Application of Information technology to Maintenance Management of Civil Infrastructure with BIM Collaboration Platform

BIM プラットフォームで連係した情報技術のインフラ維持管理マネジメントへの適用

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ABSTRACT

Civil infrastructure, such as steel structures and reinforced concrete structures constitutes the foundation of our society. To ensure safety and serviceability of infrastructure during design service life, long-term maintenance management should be thoroughly conducted. Maintenance management aims to make timely maintenance decisions and to implement the maintenance actions; and its efficiency depends on the quick response to structural failure by making full use of information. Decisions related to maintenance requires assistance from information usually available in many different types, scales, and formats. The various information originates from loosely coupled and dispersed resources that are strongly interdependent. Managers decide whether the infrastructure needs to be repaired by comprehensive consideration especially on the following three kinds of information: (1) historical document information, such as documents generated from design, construction and previous maintenance; (2) on-site monitoring and inspecting data; and (3) professional analysis results for understanding the structural durability, safety, economy, etc. A key factor adversely affecting civil infrastructure maintenance is a conventional method for information management. It is inefficient for information storage and retrieval due to paper-based form and unsystematic database. The discrete and non-visual storage of information makes it difficult to quickly obtain and locate information in the real world of civil infrastructure. There is an inefficient in the management of professional analysis information. Usually, managers need to spend a lot of time to consult experts one by one to obtain the results of different professional analysis because experts usually share only the analyses results with managers every time, instead of helping managers do professional analysis and obtain the analysis results independently.

This paper focuses on the management of maintenance information by using information technology with the BIM collaboration platform. Three main tasks are completed:

(1) Firstly, an information platform is independently developed to integrate various information in modularity. This platform innovatively provides a visual 3D real-world model environment for the project by utilizing Building Information Modelling (BIM) and Geographic Information System (GIS). Modular information such as electronical document information and structural health monitoring data is linked to the corresponding location in the model and integrated in this platform. The professional analysis module is integrated in this platform and inserted by using browser and network technology, which can share professional analyses.

(2) Secondly, how to achieve the sharing of professional analysis from experts to non-experts is focused, which included sharing professional knowledge and analysis tools. This research proposes a method of professional analysis sharing based on knowledge management. Taking numerical simulation as an

example, experts use professional knowledge to create simulation prototypes through professional software and then simplify the prototype into an application in form of an open parameter model. Finally, they release the application to the professional analysis module in the developed information platform through network. Non-experts (maintenance managers) can run the application in the platform without restriction of professional software and professional knowledge.

(3) Finally, the numerical simulation is explored on the chloride ion penetration into tunnel concrete over time under external hydrostatic pressure, which is studied as an example to form a simulation prototype. A theoretical diffusion-convection model describing the process of chloride ion penetration into concrete under external water pressure is described by considering multiple affecting factors such as unsaturated flow, fluid-solid coupling, and chloride binding. A numerical model of unsaturated concrete is built to simulate the coupled process. Based on this model, the classic expression of effective diffusion coefficient is modified by considering a constrictivity factor, and the sensitivity analysis is carried out on five sets of parameters (i.e. effective diffusion coefficient, saturated permeability, van Genuchten parameters, initial saturation, and binding capacity parameters) aiming at evaluating the robustness of the model. The simulation results show that the multi-mechanism penetration model is computationally feasible, and the multiphysics coupling model can well reproduce the chloride ion transfer process in a microscopic perspective. Furthermore, the sensitivity analysis results indicate that the parameters governing moisture transport process are more sensitive to the prediction of the chloride ion penetration into undersea tunnel concrete. This simulation model shows high value in the research of chloride ion penetration into concrete structures under hydrostatic pressure.

In this paper, firstly, theoretical studies are performed to define the conceptual framework and demonstrate the implementation on the subject matter. Then, information development technology supports to realize the development of the integrated information platform. Finally, case studies prove the successful application of the proposed approach.

The information management method proposed in this paper overcomes the limitations of conventional method in maintenance information management of civil infrastructure and will greatly improve the efficiency of maintenance management.

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1 INTRODUTION

1.1 BACKGROUND

Civil infrastructure constitutes the foundation of our society. Most of our infrastructures, including bridges, viaducts, buildings, dams, tunnels, and reservoirs are constructed in reinforced or prestressed concrete. With the development of economy in the latter half of the 20th century in Japan, an immense stock of infrastructure is accumulated. From 1955 to 1975 (the high economic growth period in Japan), new construction of bridges increased yearly, after that, the boom period of bridge construction lasted for 20-30 more years. The total construction number of bridges in Japan by 2017 is shown in Fig. 1-1. With time goes by, the civil infrastructure in Japan faces the aging problem. The proportion of bridges that serves over 50 years after construction is about 27% until 2019, but 10 years and 20 years later, it jumps to about 52% and 74%, respectively as shown in Fig. 1-2 [1].
For considering the "composition of a sustainable society" for the 21st century and keeping the required performance of the structures, efficiently and effectively maintaining these existing structures is indispensable [2]. This means that an extremely large number of structures might need to be repaired, strengthened, or replaced during the next several decades.

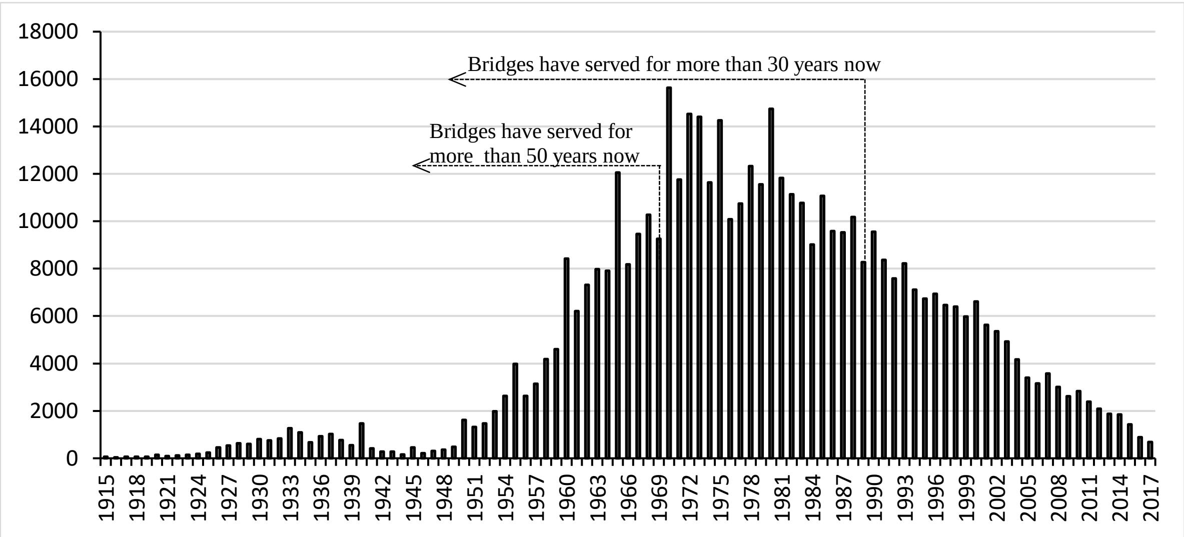


Fig. 1-1. Number of bridges by construction year in Japan.
(Japan Bridges Association)

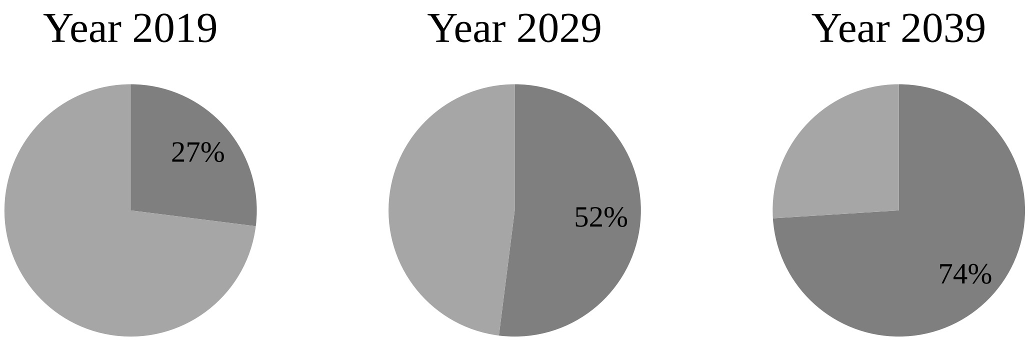


Fig. 1-2. Proportion of bridges in service for more than 50 years.

Reinforced concrete is a very durable construction material used worldwide. Under normal conditions, the service life of concrete structures normally can reach 50 to 100 years or exceed 100 years. However, its durability can be affected by various causes, including [3], including: (1) initial defects: design and construction faults, use of inferior materials and so on; (2) instantaneous damage: impacts by highway, waterborne, or railway vehicles, unauthorized overloads, explosions or fires, acts of terror, and natural disasters such as earthquakes, tornados, extreme cold or heat, scour, flood, and so on; and (3) exposure to aggressive environment: carbonation, chloride attack, chemical erosion, alkali-silica reaction, fatigue, abrasion, and so on. Initial defects and instantaneous damage can be easily identified and be quickly dealt with as emergency treatment. The rate of performance degradation of concrete structures due to deterioration influenced by aggressive environment would change with time. Especially for aging structures, deterioration can strongly affect the performance year by year; therefore, sufficient maintenance of concrete structures is of great importance to prolong its service life.

The maintenance of concrete structures is a work of multi-professional cooperation where information is a very important factor. Maintenance managers need to make decisions on whether remedial action is taken or not. They have to implement maintenance in order to manage the concrete structure in the best possible way based on the condition of structures. The condition of structures is diagnosed through the analyses of a large amount of information. Some information is preserved as historical records for future troubleshooting:

(1) Historical document

- Design drawings, contract documents, etc. during design stage.
- Bill of quantities, construction records, completion drawings during construction stage.
- Inspection results and past maintenance records during service.

(2) Specification file

- Design specifications, construction specifications, and maintenance specifications.

Usually, historical records are stored in paper-based such as textbooks, manuals, manufacturers' recommendations, and past maintenance record as shown in Fig. 1-3. It is difficult to update the paper-based data because they are handwritten. Furthermore, it is inflexible for managers to retrieve information in specific time and location based on paper-based data. The existing unsystematic databases were made with using Microsoft Word and Microsoft Excel to form intensive paper-based documents, which is lack of the linkage between information and its location in the real project. Sometimes a maintenance manager misplaces many paper reports, which leads to the loss of information in later retrieval. Eventually, it will cause improper document management and maintenance backlogs.

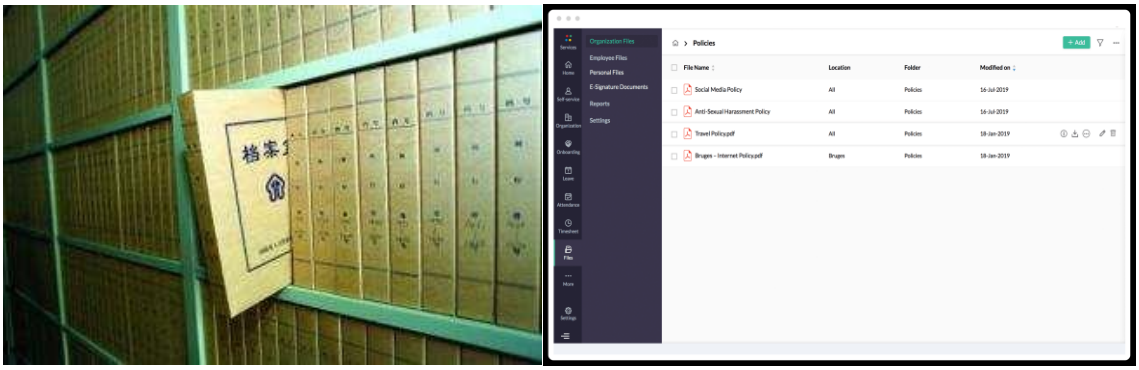


Fig. 1-3. Paper document and unsystematic database.

In the maintenance management, the manager needs some professional analysis results such as deterioration analysis to assist the decision-making of maintenance. It is necessary to use professional knowledge to conduct a professional analysis. Moreover, since these professional knowledge for analysis covers a wide range of subjects, it is almost impossible for a single expert or team to master all the assessment fields. Usually a manager in charge of maintenance management is not a comprehensive expert. Therefore, if a manager wants to make a deep understanding of the structure condition, consultation to other experts of corresponding field one by one is a must choice (Fig. 1-4), which will absolutely cost a lot of time and energy. In this consultation mode, knowledge is “closely tied to the person who developed it and is shared mainly through direct person-to-person contacts.” The scalability and reusability of knowledge are low.

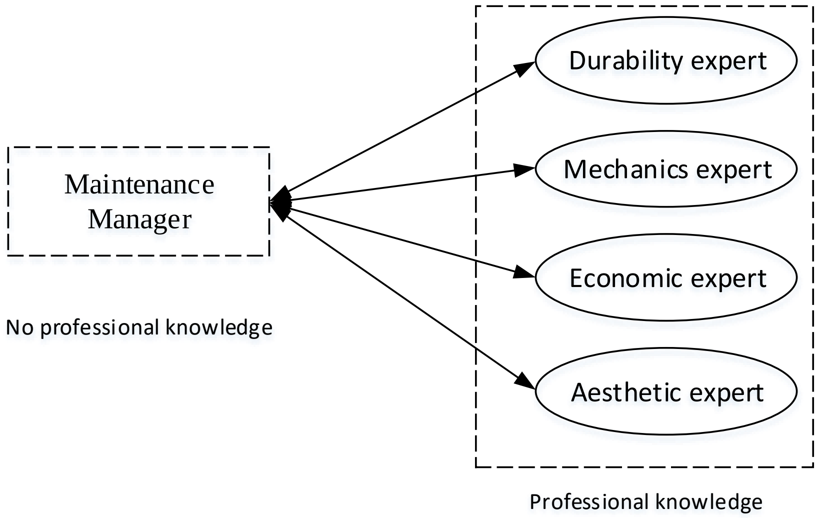


Fig. 1-4. Diversified requirements and distribution of professional knowledge.

A concrete structure serves for a long period. Excellent maintenance management is essential for a concrete structure to retain its safety and serviceability. An excellent maintenance management is always considered as the results of efficient information communication including expertise.

According to Labib [4], Information Technology (IT) applications for facilities maintenance management are now commonplace for reducing accumulation of paperwork in the office and increase the effective information management of the target project. According to Kans [5], maintenance management has set the goal to transform its processes into sophisticated application using Information and Communications Technology.

It is important to establish an information system, gathering information timely and accurately as well as containing the expertise of the corresponding assessment by using information technology. Many maintenance management platforms have been developed to assist it, such as PONTIS [6, 7], that is a bridge management system developed by the Federal Highway Administration (FHWA) in conjunction with six state DOTs. The system stores inspection data for each of a bridge's structural elements and recommends a bridge preservation policy. An expert system is a computer-aided knowledge system. Knowledge can be gathered from books, journals, reports and/or knowledgeable individuals. In civil engineering, the expert system has made benefit to areas of design analysis, damage assessment of structures, maintenance of structures, etc. For example, Concrete Bridge Rating Prototype Expert System with machine learning [8] evaluates the structural serviceability of concrete bridge based on several conditions and finally provides five conditions: safe, relatively safe, moderate, slightly dangerous, and dangerous. FPNES (Fuzzy Petri Net Based Expert System) is an application for damage assessment by an integrated expert system based on proposed fuzzy petri nets [9]. Other expert systems were also developed for assessment of deterioration or optimization of maintenance based on a lot of knowledge such as fuzzy logic theory, simulation, experience accumulation and so on.

These systems can solve the analysis and judgment with a large amount of maintenance data. However, these analyses are performed at a macro level, and detailed analyses cannot be performed for specific degradation analysis for a structure as mentioned above. At the same time, there is no visual storage in these information stores, which brings inconvenience to information retrieval. In recent years, building information modeling (BIM) has become the most flourishing technology in the building industry, and it has been extended to infrastructure engineering. This technology is a new approach and can be used for design, construction, and facilities management of structures, wherein a digital representation of the building process is used to facilitate the exchange and the interoperability of information [10].

The concept of BIM has existed since the 1970s [11]. However, the terms 'Building Information Model' and 'Building Information Modeling' (including the acronym "BIM") did become popular to be used until many years later. In 2002, Autodesk released a white paper entitled "Building Information Modeling"[12]. BIM is a digital representation of physical and functional characteristics of a facility. BIM is a shared knowledge resource for information about a facility forming a reliable basis for decisions during its lifecycle [13].

BIM provides 3D digital models of buildings. BIM is the virtual model of reality, which is not only a pure geometric figure, but also some beautiful textures can casted on it for visualization. The elements in BIM have all the characteristics of their actual counterparts-physical and logical.

In China, the Ministry of Construction announced BIM is the key application technology of informatization in *"Ten new technologies of construction industry"* (by 2010) [14]. In Japan, the Ministry of Land, Infrastructure and Transport (MLIT) announced "Start of BIM pilot project in government building and repairs" (by 2010) [15]. In May 2011 UK Government Chief Construction Adviser Paul Morrell called for BIM adoption on UK government construction projects [16]. Today, BIM has been adopted worldwide, especially in the phase of design and construction. It is a trend for maintenance management.

BIM can benefit the information management in the structures' maintenance management. The 3D digital model itself can provide a lot of basic information such as geometric information, physical information, and material information. Then information generated during use stage can be paired between the assets in reality and objects' data in documents visually by sticking relative information into the 3D BIM model. The information contained by a visualized BIM model can be easily understood by entrained manager comparing with tables and written documents. It means the time and manpower costs can be saved with the use of BIM.

1.2 RESEARCH OBJECTIVES

The research aimed to improve the efficiency of maintenance management of civil infrastructure with various information technologies. The main goal of this research is to develop a visual and knowledge-based integrated information system. The system will assist a maintenance manager in fully understanding the condition of civil infrastructure including the deterioration condition, the repair history, the location, and so on, so that timely and practical maintain solutions can be determined. Specifically, the research was driven by the following objectives:

1) To eliminate the knowledge gap between experts who have gained the professional knowledge and non-experts who have little professional knowledge but need to use the knowledge.

2) To explore the visual platform of maintenance information for civil infrastructure. Integrating BIM into GIS to realize the visualization of the inner and outer environment for a civil infrastructure.

3) To establish the visual integration platform of maintenance information for civil infrastructure. Linkage of knowledge and information to the visual platform was supported, which includes electronical document information in various media formats, monitoring data transmitted back from the field in real time, expertise comes from experts, information generated during the maintenance implementation.

1.3 RESEARCH APPROACH

Following approaches are taken to complete the study:

- Literature review on the theory of maintenance management, durability analysis and informatization
- Exploring the principles of information integration platform, including functional requirement analysis, module implementation principle, platform development principles. This research applies the principles of grounded theory as well as conceptual structure of a proposed integrated information platform.
- Exploring the application principles and technical realization of knowledge management in maintenance management.
- Implementing a case study to explain the process of knowledge management.
- Development of the integrated information platform by using a series of information technology.

1.4 THESIS ORGANIZATION

Along with the objectives defined above, the thesis is organized through the following chapters:

Chapter 1 presents the background, objectives and approach and organization of this research.

Chapter 2 is literature survey of maintenance management, durability analysis and information system.

Chapter 3 proposes an integrated maintenance information platform. The structure of the platform and the realization principle of each module are described in detail, especially for visualization module.

Chapter 4 focuses on sharing the knowledge of concrete structures condition judgement caused by deterioration. Many analyses referred to expertise need to be performed to assess the deterioration condition. Two aspects of sharing need to be considered: The first is to remove the barriers to knowledge gap between different groups. The professional knowledge itself is shared from experts to non-experts (such as the actual executives of maintenance management), which makes non-experts possible to perform degradation analysis by simple operations. The second is to eliminate the space and time barriers of knowledge with the help of platform proposed in Chapter 3, in which users can use the visualized knowledge anytime and anywhere through network technology.

Chapter 5 deals with a case study to verify the knowledge sharing method proposed in this thesis.

Chapter 6 describes new findings and innovations during this research with conclusions. This chapter also describes the research contributions and limitations and it lists the proposed recommendations for further enhancements of the research.

2 LITERATURE STUDY

2.1 MAINTENANCE MANAGEMENT OF CIVIL INFRASTRUCTURE

Lifetime of civil infrastructure contains a series of stages: planning, design, construction, service and demolition. Normally the service duration for civil infrastructure can reach 50 to 100 years, some even exceed 100 years, maintaining the structure to satisfy the requirement of use is of great importance during the long period. The acts of maintaining the performance of a civil infrastructure within the allowable range during its service period is named maintenance. The ISO 15686-1 [17] defines maintenance as "combination of all technical and associated administrative actions during the service life to retain a building, or its parts, in a state in which it can perform its required functions".

It can be seen that maintenance is, essentially, a management problem concerned with issues of:

- Maintaining a defined quality of service
- Resources of people, materials and equipment
- Activities and procedures
- Location on the civil infrastructure
- Timing of interventions.

If maintenance is not implemented, the degradation process of a concrete structure is much more accelerated. According to Kurt [18], seven basic steps should be carried out for successful maintenance action: determine the cause(s) of damage; evaluate the extent of damage; evaluate the need to repair; select the repair method and material; prepare the existing concrete for repair; apply the repair method; cure the repair properly. It can be simply summarized as two core steps: condition judgement of the civil infrastructure and maintenance implementation. Based on the condition assessment of civil infrastructure, managers need to define the urgency of interventions and choose the appropriate maintenance options.

JSCE guidelines described maintenance process as Fig. 2-1. When a concrete structure is put into use, an initial maintenance plan is designed based on experience. With time goes by, the need for a maintenance action is primarily dictated to performance condition of the civil infrastructure. Maintenance decision for civil infrastructure needs to be decided based on condition assessment with the field inspection and professional analysis. Field inspection provide managers the visible defects of civil infrastructure or simple judgment, the investigations should be conducted timely, then professional analysis provides more in-depth judgment, such as safety analysis, serviceability analysis and durability analysis, etc. which can help managers understand the condition of concrete structure in detail, so as to make wise decision. Finally, the recording function provides good feedback information, which can be acted as the historical information of a structure.

