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Abstract

A construction project is a trade-off between cost, time, and quality. A successful project, therefore, must satisfy the following criteria: finishing on-time, on budget and based on the expected/required quality. In this report, potential problems regarding quality control (QC) in bridge construction projects are addressed and also the way in which Bridge Information Modelling (BrIM) can improve or solve the problems are discussed. We have scoped the entire design – construction life cycle (from the pre-design to commissioning). This report mostly focuses on the potential value of BrIM to address internal and external problems associated with involved parties with quality control in bridge construction phase of projects running through engineering, procurement, and construction (EPC) delivery method. The case study of a post-tensioned pre-stressed concrete slab bridge project with an EPC delivery method in which the construction QC has been subcontracted to an external consulting engineering company, is used to discuss in action and the flow of information through BrIM that can support the input and output of the quality management processes in such conditions is studied. Finally, a BrIM-based quality control system related to the construction phase of concrete slab bridge projects is proposed and its applications are discussed in detail through the case study.

Chapter 1. Introduction

Quality management is one of the most important aspects that can minimize the failure of a construction project if considers and performs properly during the design and construction phases [1]. Quality control is associated with the resources, procedures, plans, and organization that are done by design and construction professionals in their related periods of facility life cycle. Quality control by construction professional is essential for controlling the construction quality to guarantee that project is proceed based on contract documents. Quality control by design professionals is essential for controlling the quality of contract documents to guarantee their conformance with associated standards, criteria, and codes. Quality control consists of calculations, inspections, observations, documentations, and tests that guarantee the effectiveness of system and quality processes for obtaining the appropriate level of quality [2].

Quality assurance (QA) is associated with the systematic and scheduled activities that are provided by the client or its representative for defining a confidence level in which the project design documents meet the standards, appropriate codes, and also construction outcomes meet the criteria of contract documents. In fact, QA determines how much the constructor and design professional’s QC tasks are effective. The difference between QA and QC concepts is that QA is related to actions that are done by the client or its representative for assuring project quality, while QC is associated with quality control activities which should be done by construction and design professionals [2].

In the 1970s, computer product modeling was generated as a set of interacting technologies, processes, and policies that created a methodology for managing the crucial project data and building the design information during buildings life cycles via a digital format [3]. In fact, the basis of building information modelling (BIM) was established in this decade. Dr. Charles Eastman (the professor in the colleges of architecture & computing Georgia Institute of technology) defines BIM as a process involving the generation and management of digital representations of physical and functional characteristics of a facility, or it can be defined as a digital representation of the building process to facilitate exchange and interoperability of information in digital format. The same concepts in bridge construction projects is known as bridge information modelling (BrIM).

Nowadays, BrIM has become a helpful tool in bridges construction projects because it can geometrically and intelligently represent bridges due to the possibility of providing the important information that are required for bridges during their life cycles. In addition, it can be used in selecting appropriate construction approaches and planning site activities for preventing space conflicts [4].

Quality objectives in construction project have to be determined firstly by the owner as the most dominant participant of project and this is done by conducting related activities and initiatives. The owner determines the required investment to achieve the considered quality. Design and constructor professionals are responsible to provide the project design and construction QC plans and then they will be applicable if the owner approves them. In general, the owner's role in project quality purposes can be explained as:

- Determining the importance of project quality.
- Conducting QC initiatives and activities.
- Required QA/QC related investments [2].

The Resident project representative (RPR) is an entity or individual (mostly a construction manager or design professional) that is selected by the owner. The RPR's main duty is directing the construction contract but his/her responsibilities related to project quality control are as follows:

- Recording assessment and control of the quality objectives by performing the procedures determined in contract documents.
- Ensuring achievement of quality goals by implementing and managing QA functions.
- Controlling contract documentation and confirming the documents provided by design professionals.
- Confirming materials that are utilized by the contractor [2].

Typically, the construction QC can be considered in two general areas including material and workmanship in which the design professional and constructor's QC performances during construction phase of facility life cycle are considered [2].

The motivation for preparing this report is to get advantage of using BIM or BrIM for quality purposes in construction projects specifically for finding a way to decrease common problems associated with QC processes in the construction phase of concrete slab bridge projects.

The outline of this study is as follows: the first chapter as mentioned above, discusses an introduction, the second chapter explains the QC process in concrete bridge design and construction phases, the third chapter is about the application of BrIM in QC of bridge construction projects, the forth chapter investigates a case study related to the QC process of a concrete slab bridge project associated with its construction phase, and in the sixth chapter the conclusion of this report will be discussed.

Chapter 2. Quality Control Processes Associated with Design Professionals in The Design, Bidding, and Construction Stages of Construction Projects

2.1 Design Professionals' QC Activities in The Design Stages of Construction Projects

Design professionals define required QC activities associated with project design phases. The design QC plan could be submitted within the different intervals determined by the owner (e.g. after finishing a major design milestone or on a weekly basis). In general, QC plan prepared by design professionals includes [2]:

- Adequate number of personnel who have sufficient experience.
- Contacting with the owner to determine the project priorities based on the owner's benefits.
- Communication among the design team members.
- Approving field, regulatory standards, codes, and safety conditions which can impact the design.
- Plan for providing the owner's satisfaction during design activities in design phases.
- Review, coordination, and preparation of interdisciplinary design, project specifications, drawings, and cost estimates.
- Planning to perform design reviews, audits, and reporting progress for controlling the design team.
- Offering consultants in the field of design, construction, operation, and maintenance who are not involved in a daily design works and process.

Agreement about design QC plan is achieved in the pre-design phase of the project and then based on the collaboration between the owner and design professional, components of design QC plan and goals are provided.

In schematic design phase, QC activities consist of surveying design alternatives that can meet the project plan criteria. This can be done based on a collaboration between the owner and design professional, or performed in-house that should be approved by the owner.

In design development phase, QC activities comprise selecting the best cost estimations and design alternatives that completely meet the project plan criteria. The design development report provided by the design professional in this step has to be approved by the owner [2].

In general, the QC activities of design professionals in design phases can be mentioned as below [2]:

- Negotiating with the owner about design QC plan, determining components of design QC plan, and determining goals of design QC plan (related to the pre-design stage).
- Investigating design alternatives (related to the schematic design stage).
- Selecting the best cost estimations and design alternatives (related to the design development stage).

2.2 Design Professionals' QC Activities in The Contract Documentation Stage

In this step that the contractor defines the contract documents, design professionals' QC activities can be mentioned as follows [2]:

- Determining the elements that should be considered in constructor's QC plan.
- Detailed control of quantity take-offs, project drawings, and computations.
- Checking project specifications and pay items.
- Controlling project constructability.

2.3 Design Professionals' QC Activities in The Bidding Stage

There could be some uncertainties about the project during the bidding phase. Therefore, pre-bid conference in addition to visiting project site are the opportunities for bidders to get their answers about bid documents and project site conditions. Design professionals' QC activities in this step include [2]:

- Providing precise and clear information about bidding documents and conditions of the project (related to the pre-bid period).
- Answering the bidders' questions to clarify their uncertainties and mistakes associated with the bidding documents (related to bidding period before its due date).

2.4 Design Professionals' QC Activities in Construction Phase

The design professional and/or RPR could have a QA role as the owner's representatives during the construction phase. These roles include [2]:

- Controlling and confirming construction technicals and submittals.
- Visiting site.
- Answering questions from construction professionals about the specifications and plans interpretation.
- Correcting contract documents defects' and mistakes.
- Checking QC reports on a daily basis.
- Controlling test reports.
- Visual observation of the work process.
- Mock-up review and confirmation.
- Controlling tests or companion testing to approve the QC testing results.
- Documenting quality assurance activities.

2.5 Quality Control of Construction Materials

Materials can be divided to two categories [2]:

1) In situ materials.
2) Materials that should be procured.

In situ materials usually contain existent rocks and soils in construction site. For identifying appropriateness of in situ materials, engineering assessments and tests in laboratory are performed based on the contract documents [2].

Typically, qualification methods and minimum quality standards are defined in contract documents for materials that should be procured. For example, in contract documents it might be mentioned that chemical and physical tests and analysis have to be done for some materials to approve their qualities. Performing specific tests or qualifications are not required for materials that are bought with approved certifications and performance guarantees. Required information about materials QC is as follows [2]:

- Engineering assessments and required tests.
- Qualification process.
- Minimum quality standards.
- Date of test.
- Individual’s signature who performs the test.
- Test results.
- Reports related to unacceptable results.
- Location in which tests have been performed.
- Acceptable certifications and performance guarantees provided by supplier.

2.6 Constructor’s QC Plan

Providing and performing constructor’s QC plan are the responsibility of constructor if it has been determined in contract documents. This QC plan also tries to simplify the subcontractors’ communications, promote construction processes, and clarifying the project specifications and drawings. In general, constructor’s QC plan includes [2]:

- Employment and assigning of skilled crew.
- Quality control organization.
- Submittal schedule.
- Inspections.
- Sample construction, mock-ups provision and check.
- Quality control testing plan including specific inspections.
- Quality control activities documentation.
- Plan for providing corrective action when proper QC criteria are not achieved in construction.

Usually the RPR or design professional control the constructor's QC plan prior to the beginning of any construction off-site fabrication, production, and check the constructor's submittals related to their QC plans. The minimum quality level that should be obtained by constructor is mentioned in the contract documents. In general, constructor's QC roles can be determined as follows [2]:

- Taking over the QC responsibility associated with the subcontractors' material suppliers, fabricators, vendors, activities, and manufacturers.
- Considering QC issues related to the public agencies that force contractors to manage for example the dangerous and toxic materials, grant permits, disposal and storage regulations, applicable codes, etc.
- Guaranteeing the construction consistency with the project drawings and specifications by considering the quality of workmanship, functional performance, materials, finishing, sample construction, field testing and documentation, construction, inspection, reporting, resolution of non-conformances, and mock ups.

In general, the explained QC process is applicable for all bridge construction projects with a design-bid-build delivery method but it should be taken into consideration that since different types of bridges could have diverse components and construction methods, the QC items and processes could be completely different. In this report, the QC processes of a post-tensioned pre-stressed concrete slab bridge construction project (300 considered as its level of development {LOD}) is studied.

Chapter 3. Application of BrIM in QC of Bridge Construction Projects

As explained in the introduction part, bridge information modelling (BrIM) has the same concepts as BIM but it is used in the field of bridge construction projects. In this chapter the software and tools that mostly can be used directly in the different phases of bridge construction projects lifecycle, are investigated.

