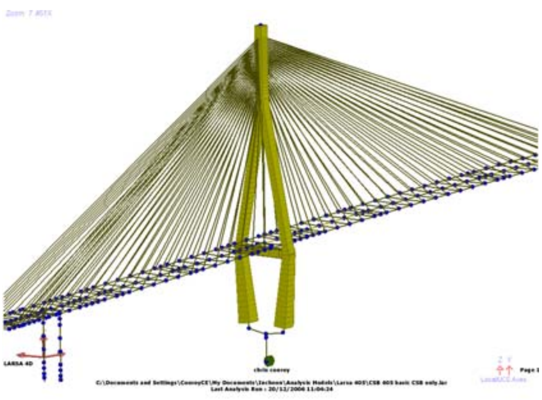

Fig. 4 *LARSA model for pylon check*

Meeting the fast track requirements of the project was particularly demanding for the cable stayed bridge. Only 12 weeks were available between the CCE starting work and the scheduled date for certification of the pylon piles.

As well as geotechnical capacity and reinforcement checks for the piles, this initial certification required review of the design basis and a full global analysis of the structure including both wind buffeting analyses carried out using *TDV* RM2000 and response spectrum seismic analyses with mode specific damping carried out using *Oasys* GSA. Furthermore the feasibility of the complete structure had to be reviewed in order to provide a reasonable degree of security that the foundation loads would not be increased as design of the pylon, deck and articulation progressed.

The CCE approached this demanding schedule by working with a high degree of interaction with the designer. Key design data was checked and agreed upon and foundation loads compared prior to production of the reinforcement drawings by the designer for checking and certification.

The analysis package LARSA was also used to check the pylon (Fig. 4) and backspan piers.

Although both the LARSA model and the RM2000 model were created using common geometry and modelling assumptions derived from the GSA model, the use of three different analysis packages operated by three different engineers provided a degree of internal checking of analysis output and allowed direct comparison of results. For example, mean wind analysis results from RM2000 could be compared with pseudo-static wind load results from GSA as a check of the application of wind load (which differs conceptually between the packages).

5. Approach bridges

Fig. 5 *Balanced cantilever construction*

The transition from the low level viaducts to the main cable stayed bridge is accommodated by the two approach bridge structures which comprise 5-span continuous concrete box girders. The twin prestressed concrete box girder superstructures are erected by the balanced cantilever method using precast segments. The pier head segments are permanently stressed down to the top of the piers to form a fully fixed or built-in connection (Fig. 5). Bridge bearings are therefore only required at the ends of the structure thus minimising future maintenance requirements. Checking and certification of the substructure was completed and construction commenced prior to checking and certification of the superstructure to ensure that a fast track construction programme could be achieved.

The non-linear structural analysis package LARSA was used to model the staged construction sequence which accounted for the time dependent effects of creep and shrinkage. Stress checks during all stages of construction were carried out and predicted camber curves were verified.

The software package REPUTE was used to model the large diameter reinforced concrete piled foundations. This package allows the non-linear analysis of pile groups in multiple soil strata.

6. Low level viaducts

The majority of the bridge is constructed as low level viaducts with 50m spans and 250m long five span bridge units. The soffit of the bridge is typically 4.5 m above H.H.W.L. and the substructure generally consists of pile bents with pile caps only adopted in deeper water. The 50m spans are pre-tensioned and precast in a single pour in the contractor's specially constructed casting yard.

Fig. 6 *Viaduct and launching gantry*

The spans are then erected using the Full Span Launching Method (FSLM). Since much of the viaduct is in shallow water and tidal flats which are inaccessible by floating cranes a self launching overhead gantry system erects the deck (Fig. 6). However, the end of the viaduct is in deeper water and so each 1,350 t precast span is lifted by floating crane onto multi-wheel transporter units which then deliver the span to the erection front. The passage of the loaded transporter units along the previously erected spans is a governing design load for parts of the superstructure.

The launching gantry was a major temporary works item which was independently checked by the CCE. In addition, the CCE provided expert advice on weld remedial works which were required during fabrication.

7. Temporary Works

The temporary works were classified in 3 categories namely, Major Temporary Works (MTW), Temporary Works (TW) and Method Statements (MS) all of which required checking to different levels. The MTW's, which were identified as temporary works that could impose significant loads on the permanent works or temporary works which represented a significant safety risk, required a complete independent design check as was required for the permanent works. These included:

- 2 kilometre long temporary access jetty for the low level viaducts
- Temporary backspan piers to support the cable stayed bridge deck during construction
- Temporary struts to prop the inclined legs of the pylon during jump forming
- Self-launching overhead gantry for viaduct construction

The TW's and the MS's required only a detailed review where both drawings and calculations were provided and these were certified accordingly.