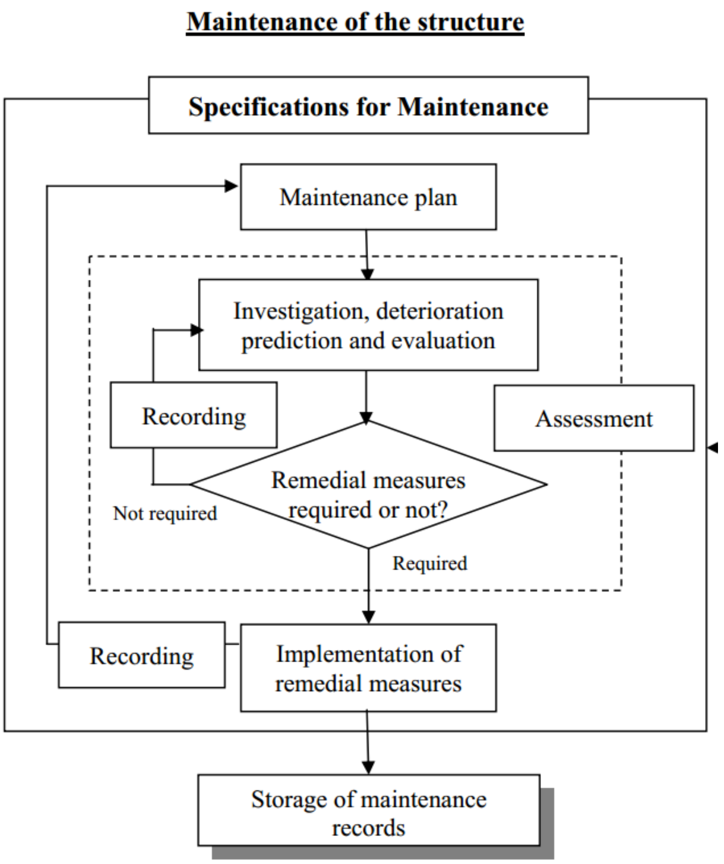


Fig. 2-1. Maintenance management process of structures.

Investigation information can provide us the macro performance of structures, before carrying out the repair strategy, the professional assessment should also be conducted for deep understand the mechanisms of defects, which is important information to help manager to make right decision. To evaluate the performance of an ordinary structure, a series of indexes such as safety, serviceability, durability and so on should be fully considered. For safety analysis, the mechanical analysis of structures can be made; for durability analysis, the deterioration mechanism should be made clear. For serviceability analysis, the social factor, economical factor, environmental factor, landscape, esthetic appearance etc. should be take into consideration. As we can see, every analysis is quite different in subject, therefore if the decision maker wants to make a deep understand of the influence factors, she should consulate experts of corresponding field one by one, which will absolutely cost a lot of time and energy. However, the problem for reinforcement concrete structure has commonality, such as deterioration caused by factors including carbonation, chloride attack, frost attack, chemical erosion, alkali-silica reaction, fatigue and abrasion and so on.

2.2 DURABILITY ANALYSIS OF CONCRETE STRUCTURES

Durability is mainly dealt with as the target for the maintenance management. Durability expresses the ability of the material to keep its original properties unchanged over time [19]. Usually structure with inadequate durability fails to reach its expected service life, thus generating a huge amount of maintenance cost every year. Furthermore, it also causes reduction in strength and may threaten the safety of the structure.

When it comes to durability assessment, deterioration is a major influencing factor. Deterioration can result in loss of strength and unsafe condition. Concrete structures deterioration typically occurs when the material is exposed to weather, water or chemicals over an extended period of time. For reinforcement concrete, corrosion of reinforcing steel is leading cause of deterioration in concrete. Concrete cover is acted as a physical protection barrier for reinforced steel, protecting it from corrosion. However, the concrete cover is not perfect due to the porous structures of concrete， combining with the physicochemical properties of the concrete (internal factor) and the atmosphere that it exposed to (external factor), aggressive species can enter into the steel/concrete interface by diffusion/transport, therefore initiating the corrosion of the reinforced steel. The volume of corrosion products formed, due to the presence of aggressive species, is about 4 to 6 times higher than the steel [20]. Therefore, the evolution of corrosion in RC structures causes forces of expansion in the vicinity of the metallic parts. This expansion creates tensile stresses in the concrete, which can eventually cause cracking, spalling, and delamination (Fig. 2-2).

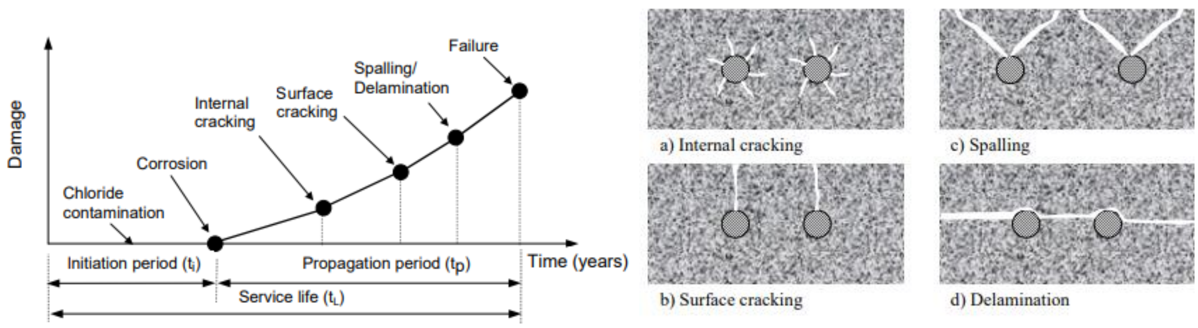


Fig. 2-2. Durability problem caused by deteriaration.

Deterioration of concrete structures is caused by a number of adverse factors. It can result in concrete degradation and reinforcement corrosion degradation as shown in Fig. 2-3.

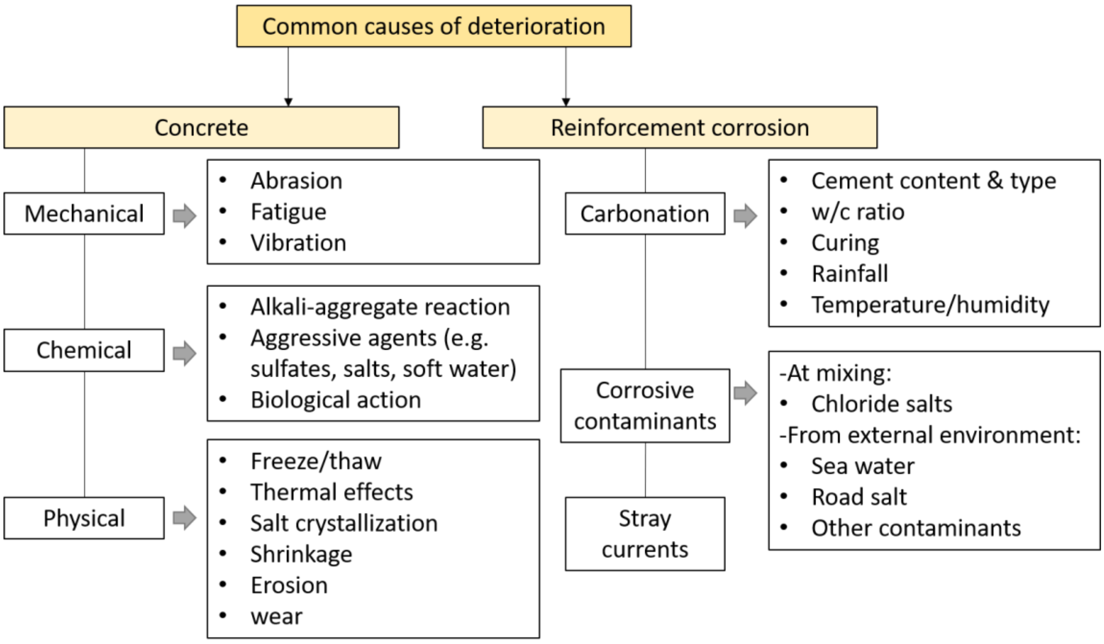


Fig. 2-3. Common deterioration for reinforcement concrete structures.

(1) Reinforcement corrosion

For corrosion of steel to occur, four elements must be present: There must be at least two metals (or two locations on a single metal) at different energy levels, an electrolyte, and a metallic connection. In reinforced concrete, the rebar may have many separate areas at different energy levels, which set up the electrochemical cell: anodic and cathodic regions occur. Porewater in the concrete acts as the electrolyte, and the metallic connection is provided by wire ties, chair supports, or the rebar itself.

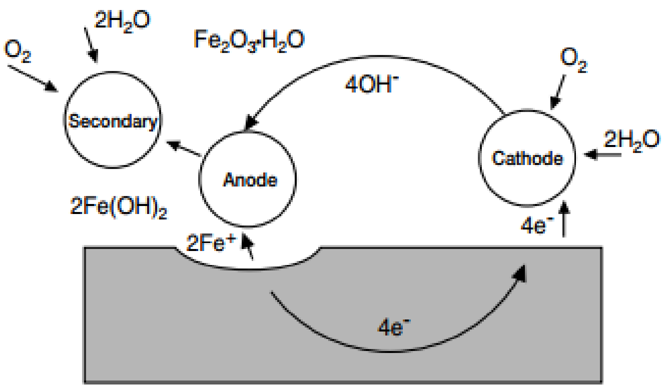


Fig. 2-4. Diagram of reinforcing steel corrodes.

Corrosion is an electrochemical process involving the flow of charges (electrons and ions). Fig. 2-4 shows a corroding steel bar embedded in concrete. At active sites on the bar, called anodes, iron atoms lose electrons e^- and move into the surrounding concrete as ferrous ions Fe^{2+}. This process is called a half-cell oxidation reaction, or the anodic reaction, and is represented as:

$$\mathbf{2Fe \rightarrow 2Fe^{2+} + 4\boldsymbol{e}^-}$$

The electrons remain in the bar and flow to sites called cathodes, where they combine with water and oxygen in the concrete. The reaction at the cathode is called a reduction reaction. A common reduction reaction is:

$$\mathbf{2H_2O + O_2 + 4\boldsymbol{e}^- \rightarrow 4OH^-}$$

To maintain electrical neutrality, the hydroxyl ions (OH^-) migrate through the concrete pore water to these anode sites where they combine with the ferrous ions to form ferric hydroxide, which is converted by further oxidation to rust:

$$\mathbf{Fe^{2+} + 2OH^- \rightarrow Fe(OH)_2 \ \ (ferrous\ hydroxide)}$$

$$\mathbf{4Fe(OH)_2 + 2H_2O + O_2 \rightarrow 4Fe(OH)_3 \ \ (ferric\ hydroxide)}$$

This initial precipitated hydroxide tends to react further with oxygen to form higher oxides. The increases in volume as the reaction products react further with dissolved oxygen leads to internal stress within the concrete that may be sufficient to cause cracking and spalling of the concrete cover.

steel embedded in concrete does not corrode because the concrete provides reinforcing steel a benign, corrosion-free environment. The Portland cement provides the steel a high pH, or alkaline, environment. In the alkaline cement, carbon steels are passive to corrosion and their behavior is similar to that of stainless steels. Alkaline environment of concrete (pH of 12 to 13) provides steel with corrosion protection. At the high pH, a thin oxide layer forms on the steel and prevents metal atoms from dissolving. This passive film in concrete reduces the corrosion rate of steel to an insignificant level. For steel in concrete, the passive corrosion rate is typically 0.1 µm per year. Without the passive film, the steel would corrode at rates at least 1,000 times higher [21]. The destruction of the passivating layer occurs when the alkalinity of the concrete is reduced or when the chloride concentration in concrete is increased to a certain level.

Chloride ion induces the depassivation of steel reinforcement in concrete and accelerates the corrosion process. Chloride ions can activate the surface of the steel to form an anode, the passivated surface being the cathode. The reactions involved are as follows:

$$Fe^{2+} + 2Cl^{-} \rightarrow FeCl_2$$

$$FeCl_2 + 2H_2O \rightarrow Fe(OH)_2 + 2HCl$$

Chloride ion penetration into concrete by transport of water solution, as well as by diffusion of the ions in the water, and by absorption. Prolonged or repeated ingress over time can result in a high concentration of chloride ions at the surface of the reinforcing steel, leading to corrosion of steel as shown in Fig. 2-5.

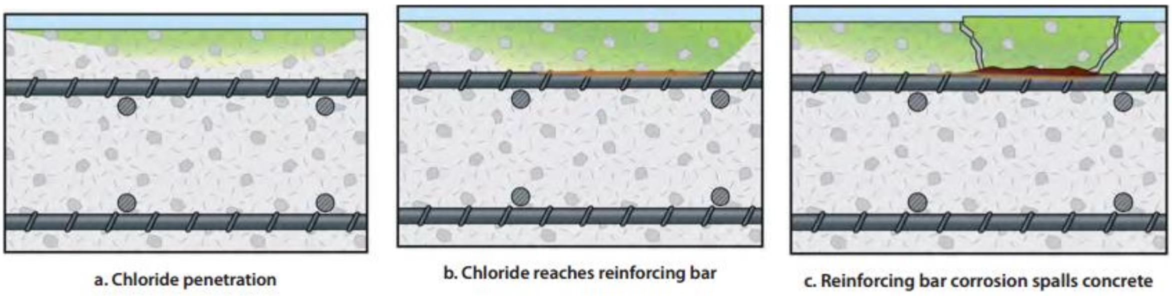


Fig. 2-5. Chloride ion-induced corrosion of reinforced concrete structures [22].

Carbonation occurs when carbon dioxide (CO_2) from air penetrate the concrete and reacts with hydroxides, such as calcium hydroxide ($Ca(OH)_2$), to form carbonates. calcium carbonate (CaCO3). Thus, the alkalinity is reduced, and the pH of the pore solution falls from 13 to about 9 [23]. If the pH of the pore solution falls below 11, the protective function of the concrete cover disappears, and the steel is exposed to corrosion. Carbonation is highly dependent on the relative humidity of the concrete. The highest rates of carbonation occur when the relative humidity is maintained between 50% and 75%. Below 25% relative humidity, the degree of carbonation that takes place is considered insignificant. Above 75% relative humidity, moisture in the pores restricts CO_2 penetration [24]. Carbonation-induced corrosion often occurs on areas of building facades that are exposed to rainfall, shaded from sunlight, and have low concrete cover over the reinforcing steel as shown in Fig. 2-6.

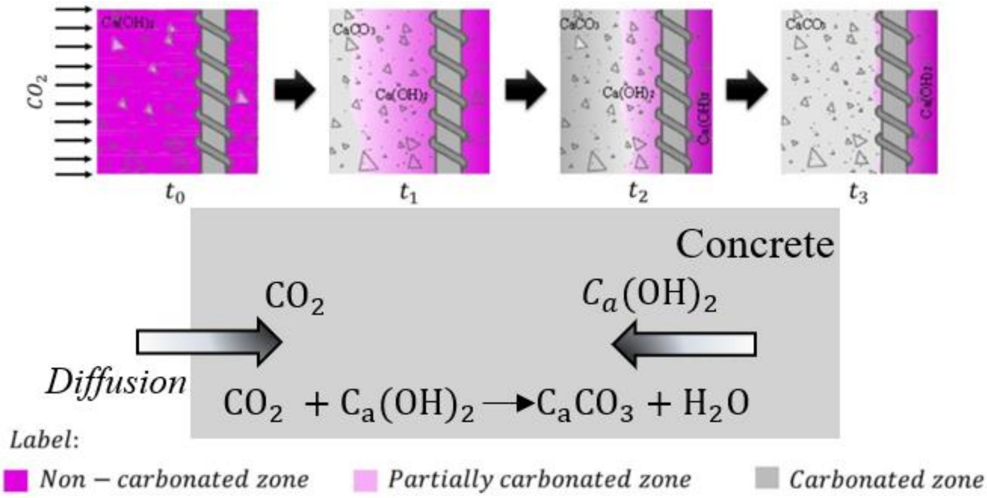


Fig. 2-6. Schematic representation of the carbonation of concrete [25].

(2) Concrete degradation

freeze-thaw deterioration: When water freezes, it expands about 9%. As the water in moist concrete freezes, it produces pressure in the capillaries and pores of the concrete. If the pressure exceeds the tensile strength of the concrete, the cavity will dilate and rupture. The accumulative effect of successive freeze-thaw cycles and disruption of paste and aggregate can eventually cause significant expansion and cracking, scaling, and crumbling of the concrete as shown in Fig. 2-7. D-cracking is a form of freeze-thaw deterioration that has been observed in some pavements after three or more years of service. Due to the natural accumulation of water in the base and subbase of pavements, the aggregate may eventually become saturated. Then with freezing and thawing cycles, cracking of the concrete starts in the saturated aggregate at the bottom of the slab and progresses upward until it reaches the wearing surface. Aggregate freeze-thaw problems can often be reduced by either selecting aggregates that perform better in freeze-thaw cycles or, where marginal aggregates must be used, reducing the maximum particle size. Concrete with low permeability is better able resist the penetration of water and, as a result, performs better when exposed to freeze-thaw cycles. The permeability of concrete is directly related to its water-to-cement ratio—the lower the water to-cement ratio, the lower the permeability of the concrete.

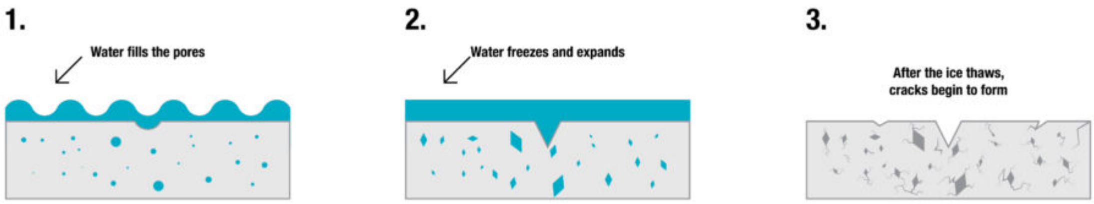


Fig. 2-7 the freeze-thaw theory [26].

Chemical attack: Some chemical environments can deteriorate even high-quality concrete. Aggressive chemicals must be in solution and above minimum concentration to produce significant attack on concrete. Some of the chemical attack are listed as follows:

(1) Acids: in general, Portland cement concrete does not have good resistance to acids. Acids react with the calcium hydroxide of the hydrated Portland cement.

(2) Salts and alkalis: The chlorides and nitrates of ammonium, magnesium, aluminum, and iron all cause concrete deterioration, with those of ammonium producing the most damage. Most ammonium salts are destructive because, in the alkaline environment of concrete, they release ammonia gas and hydrogen ions. These are replaced by dissolving calcium hydroxide from the concrete. The result is a leaching action, much like acid attack. Strong alkalies (over 20 percent) can also cause concrete disintegration ([27]).

(3) Sulfate attack: Sulfates can attack concrete by reacting with hydrated compounds in the hardened cement. These reactions can induce sufficient pressure to disrupt the cement paste, resulting in loss of cohesion and strength.

(4) Calcium sulfate attacks calcium aluminate hydrate and forms ettringite.

(5) Sodium sulfate reacts with calcium hydroxide and calcium aluminate hydrate forming ettringite and gypsum.

(6) Magnesium sulfate attacks in a manner similar to sodium sulfate and forms ettringite, gypsum, and brucite (magnesium hydroxide). Brucite forms primarily on the concrete surface, consumes calcium hydroxide, lowers the pH of the pore solution, and then decomposes the calcium silicate hydrates.

To prevent deterioration from chemical attack, Portland cement concrete generally must be protected from chemical environments with surface protective treatments. Unlike limestone and dolomitic aggregates, siliceous aggregates are acid-resistant and are sometimes specified to improve the chemical resistance of concrete, especially with the use of chemical-resistant cement. Properly cured concrete with reduced permeability experience a slightly lower rate of attack from chemical ions.

Alkali-aggregate reactivity: In most concrete, aggregates are more or less chemically inert. However, some aggregates react with the alkali hydroxides in concrete, causing expansion and cracking over a period of years. This alkali-aggregate reactivity has two forms—alkali-silica reaction (ASR) and alkali-carbonate reaction (ACR). ASR is of more concern than ACR because aggregates containing reactive silica materials are more common.

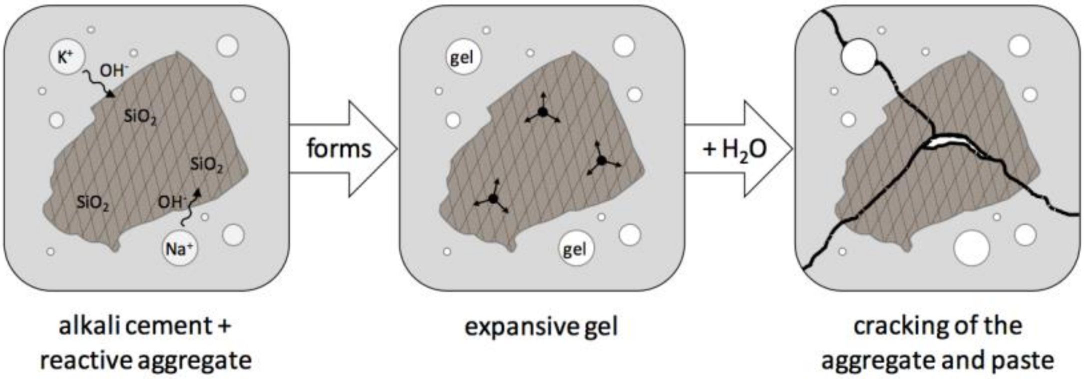


Fig. 2-8. schematic representation of alkali-silica reaction in concrete [28].

The conceptual model for ASR is shown schematically in Fig. 2-8, which was taken from Deschenes et al. [28]. Inside the concrete are reactive aggregates containing siliceous or microcrystalline silica phases. The hydroxyl (OH-) and alkali species (e.g., K+ and Na+) are in solution and react with the siliceous phases to form an expansive hydroscopic gel. As the gel absorbs water, it expands, generating stresses that can be in excess of 10 MPa [29]. These stresses are sufficient to generate cracking, both in the aggregate and in the surrounding hardened cement paste and can even cause macroscopic expansion of the structure.

1) Aggregates containing certain forms of silica will react with alkali hydroxide in concrete to form a gel that swells as it draws water from the surrounding cement paste or the environment. In absorbing water, these gels can swell and induce enough expansive pressure to damage concrete:

1. Alkalies + Reactive Silica → Gel Reaction Product

2. Gel Reaction Product + Moisture → Expansion

Typical indicators of alkali-silica reactivity are map (random pattern) cracking and, in advanced cases, closed joints and spalled concrete surfaces. Cracking usually appears in areas with a frequent supply of moisture, such as close to the waterline in piers, from the ground behind retaining walls, near joints and free edges in pavements, or in piers or columns subject to wick action. The reactivity can be virtually stopped if the internal relative humidity of the concrete is kept below 80%.