3.1 Bridge Information Modelling Software and Tools

3.1.1 Structural Bridge Design

- Created by Autodesk company.
- Used for implementing complete loading, analysis, code checking, and design reports of bridges with small to medium span [5].

3.1.2 Revit Extension

- Created by Autodesk company.
- Add some capabilities to Revit, Revit MEP, Revit Architecture, and Revit Structure software and to important parts such as modeling, construction documentation, interoperability, structural analysis, and reinforcement [6].

3.1.3 Tekla BIMsight

- Created by Trimble Solutions Corporation.
- Used for construction project collaboration
- Models Combining and sharing
- Conflict checking
- Using notes for communication [7].

3.1.4 InfraWorks 360

- Created by AUTODESK company.
- Can be used in preliminary design phase by providing data-rich and realistic civil structure models. This software accelerates and simplifies bridge design, focuses on the bridge girder design concepts, and provides steady context and data [8].

3.1.5 AutoCAD Civil 3D Bridge Modelling

- Created by AUTODESK company.
- Providing bridge components such as bridge piers, bearings, barriers, deck, and abutments. Can be used in bridge analysis and modeling for placement on the basis of the roadways surface and geometry. Extract string components, barriers, and girders for creating Civil 3D profiles [9].

3.1.6 SUPERLOAD Bridge Analysis

- Created by Bentley Systems company.
- Utilized in controlling suitability of routes by checking the vehicle weight/size, conditions, and roads restrictions.
- Analyzing bridge live-load in addition to considering bridge clearances and temporary restrictions to create an optimal routing possibility.
- Making models including bi-directional clearances, detailed interchange configurations, structures location, and all temporary limitations. It also can be used for analyzing route split-second of horizontal and vertical clearances [10].

3.1.7 LARS Bridge

- Created by Bentley Systems company.
- Used for streamline bridge modelling and implementing load-rating analysis on planned and existing bridges in a sequential process.
- Analyzing substructure, superstructure, designing in the single information-rich condition to create an integrated bridge model, creating comprehensive reports, 2D drawings, 3D modelling for elevations, framing plans, and sections [11].

3.1.8 LEAP Bridge Concrete

- Created by Bentley Systems company.
- Designing, load rating, and analysis for slab bridges, T-beam, reinforced, and post-tensioned concrete box girder.
- Designing, load rating, and analysis for multi-span and simple precast and pre-stressed concrete bridges.
- Designing and analysis of reinforced concrete foundations, piers, and abutments.
- Designing and analysis of spliced of bridge girders with pre-stressed/precast system [12].

3.1.9 LEAP Bridge Steel

- Created by Bentley Systems company.
- Used for intuitive interface to design, analyses, and rate steel bridges.
- Used for automatic advanced calculations to accelerate the complex bridge projects delivery.
- Used for sharing data with all MicroStation and OpenRoads applications.
- Providing an intelligent 3D model for capturing design concepts on the fly.
- Simplifying survey of the design alternatives for a better scheduling and rising of cost savings.
- Generating automatic virtual bridge models (i-models) that provides easy interacting and sharing system for the whole project team with complicated project data [13].

3.1.10 MicroStation

- Created by Bentley Systems company.
- Modelling, documenting, and visualizing every project with any complication and size.
- Can be used in design, construction, and operations phases [14].

3.1.11 RM Bridge

- Created by Bentley Systems company.
- Implementing bridge design, analysis and construction simulation to assess resiliency within natural and seismic incidences, and analyzing rolling stock.
- Providing visual processes that can create information quickly from multiple disciplines in order to make engineering decisions.
- Interoperability with OpenBridge Modeler and OpenRoads provides a visual assessment about the effects of the proposed bridge on the proposed and existing project components.
- Visualizing the magnitudes, directions, and positions of loads graphically [15].

3.1.12 OpenBridge Modeler

- Created by Bentley Systems company.
- Provides quick and iterative computational design, adjust design with the roadways, access ramps, terrain, decreases the costly construction delays with construction and traffic simulations to the lowest level, and using clash detection tools to decrease interference issues for controlling costs before construction beginning.
- Managing changes of design by considering user-defined relations between bridge referenced DGN models, built-in, and elements during the life cycle of project.
- Making complete reports associated with bridge geometry in addition to creating deck and beam seats elevations, bridge components report, quantities and cost estimating correspond with reports, providing 2D drawings and 3D models for elevations, and sections and plans framing. Complete interoperable with other Bentley's bridge analysis software and applications [16].

3.1.13 OpenRoads ConceptsStation

- Created by Bentley Systems company.
- Quick generating conceptual designs to help the decision-making process.
- Providing real world data and analysing costs in the conceptual design stage to obtain better project results.

- Providing models similar to the reality, conceptual design, and data acquisition for high risk and cost items evaluation in the preliminary design and planning project phases.
- Rapid context data provision from various sources such as 3D reality meshes, terrain data, point clouds, images, and geospatial information for creating project real world settings.
- Creating user friendly 3D models by using engineering sketching that can conceptualize bridge and road infrastructure rapidly.
- Rapid 3D layouts creation associated with project costs, sharing with project teams and stakeholders to choose the best option.
- Rapid project delivery provided by the accepted 3D model improvement in detailed design phase.
- Sharing precise visualizations with public and stakeholders for improving public engagements, making feedback, and accelerating project approvals [17].

3.1.14 Tekla Structures

- Created by Trimble Solutions Corporation.
- Providing detailed, accurate, and reliable required information in construction execution, and simpler workflow and constructible models of all complicated structures.
- Interoperability with Revit [18].

3.1.15 Tekla Civil

- Created by Trimble Solutions Corporation.
- Provides proper tools for updating plans, creating information models, combining models for 3D visualizing, easy cooperation, and communicating on the basis of the real-time and multi-user atmosphere for managing proper information during the project.
- Availability of all the correlated accurate information for all users in the way that all of the model updates and changes will be updated at the same time for all related persons in the projects who use Tekla Civil.
- Monitoring the whole project based on the all required infrastructure data.
- Using combination models for controlling the project constructability, buildings, equipment, simplifying potential problems, and conflict detection [19].

3.1.16 Sofistik Bridge Design

- Created by Sofistik company.
- Providing force optimization to frame bridges, steel bridges, and shop form computations of parametric design associated with the large span post-tensioned concrete bridges.
- Seismic simulations, wind-dynamics, and soil-structure interaction can be done with this software.
- Including Sofistik Structural Desktop (SSD) that can perform and check the computation with a graphical workflow [20].

3.1.17 CSIBridge

- Created by Computers and Structures, Inc (CSI).
- Bridge structures modeling, design, and analysis.
- Defining complicated bridge boundary conditions, load cases, and geometries.
- Parametric modelling, using known terms to bridge engineers including spans, layout lines, post-tensioning, abutments, bearings, hinges, and bents.
- Automatic updating when the definition of the bridge elements is altered by generating shell, spine, or solid object models.
- Easy and rapid retrofitting and design of concrete and steel bridges.
- Providing practical and simple Gantt charts for simulating construction steps and scheduling.
- Providing shrinkage and creep analysis, construction steps, determining forces in cable tensioning, geometric nonlinearity (P-delta and large displacements), shape and camber finding, in addition to material nonlinearity (bearings, soil supports, substructure and superstructure) dynamic, static, and buckling analysis.
- Automated load combinations, superstructure and latest seismic design based on the AASHTO LRFD bridge design specifications [21].

3.1.18 LARSA 4D BRIDGE

- Created by LARSA, Inc.
- Advanced bridge analysis with complicated inelastic or geometry properties.
- Providing Staged Construction Analysis by segmental construction methods, Inelastic analysis, analysis scenarios, and nonlinear time history analysis [22].

3.1.19 IDS Bridge Software

- Created by Interactive Design Systems company.
- Time-dependent construction simulation and geometry control.
- 2D and 3D bridge design and analysis.
- Geometry creator.
- Check geometry issues in segmental Precast bridges [23].

3.1.20 OpenBrIM

OpenBrIM can be explained as a consensus standard correspond with bridge industry for modeling, engineering data description, and interoperability for bridge structure life cycle, design, and construction management. It provides a way to exchange BIM or BrIM data through various users' application, organizations, and platforms, and can be used for defining digital record of bridge files. OpenBrIM includes materials, parameters, geometrics, sections, etc. that usually are used to describe bridge components and elements and also can cover the syntax, workflows, formatting, schema, etc. that are required for providing standard digital description. It should be taken into consideration that OpenBrIM is not a software and in fact it is completely software independent [24]. OpenBrIM properties can be mentioned as follows [24] [25] [26]:

- Adaptable, expandable, and customizable based on the stakeholder distinct needs.
- Providing modeling and development for bridge information concepts such as information in the planning, design, fabrication, construction, and operation phases.
- Used with a standard XML data format to identify data parameters such as dimensions etc. related to the required information in bridge engineering.
- Parametric objects in bridge component library are created and can be used for many times to create similar components that should have some changes in physical or geometric data.

Data can be determined globally during a project and can update all influenced objects automatically.

- Providing standards development for bridge community and determining required data for the standard bridge components.
- Providing a component standards library and uniform on-cloud data storage for bridge models. All legal users can access the bridge model data for the project and based on that there is no need to exchange file physically.
- Requires the minimum hardware resources and an online web browser. For instance, inspectors on site can use their smartphones to approve a bridge component, or during a meeting in a conference room, the rapid access to a model is possible via computers.
- Adding different languages for using standards internationally.
- Manipulating, reviewing, and building projects in OpenBrIM without having high programming knowledge or special capability for reading computer codes.
- Improving collaboration in the industry to provide new objects correlated with the developed standards based on the access that everyone can have to the bridge component standards library.

3.1.21 ADAPT-ABI

- Created by ADAPT Corporation.
- Used for conventionally or segmentally constructed pre-stressed concrete bridge design and analysis.
- Providing data for stress control and geometry through construction in addition to design values for service load.
- Providing 3D modeling and 4D time dependent analysis for concrete frames and bridges through and after the construction phase.
- Examining the impacts of recently placed concrete, shrinkage, relaxation, creep related to pre-stressing over time, and temperature changes.
- Showing shears, moments, deformations, and stresses in the different stages of construction.
- Can be used for handling precast, non pre-stressed, post-tensioned or pre-tensioned frames, and cast-in-place concrete.

- Can be used for incrementally constructed frames and bridges, concrete frames retrofit of current members, adding new members, adding new concrete, and frames demolition.
- Modelling cable stayed structures and composite construction [27].