8. Technical Reports by others for review

A number of studies were carried out by SCJV during the design development period which were independently reviewed and certified by the CCE. These included:

- Probabilistic Seismic Hazard Assessment
- Oceanographic Investigations
- Ground Investigations
- Pile Load Tests
- Wind Tunnel Testing
- Ship Impact Protection Test Programme

Each of these investigations were summarised by SCJV in a Technical Report which the CCE reviewed and certified with regard to the appropriateness of the content, methodology and general principles. Two key sets of studies are described in more detail below.

8.1 Wind Tunnel Testing

Wind tunnel testing was carried out to determine the aerodynamic force coefficients for the deck and tower and to investigate flutter and vortex shedding stability.

Sectional model tests were carried out at 1:100 scale for a variety of cross sections investigating different configurations of the leading edge and a 1:50 scale confirmatory test was carried out for the preferred cross section. The deck section was shown to be stable.

A confirmatory aeroelastic full bridge model test at 1:150 scale also showed the bridge to be aerodynamically stable. In addition an aeroelastic model test was carried out for the free standing tower which did not indicate any unacceptable aerodynamic effects.

In addition to the wind tunnel testing carried out by SCJV, a wind climate analysis was provided by KODA which confirmed that the PPR design wind speed was conservative and also recommended turbulence characteristics for use in wind buffeting analyses.

8.2 Ship Impact Protection

Ship impact protection is provided in the form of circular sheet piled dolphins filled with crushed rock and tied together with a reinforced concrete cap. The dolphins were designed to provide both deterministic and probabilistic protection, the former being to stop a 100,000 DWT design vessel travelling at 4.5 m/s directly towards the cable stayed bridge pylon and the latter being to reduce the annual collapse frequency to less than 1 in 10,000 when considering a distribution of design vessels heading towards any point on the bridge axis in any direction. The probabilistic design was carried out in accordance with the method detailed in AASHTO LRFD based on an initial ship velocity of 10 knots.

The dolphins work by dissipating energy through various mechanisms; crushing of the ships bow, local deformation of the dolphin, passive resistance of the soil and friction between ship and dolphin. A large portion of the energy dissipation comes from mobilising the passive resistance of the soil. A reliable way to estimate impact dissipation in soil structures is through testing of a physical model in a centrifuge which allows earth pressures to be correctly modelled at a reduced scale. However, due to the time and expense required for centrifugal model testing it is preferred to use the results to calibrate a non-linear finite element analysis which will then allow analysis of different configurations. This method, which had previously been adopted for Stonecutters Bridge [1], was followed for the design of the Incheon Bridge ship impact protection.

After establishing the behaviour of an individual dolphin by this method, a series of impact simulations were carried out to determine the behaviour of the dolphin configuration. These analyses were independently checked by the CCE using the Arup in house programme IMPS.

In certifying the ship impact protection, the CCE reviewed and certified all of the documents related to the test programme and impact simulations which demonstrated the stopping capacity of the dolphins. The design drawings were also checked and certified to confirm the construction details and the ability of the dolphins to withstand gravity and hydraulic loads as well as a short return period seismic event.

9. Technical Reports by Halcrow/Arup

During the design development stages a total of 29 Technical Reports were produced by Halcrow and Arup to address a number of queries raised by SCJV. These reports covered many different aspects of the design and construction from interpretation of design codes, assessing construction details, proposing changes/additions to the Design Manual, performance of cable stays etc, etc. By using the combined international knowledge and experience of Halcrow and Arup, the CCE was able to provide SCJV with reliable technical advice where necessary during this period and in particular give SCJV confidence and assurance on the quality of a number of technical proposals they submitted to their client to help procure the design and construction of Incheon Bridge.

10. Conclusion

For a bridge of this scale a full independent check including independent analysis and verification is essential for ensuring safety. However, introduction of an Independent Checking Engineer in a traditional role would inevitably lead to delay in a fast track project.

By working within the contractor’s organisation, the CCE is able to work in parallel with the design team rather than waiting until completion of the design before commencing work. This allows an interactive checking process whereby analytical results can be compared prior to production of all detailed drawings. The CCE is also able to take a proactive role providing technical advice and helping developing solutions to design problems which inevitably arise during the design process.

However, by breaking down some of the barriers of independence between designer and checker there is the risk of collaborative errors leading to failure of the checking process. However, for the Incheon Bridge project this risk is mitigated by the consultant's experience of independent checking and understanding that the risk is present. With the check teams established in different offices to the design team and a controlled approach to the exchange of information, the check has been carried out with independent thinking as well as independent analysis and verification.

The CCE is playing a vital role in ensuring the delivery of this complex project safely and on time.

Completion of construction is planned for October 2009.

11. Acknowledgement

This paper has been published with the permission of the Samsung Construction Joint Venture and KODA Development. Figures 1, 3, 5 and 6 were provided by the SCJV.

12. References

[1] LEE D.M., and PEIRIS N., “Modelling of Ship Impact on a Bridge Foundation”, *IABSE Symposium Shanghai 2004: Metropolitan Habitats and Infrastructure*, IABSE Report, Volume 88, 2004.