Alkali-silica reactivity can be controlled using certain mineral admixtures. Silica fume, fly ash, and ground-granulated blast furnace slag have significantly reduced alkali-silica reactivity. Class F fly ashes have reduced reactivity expansion up to 70% or more in some cases. In some cases, lithium compounds have been shown to effectively reduce ASR.

Dedolomitization, or the breaking down of dolomite, is normally associated with expansive alkali-carbonate reactivity (ACR). This reaction and subsequent crystallization of brucite may cause considerable expansion. The deterioration caused by alkali-carbonate reaction is similar to that caused by alkali-silica reaction; however, alkali carbonate reaction is relatively rare because aggregates susceptible to this reaction are less common and are usually unsuitable for use in concrete for other reasons, such as strength potential.

Abrasion/erosion: Abrasion damage occurs when the surface of concrete is unable to resist wear caused by rubbing and friction. As the outer paste of concrete wears, the fine and coarse aggregate are exposed, and abrasion and impact will cause additional degradation that is related to aggregate-to-paste bond strength and hardness of the aggregate. Although wind-borne particles can cause abrasion of concrete, the two most damaging forms of abrasion occur on vehicular traffic surfaces and in hydraulic structures, such as dams, spillways, and tunnels.

Fire/ heat: when exposed to fire or unusually high temperatures, concrete can lose strength and stiffness. Numerous studies found that concrete that undergoes thermal cycling suffers greater loss of strength than concrete that is held at a constant temperature; Concrete that is under design load while heated loses less strength than unloaded concrete, the theory being that imposed compressive stresses inhibit development of cracks that would be free to develop in unrestrained concrete; Concrete containing limestone and calcareous aggregates performs better at high temperatures than concrete containing siliceous aggregates [30].

2.3 INFORMATION SYSTEM OF MAINTENANCE MANAGEMENT

Information is an essential resource for setting and meeting management objectives, the role it plays within the organization is of vital importance as it helps to build knowledge and measures the overall performance of the organization. Getting appropriate and reliable information about a structure (e.g. design information, construction data, inspection data, analysis results, etc.) is pivotal for enabling maintenance managers to support decision making, planning and execution of activities, particularly during service period.

There is no doubt that information is the guarantee for efficient management. Maintenance management for concrete structure is faced with the problems of large number of participants, long management period, diverse information and so on. Therefore, issues need to be considered including how to efficiently promote information exchange and knowledge sharing among different participants from different backgrounds, and how to preserve the information for a long time. As a result, information systems (IS) which can integrate varies of information are used to supply support to the operation of maintenance management. The role of information system as component for interaction with user enables people to update information and immediately retrieve information and it is a special important for maintenance management. Conventional methods (paper-based reports/unsystematic database) for information system restrict managers from being involved in the knowledge sharing in expertise and are difficult to retrieve information.

New information technologies bring us improvement toward job and live. There are many studies focusing on improving the information management by information system in maintenance management of civil structures. Hamzah et al. [31] built up an integrated system to record, diagnose and analyze information, and also built up a decision-making support system in diagnosis in building maintenance. Liu et al. [32] proposed the concept of integrate knowledge in building information modeling (BIM) to improve information management.

Simultaneously, scholars are starting to pay more attention towards the study of BIM-based information management systems. Building Information Modelling (BIM) enabled approach that allows design integrity, virtual prototyping, simulations, distributed access, retrieval and maintenance of the building data. BIM simulates an accurate virtual model of a building digitally. This model contains precise information to allow collaborative, improving communication, improving service delivery, improving commutation among participants in different stages of an infrastructure project – design, procurement, fabrication, construction and even operation and maintenance activities. (BIM) is “an IT enabled approach that involves applying and maintaining an integral digital representation of all building information for different phases of the project lifecycle in the form of a data repository” [33]. It is a set of ICT technologies able to insert, extract, update or modify information of the facility model, and supports stakeholders’ collaboration over the project’s life cycle as shown in Figure 2-9. It is expected that in an ideal BIM project the different stakeholders such as the designers, client, contractors, subcontractors and suppliers can work with a shared BIM and access the latest information. The use of a shared database in BIM can ensure that the different model views and data can be checked and updated for consistency and conflict resolution. The model can be used to demonstrate the entire building lifecycle from conceptual design to demolition.

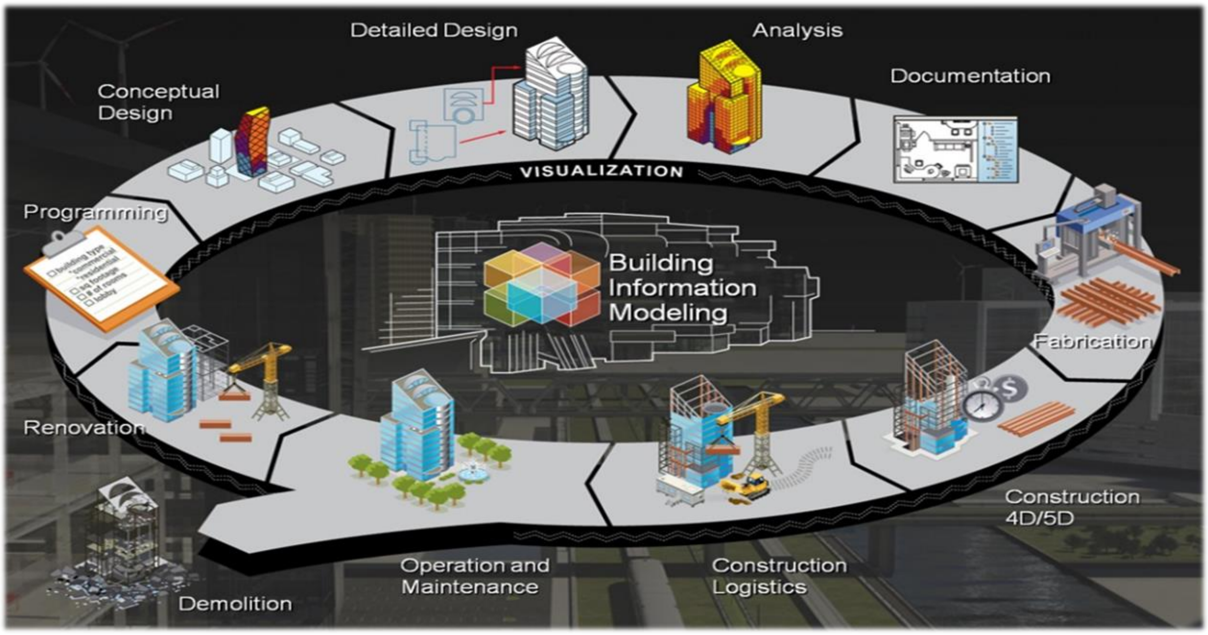


Fig. 2-9. BIM project's life cycle application (Source: smrtenr.com [34]).

BIM can provide a visual environment with 3D model for the information system in the maintenance management of concrete structures. BIM collaboration platform is expected to be the source of all the project information linked through a shared database. A BIM collaboration platform offers the maintenance manager all the necessary working tools free access to all the essential project information by using technology to integrate the various information involved in the project. Such as:

- An electronic document management system for an easily retrievable historical record for project;
- A persistent follow-up or tracking system for an accurate real-time update of available information to ensure that project preforms well under monitoring;
- A knowledge-based or expert system useful for knowledge exchange;

3 MAINTENANCE INFORMATION PLATFORM

3.1 INTRODUCE

Maintenance management of civil infrastructure is a difficult and complicated work because maintenance period is long, and a lot of information is likely to be generated [35]. Managing maintenance information contributes to successful maintenance management. Traditional information storage and treatment were based on hardcopy documents in a scattered and invisible manner with little or no linkage to the real assets visually.

Managers need to manually retrieve information from massive paper drawings and documents, and then match to the spatial locations according to the description in the documents, which results in difficulty and inefficiency of information retrieval. Quickly accessing comprehensive information at the right time is very difficult to achieve and this has led professional institutions to stress the need or quality assurance procedures which could assist in creating an organised pool of information. With the development of information technology, information management system that links information in form of electronic documents with visible physical models is widely concerned as the most effective way of manipulating information. Electronic management of information with visualization through the use of IT is allowing users/managers to store and retrieve information easily, gain faster, complete and accurate responses, and to be better informed of the relevant issues.

Many countries have developed or are developing information platform for bridge management systems. Among the most widely known computerised bridge management systems are Pontis [7, 36, 37]. These systems improving management efficiency by providing an integration of information in the service period, but the lack of linkage between information and actual items is still problem.

With the introduction of information technology in the construction industry, the visual digital model led by BIM provides more efficient cooperation and management for the entire life cycle of the project. The goal for BIM is to help relevant parties involved in maintenance management to make use of the reality-modeled data. Many researchers also try to introduce BIM in maintenance management. Akcameter, et al. [38] stresses the possibility of using Information Communication Technologies (ICT) systems (such as BIM) to retrieve past project information quickly. The increased interest in both building and facility management information. Su [39] proposed a BIM based Facility Management (BIMFM) system to track and manage the related maintenance information in the 3D environment. Ahn [40] mentioned that information should be embedded in 3D model to effectively feedback to maintenance stage.

An information platform is a software that attempts to provide complete information in maintenance phase. It will help you to effectively manage maintenance by organizing and tracking the myriad of data required to run maintenance operations effectively. The 3D model created by BIM serves as an interdependent, multi-disciplinary data repository on integrating information from design to demolition. A good maintenance program will involve regularly scheduled inspections. Suspect areas should be monitored. Photographs and notes should be collected and stored to establish a record that can be reviewed later. Photogrammetric or other methods to generate three dimensional (3D) models of the condition of civil infrastructure can provide valuable information. The information can be used to relatively easily quantify the progression of damage, changes in cracking, or movement of slabs and walls.

This paper proposes a new and practical method to manage information by using Building Information Modeling (BIM), Geographic Information System (GIS) and database technology. A visual integration information platform is developed, in which BIM and GIS are integrated to create multiscale and multiple precision visualization environment, while the maintenance information including expertise is stored in database in the form of electronic documents and linked to the corresponding location in the visualization models.

3.2 FRAMEWORK OF INFORMATION PLATFORM

3.2.1 Industry survey

An industry survey has been conducted to discuss the current demand on information management platform development at August 2, 2018. Participants in different industries expressed their needs: Mr Kazutoshi Shizukuishi (maintenance consultant, Docon) believed that it is important to gather all the information especially for information importance for maintenance decision together by information management tool. Dr. Yoshihiko Fukuchi from Autodesk company thought that it is necessary to develop an integrated information platform with different source of information targeted for maintenance management independently. Dr. Yasuo Fujisawa (CIM promotion office) pointed out that it is necessary to manage data by adopting the concept of Construction Information Modeling (CIM) when developing the platform, that is, to enable integrated information management with relevance of 3D model. Ms. Miss Nakamura Misako (maintenance consultant, Docon) considered that it is also necessary to consider introducing 3D map into the platform. Therefore, this research will focus on developing such an integrated information platform for maintenance management.

3.2.2 Function requirements analysis

Multiscale and multiple precision visualization environment which can reflect the real civil infrastructure can advance maintenance management. 3D model created by BIM can provide the indoor environment of civil infrastructure, here the benefits of using BIM would be having real-time facility related information in an visual integrated form so that maintenance operators and managers have a more holistic understanding of what is happening throughout the life cycle of civil infrastructure. Outdoor environment as a supplement to visualization also shows an important role that cannot be ignored. For example, there are relationships between the external environment and deterioration mechanisms of concrete structures as shown in Table 3-1. Therefore, it is also helpful for better maintenance management to know the geographical location of the concrete structure.

Table 3-1. Possible deterioration mechanisms relation to the location, environmental condition and service condition of the structure.

Extrinsic deterioration factor		Possible deterioration mechanisms
Location of the structure	Coastal area	Chloride induced deterioration
	Cold district	Frost attack Chloride induced deterioration
	Spa	Chemical attack
Environmental conditions and service conditions of the structure	Cyclic wetting and drying	Alkali-silica reaction Chloride induced deterioration Frost attack
	Use of de-icing salt	Chemical attack Alkali-silica reaction
	Cyclic loading	Fatigue Abrasion
	Carbon dioxide	Carbonation
	Acidic water	Chemical attack
	Flowing water, vehicles, etc.	Abrasion

BIM technology has great shortcomings in precise geographic location, spatial geographic information analysis and overall display of the surrounding environment of structures. The three-dimensional GIS can complete the geographic location of the structure and its spatial analysis, and it can improve the display of the large scene, ensure the integrity of the information, and make the information more comprehensive.

GIS is an organized collection of computer hardware, software and geographic data designed to efficiently capture, store, update, manipulate, analyze, and display all forms of geographically referenced information. GIS can significantly enhance an information management platform by providing the ability to access, use, display, and manage spatial data. The ability to effectively use spatial asset data is important for maintenance management of civil infrastructure with geographically dispersed. Field crews that maintain civil infrastructure rely on maps to get to the location of civil infrastructure problems. Maps are often developed and published with GIS. However, printed map atlases are notorious for being out of date and having missing pages. The ability to include current and accurate map with work orders can greatly increase the efficiency of the field crews. In general, full visualization of the real asset should be built up by using BIM to provide indoor environment with high level of detail and using GIS to have a wider span focusing on the entire outdoor environment. BIM+GIS in the information platform is acted as an information repository container and offers the reality model with maps, which can track the location of parts what needs to be maintained.

During the lifetime of civil infrastructure, it will inevitably generate a variety of information, including design drawings, construction plans, material properties, maintenance history, etc. This information comes from different period and many sources. A place where information can be continuously stored and retrieved is necessary. The traditional method is to establish a file room. The information is stored in the form of a paper document independent of the visualization model, which will cause a large amount of information loss and retrieval difficulties. Currently, information is carried by different media formats, including video, sound, animation, etc., which cannot be accurately recorded by using only paper documents. There is necessary to build up the integration electronic document information where information can be associated with visual model and information can be upgraded with time.

Maintenance activities is mainly determined according to the performance of the structure. Early damage detection is particularly important because it leads to appropriate and timely interventions. If the damage is not detected, it continues to propagate, and the structure no longer guarantees required performance levels. Late detection of damage results in either very elevated refurbishment costs or, in some cases, the structure has to be closed and dismantled. Structural Health Monitoring technology has emerged as an increasingly important tool in Civil Engineering to timely understand how structures behave during service phase. Monitoring allows to increase the safety margins without any intervention on the structure. Monitoring during service can provide timely information related to structural behavior in-situ. Monitoring data can help engineers better estimate actual performance and is useful for damage detection, evaluation of safety and determination of the residual capacity of structures, so that more appropriate remedial measures can be taken. Monitoring data can be integrated in maintenance management systems and increase the quality of decisions by providing reliable and unbiased information.

Efficient management requires a lot of information. For maintenance management of civil infrastructure, there is requirement that integrate information from different people, such as on-site staffs feedback inspection data, and then the experts conduct professional analysis based on these data. Both of the inspection data and analysis results can be used to assist manager with correctly and comprehensively understanding the structures condition, so as to make the optimized maintenance decision. This information is dynamically upgraded as well as comes from different software that different analysis needs different simulation software. Improved data-exchange method is needed to allow full interoperability of data from many information systems. It can promote the exchange and cooperation of different specialties.

In short, the function requirements can be concluded as follows:

(1) Achieve the multi-scale visualization during the management by integrating BIM with GIS. It makes the information system easy to understand and easy to grasp for people. It stores maintenance information in a proper digitized format such as image, data, or file, and links information to the 3D model of the civil infrastructure.

(2) Have a unified electronic document database. The database of the information system should support different kinds of data. Information should have the same coding rule so that all data can be searched, retrieved, and analyzed. It will finally allow the maintenance team to view the historical information faster by filling-up the electronic-form even after a long time.

(3) Realize the function of structural inspection and monitoring. Condition of the civil infrastructure reveals the safety of the structures. Structural inspection, health monitoring, as well as the performance evaluation are therefore the most important in the management system.

(4) Realize the collaborative management of information from different information systems. By collaborating, all people with different jobs work together; collaborative management is a key issue to increase the efficiency of the management.

3.2.3 Structure of the information system

Information system is becoming an important tool for achieving efficiency and effectiveness within maintenance, providing the relevant and complete information for manager to understand the condition of civil infrastructure. The proposed system includes 4 modules: 3D model visualization module provides the visual environment as the carriers of information; Electronic document information module provides efficient management of electronic documented information as an archive rooms; Real-time monitoring provides on-site dynamic monitoring results; Research results provides professional analysis sharing from different specialties and software; shown in Fig. 3-1.

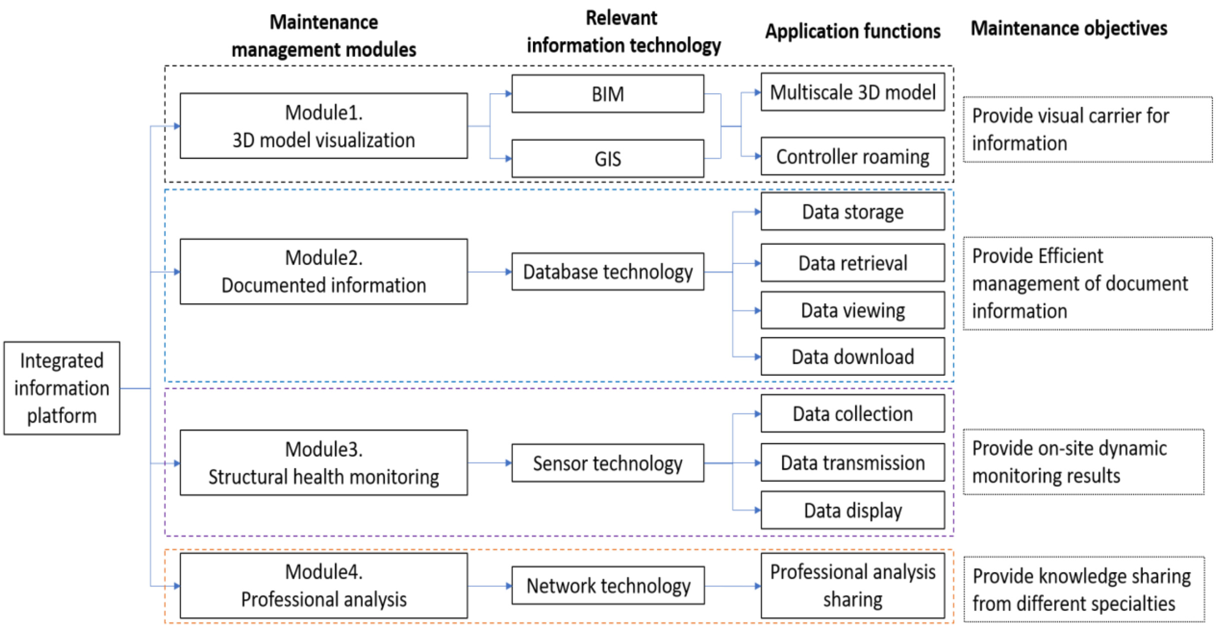


Fig. 3-1. Structure of the integrated information platform.

3.3 DESIGN OF EACH MODULE

3.3.1 Visualization module

A BIM is a digital tool for describing 3D object-oriented CAD, which contains precise geometry and relevant data to support the generation and management of project data during the life cycle [41]. BIM is widely accepted as one of the major technological advances that has increasingly impacted the construction industry over the years. GIS is an organized collection of computer hardware, software and geographic data designed to efficiently capture, store, update, manipulate, analyze, and display all forms of geographically referenced information. In general, BIM provides indoor environment with high level of detail while GIS has a wider span focusing on the entire outdoor environment. Integration of BIM and GIS provides the power to build a robust real-world context model where geographic information and infrastructure data are brought together, helping to better understand how civil infrastructure interact within the context of a real place and geography.

Integration of BIM and GIS is not a novel idea. However, these two data formats hold different kinds of information at different data structures and data standards, which eventually leads to interoperability issues. BIM models use different proprietary data formats depending on the software series, such as models of Autodesk Revit series are stored in the *.rvt file format, models of Bentley MicroStation series uses the *.dgn file format; and models of Catia series products use *.catPart. Different GIS information systems support different data formats: ArcGIS platform supports “Shapefiles”, “Coverage”, and “E00” file formats; MapInfo platform supports “MIF” file format and “Tab” file format; SuperMap/ MapGIS supports “VCT”, etc. [42]. Therefore, integration of BIM and GIS needs to consider the fusion of two different data formats.

Files of BIM and GIS shows difference in many places.

(1) Difference in geometries. Industry Foundation Classes (IFC), as a universal data model standard (ISO 16739) in the field of BIM, is the most comprehensive and detailed specification for building information description as well as main exchange format for BIM files, enabling data between different model formats to be shared and interoperable [43]. The organization of building model in IFC described by Unified Modelling Language (UML) is shown in Fig. 3-2 [44].

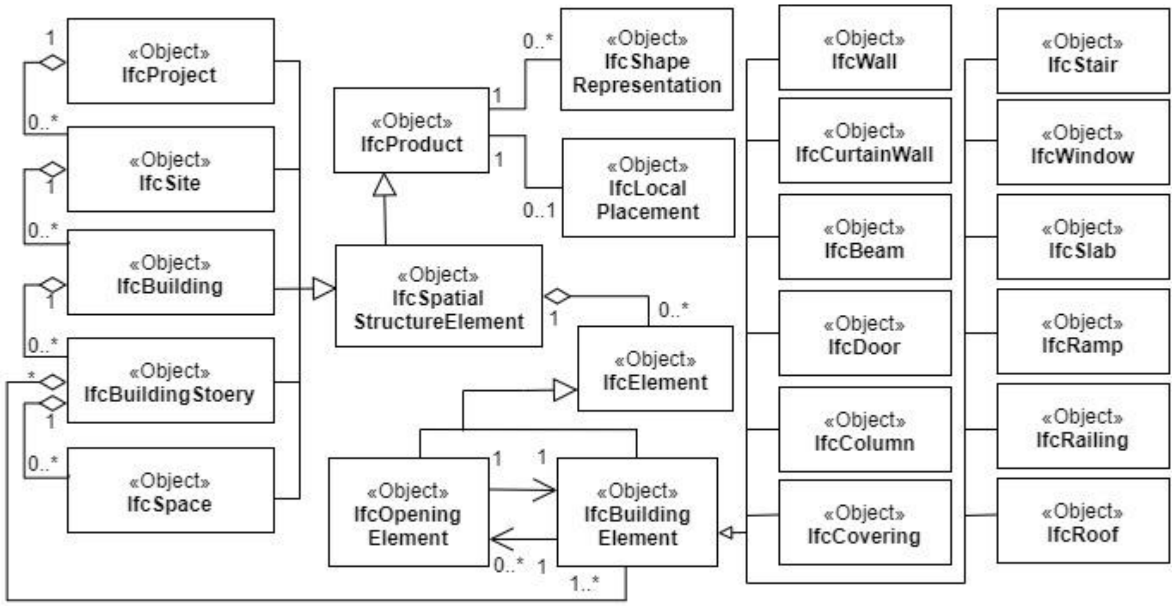


Fig. 3-2. IFC building model.