3.2 Applicable BrIM Software and Tools Table in Bridge Construction Projects Life Cycle

As a conclusion of this chapter, the characteristics of the software mentioned above are summarized in table 1. In general, these characteristics can be categorized as follows:

- Product name.
- Product vendor or investor.
- Visualization capabilities (2D, 3D, 4D, and 5D).
- Design, modelling (i.e. professional modelling abilities), and analysis capabilities.
- Interoperability.
- Covered project phases (i.e. planning, schematic design, design development, construction documentation, construction, and operation & maintenance that have been shown in the table as P, SD, DD, CD, C, O respectively).

Note: Not available (N.A) in table 1 means that the author has not found the relevant data associated with its column title.

Product Name	Vendor or Investor	Visualiz-ation	Design, Modelling & Analysis	Interoperability	Covered project phases					
					P	SD	DD	CD	C	O & M
Structural Bridge Design	AUTODESK	2D,3D	D, A	N.A	-	-	✓	✓	-	-
Revit Extension	AUTODESK	2D,3D	M,A	Export to CAD formats, ADSK, FBX, gbXML, DWf/DWFx, ODBC, image and animation, and IFC files. Import from CAD files.	✓	✓	✓	✓	✓	-
Tekla BIMsight	Trimble Solutions	2D,3D	A	Import IFC, IFC XML, IFC ZIP, DWG, DGN, and XML files. Export to TBP, PNG files.	✓	-	-	✓	✓	-
InfraWorks 360	AUTODESK	3D	M,D,A	N.A	✓	✓	✓	-	✓	-
AutoCAD Civil 3D Bridge Modelling	AUTODESK	2D,3D	M, A	Export to Autodesk Revit files. IFC files import & export.	✓	✓	✓	✓	-	-
SUPERLOAD Bridge Analysis	Bentley Systems	2D	M,A	Import from LARS bridge and AASHTOW bridge management files.	-	-	✓	-	-	-
LARS Bridge	Bentley Systems	2D,3D	M,D,A	Direct connect to AASHTO BRIDGE database.	-	-	✓	✓	-	-
LEAP Bridge Concrete	Bentley Systems	2D, 3D	M,D,A	Reuse data from GEOPAK, Bentley InRoads, or MXROAD, and import from LandXML files.	-	✓	✓	✓	✓	-
LEAP Bridge Steel	Bentley Systems	2D,3D	M,D,A	Reuse data from GEOPAK, Bentley InRoads, or MXROAD, and import from LandXML files. Share data with OpenRoads, MicroStation.	-	✓	✓	✓	✓	-
MicroStation	Bentley Systems	2D,3D	M	Export & import from DWG/DXF, FBX, STL, SKP, JT, IGES, Parasolid XMT, ACIS SAT, CGM, STEP AP203 & AP214, and Acute3D (.3mx).	-	✓	✓	✓	✓	✓
RM Bridge	Bentley Systems	2D,3D,4D	M,D,A	Reuse data from GEOPAK, Bentley InRoads, or MXROAD, and Import from LandXML files. Interoperability with OpenRoads and OpenBridge Modeler. IFC files export.	-	✓	✓	✓	✓	✓
OpenBridge Modeler	Bentley Systems	2D,3D, (4D CONNECT Edition)	M,D	Reuse data from GEOPAK, Bentley InRoads, or MXROAD, and Import from LandXML files. Compete interoperability with Bentley's bridge analysis apps.	-	✓	✓	✓	✓	-
OpenRoads conceptsStation	Bentley Systems	2D,3D	M,D	N.A	✓	✓	✓	✓	-	-
Tekla Structures	Trimble Solutions	2D,3D,4D	M	Revit and IFC files import & export.	✓	✓	✓	✓	✓	✓
Tekla Civil	Trimble Solutions	3D	M,D	Export and import data from common GIS and CAD formats such as DGN, DWG, LandXML, DXF, MIF and Shape.	✓	✓	✓	✓	✓	✓
Sofistik Bridge Design	Sofistik	2D,3D	D,A	Import Autodesk AutoCAD files, data exchange with Dynamo and Revit.	-	✓	✓	✓	✓	-
CSIBridge	CSI	3D	M,D,A	Import and export data using IFC standards.	-	✓	✓	-	-	-
LARSA 4D BRIDGE	LARSA	2D,3D,4D	D,A	N.A	✓	✓	✓	✓	✓	-
Bridge Design software	IDS	2D,3D	M,D,A	Export to Excel and geometry control programs such as the IDS MC3D™ Geometry Control, AutoCAD, and MicroStation CAD files (3D Bridge Modeler GEOM3D™).	✓	✓	✓	✓	✓	-
OpenBrIM (version 1, 2, &3)	FHWA	2D,3D	M,D	Import from Autodesk AutoCAD, LARSA 4D, CSI SAP 2000, and Bentley MicroStation files.	✓	✓	✓	✓	✓	✓
ADAPT-ABI	ADAPT	2D,3D,4D	M,D,A	Import & export AUTOCAD, DXF drawing files.	-	✓	✓	✓	✓	✓

Table 1. Applicable BrIM software and tools in bridge projects life cycle [28] [29] [30] [31].

Chapter 4. BIM and BrIM-Based Construction QC Models

4.1 Literature Review

Usually BIM as created by design professionals, does not necessarily include some specific information such as construction methods, participants, and processes associated with construction quality management. Therefore, a quality model including standard POP (product, organization, and process) model, standard scheduling, and BIM is required as a BIM-based construction quality model to provide all elements information, relationships, and evaluation criteria [32].

Virtual design and construction methods can be completed by using POP models [33]. POP modeling consists of three sections including product, organization, and process templates. The product template comprises three parts including quality properties, entity object, and corresponding inspection criteria that are determined on the basis of the construction codes and standards [32]. The POP models make the 3D product models more comprehensive by adding organization and process models to them and they provide a better visualization, planning, and coordination compared to the traditional practice [33].

Contactors can use a construction BIM-based model to determine the works which require inspection and then they can provide and submit their requests for inspection. When inspection request is approved, the contractor, project manager, job foreman, superintendent, and fulltime quality inspector involved in these activities are determined in the organization template [32].

In the process template, sequential inspection criteria are determined in the construction process and after that, the time for approving the quality will be predicted based on each controlling item schedule in a construction period. Figure 1 shows the BIM-based quality model associated with execution of construction quality management inspection plan, figure 2 indicates BIM-based framework of construction quality model, and figure 3 shows BIM-based construction quality model workflow of the construction quality model proposed by Chen and Luo (2014) [32].

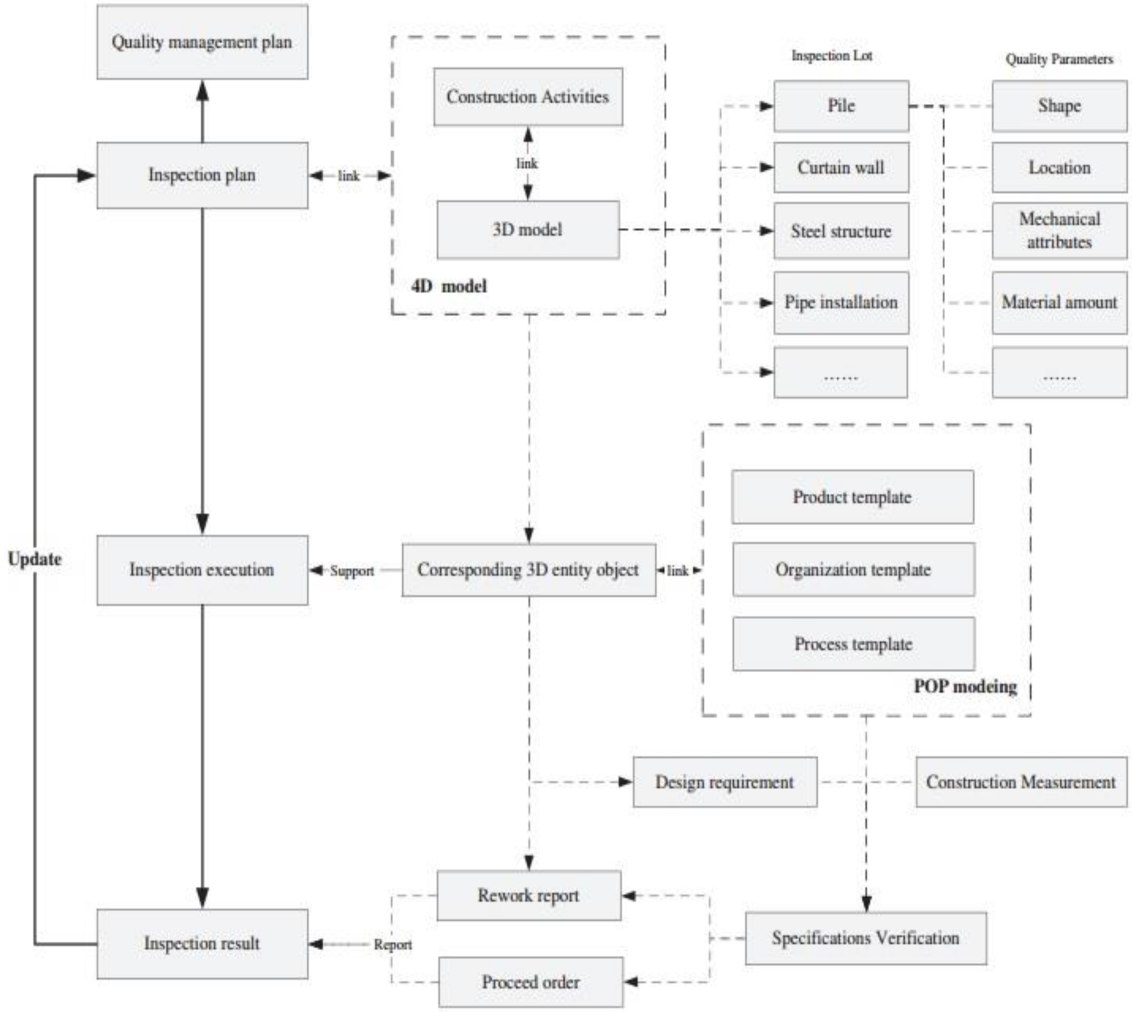

Figure 1. Chen and Luo’s (2014) BIM-based quality model associated with execution of construction quality management inspection plan [32].

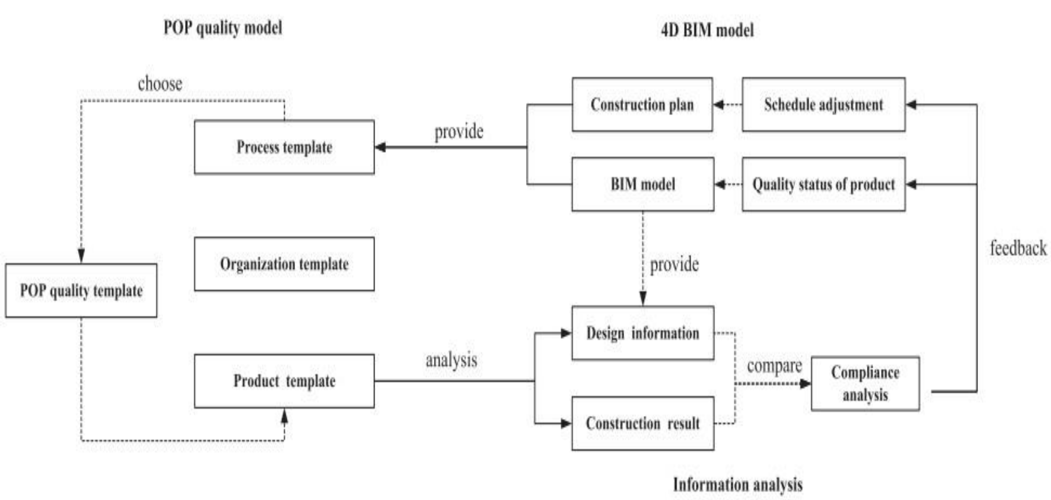

Figure 2. Chen and Luo’s (2014) BIM-based framework of construction quality model [32].

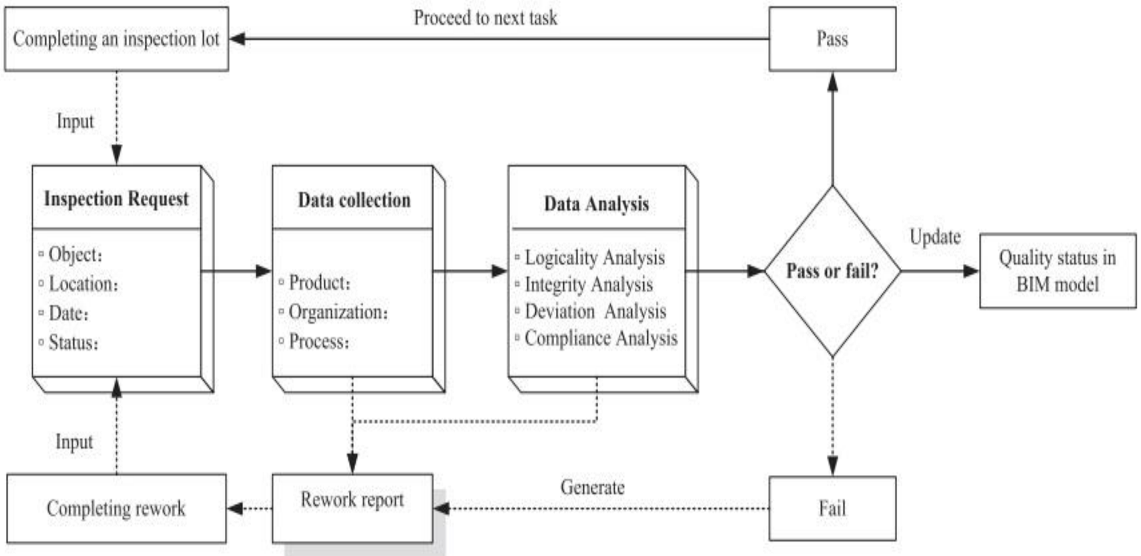

Figure 3. Workflow of the Chen and Luo's (2014) BIM-based construction quality model [32].

Based on the proposed model workflow, in the first step an inspection lot associated with the last task that recently has been completed, should be prepared and then an official request for that should be issued. These steps should be done before starting the successive task. After that, based on the data provided from the construction site, the templates ought to be completed for real time and continuous data, logic analysis, integrity analysis, deviation analysis and compliance analysis [32].

The process in a BIM-based construction quality model is based on the successive steps related to the construction process. Each unit consists of sub-units that their related inspections should be completed before starting inspection of the successive unit. Firstly, inspection lots items will be filled and surveyed by reliable staff who have the required professional background. These processes are known as the logicality analysis [32].

The BIM-based quality model confirms input data with data validity rules to avoid errors in input data. These data validity rules include rational data expectations and make the quality model smart for accepting appropriate data. These processes are known as the integrity analysis [32].

Construction parameters, official construction codes, and design data are available in the BIM-based quality model and based on them, the quality control data collected from the site are assessed. In this model, value deviations and the deviation levels can be determined by applying different symbols (e.g. circle, triangle, etc.) represent the warning and based on them, unacceptable inspection results will become clear. These processes are known as the deviation analysis [32].

Entire process of construction project quality can be managed in a multi-level acceptance sequence in a BIM-based quality model. The model includes analysis of each QC item and shows whether the results of site quality testing meet the associated codes mentioned in the deviation analysis part of the model. These processes are known as the compliance analysis [32].

Lastly, the quality status of construction components can be divided into two general parts as before inspection and after inspection statuses in which the situation of construction and inspection results are indicated based on a color metaphors (figure 4) [32].

	Quality state	Color coded metaphor
Before inspection	Before construction	
	Under construction	
	After construction	
After inspection	Failed	
	Passed	

Figure 4. Chen and Luo’s (2014) BIM-based quality model status using color metaphors [32].

If the inspection lot will be approved based on the inspection criteria, the successive task can be started. Otherwise, a non-conformance report (NCR) consists of corrective actions will be prepared and issued. After preparing the works on the basis of the corrective actions, the mentioned process will repeat [32].

The mentioned BIM-based QC processes and results can be shared, monitored, and followed easier and more effective in comparison with the traditional QC processes. In addition, it results in a considerable decrease of input data repetition in different forms that are used for data sharing, communication, and analysis [32].

Ma et al. (2016) have proposed a 3D BIM-based quality supervision model as shown in figure 5. This model can be explained in three parts as follows:

1) Providing inspection lots related to each project item.
2) Updating the elements of provided construction 3D model based on the required quality inspection data.
3) The QC processes.

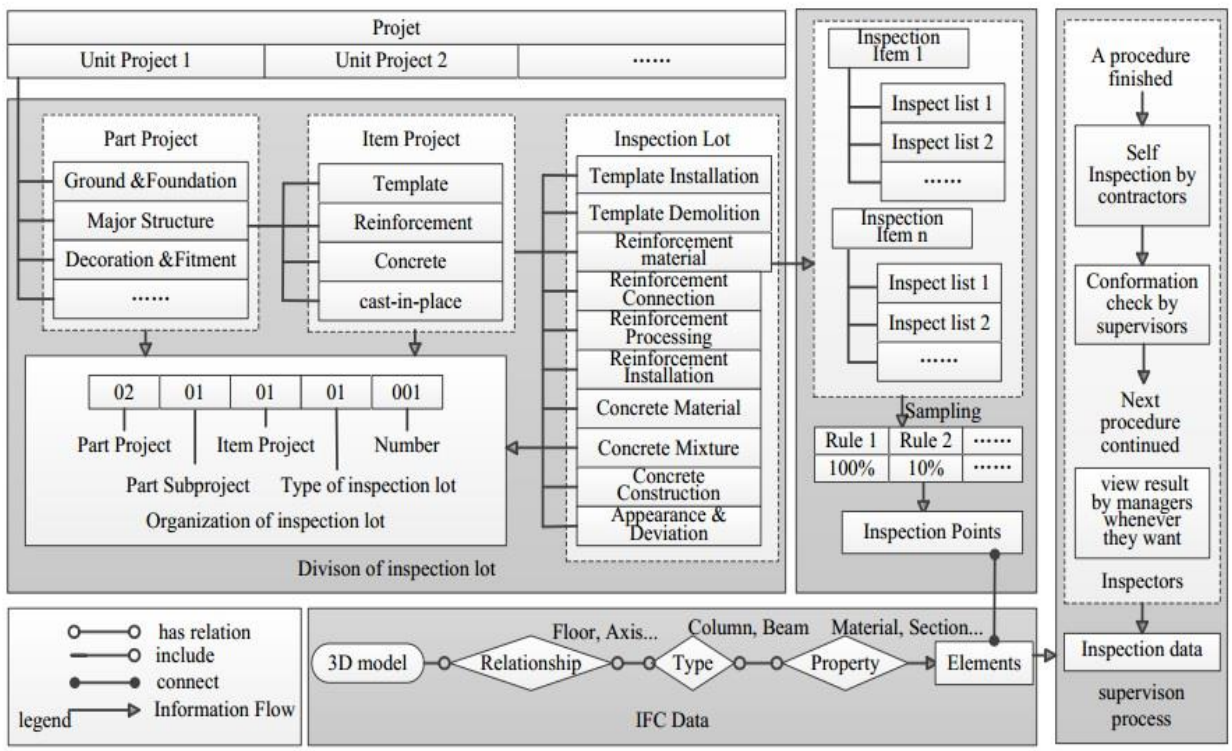

Figure 5. Ma et al.'s (2016) 3D BIM-based quality supervision model [34].

Evaluation (shortcomings and comparison) of the two studied BIM-based quality models (model of Chen & Luo as the first model and model of Ma et al. as the second model) shows [32]:

1) Neither models includes temporary construction works (e.g. falsework, and formwork).
2) Both models need competent electronic devices such as laptops, tablets, and smartphones to be used for running BIM-based quality models among the involved project participants. This is not a big deal for those participants and personnel who work in offices but it may

create difficulties for staff who work in construction sites due to some problems such as availability of internet connection, etc.

3) The first model is more detailed and comprehensive than the second model in the field of quality inspection and decision-making processes. In fact, the processes of providing and updating of inspection plan, performing inspection, and providing results from performing the inspection and using them for updating the inspection plan, are not included clearly in the second quality model. In addition, in the second quality model, the processes related to making decisions by inspectors and successive consequences and steps have not been explained clearly. These processes consist of approval or rejection of the performed activity. In the both situations (activity quality approval or rejection), related proceed order and rework report (including corrective operations) should be created and then the final results should be used for updating the quality inspection plan.

4) The first model is a 4D BIM-based quality model while the second model is a 3D BIM-based quality model, therefore quality control management is easier and more effective in the first model compared to the second model.