CityGML has been developed as a common semantic information model representing different 3D urban and geographical objects that can be shared among different GIS applications ([45]). UML for the CityGML building model is shown in Fig. 3-3.

From Figs. 3-2 and 3-3, we can see the difference of geometric expression of BIM and GIS: the model of BIM is organized as an element-based volume model while that of GIS is organized as a surface model. It is necessary to convert the geometries between the two data formats.

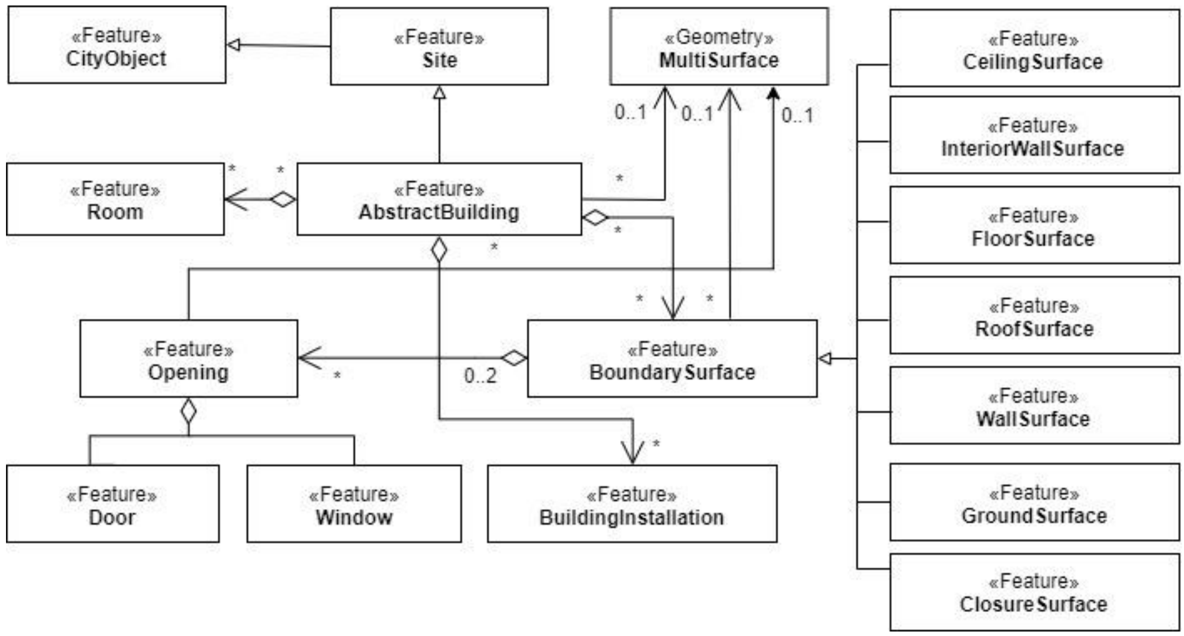


Fig. 3-3. CityGML building model.

(2) Difference in semantic information. The model of BIM contains rich of semantic information (referring to non-geometric characteristics and relationships among the entities) for building components including shape representation, spatial positioning, topological relationships, and attributes information and so on. Semantic information in different storage structures between BIM and GIS. BIM defines attributes information by defining attribute sets, and links attribute sets with building components or other entities directly, while attribute information in the GIS is defined by tags in xml format (Extensible Markup Language). For example, GIS defines the classification function and actual use of building through "class', 'function', 'usage' and other fields, and then adds the corresponding attribute information in the sample document. It is necessary to convert the semantic information between the two data formats.

(3) Difference in coordinate system. BIM and GIS support different coordinate systems (Table 3-2). Generally, BIM adopts a spatial rectangular coordinate system where the coordinate origin is selected based on the project, which is also regarded as a relative coordinate system describing the relative spatial position of project components. GIS uses a unified absolute coordinate system and a geodetic coordinate system for determining the spatial geographic location for project [46].

Table 3-2. Different coordinate systems.

BIM	**GIS**
relative coordinate system	absolute coordinate system
spatial rectangular coordinate system	geodetic coordinate system

There are two steps required to convert a coordinate system in BIM to that in GIS.

Firstly, a relative coordinate system is converted into absolute coordinate system in BIM by coordinate rotation and translation. Point p (x, y, z) is a point in original coordinate system and p' (x', y', z') is the corresponding point in the new coordinate.

1) Conversion by coordinate translation: t_x, t_y, and t_z, are the translation distances in the x, y, z directions, respectively.

$$\begin{bmatrix} x' \\ y' \\ z' \\ 1 \end{bmatrix} = \begin{bmatrix} 1 & 0 & 0 & t_x \\ 0 & 1 & 0 & t_y \\ 0 & 0 & 1 & t_z \\ 0 & 0 & 0 & 1 \end{bmatrix} \cdot \begin{bmatrix} x \\ y \\ z \\ 1 \end{bmatrix}$$

$$p' = T(t_x, t_y, t_z) \cdot p$$

2) Conversion by coordinate rotation: θ is an angle of rotation in counterclockwise direction.

Rotation around the Z axis:

$$\begin{bmatrix} x' \\ y' \\ z' \\ 1 \end{bmatrix} = \begin{bmatrix} \cos\theta_z & -\sin\theta_z & 0 & 0 \\ \sin\theta_z & \cos\theta_z & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix} \cdot \begin{bmatrix} x \\ y \\ z \\ 1 \end{bmatrix}$$

$$p' = R_z(\theta_z) \cdot p$$

Rotation around the Y axis:

$$\begin{bmatrix} x' \\ y' \\ z' \\ 1 \end{bmatrix} = \begin{bmatrix} \cos\theta_y & 0 & \sin\theta_y & 0 \\ 0 & 1 & 0 & 0 \\ -\sin\theta_y & 0 & \cos\theta_y & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix} \cdot \begin{bmatrix} x \\ y \\ z \\ 1 \end{bmatrix}$$

$$p' = R_y(\theta_y) \cdot p$$

Rotation around the X axis:

$$\begin{bmatrix} x' \\ y' \\ z' \\ 1 \end{bmatrix} = \begin{bmatrix} 1 & 0 & 0 & 0 \\ 0 & \cos\theta_x & -\sin\theta_x & 0 \\ 0 & \sin\theta_x & \cos\theta_x & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix} \cdot \begin{bmatrix} x \\ y \\ z \\ 1 \end{bmatrix}$$

$$p' = R_x(\theta_x) \cdot p$$

Then, it comes to convert a spatial rectangular coordinate system in BIM to geodetic a coordinate system in GIS. The WGS-84 (World Geodical System-84) coordinate system is a current geodetic coordinate system used by GPS. The coordinate origin of WGS 84 is meant to be located at the Earth's center of mass; The WGS 84 meridian of zero longitude is the IERS Reference Meridian, 5.3 arc seconds or 102 metres east of the Greenwich meridian at the latitude of the Royal Observatory. The WGS 84 datum surface is an oblate spheroid [47]. T (X, Y, Z) is a point in the spatial rectangular coordinate system, and T' (L, B, H) is the corresponding point in the geodetic coordinate system as shown in Fig. 3-4. In this coordinate system, the position of point T' is represented by L, B and H referring to the longitude, latitude, and altitude, respectively.

The conversion formula of the space geodetic coordinate system to the spatial rectangular coordinate system is as follows:

$$\left.\begin{array}{l} X = (N + H)\cos B \cos L \\ Y = (N + H)\cos B \sin L \\ Z = [N(1 - e^2) + H]\sin B \end{array}\right\}$$

Where $N = \frac{a}{\sqrt{1 - e^2 \sin^2 B}}$ is the radium of curvature of the first vertical; a=6378.137km is the semimajor axis of the ellipsoid; $e = \frac{\sqrt{a^2 - b^2}}{a}$, the first eccentricity of the ellipsoid; b=6356.7523141 is the semiminor axis of the ellipsoid [48].

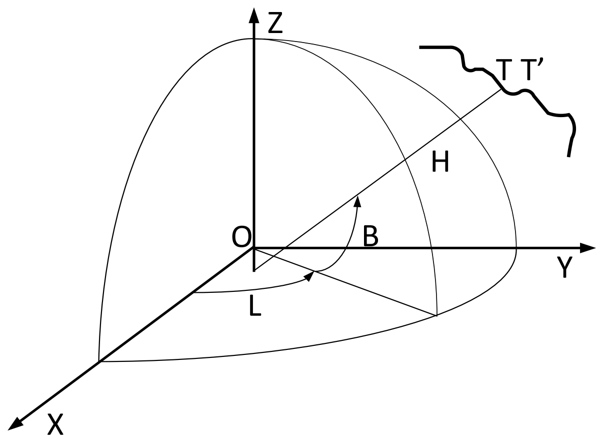


Fig. 3-4. Spatial rectangular coordinate system and geodetic coordinate system

In summary, to realize the transformation and fusion of BIM and GIS models, we need to consider transformation of geometry, semantics and coordinate systems.

BIM and GIS belong to two different data formats, and the conversion methods, including three methods based on programming as shown in Fig. 3-5.

1) External data exchange mode: An operator writes a program to read the graphic data and attribute data in the source data file and writes it into the target file to implement data format conversion. To use this method for data format conversion, the operator needs to be familiar with the two data formats that are converted to each other.

2) Universal data file mode: The data of all different systems are converted into a unified standard format, which is used by different systems through this intermediate bridge bidirectionally.

3) Direct data access mode: The target software access to the data format of original software by using a data reading function, which can directly convert internal data files of one system into internal data files of another system.

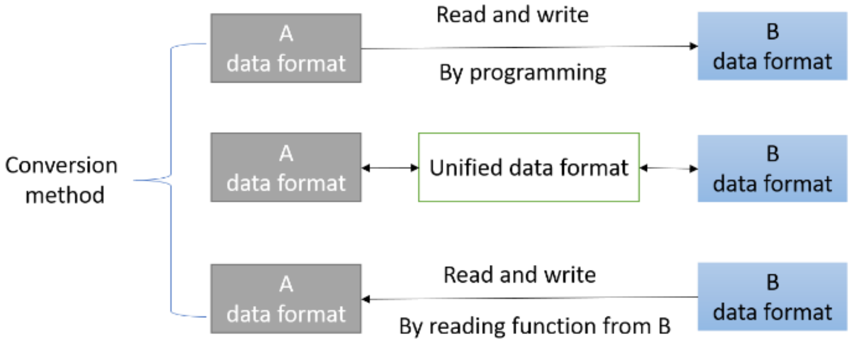


Fig. 3-5. Three conversion methods.

3.3.2 Electronic documented information module

Information usually presented in different media file formats such as word, excel, video, sound, plays an important role in maintenance management. Comprehensive information can help managers make timely and accurate decisions. The service period of civil infrastructure can last for a long time and many people participate in maintenance work, leading to problems such as fragmentation and loss of information. A good solution is to integrate information on a unified platform where information can be exchanged at different times and among different groups. Database technology is adopted to achieve information integration.

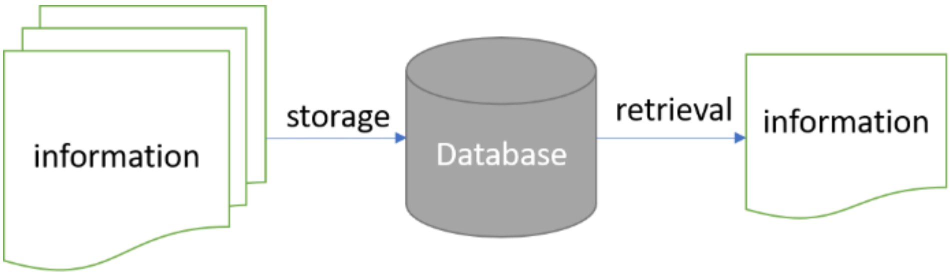


Fig. 3-6. Database technology principles.

Database technology includes two parts as shown in Fig. 3-6: the information storage is to store the processed and organized information on a specific carrier in form of information collection at a certain format and order. The information retrieval is that a user uses a certain method and a search tool to find the required information from the information collection.

Relational database systems that use a relational model (e.g. a two-dimensional table model) to organize data have been the dominant form of data storage and manipulation for the last 30 years. Relational databases have a specific format by storing the associated data in the pre-defined tables, and the standardized SQL (Structured Query Language) is used to manage the relational database. Popular examples of relational databases include SQL Server, Oracle, MySQL, PostgreSQL. The main advantage of relational databases is that they enable users to easily categorize and store data that can later be queried and filtered to extract specific information for reports. The other advantages for relational database are given in Table 3-3.

Table 3-3. Advantages of relational database.

advantages	description
Accuracy	Data is stored just once, eliminating data deduplication
Flexibility	Complex queries are easy for users to carry out
Collaboration	Multiple users can access the same database
Trust	Relational database models are mature and well understood
security	Data in tables within relational database can be limited to allow access by only particular users.

Relational databases have many advantages when managing structured data as it shows good functionality that it enables users to easily categorize and store data that can later be queried and filtered to extract specific information for reports. However, it is difficult to manage unstructured data and semi-structured data. Unstructured data refer to an irregular or incomplete data structure without any predefined data model, and inconveniently represented by two-dimensional logical tables, such as office documents (Word), text, pictures, HTML, various reports, video and audio, etc. Moreover, scalability and performance for relational databases are weak because the storage format is predefined, which makes it difficult to manage databases expanding over time. NoSQL (Not Only SQL) systems have been proposed to make up for the shortcomings of relational databases. NoSQL systems are schema-free with not requiring any sort of definition of the schema of the data and are designed to handle larger data volumes at better performance than relational systems.

There are several different types of NoSQL systems including Column-based stores (e.g. HBase); Key-Value stores (e.g. Redis); Document stores (e.g. MongoDB, CouchDB); MapReduce systems (e.g. Pig, Hive) and graph databases (e.g. Neo4J). Column-based storage is a database that stores data in a column-related storage architecture. Key-value stores provide the simplest interface allowing storing and retrieving values using a hash interface. Document stores allow a structured document to be attached to a key. MapReduce systems, typically based on Hadoop, allow for large-scale processing of massive data sets on a cluster [49].

MySQL and MongoDB are typical representative of relational database and NonSQL database, respectively. MySQL stores data in tables and uses structured query language (SQL) for database access. Developers predefine the database schema and set up rules to govern the relationships between fields in the tables. MongoDB stores data as JSON-like documents (usually the representation format is BSON (Binary encoded JSON)). Documents store related information together and use the MongoDB query language (MQL) for access. Fields can vary from document to document - there is no need to declare the structure of documents to the system, as documents are self-describing. Optionally, schema validation can be used to enforce data governance controls over each collection. Table 3-4 lists the differences between MySQL and MongoDB in terms of a storage method, a query method, etc.

Table 3-4. Features for MySQL and MongoDB

	MySQL	**MongoDB**
Data organization	Table	Collection
Single data store	by "row"	by "document"
Fields	Predefined Tables and Fields	No fixed format
Query method	Structured Query Language (SQL)	MongoDB query language (MQL)
Structure update	Lock and update data one by one	Directly insert new data
Scaling and balancing	Manual assignment and setup	Automatic assignment of new nodes

Electronic document information can be management more efficiently through cooperation with the visualization model. This research focuses on link the database that carries electronic document information with BIM collaboration platform. Electronic information can be stored in its original media format and linked to its physical location (shown in Fig. 3-7).

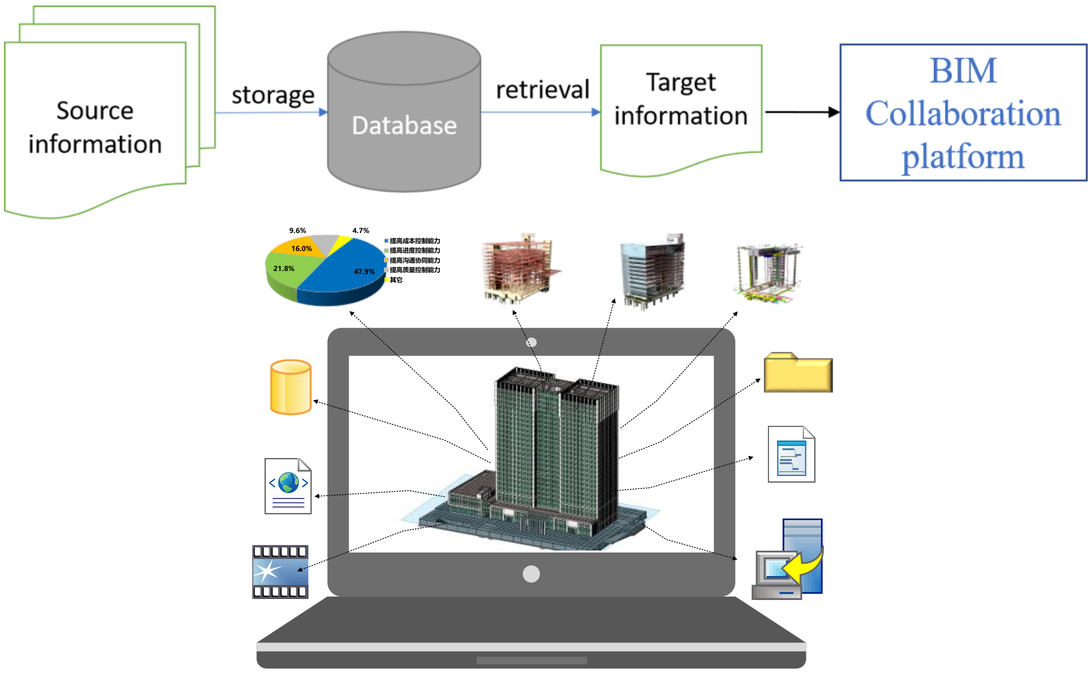


Fig. 3-7. Visual electronic documented information management.

3.3.3 Structural health monitoring module

Structural health monitoring (SHM) of civil infrastructure is defined as the continuous collection and interpretation of in-situ parameters of the relevant component for the purpose of identifying the state and trends of structure performance**.** The information gathered can be used to assess key structural performance parameters to derive conclusions about the health condition or performance of concrete infrastructure, which can then be used to aid the decision making in terms of making or altering the maintenance plan or determining if a repair task needs to be assigned. There are many successful application examples for monitoring techniques used to ensure the optimal durability of infrastructures, such as Hangzhou Bay Bridge, Arch shell structure of the Allianz-Arena soccer stadium in Munich, Idifor's Prestressed Concrete Floating Rafts in the Basque Country, Tamina Bridge in Switzerland [50]. SHM System's elements include: Structure; Sensors; Data acquisition systems; Data transfer and storage mechanism; Data management.

The advances in sensor technologies, wireless communications, data processing techniques, and artificial intelligence, in conjunction with the ever-growing number of aging structures and the pressure to minimize maintenance costs, reducing in-service failure and unforeseen downtimes have promoted the development of real-time monitoring techniques. The development of integrated monitoring systems for new reinforced concrete structures would provide an early warning of incipient problems enabling the planning and scheduling of maintenance; and, could reduce costs by allowing a more rational approach to the assessment of repair options. The installation of a monitoring system during the construction phases allows monitoring to be carried out during the whole life of the structure.

It should be noted that, not all information directly indicates the status of structure components. Some of them directly present the status of structure components, for example, sensors of deformation and cracks shows the level of damage condition. But some others are just external environment parameters, such as temperature, humidity and pressure. Therefore, usually we need to use other failure prediction analysis to diagnose condition of structure components and predict future failure time and service lifetime according to these parameters.

The sensor technology used for condition monitoring was firstly used for machines in the manufacture industry. According to Moubray [51], vibration monitoring and lubricant analysis are the most effective, proven and validated techniques for condition monitoring in countless industries. In concrete structure condition monitoring, 5 typical monitoring aspects of sensor for concrete structures include temperature, humidity, corrosion rate, pH, strain/stress/crack [52].

Sensors were installed in both precast concrete and in-situ concrete elements which provide rich information about the actual structure performance when subject to actual structural and environmental. Advanced sensor technologies currently used in concrete structure monitoring as shown in Fig. 3-8 are (1) Fiber Optic and Bragg Grating sensors based on changes in the characteristics of the light signal transmitted along the fiber. (2) piezoelectric sensors based on piezoelectric effect. (3) electrochemical sensors based on the detection of specific chemical element, which is a popular approach to corrosion monitoring of reinforced concrete structures. (4) wireless sensors, which eliminates the need for extensive wiring between sensors and the data acquisition system based on mobile computing and wireless communication elements such as Bluetooth, WiFi and cellular networks. (5) self-sensing based on piezoresistivity principle and changes in the volume of electrical resistivity of electrically conductive concrete. Deformation and damage disturb the conducting network leading to a change in the electrical resistivity. It indicates that an increase in the electrical signal is due to crack generation or propagation, while a decrease in the resistivity is due to crack closure concrete [52].