4.2 Methodology

4.2.1 Quality Control Framework of Post-Tensioned Pre-Stressed Concrete Slab Bridge Construction Projects

In general, all bridge structures can be divided into two main parts as substructure and superstructure in which in every part, the quality of all the bridge structure components has to be checked and controlled based on project criteria, specifications, drawings, related standards and codes. The bridge superstructure consists of bridge deck and substructure includes the following components:

- Cast in place concrete board piles.
- Pile caps.
- Concrete piers, pier caps, and abutments.
- Bearing pads.

Work breakdown structure (WBS) related to a post-tensioned pre-stressed concrete slab bridge construction project (LOD 300) has been illustrated in figure 6.

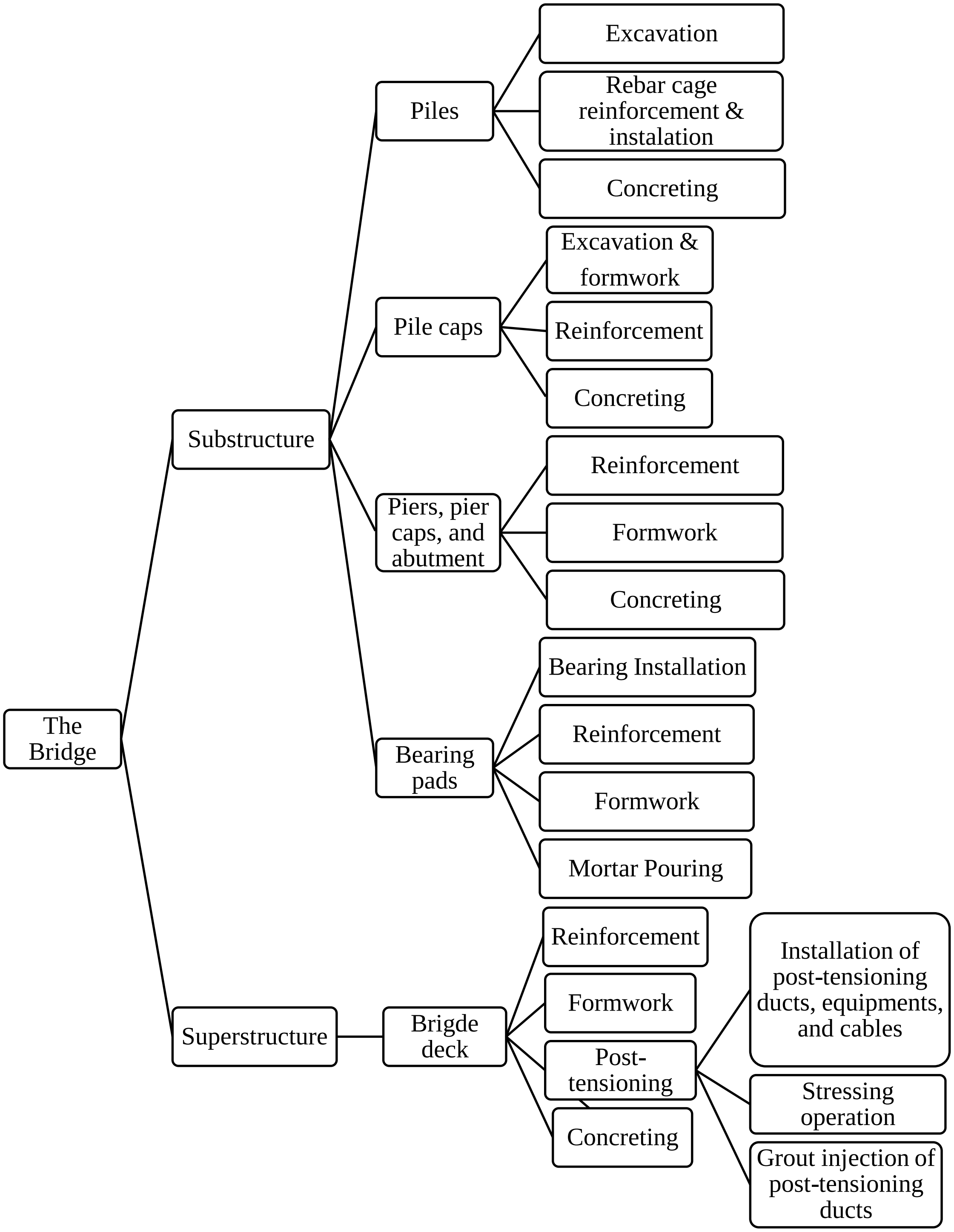

Figure 6. Work breakdown structure of a post-tensioned pre-stressed concrete slab bridge (LOD 300).

4.2.1.1 Substructure QC Items

The QC items that should be checked by QC supervisors related to the bridge substructure components are as follows:

Cast in place concrete board piles	
Hole excavation: • Hole location. • Hole depth. • Hole diameter. • Hole shape. • Hole dryness. • Hole verticality. • Hole walls soil stability.	Reinforcement: • Rebar shape. • Rebar type. • Rebar mechanical tests (tensile, bend, fatigue tests, etc.). • Rebar length. • Rebar cleanness. • Rebar size. • Rebar arrangement. • Rebar distances. • Cage diameter. • Concrete cover. • Rebar number. • Overlap specifications. • Cage installation.
Concreting: • Concrete contents properties. • Concrete placement. • Concrete slump. • Concrete air content. • Concrete mixture. • Concrete temperature. • Sampling. • Concrete additives. • Batch plant equipment calibration. • Fresh concrete density. • Concrete aggregate tests (e.g. gradation test, sand equivalent, etc.).	

Table 2. Quality control items related to cast in place concrete piles [35] [36] [37] [38] [39].

Pile caps	
Excavation: • Pile cap location. • Pile cap width, length, and depth. • Pile cap bottom lean concrete.	Reinforcement: • Rebar shape. • Rebar type. • Rebar mechanical tests (Tensile, Bend, Fatigue tests, etc.). • Rebar length. • Rebar cleanness. • Rebar size. • Rebar arrangement. • Rebar distances. • Rebar number. • Overlap specifications. • Installed pier rebar.
Formwork: • Formworks stability. • Formworks location. • Concrete cover. • Formworks cleanness. • Formworks level of being oily. • Formworks shape. • Formworks moisture before concreting. • Formwork joints insulation.	Concreting: • Concrete contents properties. • Concrete placement. • Concrete slump. • Fresh concrete density. • Concrete air content. • Sampling. • Concrete mixture. • Concrete temperature. • Concrete additives. • Concrete curing and protection. • Concrete consolidation. • Batch plant equipment calibration. • Insulation. • Concrete aggregate tests (e.g. gradation test, sand equivalent, etc.).

Table 3. Quality control items related to pile caps [35] [36] [38] [39].

Piers, pier cap, abutments, and bearing pads	
Reinforcement: • Rebar shape. • Rebar type. • Rebar mechanical tests (Tensile, Bend, Fatigue tests, etc.). • Rebar length. • Rebar cleanness. • Rebar size. • Rebar arrangement. • Rebar distances. • Rebar numbers. • Overlap specifications. • Install items.	Formwork: • Shape. • Location. • Concrete cover. • Stability. • Cleanness. • Level of being oily. • Drainage system (deck structure). • Formwork joints insulation. • Bearing pads plates and accessories (condition, supports, location).
Concreting: • Concrete contents properties. • Concrete placement. • Concrete slump. • Fresh concrete density. • Concrete air content. • Sampling. • Concrete mixture. • Concrete temperature. • Concrete additives. • Concrete consolidation. • Concrete curing and protection. • Insulation. • Batch plant equipment calibration. • Concrete aggregate tests (e.g. gradation test, sand equivalent, etc.).	Bearing pads and their upper and lower mortar pads: • Physical properties (hardness, tensile strength, and ultimate elongation). • Heat resistance test. • Compression sets test. • Low temperature brittleness test. • Instantaneous thermal stiffening test. • Ozone test. • Tear test. • Oven aged test. • Adhesion test. • Low temperature test. • Shear modulus and creep properties test. • Mortar pad fresh concrete properties, reinforcement and formwork as explained in previous sections.

Table 4. Quality control items related to concrete piers, pier cap, abutments, and bearing pads [35] [36] [38] [39] [40].

4.2.1.2 Superstructure QC Items

Bridge deck construction can be categorized in five parts including falsework, formwork, reinforcement, concreting, and post-tensioning operations. The post-tensioning components can be determined as below [41] [42] [43]:

- Pre-stressing strands.
- Bearing plate anchorage system.
- Couplers.
- Ducts.
- Grouting system.

<table>
<tr><th>Bridge deck falsework</th><th>Bridge deck formwork, reinforcement, and concreting</th></tr>
<tr><td>• Foundation conditions and drainage.
• Mudsills type, grade, size, and condition.
• Layout, dimensions, materials, condition, and location of falsework elements.
• Ledgers and joins conditions.</td><td>• Same items as explained in substructure components QC in addition to controlling deck concrete level.</td></tr>
<tr><th colspan="2">Post-tensioning QC inspections</th></tr>
<tr><td>Post-tensioning QC inspections before bridge deck concreting:
• Materials conditions, specifications, and tests (e.g. strand tensile test, etc.).
• Components location.
• Components stability.</td><td>Post-tensioning QC inspections after bridge deck concreting:
• Concrete compressive strength.
• Wedges, wedge plates and grout caps conditions.
• Post-tensioning Jack and pump calibration certificate.
• Stressing steps.
• Tension force.
• Cables elongation.
• Grout mixture.
• Grout injection pressure.
• Grout sample for compressive strength tests.</td></tr>
</table>

Table 5. Quality control items related to post-tensioned pre-stressed concrete slab bridge deck construction [36] [42] [44].

4.2.2 Proposed 4D BrIM-Based QC Model Related to The Construction Phase of a Post-Tensioned Pre-Stressed Concrete Slab Bridge Project

The BIM-based QC model for concrete slab bridge construction that is going to be proposed in this report, has been derived based on the BIM-based QC model in general construction that has been proposed by Chen & Luo (2014).

Temporary construction works such as falseworking and formworking are very important structures and activities in concrete bridge construction projects and because of that, their quality should be monitored and controlled properly.

Since post-tensioned pre-stressed concrete slab bridge is one of the most prevalent types of concrete bridges, these types of bridges were chosen to be investigated in this part. In addition, based on the fact that the Chen & Luo's (2014) BIM-based QC model does not include temporary construction works, a 4D BrIM-based QC model has been proposed for a post-tensioned pre-stressed concrete slab bridge related to the construction phase (figure 7) regarding the basis of Chen & Luo's (2014) QC model but with this difference that the proposed QC model includes both the permanent and temporary structures and activities associated with the bridge construction phase. This 4D BrIM-based QC model has the same framework and workflow as explained for the Chen & Luo's (2014) QC model in the literature review.