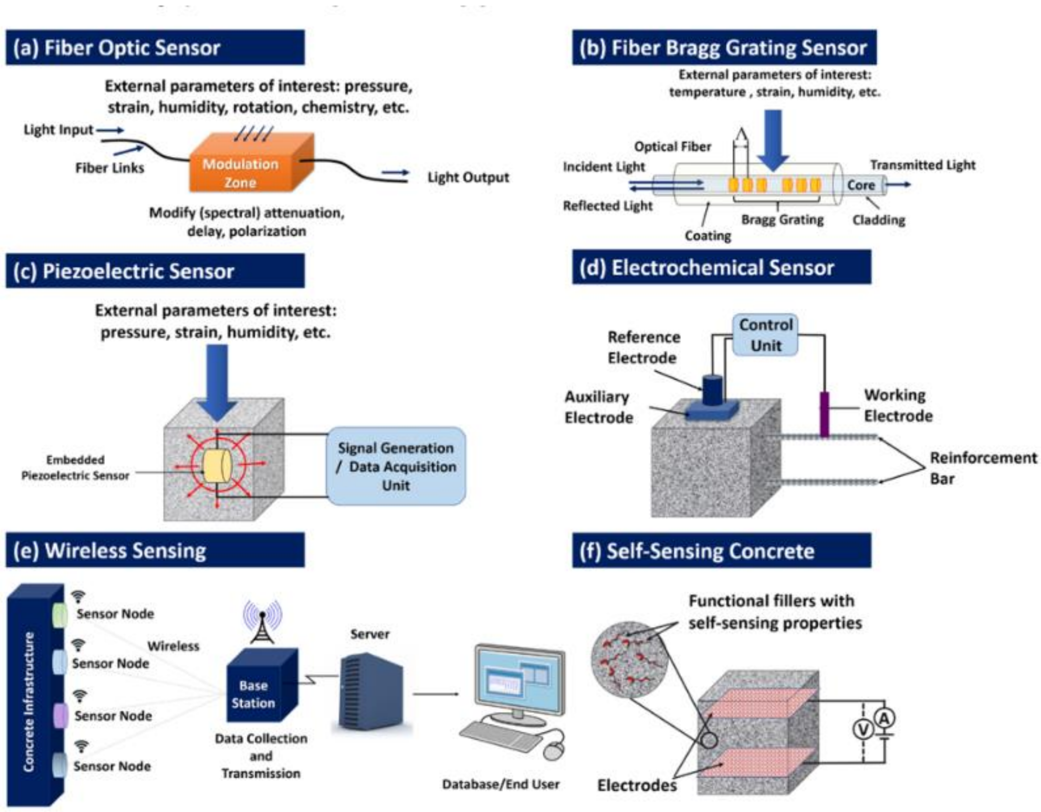


Fig. 3-8. Illustration of different types of sensors. Adopted from [52].

Real-time monitoring data from the sensor can be recorded by BIM graphically or statistically. There have been already some studies on the combination BIM with sensor. Akanmu et al. [53] proposed a cyber-physical system, which utilized sensors to link the virtual model with real world. However, there is lack of study on using sensor on BIM-based concrete structure maintenance management.

According to the data processing procedure and sustainability requirements, a monitoring system based on data visualization has been established in this study. The process is as following (in Fig. 3-9): (1) Install sensors into building components according to different service systems. Sensors can be used to collect a wide range of data from the concrete cure up to its daily performance, as well as its appearance or progress of corrosion (in concrete or rebar) at different points in its life cycle. Embedding sensors in concrete structures is a promising, non-destructive, approach that has the power to collect unprecedented amounts of data. (2) Data collected are either transmitted via a lead wire or a wireless transmission system. Pre-process obtained sensor data in control box through signal decoding, and some indicated condition parameters and external environmental parameters can be achieved. (3) Collected data is integrated into a central database and store monitoring data into database (DB) for future analysis and (4) associate sensor with monitoring data into BIM model for visualization.

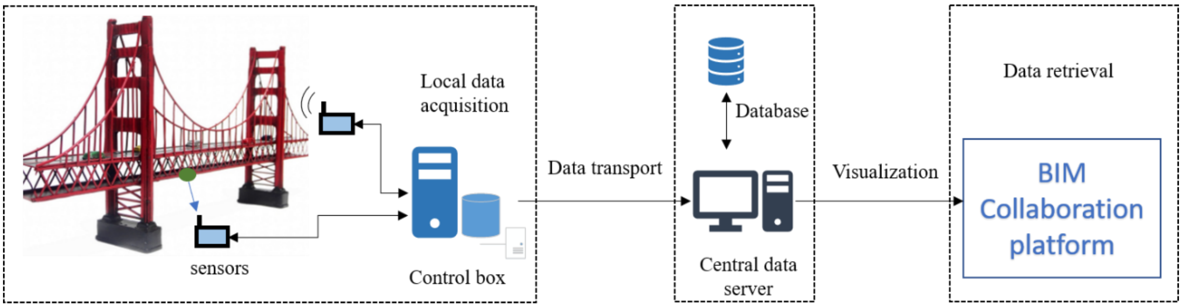


Fig. 3-9. The flow of data in monitoring system.

It uses database to store and manage information collectively, and then maps sensing data into BIM models, finally presents information through a 3D visual interface so that the real-time status of the facility reflected by the monitoring information can be captured by the manager in time.

3.3.4 Professional analysis module

In the past few decades, the use of knowledge-based and expert systems in structural engineering applications, has witnessed significant advances. The knowledge is the repository of information available within a particular domain, and it consists of well-established and documented definitions, facts, rules as well as judgmental information and heuristics. The "knowledge" level refers to the knowledge of the experiences and summarizes the involved analysis (knowledge from the domain experts), the obtained knowledge (measurement or prediction) and the generalized rules from this set of experiences (e.g. rules from failure investigations).

In maintenance management, assessment of concrete structures is needed to determine the maintenance activity decisions. These assessments cover many aspects such as concrete structure durability analysis, bearing capacity analysis, economic analysis, etc. Usually, these assessments can be conducted by professional people with use of professional knowledge and professional software.

The establishment of a knowledge-based and expert system is to integrate and share these different professional analyses, so that manager (who is not a professional person for analysis) can efficiently view different analyses and obtain the analysis results in time. The two main problems in establishing this system is that first professional analysis usually uses professional software. This is a burden for a computer to install a lot of professional software to do analysis. Then even for one kind of professional analysis, the analysis process changes dynamically. The same analysis such as analysis of chloride ion induced deterioration in different concrete structures and structures at different times are also different with change of different input parameters.

If all the professional analysis software is installed into one computer, memory limitation can have a serious impact on the development of the information platform.

The popularization of the Internet has been responsible for important changes in society. The internet technology can help to establish the expert system. Interment promotes information transfer in different computers. Internet and browers (Chrome, Edge, Safari) will serve as a medium for centralizing and sharing professional analysis bases as well as a means for communicating ideas and issues among researchers. Potential benefits are the abilities of users to more readily convert between systems and to borrow knowledge models originally built to run in other systems. Internet allow the sharing of knowledge in a mode of more flexible, easier to update, and easier to query. Internet allow manager to collaborate with the various professions by integration of the analysis processes free from software constraint.

The advantages of internet using for knowledge sharing are as follows:

(1) Internet can exchange information without space restrictions.

(2) Information exchange is time domain (fast update speed)

(3) The exchange of information is interactive (people to people, people and information can interact and communicate)

(4) Information exchange can exist in many forms (videos, pictures, text, etc.)

For this study, the most significant of these changes is the possibility of expression and socialization by means of computer-mediated communication tools. Professional analysis with knowledge can transfer between different "entities": individuals, teams, intra-organizational units, organizations, and even inter-organizational networks. Web-based transfer for knowledge can eliminate the barriers of knowledge transfer in time and space. The Internet technology also enables the simulation process is not constrained by specific software to realize the across-platform applications integration. The network acts as a link bridge between the server computer with specific software and the client without the specific software, and the browser enables users in client computer to directly manipulate the simulation model in server computer, such as viewing and calculating the simulation model with the different parameters.

Seen in Fig. 3-10, professional people with professional knowledge finish the professional analysis in server computer with specific software, then distribute the analysis results to internet. For maintenance manager without professional knowledge, they can click on the website linkage and move to web browser to access the professional analysis results to help them make maintenance decisions. Internet technology can make professional knowledge even more accessible and more transferable.

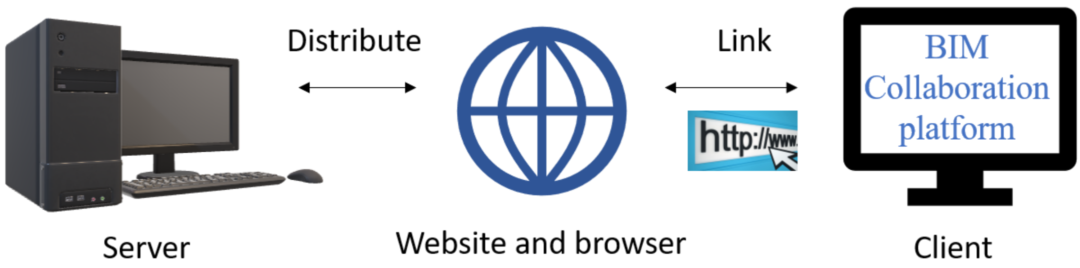


Fig. 3-10. Share of professional analysis results by internet technology.

3.4 PLATFORM DEVELOPMENT

The purpose of information platform development is to integrate information from different sources onto a unified platform. First, integrate the 3D model provided by BIM and GIS to form a multiscale visual environment as the basis. Then link the information from different sources into the 3D model. Finally, a user-friendly display interface is developed to enable users to browse and operate information. Application programming interface (API) and semantic web-based data storage provide the computing interface of information interactions between multiple software intermediaries as shown in Fig. 3-11.

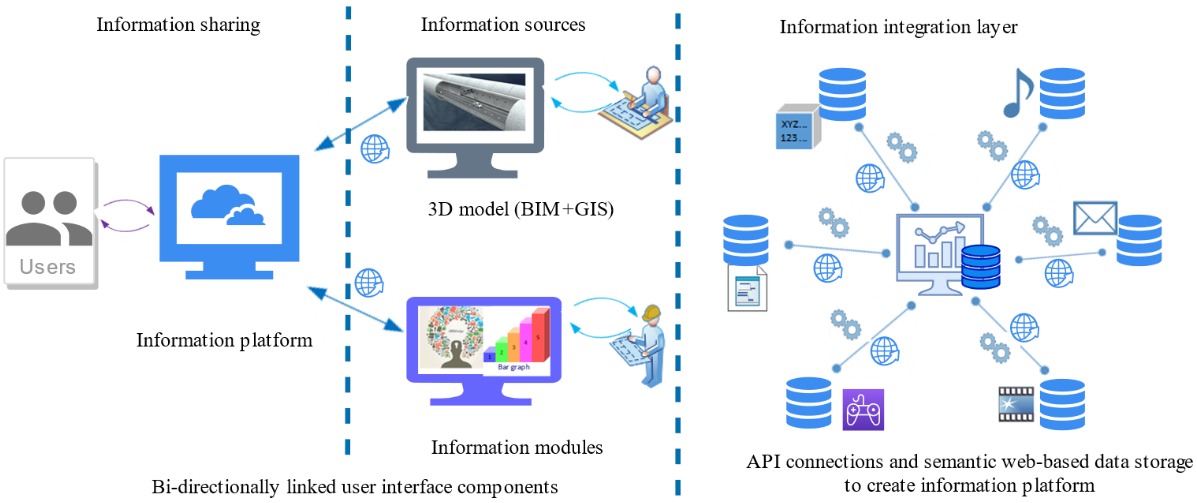


Fig. 3-11. Development of the information platform.

Information management system is established by software development technology in order to link graphical interface with database for quick access to database and visualization of information. Two architectures can be used for system development, Client/Server(C/S) and Browser/Server (B/S).

The C/S structure (Fig. 3-12) divides an application into two parts: front-end (client) and back-end (server). The database server is a logical system responsible for data management including storage, retrieval, and protection of the database, while the client provides a friendly graphical user interface (GUI) for users to input data, submit query and display query results, etc.

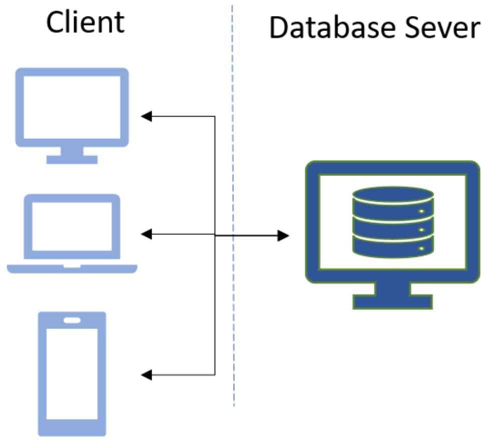


Figure. 3-12. C/S structure.

The data access in the B/S structure (Fig. 3-13) starts from the presentation layer (client with browser) to the application layer (Web Server) and then to the database layer. Browser only has simple input and output functions, which can be used to access information on the Internet by users. Web Server plays a role of information transmission. When users want to access the database, they will first send a request to the Web server. After collecting them and making a unified request, Web server will send a request to the database server to access the database. Database server stores a lot of data. When the database server receives the request from the Web server, it will process the query and send the returned results to the Web server so that the Web server can send the received data results to the browser.

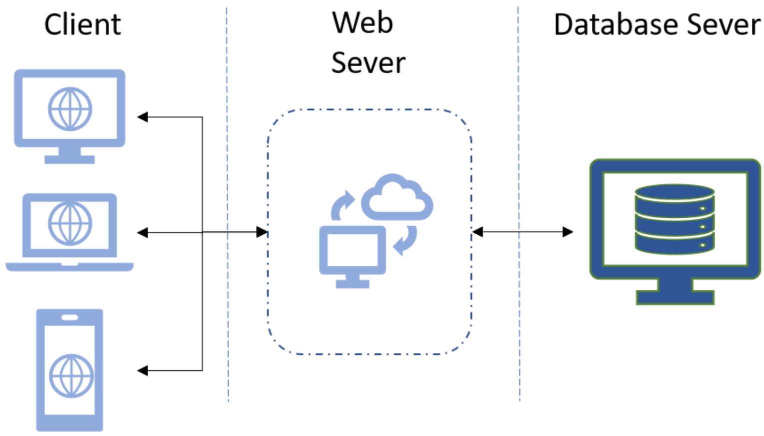


Fig. 3-13. B/S structure.

The comparation for the two architectures is given in Table 3-6. It can be seen that both of them have advantages and disadvantages. Developers need to choose the appropriate architecture based on software requirements.

Table 3-6. characteristic for C/S and B/S.

	C/S	**B/S**
Hardware environment	Private network	WAN
Safety requirements	Strong ability to control information security for a relatively fixed user group	The ability to control security is relatively weak for the unknown user group
system maintenance	Difficult to upgrade	Easy to upgrade
Problem handling	integrated	dispersed
User interface	Closely related to the client system	Closely related to the browser
Information Flow	Low interactivity	High interactivity

3.5 CONCLUSION

This chapter introduces the development of the maintenance management information platform aiming at integrating different kinds of information among different participants.

An approach to the design of information systems in the domain of maintenance management of civil infrastructure has been discussed in this chapter. It is based on the usage of different methods and techniques, as well as software tools. The development is centered around the representation and manipulation of different kinds of information from different source and form. The information technologies applied correspond to them: BIM, GIS, database, sensor, internet and browser, as well as procedural programming language and software development. These tools are widely known, commercially available or can be programmed independently, and their integration in a single software system is relatively simple. Therefore, a complete information system development process is introduced including functional requirements analysis, functional module design and platform development. All of the information can effectively assist maintenance manager in making decisions whether maintenance action should be implemented. In this platform, many innovations have been proposed:

- Propose the integration of BIM and GIS models to build a multi-scale, full-range visualization environment.

- The information recorded in the form of documents is stored in the database as an electronic file. By using the visual model, information in electronic file can be bound to the corresponding location in the model for storage and retrieval.
- A persistent follow-up or tracking system to monitor that concrete structures are performed well or not onsite. The monitoring data can also be stored and retrieved in the corresponding location in the visual model.
- Propose the knowledge-based and expert systems by use of the network communication in this platform. Professional analysis results can be integrated in this platform and shared from professional person to maintenance manager through this platform.

4 PROFESSIONAL ANALYSIS SHARING IN MAINTENANCE MANAGEMENT

4.1 INTRODUCTION

In Maintenance management, Troubleshooting is a maintenance action that involves the normal investigation and professional analysis. Professional analysis of the structure including durability analysis and evaluation is required to make optimal maintenance decisions. Professional analysis inevitably requires professional knowledge. Durability analysis includes different domain of knowledge, because there are many factors that cause deterioration such as deterioration caused by factors of Carbonation, Chloride attack, Frost attack, Chemical erosion, Alkali-silica reaction, Fatigue and Abrasion and so on, among them, the mechanism and methods of deterioration prediction is different. Table 4-1 shows the method of deterioration prediction, (the maintenance part in the JSCE standard specifications for concrete structures).

Table 4-1. Outline of methods of deterioration prediction.

Mechanism	Methods of deterioration prediction	
Carbonation induced deterioration	Prediction of carbonation depth	Prediction of reinforcement corrosion
Chloride induced deterioration	Prediction of chloride concentration in concrete	Prediction of reinforcement corrosion
Frost attack	Evaluation on probability of frost attack	Prediction of deterioration depth induced by frost attack
Chemical attack	Prediction of erosion depth induced by chemical attack	Prediction of reinforcement corrosion
Alkali aggregate reaction	Evaluation on probability of reaction	Prediction of reaction process
Fatigue of reinforcement concrete slab	Prediction of crack patterns from present crack formation obtained by inspections	

Therefore, a complete durability analysis inevitably requires the cooperation of experts from different professional domains. General deterioration analysis process is shown as in Fig. 4-1: First determine the deterioration mechanism and factors; Then determine the index required for the deterioration analysis; Then establish the simulation model for deterioration analysis; The deterioration level and rate can be obtained from the analysis results; and finally the structural performance can be determined. Numerical simulation methods can be used to conduct this deterioration analysis: Firstly the governing equations should be determined with professional knowledge; then the professional software should be used to build up the simulation model, calculation the simulation with input parameters of initial and boundary condition; finally the simulation results can be obtained right from the software.

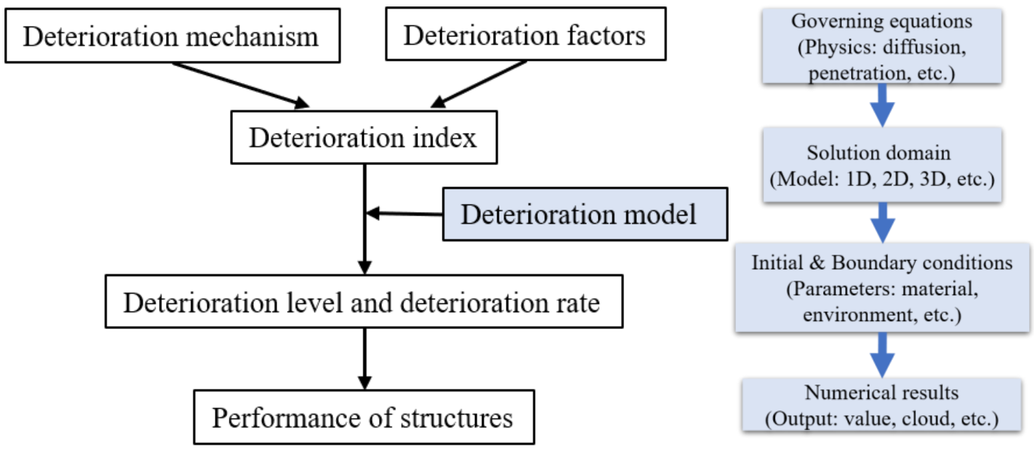


Fig. 4-1. Procedure of deterioration analysis by numerical simulation methods.

However, in general, expertise shows commonality not only in the procedure but also in its principle of simulation when applied to analysis of deterioration problem for reinforcement concrete structure. Once experts create one kind of deterioration model (such as deterioration caused by chloride ion) for assessment of one concrete structure, it can be adopted to do same deterioration analysis to new concrete structure by changing the simulation parameters. Relatively little effort is required to adopt the model to new project facing the same analysis needs.

A lot of professional software exists for every type of simulation. Available simulation tools are primarily aimed at the expert and allow expert to build up the simulation model, input the data needed, run the simulations and interpret the results. Maintenance managers are not an all-round expert, usually they do not have all the degradation simulation expertise and do not have all simulation software. However, if they can autonomously perform degradation analysis, it can efficiently assist them in making decisions.

This chapter discusses in detail how to share professional analysis from experts to non-experts. It mainly includes two aspects, how to transfer the knowledge of simulation process to allow the non-experts independently perform the same simulation and how to get rid of the constraints of specific simulation software. The value that knowledge management brings to mixed groups results from the potential for enhancing and controlling the flow of knowledge among heterogeneous sources across space, time and personnel. Therefore, knowledge management can be adopted to illustrate the professional analysis sharing process and the information tool serves as a relay station for information transmission.

4.2 THEORY OF KNOWLEDGE MANAGEMENT

Knowledge management (KM) is the process of acquisition, sharing, using and managing the knowledge and information of an organization [32, 54]. The most fundamental purpose of KM is to effectively manage the knowledge acquired by individuals and groups.

The first core step in KM is acquisition knowledge. The conversion of two categories of knowledge from tacit knowledge into explicit knowledge could be used to illustrate the acquisition process. Tacit knowledge is the abstract items that cannot be found in manuals, books, databases and files such as ideas, experiences, theories, and so on. Tacit knowledge is personal, context-specific knowledge that is difficult to record, articulate and it cannot be converted into words easily; it is stored in the heads of people normally [55, 56]. It is extremely difficult to communicate tacit knowledge without medium. Explicit knowledge, on the other hand, is structured and codified in formal language (manuals, expressions, patents, copyright, and so on) and is stored in tangible forms such as words, audio or video recording, images etc. It provides the basis for systematic storage and dissemination of information and assist organizations with solving similar problems in the future [57]. The defining feature of explicit knowledge is that it can be easily and quickly transmitted from one individual to another, or to another ten-thousand or billion. It also tends to be organized systematically. Successful knowledge management requires the transformation of intrinsic tacit knowledge into external explicit knowledge that allows individuals to absorb and interpret knowledge of various codes. Because even if knowledge is the base of human activity, only a part of it (‘‘explicit knowledge’’) is easily accessible, can be stored in information systems and can be efficiently reused. Making explicit the ‘‘tacit knowledge’’ is the objective of Knowledge Management. The transform pattern is called “externalization” as one of the Nonaka’s four knowledge conversion processes [58]. Externalization is a very important step for knowledge sharing. It uses information technology to carry tacit knowledge, making the communication of knowledge more efficient. After the externalization of tacit knowledge, it is necessary to focus on the generalization and simplification of the knowledge form in order to facilitate the sharing of knowledge among people with different backgrounds, because different levels of detail for knowledge are required when solving problems. For specific engineering projects, the form of sharing information can be customized through participant negotiation. The knowledge will be transferred to users who will apply it to new project and update it when necessary. Therefore, the knowledge management process can be summarized as two main steps: acquisition and sharing (shown in Fig. 4-2).