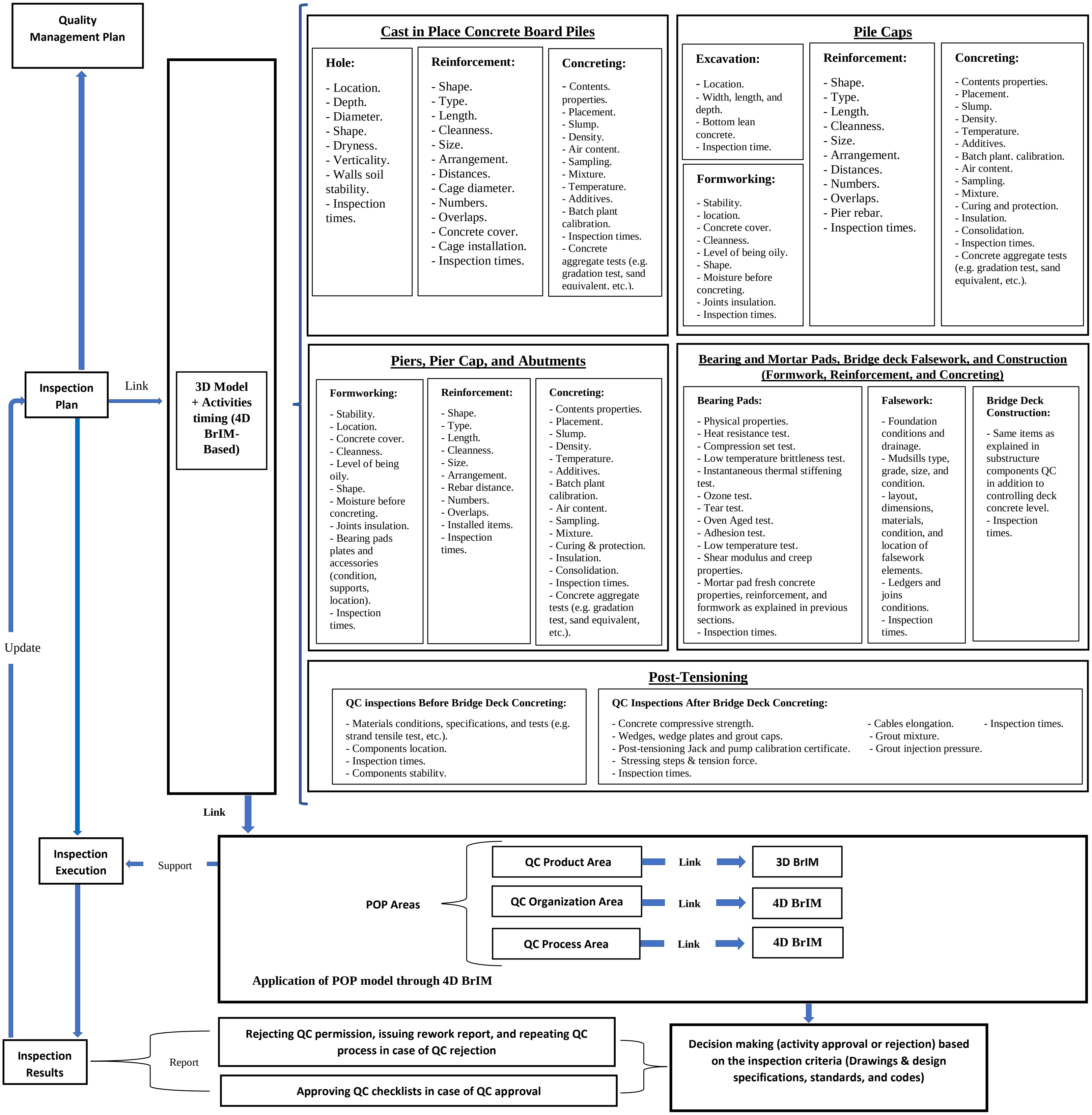

Figure 7. Proposed 4D BrIM-based QC model related to the construction phase of a post-tensioned pre-stressed concrete slab bridge project.

Chapter 5. Case Study

5.1 The Case Study Specifications

In this chapter at first the general specifications of a post-tensioned pre-stressed concrete slab bridge (LOD 300) that is going to be studied as the report case study, is introduced and then the traditional construction QC process associated with that will be explained. In the next step, the modelling procedure related to the case study will be illustrated and then the applicable use of the BrIM-based QC model will be surveyed and discussed for the case study.

It is assumed that this project is completed based on an EPC delivery method in which the construction QC by the general contractor is subcontracted to an external consulting engineering company. In this project, the parties that are directly involved in the construction QC include the general contractor, QC team, and client’s consultant from a consulting engineering company. Figure 8 shows the case study concrete slab bridge with a two lanes road.

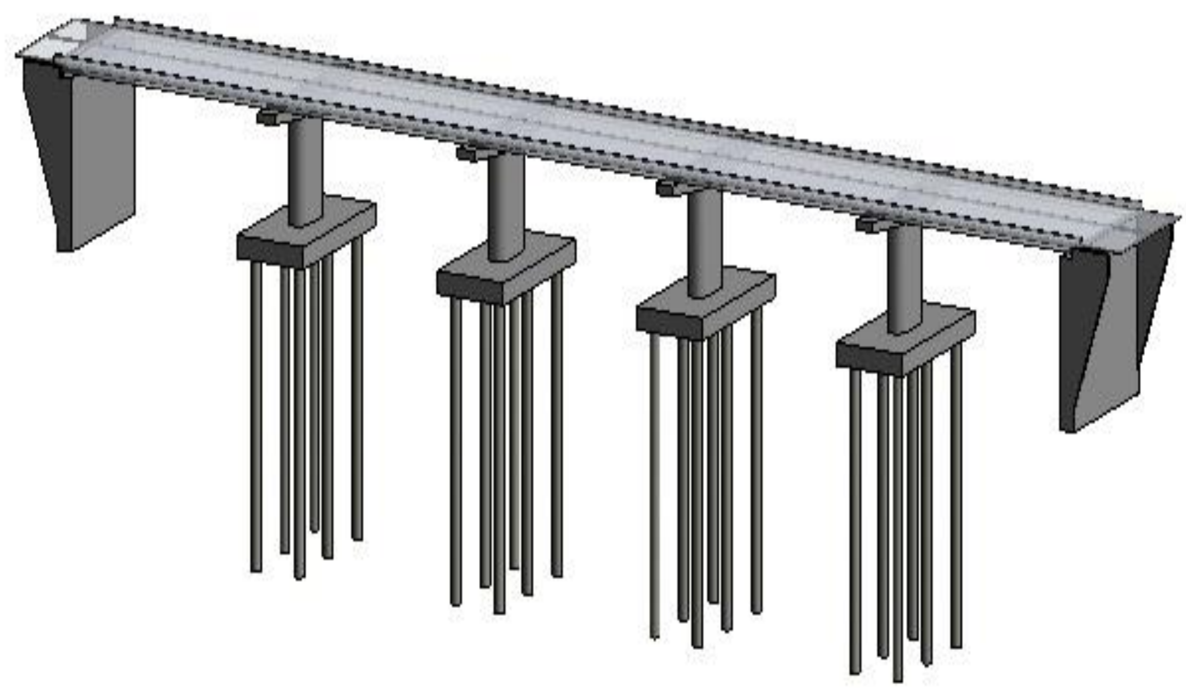

Figure 8. The case study concrete slab bridge.

The bridge components consist of:

- Six cast in place concrete board piles (dry construction method) for each bridge pile cap.
- Four pile caps.
- Four concrete piers and pier caps.
- Two abutments.
- Four bearings pads for each pier cap (two for each lane).
- One post-tensioned pre-stressed concrete slab deck.

5.2 Basis of the Traditional QC Process in The Bridge Construction Phase

In the bridge construction phase, contractors are allowed to start new activities when properly complete the related predecessor activities and get the signed official permission from the site QC team associated with them. The basis of the traditional QC process in construction phase of the case study bridge can be mentioned as follows:

1) It is the responsibility of the QC team or the general contractor (with coordination with the QC team) to make the QC checklists for all of the bridge structural components. These QC checklists have to be prepared for three parties that are involved in the construction quality control (i.e. the general contractor, QC team, and client's consultant). The QC checklists should include the area allocated for signature and approval by the site superintendent, site QC manager and officers, and the client's consulting engineering company officers and site manager based on the QC process. In addition, The QC checklists should contain the name, location, inspection date, component specifications, QC items and their related inspection results, and the involved parties' company logo.

2) The QC officer has to control and check the completed activities based on the official request from the general contractor (signed QC checklist by the general contractor's site superintendent). If the performed activity is complete without any deficiency, the QC team manager will approve and sign the QC checklists and then the contractor should officially request the client's consulting engineering company officers by sending the signed QC

checklists by QC officers to them and then the client’s consulting engineering company officers can check the works and approve or reject the QC checklists.

3) If there is any deficiency and problem with the work, the QC officer should write them in the QC checklists and sign (usually with the red pen) and reject the contractor’s request for giving permission to perform the succeeding activity. The reasons for rejection should be mentioned in the QC checklists. The site QC manager and the client’s consulting engineering company site manager will approve and sign the QC checklist when they are signed and approved by their officers.

4) When contractors receive the rejected QC checklist either by the QC officers or the client’s consulting engineering company officers, they should solve the mentioned problems that have been written in their QC checklists and after that they should issue new QC checklists and ask the QC officers and the client’s consulting engineering company officers to check their works again. If the problems have been solved properly, the QC officers or the client’s consulting engineering company officers sign and approve them and then the contractor can start performing related successive works.

5.3 Traditional QC Process of The Case Study Bridge Components

5.3.1 Cast in Place Concrete Board Pile QC Process

After determination of the exact location of the bridge piles and pile caps by the contractor’s surveyor, the locations should be approved by surveying QC officers and if the locations are correct, the contractor can start excavating pile holes. After the pile hole excavation, they have to be approved by structural QC officers. They control all the QC items associated with the inspection of the pile holes as mentioned in chapter four.

In the next step, structural QC officers ought to inspect the rebar pile cages and control all the QC items for them as mentioned in chapter four. If all the QC items are considered properly, the structural QC officers will approve and sign the rebar pile cage QC checklists and the contractor can install them into the pile holes.