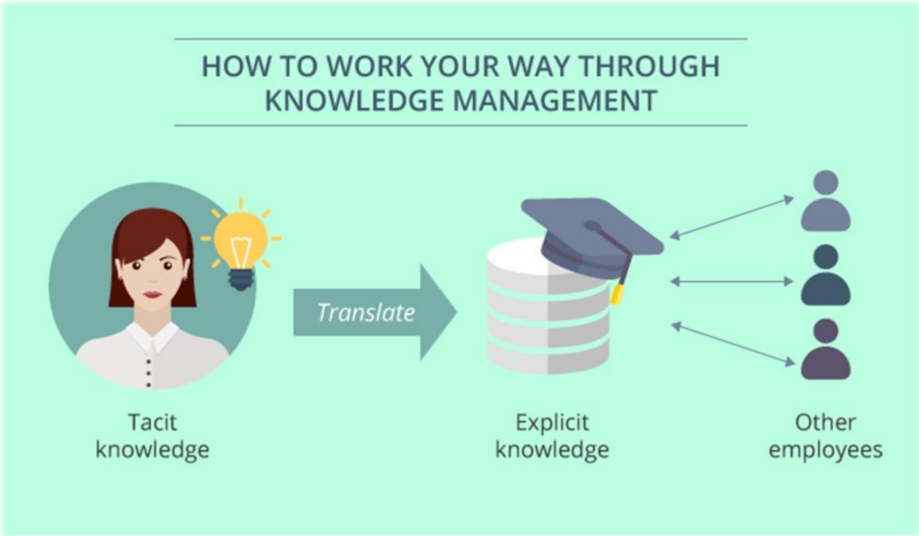


Fig. 4-2. The process of Knowledge Management.

4.3 RESEARCH METHODOLOGY

This article introduces the process of knowledge management, combined with professional analysis in maintenance management, especially for the durability analysis, explains how to popularize private knowledge,

This paper focuses on the knowledge acquisition and sharing process to build a Technology-oriented knowledge management model for concrete maintenance management. This model focuses on enabling individual knowledge public by information technologies. Two groups of people are the terminals of information transmission. Experts are regarded as knowledge providers who work on transferring knowledge carrier from the individual knowledge into materialized knowledge. After simplifying the materialized knowledge, experts deliver it to a transfer station ((by using some information carrier tool) where users with permission license can access the knowledge. The receivers can use the knowledge to accomplish their goals.

4.3.1 System framework

The KM system focuses mainly on managing the expertise required for maintenance decision-making, especially on the condition analysis of concrete structures during maintenance management. BIM technology is adopted as the information carrier. Fig. 4-3 demonstrates the flow of the KM system in this paper.

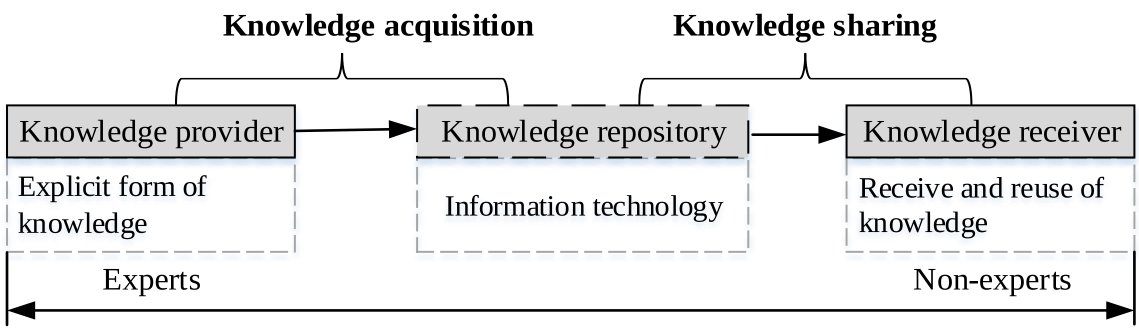


Fig. 4-3. Workflow of the knowledge management.

Two groups of people are the terminals of information transmission. Experts are regarded as knowledge providers who work on transferring knowledge carrier from the individual knowledge into materialized knowledge. After simplifying the materialized knowledge, experts deliver it to a transfer station ((by using some information carrier tool) where non-experts act as knowledge receivers can access the knowledge with permission license. The receivers can use the knowledge to accomplish their goals. To sum up, there are two main processes of the knowledge management process: knowledge acquisition and knowledge sharing. The knowledge acquisition process is based the tree sub-processes: acquisition (experts store knowledge obtained from long time learn and experience in their brain), externalization (experts create analytical prototypes using specific software), and generalization (experts should simplify the analytical prototype to common software format and make it easy to re-use even by non-experts). Knowledge sharing process is based on sub-processes of integration (choose a shared platform that can be used by both experts and non-experts, where experts can upload, update, and manage the knowledge) and retrieval (non-experts choose and re-use the relative knowledge according to their management requirements).

Other detailed explanation for the participates is as follows:

(1) From knowledge providers:

Knowledge acquisition is conducted by experts. Experts acquire knowledge by experience and study accumulating by years. Here the knowledge is implicitly stored in their minds. However, the most important function for knowledge is its application for solving problems in the reality, which requires transferring tacit knowledge into explicit knowledge. In the transferring process, experts can code their knowledge into a complete visual form (named "prototype") which is a set of procedures for solving problems by the complicated theories. A new problem of the same type can be dealt with by using the prototype. Here the prototype is a very complex form of expression with a lot of details. Advance in computer software development, such as finite element software and discrete element software, makes it feasible to develop the visual prototype from ideas for revealing physical phenomena.

(2) Through knowledge repository (transport carrier):

The prototype is the materialization of the knowledge from the expert's brain, which is also difficult for a non-expert (user) to understand. Moreover, non-experts are not concerned about the details of knowledge (e.g., the basic principles, theoretical relationships or logical framework). What they really care is how to apply the prototype to solve a new problem. Before transferring the knowledge to non-experts, experts should simplify the prototype to meet non-expert's needs. The simplified prototype hides some of the complex knowledge but reserves full functionalities. A carrier for the transfer of prototype from experts to non-experts is necessary. Application with easy-to-operate user interfaces can be made to carry the knowledge. Usually, referring to expertise of many disciplines is required to make decision for even one maintenance action; therefore, choosing a platform to store and share the knowledge can benefit the maintenance management participants. The platform can be built up by using BIM with secondary development.

(3) To knowledge receiver:

In the process of knowledge use, non-experts get the permission to access the application and then understand the usage method. It is the most important to know where to input data and control parameters as well as how to obtain the results from the user interface of the application. Non-experts can finally apply the knowledge to solve a new similar problem.

4.3.2 Technical Realization

Fig. 4-4 illustrate the detailed knowledge management process in sharing professional analysis. In the process of knowledge acquisition, experts need to externalize knowledge through professional software, and then simplify the externalized knowledge model using information tools. Knowledge sharing process is for users to receive simplified knowledge model, understand the operation methods for the model, and then apply the model to new project. It is necessary to realize that professional analysis is not restricted by professional software and professional knowledge. That is, the professional analysis process is simplified as a universal analysis process. Here, an information platform is needed to carry the knowledge model, as the bridge of knowledge exchange between experts and non-experts.

To remove the restriction of professional knowledge, we use application software as shown in Fig. 4-5. Application software is a computer program designed to help people perform an activity. It allows people to customize the user interface and simplify the complex modeling process of professional software. The process of professional analysis sharing by application software can be described by Fig. 4-5, experts create the prototype simulation model by professional software, then packed the prototype model into open parameter model application by providing friendly user interface. Non-experts perform the simulation in this open parameter model application by inputting the parameters, calculating the simulation, and obtaining the simulation results.

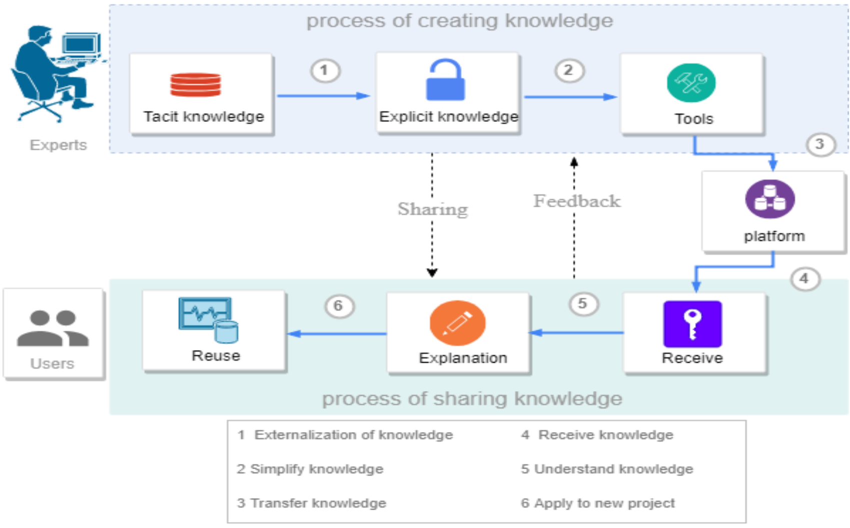


Fig. 4-4. Detailed process of knowledge management.

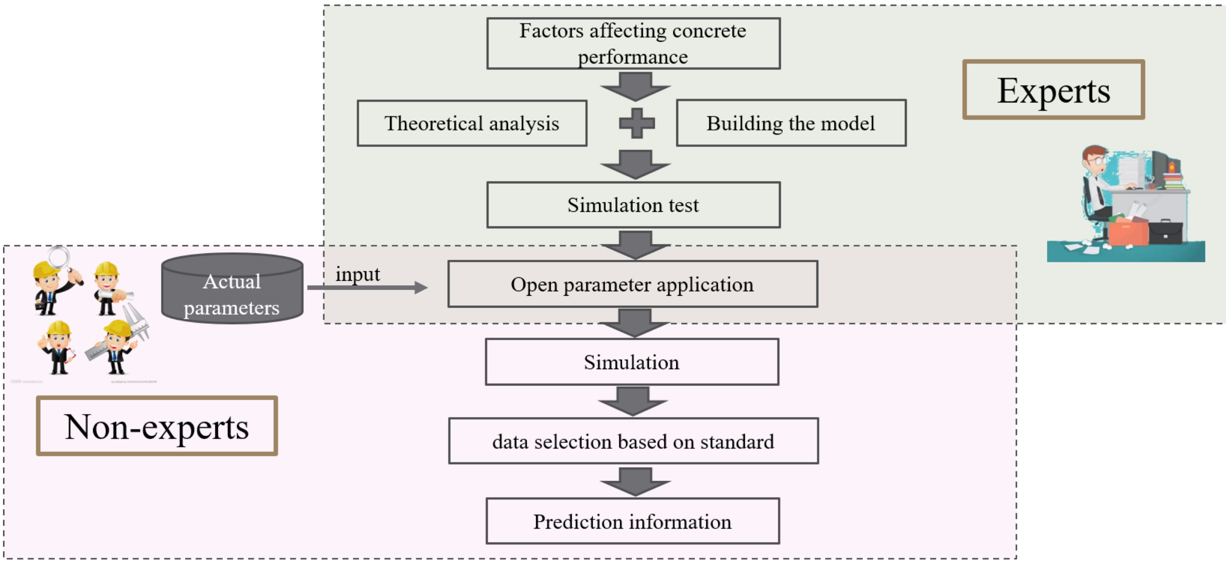


Fig. 4-5. Share of professional analysis without restriction of professional knowledge.

Network technology is used to solve the problem of the constraint of professional software to conduct the professional analysis. Network technology refers to a computer technology that uses a certain communication protocol to connect multiple independent computer systems distributed in different locations through interconnected channels (that is, communication lines) to achieve data and service sharing. Open parameter model application is released to website to be able to track via website from server computer. In client computer, people can access to the application through browsers such as IE、Chrome、Firefox、Safari. It can retrieve, display and transfer Web information resources when entering a website address. Professional analysis will be carried out through application in browser in client computer. Client computer sends orders through internet to server computer, where the professional software is installed. The real calculation is done by server computer, and server computer will send feedback to client computer and results can be shown in browser in client computer. The process shows in Fig. 4-6.

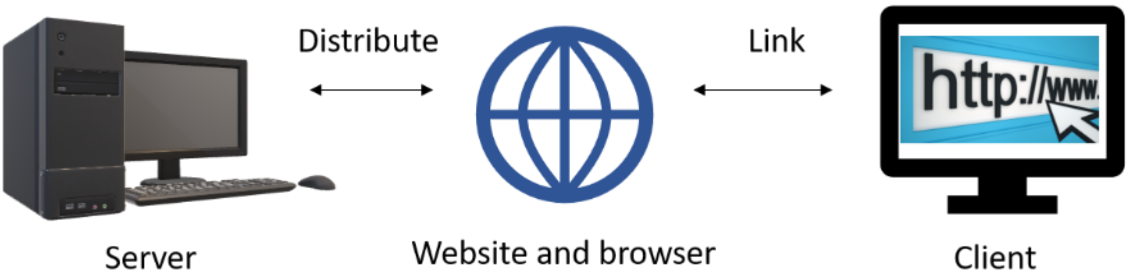


Fig. 4-6. Share of professional analysis without restriction of professional software.

During the procedure, the most important step is to set up the integrated platform, which can receive the expertise from experts as well as deliver the expertise to non-experts. An information platform that can aggregate as well as store information is efficient for long-term knowledge sharing. The information platform is with 3D visualization model proposed in Chapter 3 as shown in Fig. 4-7. This platform can realize the knowledge sharing among participants of different knowledge backgrounds and the integration of multidisciplinary knowledge based on visualization. In the information platform, a general-purpose browser can be inserted. The browser owns the same function as IE, Chrome, Firefox, Safari. It can retrieve, display and transfer Web information resources when entering a website address. So that maintenance manager (as non-expert) can do the professional analysis in the browser developed in the information platform with network access.

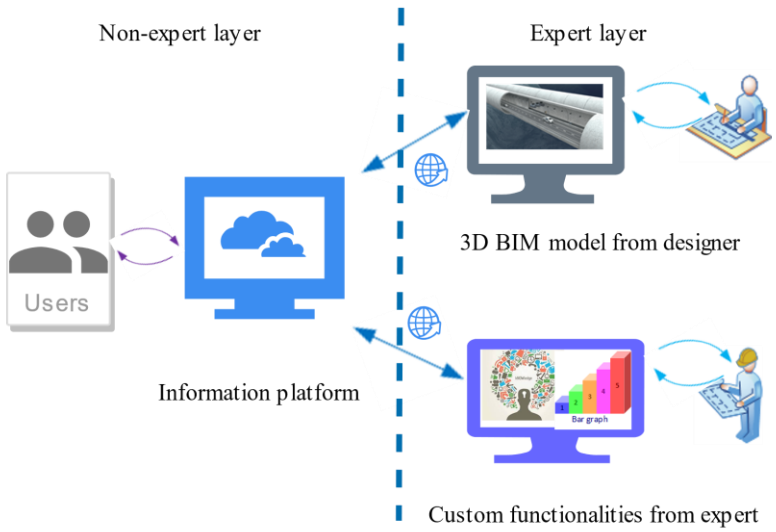


Fig. 4-7. A visual platform acts as information relay station.

4.4 CONCLUSION

For the introduction of professional analysis by knowledge management methods in maintenance management, it can realize the smooth sharing of knowledge from experts to non-experts. The obstacles in professional analysis sharing are eliminated: application software is used to get rid of restriction of professional knowledge, while network communication is used to get rid of restriction of professional software. Through this approach, professional analysis can be conducted by non-experts anywhere at any devices. The sharing process can be simplified concluded as following five phases: (1) definition of the types, assumptions, requirements, features and strategies of the deterioration analysis in concrete structures; (2) development of a prototype for the simulation process with professional software and visual tools; (3) focus on the needs of the user group and simplify the prototype to an open parameter model; (4) distribute the open parameter model to the web so that it can be operated in a browser; (5) link website of the open parameter model to the integrated information platform for long time storage and retrieval.

5 CASE STUDY AND PLATFORM DISPLAY

Due to the limitations of my research background and data access. Here we will separately realize the illustration of professional analysis sharing process and the self-developed integrated information platform through project of different background. The professional analysis sharing case is focus on a chloride ion penetration into concrete under sea water, while the self-developed integrated information platform will be displayed based on a road project.

5.1 PROFESSIONAL ANALYSIS SHARING IN MAINTENANCE MANAGEMENT

5.1.1 Background

Concrete is mostly used in engineering for its high compressive strength and relatively low cost. Prediction of deterioration progress as one of the durability analyses is conducted to estimate future deterioration of a structure caused by identified deterioration mechanism based on the results of investigations and appropriate models. Since deterioration of concrete members is induced and accelerated mainly by chemical agents, the ingress and transportation of those agents are predicted as main indices for durability performance [35]. Simultaneously, the characteristic of porosity and high heterogeneity creates conditions for the invasion of water and external aggressive ion dissolved in water, which reduces the durability of concrete structures. Chloride ion is one of the factors to degrade a reinforced concrete structure. Chloride ion induces the depassivation of steel reinforcement in concrete and accelerates the corrosion process. Many underwater concrete tunnels are used under hydrostatic pressure, high chloride ion concentration and adequate oxygen supply, which may cause deterioration of the tunnels. To analyse the deterioration process, it is particularly necessary to reveal the process of chloride ion penetration into concrete.

Chloride ion penetration into concrete is considered with different mechanisms such as free diffusion driven by concentration gradient, permeation driven by osmotic pressure, migration driven by electrical field, and capillary adsorption driven by surface tension in the capillary pores [59]. The Fick’s second law depicts the process of chloride ion penetration into concrete by diffusion. On the other hand, evidences have indicated that chloride penetration into concrete is a rather complicated process, which is always a combination of different mechanisms depends on the boundary conditions, the moisture state and properties of concrete. The external environment and internal condition of concrete play important roles on the performance of chloride ion penetration into concrete. A diffusion-convection model was proposed to describe the mechanism of chloride ion penetration into unsaturated concrete by considering many factors such as solution concentration, initial saturation, hydraulic pressure, and water-binder ratio [60, 61, 62]. Over the past decades, many researchers also investigated chloride ion penetration into concrete driven by capillary absorption and free diffusion [61, 63, 64, 65, 66]. A great number of researchers have devoted to reveal the ion transport mechanisms in unsaturated concrete system. The coupled moisture transport and ion transfer is often used to describe the penetration process.

This case study focuses on the communication of expertise in simulating the chloride ion concentration into tunnel concrete over time under external hydrostatic pressure between experts and non-experts, describing the process of expertise acquisition and sharing according to the proposed knowledge management system mentioned before.

Advances in computer software, such as a finite element software and a discrete element software, have made it possible to decode expert's knowledge into a complete visual form such as a simulation model from ideas.

5.1.2 Knowledge acquisition process

This is the professional analysis process. Authors are in role of experts. Experts should first conceive the simulation models in their minds by using a lot of scientific knowledge. From the microscopic perspective, the process is described as the diffusion-convection mechanism where the diffusion phenomenon can be influenced by concrete pore structure and the convection is described by the moisture transport in unsaturated concrete. In addition, the fluid-solid coupling interaction between porosity change and permeability change under hydrostatic pressure in unsaturated concrete cannot be ignored in the process of chloride ion penetration. To sum up, chloride ion penetration into concrete can be described as a mixed form of three parts of knowledge: (1) unsaturated moisture transport, (2) chloride ion transfer process, and (3) the fluid-solid coupling process.

1) Unsaturated moisture transport

Free water usually acts as the carrier of chloride ion. Therefore, water transport is a driving factor for multi- mechanism of chloride ions ingress into concrete. The linear Darcy's law is usually utilized to describe water flow in perfectly saturated concrete. However, from microscopic perspective, the concrete is not fully saturated in the transport process. We can assume that the interior of the concrete is dry, and the surface exposed to water is saturated initially. It is easily envisaged that water transported from the saturated zone to the dry zone under hydraulic potential and capillary suction. Fig. 5-1 shows the saturation map of water in concrete. The distribution of saturation profile in concrete changes varies with time and it delineates moisture transport process in concrete, i.e., unsaturated flow. Zhang [67] pointed out that the water permeation is co-driven by the combination effect of hydraulic pressure and matric suction in the unsaturated concrete.

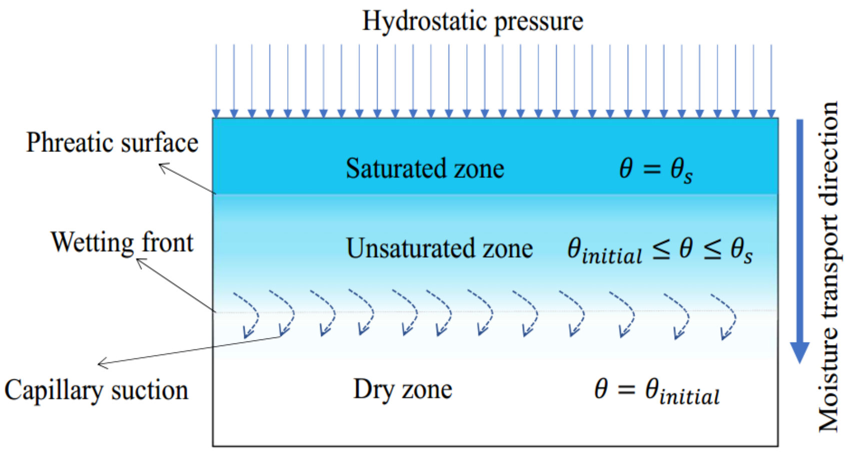


Fig. 5-1. Water ingress into concrete under hydrostatic pressure and capillary suction.