The installed rebar cages should be fixed in their correct locations in the holes and after verification of their locations by surveying QC officer, the contractor can start concrete pouring. Structural QC officer and QC lab personnel have to control all the QC items for the piles concrete pouring before and during the piles concrete pouring as mentioned in chapter four. If structural QC officer recognizes any conflict with the QC items, he/she asks the contractor to fix it. After the concrete pouring, if there is no problem for the QC of the concrete pouring, structural QC supervisor confirms and signs the concrete pouring QC checklists.

5.3.2 Pile Caps QC Process

The contractor can start pile caps excavation before (recommended method) or after the concrete piles construction (i.e. before or after the pile excavation, rebar cage installation, and concreting operation). After that, surveying QC officer should check all the QC items for the pile caps excavation as mentioned in chapter four. In the next step, contractors can commence the reinforcement and formwork operation and after completion of them, officially request the structural and surveying QC officers to check their works. In this step, structural and surveying QC officers should check all the mentioned QC items for the pile caps reinforcement and formworking as mentioned in chapter four. If everything is fine, QC officers sign the pile caps rebar and formwork QC checklists and then the contractor can start concrete pouring.

Before, during, and after the piles concrete pouring, structural QC officer and QC lab personnel should control all the QC items for the pile caps concrete pouring as mentioned in chapter four. In the next step, pile caps up to a distinct level of the piers or abutments ought to be insulated properly. If QC officers detect any problem regarding the QC items, they should ask the contractor to fix that.

5.3.3 Concrete Piers, Pier Caps, Abutments, and Bearing Pads QC Process

After finishing pile caps concreting and getting the sufficient concrete compressive strength, the contractor can start pier reinforcement. After completion of the first part of the pier reinforcement, the contractor requests structural QC team officially to check their works and if everything is fine then the QC officers can sign and approve their jobs and then they can start formworking of the completed part of the pier reinforcement. All the QC items for the pier reinforcement as mentioned in chapter four, should be checked by the structural and surveying QC officers.

In the next step, contractors can start formworking and after completing their works, they can ask structural and surveying QC officers officially to come for controlling the completed parts. All the QC items for the piers formwork as mentioned in chapter four, ought to be checked by the structural and surveying QC supervisors.

The next step will be concrete pouring in which the contractor officially requests for starting the operation. In this step, structural QC officers control all the QC items for the piers concreting as mentioned in chapter four. If QC officers recognize any problem regarding the QC items, they ask the contractor to fix it and then the concrete pouring QC checklist will be signed and approved if the operation complete properly. The same QC process should be applied for the pier caps and abutments construction. Bearing pads mostly are tested by special labs outside of the construction site and then the central QC office checks the results and based on them gives the contractor the right to use them or change them and the QC process will be repeated.

5.3.4 Bridge Deck QC Process

The first step of the bridge deck construction is the bridge deck falsworking and formworking. After finishing these parts, the contractor should inform structural and surveying QC supervisors officially to check the performed works. In this step, structural QC supervisor controls all the QC items for the falsworking and formworking as mentioned in chapter four, and then the surveying QC supervisors check the location of bridge deck formwork and after their approvals, the contractor can start the deck reinforcement and installation of the strand ducts and post-tensioning equipment.

After completion of the deck reinforcement and strand ducts and post-tensioning equipment installation, the contractor officially asks QC supervisors to check their works. In this step, structural and surveying QC officers check all the QC items for the bridge deck reinforcement, formwork and post-tensioning operations before the deck concreting as mentioned in chapter four.

If everything is fine, the QC officers approve and sign the deck reinforcement and formwork QC checklists and then the contractor can commence concreting.

Before, during, and after the piles concrete pouring, the structural and surveying QC supervisors in addition to the QC lab personnel must check all the QC items for the deck concreting as mentioned in chapter four. If QC supervisors detect any problems regarding the QC items, the contractor has to fix them and then the concrete pouring QC checklist will be approved and signed. In the next step, the contractor can start installation of strands into the bridge deck post-tensioning ducts and then can install the outside post-tensioning equipment including wedges, wedge plates and grout caps.

In the next step, when the bridge deck concrete reaches the sufficient compressive strength, the contractor officially asks structural QC officers for controlling the post-tensioning operation. In this step, the structural QC officers check all the QC items for the post-tensioning operation after the bridge deck concreting as mentioned in chapter four, and then approve or reject the post-tensioning QC checklists.

5.4 Quality Control of the Materials Used in The Bridge Construction

The materials that are used in the project including cement, sand, gravel, concrete admixtures, reinforcements, strands, bearing pads, post-tensioning equipment, etc. have to be tested by the site QC lab, central QC lab, or an organization authorized by the QC team and client’s consulting engineering company. The contractor should use these kinds of materials if the QC team and client’s engineering company verify them; otherwise, the contractor has to change them. It is the QC team’s responsibility to check the new coming materials to the site.

5.5 Responsibilities of The Quality Control Manager and Supervisor

All the QC supervisors' activities that were explained in the previous parts f the bridge components QC process in addition to preparing daily reports based on the site conditions and ongoing activities, are the QC supervisors' responsibilities. The most important QC manager's duties are as follows:

- Managing, coordination, performing and documenting inspection activities when required.
- Preparing daily QC reports and attending weekly and urgent site meetings with other parties.
- Coordination for required QC testing and controlling their results.
- Being aware of the construction activities QC problems, planning, and ensuring on-time effective actions for solving them.
- Making sure about the suitability of the site QC lab equipment conditions.
- Updating the QC process when required on the basis of the site changes.

5.6 Related On-Site QC Documentation

It is important to the site QC team to collect and document all the letters and records that directly or indirectly are related to them. These documents include:

- Approved or rejected QC checklists.
- Test results of the site QC lab.
- Internal letters among the site QC members and among the site QC members and the central QC office.
- Letters between QC team and other involved parties (i.e. the client's engineering company officers and general contractor).
- Copy of letters that are sent from the general contractor to consultant and vice versa. The content of these letters should be related to the QC team.

Except from the internal letters among the QC members that are kept only in the QC office and the QC lab test results that should be prepared in four copies (for the site QC office, site QC lab office, client's engineering company, and general contractor), QC checklists of each activity related to the bridge should be created in three similar letters for the client's engineering company officers, general contractor, and QC team.

Direct letters that are sent to a party usually have a copy section in which the other parties related to the letter are determined (related indirect parties). Therefore, a copy of them should be sent by the sender party to the related indirect party.

5.7 BrIM-Based Modelling Procedures and Applications

In this part, the author decided to model a concrete slab bridge with Revit software due to the ability to add the related QC items and their design information as attributes to the components of the bridge 3D model, and also the possibility of downloading the software free trial version. After the bridge modelling with Revit, an IFC file export will be provided to be used and imported into Tekla BIMsight software. Tekla BIMsight is used because this software can be downloaded for free and can be used for construction project collaboration, combining and sharing models, conflict checking, and using notes for communication. These abilities help the site personnel who are involved in the bridge construction QC by providing more effective, streamlined, and consistent construction QC processes (will be explained in section 5.8 and chapter 6 of the report). The mentioned modelling procedure is the responsibility of the site QC team to be made. Figure 9 shows the concrete slab bridge that has been modeled in Revit.

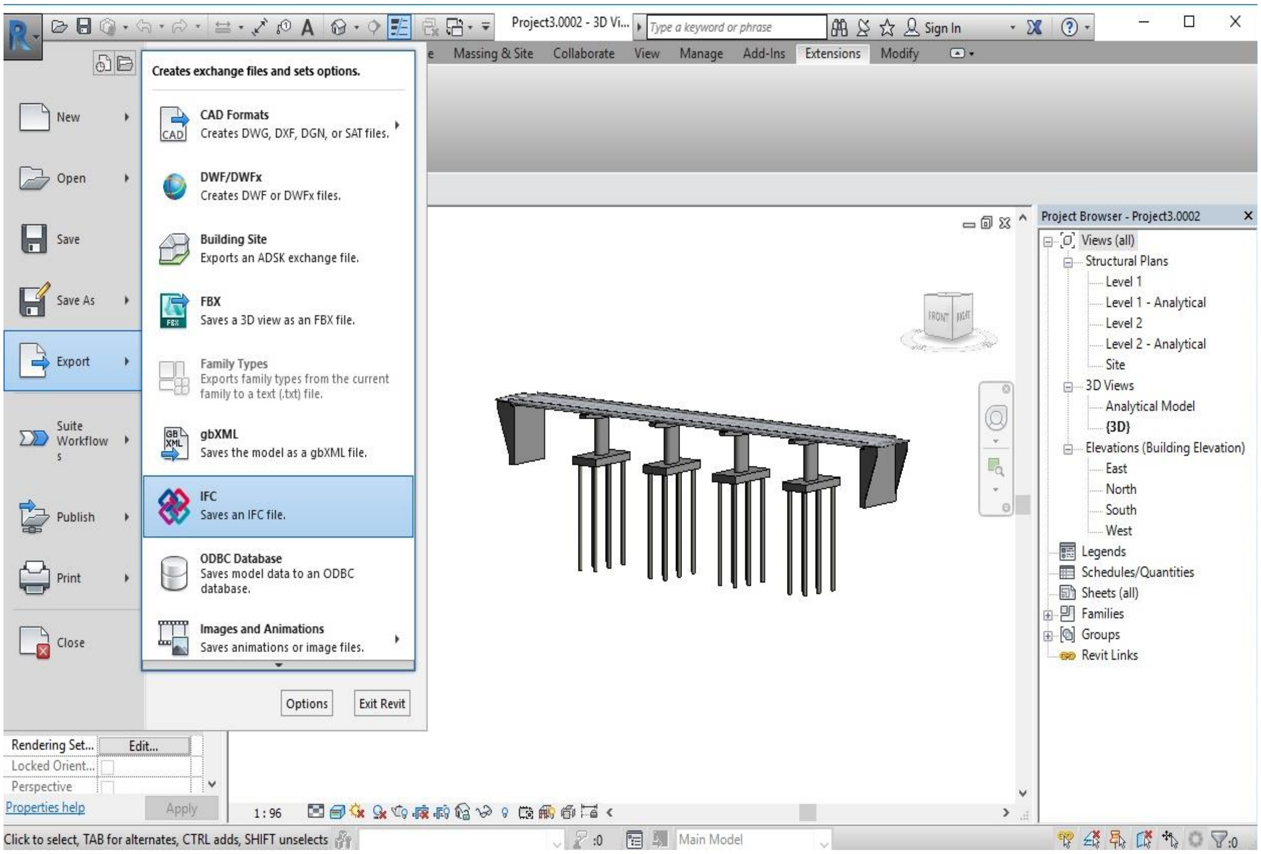

Figure 9. The case study concrete slab bridge modelling with Revit.

The proposed BrIM-based QC model (figure 7) shows that the model has been derived by a combination of the POP QC model and a BrIM-based model. In fact, the POP quality process is done through BrIM. For better understanding of the application of this model through BrIM in this case study, the following steps should be considered:

1) Complete familiarity with the basis of traditional QC processes in bridge construction phase of projects since the main concepts of these processes should be considered and followed in the BrIM-based QC system.
2) Bridge modelling by Revit software and then providing an IFC export file.
3) Importing the provided IFC export file to Tekla BIMsight software.
4) Providing the related required software and hardware supports for the involved actors in the project QC (i.e. the QC manager and supervisors, contractor's site manager, site superintendent, head and personnel of the execution and technical office, client's consulting engineering site manager and personnel).

In this BrIM-based system, the bridge QC checklists can be made, filled, and shared among the involved QC actors and also they can modify them. The QC process that was explained in the traditional QC process of the bridge components section (section 4.3), can be indicated through Tekla BIMsight software and then the whole QC process can be done by the BrIM-based QC system. The BrIM-based QC system can be applied instead or parallel to the paper based QC system. It should be taken into consideration that the QC items associated with the site permanent and temporary structures in the BrIM-based QC model can be updated. Figure 10 indicates the communication (shown in the rectangle) using Tekla BIMsight related to the quality inspection done by a QC officer associated with the bridge concrete board piles.

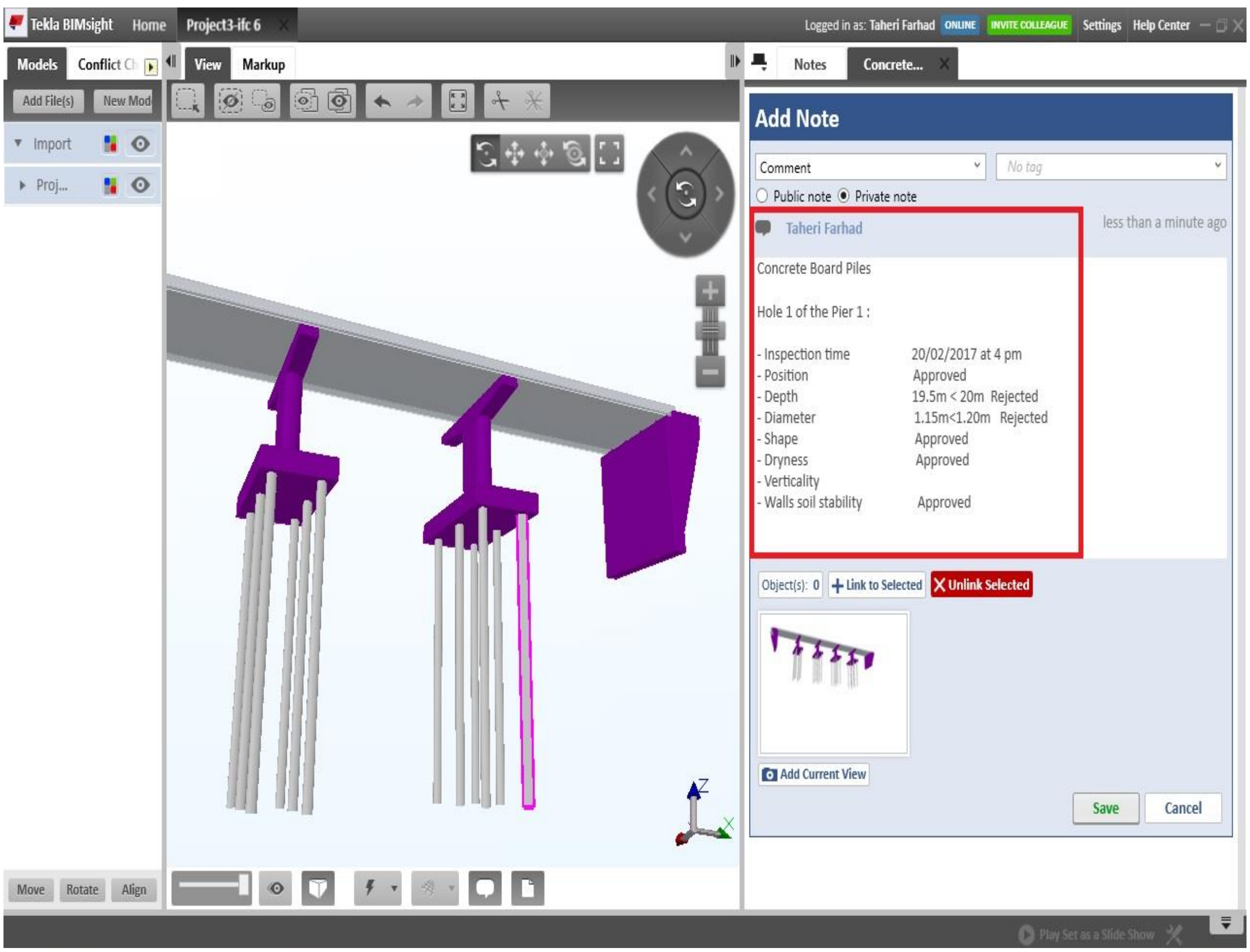

Figure 10. Communication using Tekla BIMsight related to the quality inspection done by a QC officer associated with the bridge concrete board piles.

5.8 Discussion

During communication and coordination among the general contractor and QC team, many problems which are mostly related to the disagreement between the contractors' engineers (engineers in the both technical and execution office) and QC officers can be made. The common reasons of these problems are as follows:

1) The QC problems that are mentioned by the QC officers are not technical and reasonable from the contractor's point of view. This is mainly based on the incorrect interpretation that the contractor's executive engineers have about the project specifications, drawings, and codes. By using a BrIM-based QC system, all the detailed information related to the bridge construction can be provided clearly for the contractor's executive engineers and this matter helps the prevention of making these kinds of problems.

2) Contractors believes that QC officers should check their works during the activities execution and if QC officers control the works only after the activities completion, sometimes it is impossible or difficult to correct the problems because it causes a remarkable rework and imposes considerable costs to contractors. By using a 4D BrIM-based system, the periods that a QC officer should check the works can be determined based on the construction progress that is updated through BrIM software.

3) Contractors claim that another QC officer had guided them to do their works based on his/her guidance, but the new QC officer who has checked the works, identified some problems that are caused based on performing the first QC officer guidance. In a BrIM-based system, as shown in figure 10, every QC officer who checks the work and detect some problems, can explain them and mention his/her suggestion through Tekla BIMsight. Therefore, the other QC officers can be completely coordinated with them.

4) In some cases, the QC officers believe that the contractor's engineers have faced a problem during the work implementation and they have chosen a way and implemented the work based on that without any coordination and getting permission from the QC team. This situation can happen when the number of QC officers is not sufficient in site and there are many activities to be perform ed. Through a BrIM-based system, contractors can communicate with the QC officers and get their advises in case of a problem.

5) Archiving lessons learned.
6) Computational platform that BrIM provides.

It should be taken into consideration that using BrIM could have some shortcomings such as [45] [46]:

1) Availability of human resources and time to learn BrIM for personnel.
2) Doubt about financial benefits of using BrIM for QC purposes in construction phase of projects because in addition to expenses related to providing human resources for learning BrIM for personnel, there are costs associated with providing BrIM hardware such as computers, tablets, Wi-Fi, software licensing, etc.
3) Habitual and social resistance to change from the traditional system to the BrIM-based system specially for architects in design phases.
4) Limited data transfer by project participants due to using special tools and consequently making incompatibility problems in data transmission. Solving these problems needs extra efforts by project participants.
5) There should be a very good collaboration between project participants to get the maximum advantage from using BrIM in construction projects.
6) Overall benefits of using BrIM in construction projects with collaborative approach such as Design-Build (DB) are higher than the projects with traditional approaches.
7) There are fears (e.g. low success or failure and lack of support that should be provided from company's senior leadership) from the possible consequences of using new technologies like BrIM.

During the discussion between the contractor and QC officers, if the parties can not convince each other, they refer the problem to their site managers and a meeting will be held between them in the site. If no agreement will be obtained, the problem will be discussed in a meeting between responsible persons with higher hierarchies from both parties. This meeting can be held either in the site or in one of the parties' central offices and then the agreement will be announced to the site personnel by official letters.

Chapter 6. Conclusion

In this report, QC processes in all design phases of construction projects and the QC items related to a post-tensioned pre-stressed concrete slab bridge related to its construction phase were investigated. After that, applicable BrIM software in bridge construction projects life cycle and two general BIM-based construction QC models were studied and based on their shortcomings and advantages, the framework of a 4D BrIM-based QC model was proposed and applied in a case study. In conclusion, using BrIM in addition to the benefits mentioned in the discussion section of the report (section 5.8), can provide the following advantages in construction phase of a project [32] [47]:

1) Providing an easier and more effective quality control process due to making the whole construction process more streamlined.
2) Physical conflicts in construction that usually happens between electrical, structure, plumbing, and mechanical systems can be simply determined in the initial design period and can eliminate the conflicts and helps QC process during the construction phase.
3) Improving the consistency of the quality control process based on the scheduling information that is added to the project 3D BrIM model to make a 4D BrIM model. In addition, the quality control process can be modified effectively by using BrIM when the inspection plan is updated with the ongoing construction process.
4) Increasing efficiency and accuracy in design communication and evaluation. In addition, it provides consistent and accurate information by automatically providing engineering documents.
5) Decreasing faults and disputes by making a more efficient coordination between project participants.
6) Ensuring the consistency of information from design to construction phase. BrIM make it possible to see components and their related information including types, relationships, names, metadata, and attributes. Construction product data can be used as the basis to

evaluate the differences between design and as-built conditions instead of assessing change orders and drawings manually.

Although the proposed 4D BrIM-based QC model has many advantages to be applied for QC proposes in post-tensioned pre-stressed concrete slab bridge construction projects, it has some shortcomings. For example, it is developed only for construction phase of projects. A complete BrIM-based QC model should consist of QC processes during all phases of a project life cycle. Moreover, the proposed BrIM-based QC model reflects the QC process between the QC team and general contractor but it does not show the total QC processes between all involved parties (i.e. the QC process between general contractor and client’s consulting engineering company). Therefore, it is recommended to propose a BrIM-based QC model that covers the mentioned shortcomings above.

Chapter 7. References

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