The pressure in the interior of the tunnel until intersection boundary with water is equal to atmospheric pressure. We can assume that the flow will not be influenced by air pressure. Richards' equation [68] in pressure head is used as governing differential equation for isothermal saturated-unsaturated single-phase flow:

$$[C_m + S_e S]\frac{\partial H_p}{\partial t} + \nabla \cdot [-K(\theta) \cdot \nabla(H_p + D)] = 0 \tag{1}$$

Where the specific moisture capacity C_m relates variations in fluid volume fraction θ to the matric head (i.e., $C_m = \partial\theta/\partial H_p$). The storage coefficient S addresses storage changes due to compression and expansion of the pore spaces and the water when the porous medium is fully wet. To model the storage coefficient of concrete, this example uses the specific storage option, which sets $S = \rho_f g(\chi_p + \theta\chi_f)$. Here, ρ_f is the fluid density (kg/m^3), g is the acceleration of gravity (m/s^2), while χ_p and χ_f are the compressibility of solid particles (1×10^{-8} m·s^2/kg) and fluid (4.4×10^{-10} m·s^2/kg), respectively; S_e is the effective saturation; $K(\theta)$ is a function that defines how readily the porous media transmits fluid, which increases with fluid content as $K(\theta) = k_r \cdot K_s$. Here, k_r denotes the relative hydraulic conductivity and K_s is hydraulic conductivity (m/s) in saturated concrete. The pressure head H_p (m) is a dependent variable (matric potential driven by hydrostatic pressure and capillary pressure) and D is the coordinate (for example x, y, or z) for the vertical elevation (m). The saturated permeability k_s (m^2) and the saturated hydraulic conductivity K_s (m/s) are related to the viscosity μ (Pa·s), density of the fluid ρ_f (kg/m^3), and the acceleration of gravity g (m/s^2) by $K_s/\rho_f g = k_s/\mu$.

Nonlinearities appear in the Richards equation because C_m, S_e and k_r change with H_p and θ. van Genuchten [71] adopted the Mualem model [72] to propose a simple water retention curve to describe the relationship in C_m, S_e, k_r, θ and H_p in unsaturated porous media.

$$\theta = \theta_r + S_e(\theta_s - \theta_r) \quad (2)$$

$$S_e = \frac{1}{\left[1+(aH_p)^n\right]^m} \quad m = 1 - \frac{1}{n} \quad (3)$$

$$C_m = \frac{am}{1-m}(\theta_s - \theta_r)S_e^{\frac{1}{m}}(1 - S_e^{\frac{1}{m}})^m \quad (4)$$

$$k_r = S_e^{\ l} \left[1 - (1 - S_e^{\frac{1}{m}})^m\right]^2 \quad (5)$$

The properties of concrete should be specified by the saturated and residual moisture content θ_s and θ_r, as well as constants of *a*, *n*, *m*, and *l*.

2) Chloride Ion Transfer

The process of chloride ion penetration into concrete is complicated. Under the external pressure, three basic mechanisms are mixed to govern the transport of ion into unsaturated concrete: binding, diffusion and convection (i.e. driven potential considering both capillary suction and permeation).

It was pointed out by many researchers [71, 72, 73, 74] that the chloride ion shows strong binding affinity with cementitious materials. The aluminate (C_3A) and aluminoferrite (C_4AF) phases in cement have been found to bind with chloride ion chemically, which form Friedel's salt and calcium chloroferrite. The content of amorphous calcium silicate hydration (CSH) gel in the concrete strongly influences the binding capacity of concrete [75, 76]. The chloride ion binding capacity cannot be ignored when studying the mass transport.

Referring to literatures [77, 78, 79], the mass conservation equation that describes the flux of chloride ion penetration into the concrete can be expressed as:

$$\underbrace{\frac{\partial}{\partial t}(\theta C_f)}_{liquid\ phase} + \underbrace{\frac{\partial}{\partial t}(C_{bound})}_{solid\ phase} = -\nabla \cdot J_{ion} \quad (6)$$

Where θ is the volume fluid fraction; C_f is the free chloride ion concentration (mol/m^3 of pore solution); J_{ion} is the flux of chloride ion (mol/(m^3·s)); and C_{bound} is the amount of bound chloride ion per unit volume (mol/m^3 of concrete); *t* is time (s). $C_{bound} = \rho_b C_p$, where ρ_b is the bulk density of concrete (kg/m^3); C_p is the mass of binding chloride ion per dry unit weight of concrete (mol/kg for concrete). The relationship between C_p and C_f is non-linearly described by chloride binding isotherm k_p (m^3/kg) (i.e. $k_p = \partial C_p / \partial C_f$). There are three types of chloride ion binding model. Tang and Nilsson [73] and Thomas et al. [80] pointed out that k_p obeys the Freundlich isotherm at high free chloride concentrations as shown in Eq. (7). At low free chloride concentrations, k_p obeys the Langmuir isotherm in Eq. (8), Tuutti [81] proposed a linear binding isotherm, which can be expressed in Eq. (9):

$$C_p = \alpha {C_f}^{\beta}, \quad \frac{\partial C_p}{\partial C_f} = \alpha \cdot \beta \cdot {C_f}^{\beta-1} \tag{7}$$

$$C_p = \frac{\alpha C_f}{1+\beta C_f}, \quad \frac{\partial C_p}{\partial C_f} = \frac{\alpha}{\left(1+\beta C_f\right)^2} \tag{8}$$

$$C_p = k_{pcon} C_f, \quad \frac{\partial C_p}{\partial C_f} = k_{pcon} \tag{9}$$

Where α, β and k_{pcon} are the constants which are unique for different cementitious system because of its components, such as C_3A content, supplementary cementing materials, and pH of the pore solution. The main transport process of chlorides into concrete is diffusion frequently. However, for the condition of unsaturated structures and high external water pressure, convection becomes an important mechanism in transfer process. Diffusion refers to the net motion of a substance from an area of high concentration to an area of low concentration. Convection denotes the movement of molecules (e.g., chlorides) within fluids (e.g., water). The process of diffusion and convection is shown in Fig. 5-2.

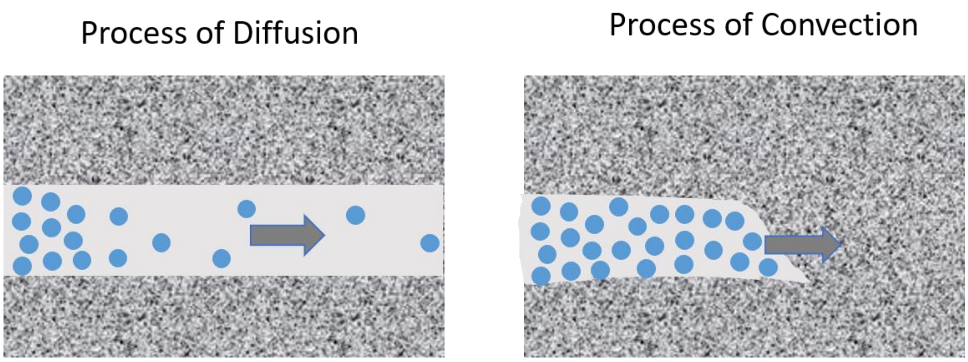


Fig. 5-2. Schematic illustration of convection and diffusion.

A convective term can be added to the Fick's second law of diffusion to explain the mechanisms of diffusion-convection [60, 82, 83, 84].

$$J_{ion} = -\underbrace{D_e \cdot \nabla C_f}_{\text{diffusion}} - \underbrace{u \cdot C_f}_{\text{convection}} \tag{10}$$

Where, D_e is the effective diffusion coefficient of chloride ion transferred within a porous media by diffusive mechanism, which shows relationship with pore structure parameters, and u is the velocity of a chloride ion transported with solution flow, which is described as follows:

$$u = K \cdot \frac{\partial h}{\partial x} \tag{11}$$

Where K is the hydraulic conductivity (m/s) influenced by the saturation of concrete as discussed in unsaturated moisture transport; and $\partial h/\partial x$ is the hydraulic gradient; Shackelford and Daniel [85] and Shackelford and Moore [86] pointed out that there is a different meaning between D_e and apparent diffusion coefficient of chloride ion transfer in concrete. Several models have been proposed to estimate D_e in porous media, where the MQ model [87] is widely adopted. In the MQ model, D_e is described by pore structures (i.e., volume fluid fraction, tortuosity factor) and D_0 (diffusion coefficient of chloride ion in bulk water (m^2/s)), which can be expressed as:

$$D_\mathrm{e} = \frac{\theta}{\tau_{MQ}} D_0 \tag{12}$$

Where $\tau_{MQ} = \theta^{-7/3}\phi^2$ is the tortuosity factor; ϕ is the total effective porosity of concrete. It is obvious that the MQ model does not consider the constrictivity factor, δ, which is used to describe the reduction effect of the pore connectivity and electric changes on the walls of the micro-pores during mass transport [78, 88]. Pore sizes are thought to be the main determinant of constrictivity. Nakarai et al. [78] defined the constrictivity factor δ as a function of the peak pore radius by Eq. (13),

$$\delta = 0.395\tanh\{4(\lg r^{peak} + 6.2)\} + 0.405 \tag{13}$$

where r^{peak} is the peak radius of capillary pores (m). The relationship between δ and r^{peak} is shown in Fig. 5-3.

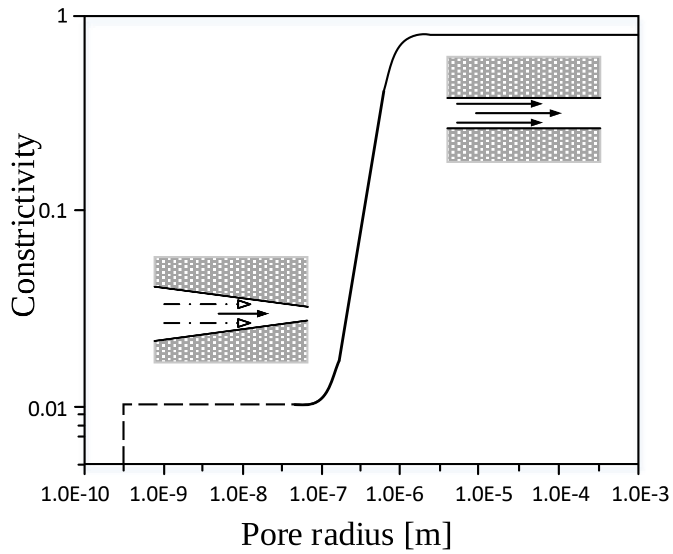


Fig. 5-3. Effect and value of constrictivity factor [78].

The value of constrictivity factor δ is often taken about 0.01 for the fine mature concrete because the small peak radius of capillary pores varying from 20 to 120 nm [88, 89]. Then, another model to calculate D_e proposed by Nakarai et al. [78] (abbreviated as the NI model) is written in Eq. (14).

$$D_e = \theta \cdot \frac{\delta}{\tau_{NI}} \cdot D_0 \tag{14}$$

Where δ is the constrictivity factor as given in Eq. (13); τ_{NI} = -1.5tanh{8.0(ϕ-0.25)}+2.5 is the tortuosity factor expressing the geometrical property of pore net, which is an intrinsic characteristic describing the actual pathway length of ion transport in the pore spaces. The relationship is shown in Fig. 5-4.

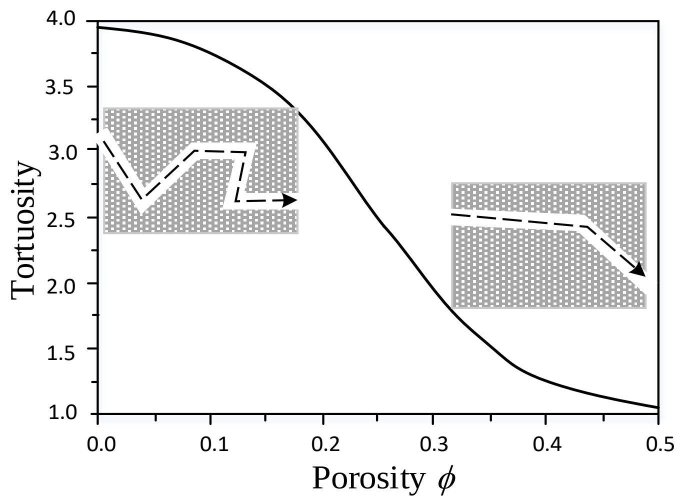


Fig. 5-4. Effect and value of tortuosity factor [78].

3) Fluid-Solid coupling

Chloride ion penetration into concrete is a multiphysics coupling problem among three physical fields: Fluid-Solid-Solute as indicated in Fig. 5-5.

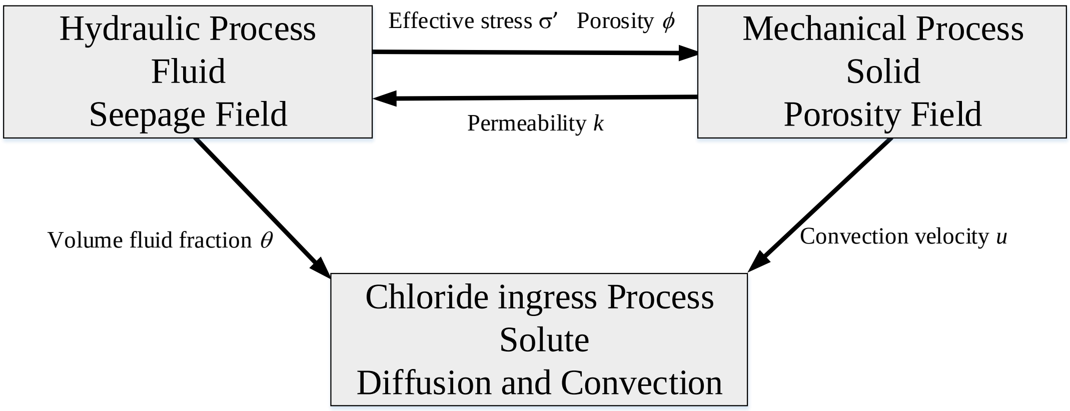


Fig. 5-5. Schematic diagram of coupling relationship in Multiphysics.

Classical fluid mechanics generally assume that the porous media (such as rocks, soils, etc.) are completely rigid, i.e., there is no elastic or plastic deformation in solid skeleton during the seepage process. However, when liquid flows through concrete under hydrostatic pressure, the coupling process between the hydraulic process and mechanical process is bidirectional and is mainly reflected in two aspects: (1) fluid to solid coupling meaning that variation of hydrostatic pressure changes the distribution of original stress in concrete, which change the pore volume of concrete; and (2) solid to fluid coupling meaning that the change of pore volume will cause the change of concrete hydraulic conductivity. Several assumptions are made to effectively discuss the fluid-solid coupling model for unsaturated concrete: (1) water is incompressible; (2) no hysteresis in solid–water characteristic curves; and (3) the air diffusion in water and the water vapor movement is ignored [90].

Based on the linear elasticity theory, the constitutive relations for the stress and strain under pore water pressure, p can be described as the following equation [91, 92, 93].

$$\varepsilon_{ij} = \frac{1}{2G}\sigma_{ij} - \left(\frac{1}{6G} - \frac{1}{9K'}\right)\sigma_{kk}\delta_{ij} + \frac{1}{3K'}\alpha_p p\delta_{ij} \tag{15}$$

σ_{ij} can be calculated by solving Eq. (15) as follows:

$$\sigma_{ij} = 2G\varepsilon_{ij} + 2G\frac{\nu}{1-2\nu}\varepsilon_{kk}\delta_{ij} - \alpha_p p\delta_{ij} \tag{16}$$

Where σ_{ij} is the total stress tensor (positive for tension); ε_{ij} is the strain tensor; $\varepsilon_{kk} = \varepsilon_{xx} + \varepsilon_{yy} + \varepsilon_{zz}$ is the volume strain which is related to effective stress rather than to total stress [91, 94]. p is the pore pressure (Pa); $G = E/[2(1+v)]$ is the shear modulus (Pa); E is Young's modulus; v is Poisson's ratio; δ_{ij} is the Kronecker delta defined as 1 for $i = j$ and 0 for $i \neq j$; $\alpha_p = 1 - K^{'}/K_s$ is the Biot's effective stress parameter which depends on the compressibility of the concrete; $K^{'} = 2G(1+v)/[3(1-2v)]$ is bulk modulus of the porous medium and K_s is the bulk modulus of the solid grains.

Combined with static equilibrium equation (i.e. $\delta_{ij,j} = -F_i$) and strain-displacement equation (i.e. $\varepsilon_{ij} = (u_{i,j}+u_{j,i})/2$), the stress control equation for concrete mass deformation in terms of the displacement u_i and pore pressures p is as follows:

$$Gu_{i,jj} + \frac{G}{1-2\mathrm{v}} u_{j,ji} - \alpha_p p_{,i} + F_i = 0 \tag{17}$$

For saturated concrete, volume V is consisted by volume V_s of concrete grains and volume V_e of voids [93]. Then, Eq. (18) is obtained.

$$\frac{1}{V}\frac{\partial V}{\partial t} = \frac{1}{V}\frac{\partial V_s}{\partial t} + \frac{1}{V}\frac{\partial V_e}{\partial t} = \frac{\partial \varepsilon_v}{\partial t} \tag{18}$$

Where the change of concrete grains volume V_s and concrete voids volume V_e can be described as:

$$\frac{1}{V}\frac{\partial V_s}{\partial t} = -\frac{1-\phi}{K_s}\frac{\partial p}{\partial t} + \frac{1}{3K_s}\frac{\partial \sigma_{ij}'}{\partial t}\delta_{ij} \tag{19}$$

and

$$\frac{1}{V}\frac{\partial V_e}{\partial t} = -\nabla q_l - \frac{\phi}{\beta_l}\frac{\partial p}{\partial t} \tag{20}$$

respectively.

Where ε_v ($\varepsilon_v = \varepsilon_{xx} + \varepsilon_{yy} + \varepsilon_{zz}$) is the volume strain; t is time (s); q_l denotes the water flux/unit area (m/s) and β_l is bulk modulus of pore water (Pa). In Eq. (19), the right two terms represent the volume change caused by water pressure and effective stress, respectively. In Eq. (20), the right two terms represent the net volume of water and water volume changes caused by water pressure respectively. Substitution of Eqs. (19) and (20) into Eq. (18) results in

$$\nabla q_l = -\frac{\partial \varepsilon_v}{\partial t} - \left(\frac{1-\phi}{K_s} + \frac{\phi}{\beta_l}\right)\frac{\partial p}{\partial t} + \frac{1}{3K_s}\frac{\partial \sigma_{ij}'}{\partial t}\delta_{ij} \tag{21}$$

Based on thermodynamics of irreversible processes, the water flux is given by $q_l = -k_r \cdot (k_s/\mu) \cdot \nabla p$ in unsaturated concrete, where k_s is the saturated permeability of concrete (m^2); μ is viscosity of water

(Pa·s); k_s/μ is the permeability tensor [$m^2 \cdot (Pa \cdot s)^{-1}$]. Then the seepage equation under the coupling of fluid-solid can be obtained [93].

$$k_r \frac{k_s}{\mu} \nabla^2 p = \alpha_p \frac{\partial u_{j,j}}{\partial t} + \left(\frac{1-\phi}{K_s} + \frac{\phi}{\beta_l} \right) \frac{\partial p}{\partial t} \tag{22}$$

It is necessary to know the relationship of parameters to solve the control equations of fluid-solid coupling; that is, Eqs. (17) and (22). According to Zimmerman et al. [95], Cui and Bustin [96] and Detournay and Cheng [92], the relationship between porosity and pore pressure is

$$\phi = \alpha_p - (\alpha_p - \phi_0) \exp\left\{ -\frac{1}{K'} [(\bar{\sigma} - \bar{\sigma}_0) + (p - p_0)] \right\} \tag{23}$$

The relationship that saturated permeability k_s varies with porosity ϕ under the effect of pore pressure p is considered as a relation $k_s \sim \phi^3$ [92, 94, 96].

In total, the governing partial differential equation of the chloride transfer can be combined as follows:

$$(\theta + \rho_b k_p) \frac{\partial C_f}{\partial t} + C_f \frac{\partial \theta}{\partial t} = \underbrace{\frac{\partial}{\partial x} \left(D_e \cdot \frac{\partial C_f}{\partial x} \right)}_{\text{diffusion}} + \underbrace{\frac{\partial}{\partial x} \left(k_r K_s \cdot \frac{\partial h}{\partial x} \cdot C_f \right)}_{\text{convection}} \tag{24}$$

From the theories mentioned above, experts can reveal the mechanism of chloride ion ingress into concrete. To transform the tacit knowledge in the expert brain into explicit knowledge, information technology such as visualization computational software is needed, which is a simulation software with function of building up the models, solving the partial differential equations and displaying the calculation results. Experts can conduct chloride ion penetration simulation with their theoretical knowledge and environmental parameters by using numerical software. The numerical software encompasses the whole workflow from modelling to simulating – from building up geometric model, defining boundaries, assigning material properties, describing specific phenomena, to finally solving and post processing models for producing accurate and trustworthy results.

A 3D concrete model of 0.3 m thick is built with external water pressure is built to simulate this coupling process, the chloride ion concentration inner concrete is supposed to be zero initially. The initial saturation of concrete is 0.8 and the external water pressure is 1.5 MPa, illustrated in Fig. 5-6.

According to IAPSO (Standard Seawater and China Primary Standard Seawater), the chloride ion concentration is set at 19000 ppm (i.e. 546 mol/m^3) in the seawater. The density of water is taken as 1000 kg/m^3 and the diffusion coefficient of chloride ion in water, D_0, is taken as 1.484×10^{-9} m^2/s [97]. For concrete, the water-cement ratio is selected to 0.5 as a reference and the value of bulk modulus and shear modulus is 17.5 GPa and 13 GPa, respectively. Referred to the related literatures, Table 5-1 lists other input parameters for the calculation as control.

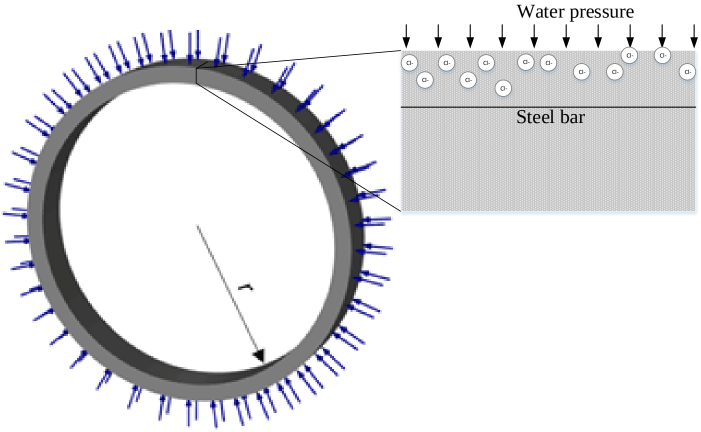


Fig. 5-6. Simulation model of tunnel concrete under water pressure.

Table 5-1. Input parameters used in the modeling (w/c=0.5).

category	parameters	value	reference
Concrete properties	Density, ρ_b (kg/m^3)	2400	[83]
	Porosity, ϕ	0.12	
	Saturated permeability, k (m^2)	3×10^{-21}	
van Genuchten	a (m^{-1})	2.8×10^{-4}	[98]
	m	0.417	
	l	0.5	
	Initial water content, θ_0	0.096	[97]
	Residual water content, θ_r	0	
binding	α	8.51	[80]
	β	0.32	

The numerical simulation was carried out by solving partial differential equations. In this simulation, the transient seepage model of concrete based on fluid-solid coupling analysis was established. Setting time as control factor in the process, solving partial differential equations (PDEs) in Multiphysics with two steps: moisture transport and chloride ion transfer. Seen in Fig. 5-7.

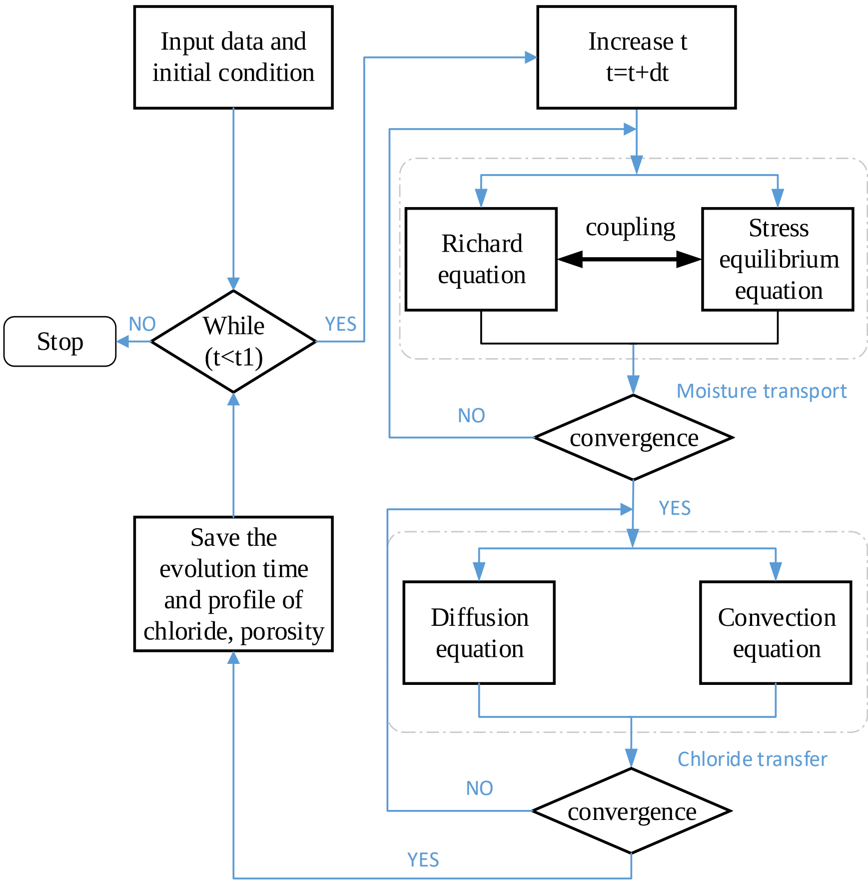


Fig. 5-7. Flow chart for calculating moisture content and chloride profiles.

During solving the governing partial differential equations of the chloride transfer, Eq. (24), it is essential to gain the definition of effective diffusion coefficient of chloride ion, D_e. While in the form of D_e, there is some discrepancy between the two models (i.e. the MQ model and the NI model) from different references, this paper compares the two models to assess their applicability. In this part, from the results of comparison of concentration profiles as shown in Fig. 10. It can be identified that the concentration of chloride ion in the same period calculated by using the MQ model is significantly larger than that by using the NI model, which implies that constrictivity factor, δ may have an immense impact on the migration of chloride ion. Therefore, based on the theory of the NI model, the factor of constrictivity with the value of 0.01 is considered to modify the MQ model. Afterwards, the calculation results of the NI model and the modified MQ model have a good agreement; thus, the modified MQ model is concluded to be reliable and acceptable and can be used for subsequent simulation.

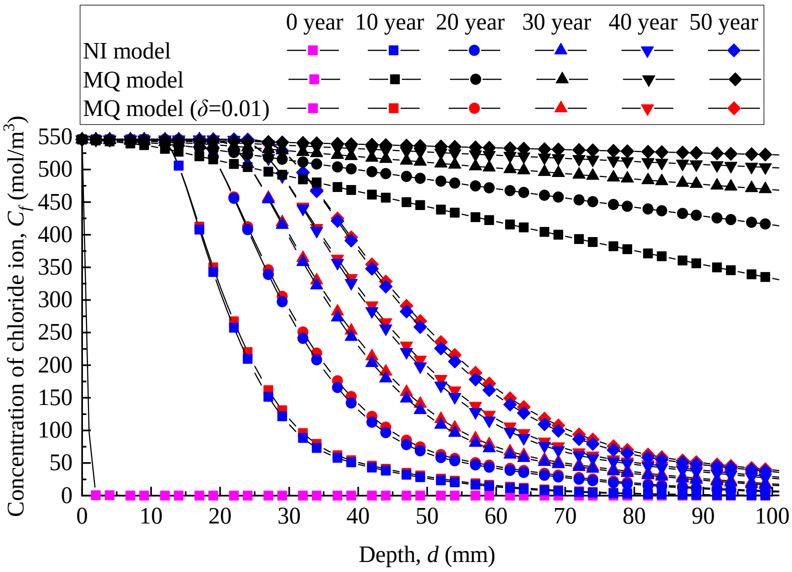


Fig. 5-8. Concentration of chloride ion by using the NI model, MQ model and MQ model modified with δ=0.01.

To verify the simulation results of proposed multi-mechanism penetration model, two different time spans of chloride diffusion are discussed for the short-term (150 days) and the long-term (30 years). For the short-term verification, the experimental results and fitted curve inferred from Long et al. [99], the numerical results and analytical prediction results by Fick's 2nd law are given in Fig. 5-9. While for the long-term verification, as it is hard to obtain the specific chloride distribution profiles through experiments or actual measurements, the apparent diffusion coefficient obtained from the rapid chloride migration test and numerical model are compared. The Fick's 2nd law is commonly used to describe chloride ion diffusion into concrete. However**,** Fig. 5-9 shows that in the analytical prediction progress, the Fick's 2nd law describes the chloride diffusion distribution profiles (black line) rather than convection. On the other hand, the fitted curve (red line) based on the experimental data cannot describe the complex distribution profiles of the chloride ion appropriately. While the numerical result (blue line) shows a better agreement with the experimental data. Thence the proposed multi-mechanism penetration can achieve the prediction of chloride distribution profiles.

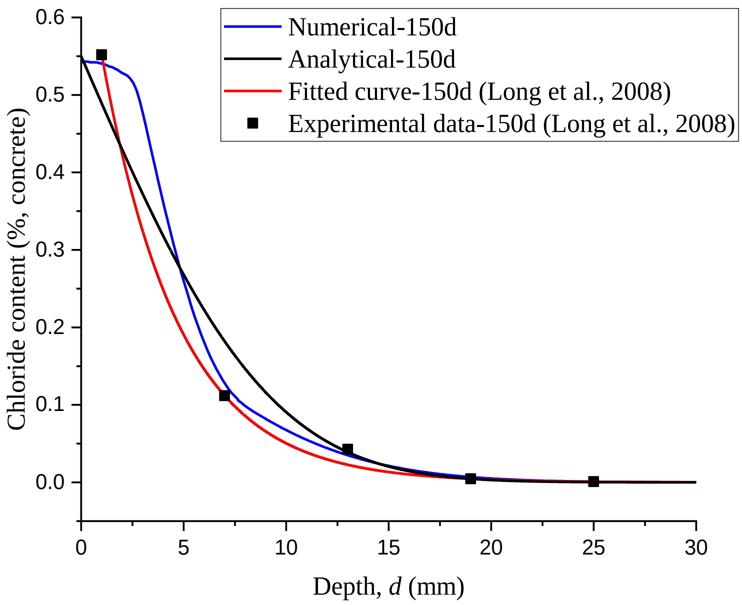


Fig. 5-9. Chloride distribution profiles of the numerical, analytical and experimental results.

Spiesz and Brouwers [100] through the rapid chloride migration test got the relationship between apparent diffusion coefficient D_a and effective diffusion coefficient D_e, as $D_e = 0.133 \times D_a$. However, the calculated D_a is about 30% larger than that obtained from the non-steady-state diffusion test. Therefore, D_a must be revised to get the non-steady-state apparent diffusion coefficient. By reviewing a large amount of literatures and experiments, Song et al. [101] concluded that the D_a obtained from experiments mostly ranges from 2.0×10^{-12} to 5.5×10^{-12} m^2/s. As shown in Fig. 5-10, it can be identified that revised D_a of the MQ model and the NI model ranges from 2.4×10^{-12} to 5.25×10^{-12} m^2/s and 2.25×10^{-12} to 3×10^{-12} m^2/s respectively, which has good agreements with the experiment results. The agreement means that the model used in this study reveals the real situation of chloride ion transfer and the multi-mechanism penetration model is computable.

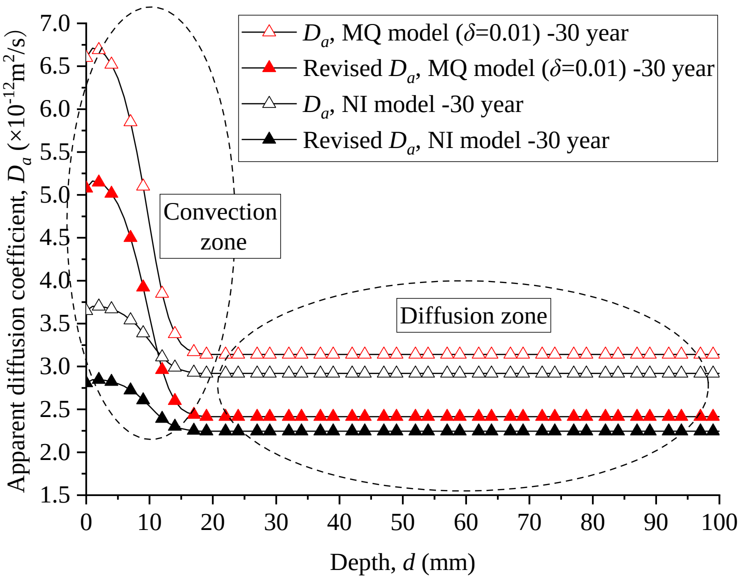
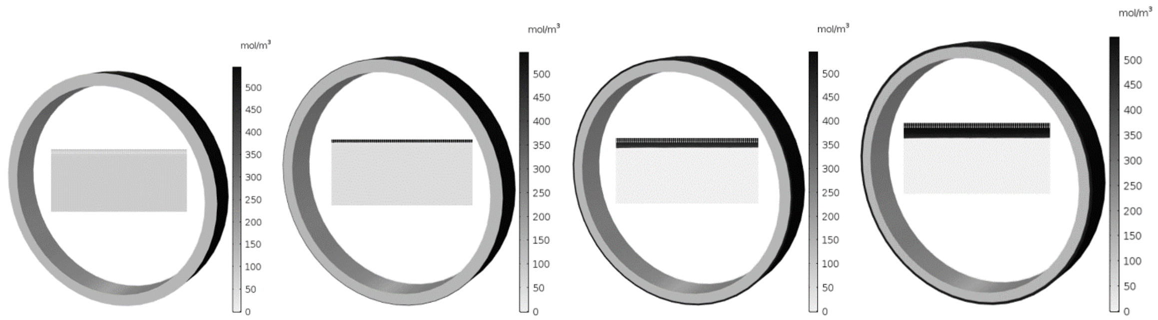


Fig. 5-10. Apparent diffusion coefficient of the NI model and modified MQ model.

After calculation, we can get the visual results. The distribution of chloride ions in concrete over time can be obtained (qualitative display shown in Fig. 5-11 and quantitative display shown in Fig. 5-12). The simulation result can assist to predict the deterioration of concrete structure caused by chloride ion penetration.



t=0 t=5 years t=50 years t=100 years

Fig. 5-11. Chlorine ion concentration distribution over time (qualitative display).

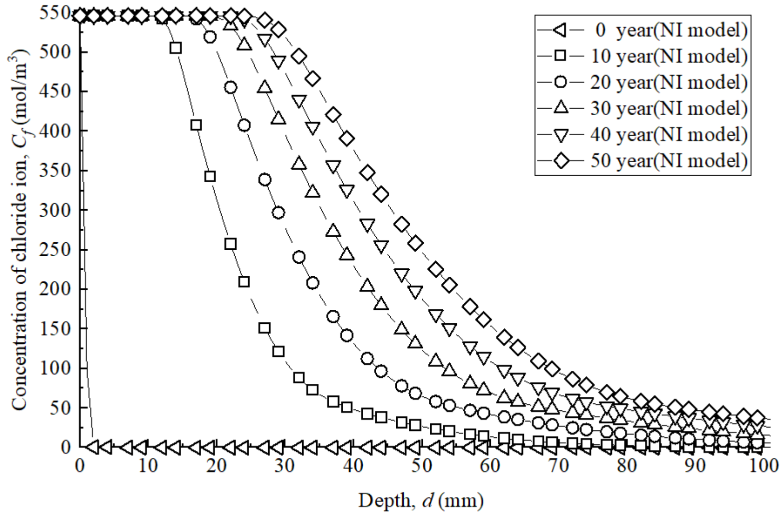


Fig.5-12. Chlorine ion concentration distribution over time (quantitative display).

Until now experts have successfully transformed the tacit knowledge into explicit knowledge. A prototype of simulation model has been built with their knowledge. This simulation process requires professional numerical software and contains very detailed knowledge, which is not conducive to the use of non-experts.

5.1.3 Knowledge sharing process

This is the universal analysis process. Experts use information technology to create the knowledge repository allowing the analysis to be reused by non-experts.

1) Sharing knowledge by application software

In the information sharing, due to the different needs and purposes of the participants, the levels of knowledge requirements are varied. The knowledge providers (experts) focus on the knowledge itself to conceive a model to simulate the reality as completely as possible, so they have high level of knowledge requirements. Since the knowledge receivers (usually as managers without professional knowledge reserve) are mainly engaged in engineering practice, focusing on the application of knowledge. They only need to carry out the durability analysis through a simulation model with simple operation, so they have low level of knowledge requirements. To eliminate the confusion caused by different levels of knowledge requirements in the process of knowledge sharing, the providers need to simplify a knowledge model and customize a user interface to meet the level of knowledge requirements of receivers. Open parameter models would be adopted to realize the simplification of the simulation model by experts, in which various theories applied in the analysis are hidden, while the parameters and one-click calculations are operational. In addition, the results of analysis in open parameter models should be visible. Knowledge receivers can access the knowledge from the user interface and reuse the knowledge through the open parameter models.

The second-development method in numerical software allows experts to create customized and easy-to-use applications based on the complicated simulation. Experts can pack the simulation process by creating and/or customizing applications with open partial parameters related to the numerical model of chloride ion penetration process (shown in Fig. 5-13). This application is with friendly user interface where the parameter can be modified in the parameter input box to appropriate to the target project, and the compute button can finish the complex theoretical calculation, and the graphics window shows the calculation results.

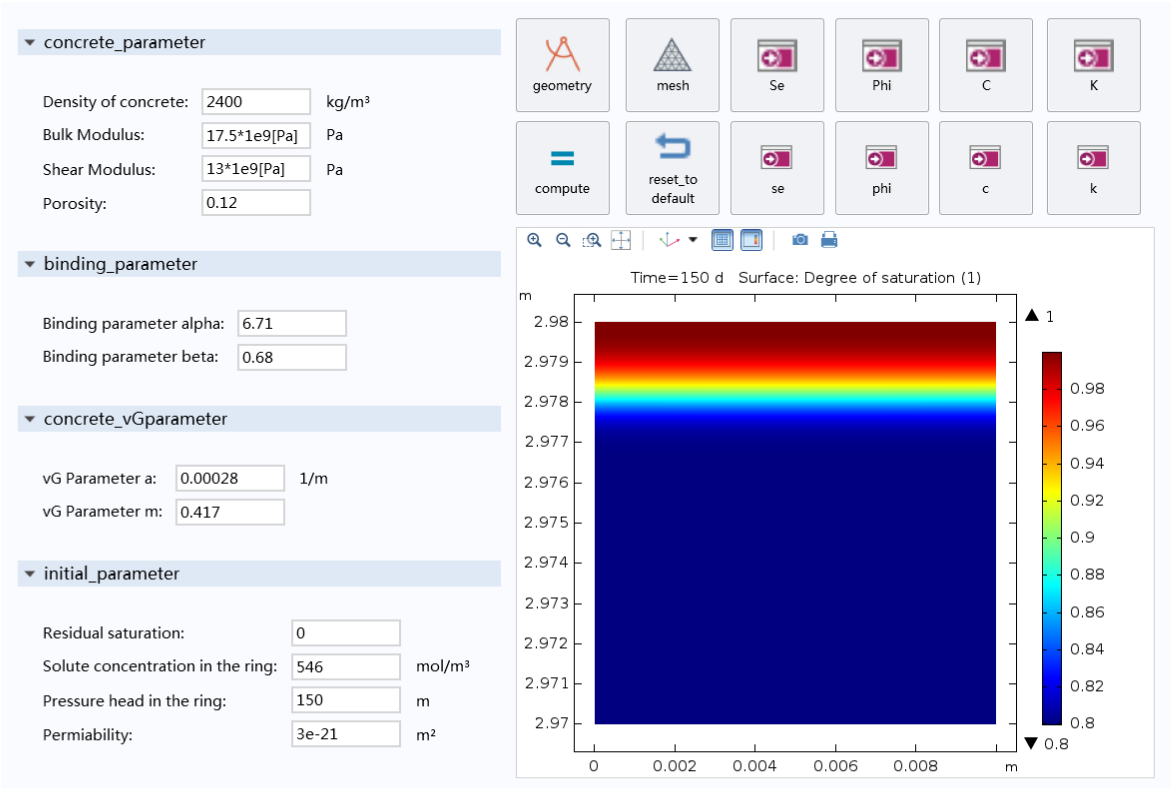


Fig. 5-13. the application of open parameter model.

This application can undoubtedly enable non-experts to do the same analysis of chloride ion penetration into concrete, as long as the non-experts input the parameters required for the calculation. The accuracy of the results is closely related to these parameters, so it is necessary to know the sensitivity of the parameters to help non-experts choose parameters. That is to say, to tell users which parameter is more important, so that they will be more careful when input this parameter.

In the sensitivity analysis, this research mainly discusses the influence of saturated permeability (k_s), van Genuchten parameters (a, m) (shorted as vG parameters), and binding capacity parameters (α, β)

on the sensitivity of chloride ion transfer. The different moisture characteristic curves (vG-1, vG-2 and vG-3) referred from different literatures and a new moisture characteristic curve (i.e. vG-4), which has same value of *a* with vG-1 and same *m* with vG-2, is defined to make comparation analysis as shown in Fig. 5-14. In addition, the different chloride ion binding relationships (shorted as CBR) are shown in Fig. 5-15. Based on the existing CBR-1, CBR-2 and CBR-3. A new chloride ion binding relationship (i.e. CBR-4) with same value of α to CBR-1 and same β to CBR-2, is defined to study the sensitivity of the binding capacity parameters.

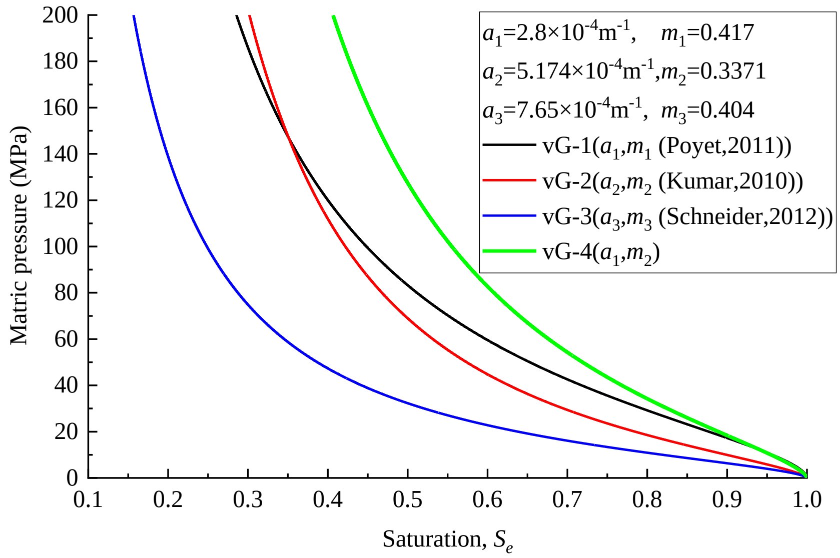


Fig. 5-14. Moisture characteristic curves for different sets of vG parameters (w/c=0.5).

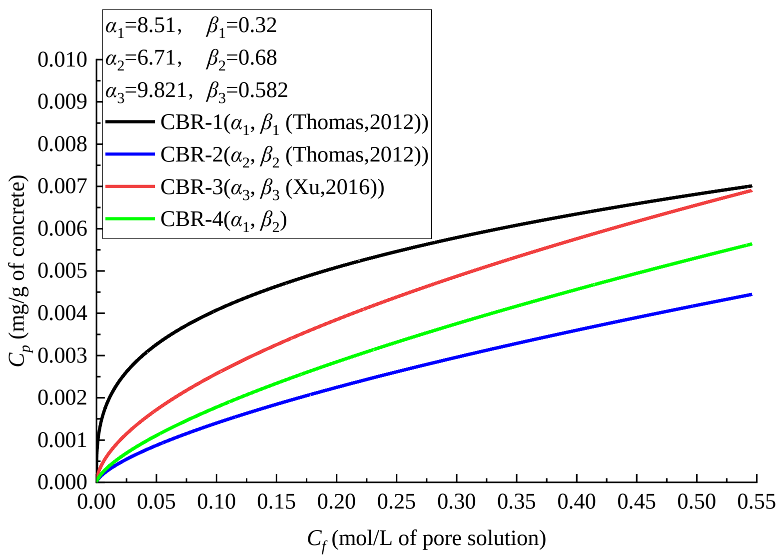


Fig. 5-15. Chloride ion binding relationship for different binding capacity parameters (w/c=0.5).

The sensitivity of input parameters is analyzed in terms of the resulting chloride profiles at a certain time of 30 years. Several interesting observations can be obtained by examining the effects of different parameters on the sensitivity of the predicted chloride ion profiles. It should be noted that the parameters are taken from many literatures to describe concrete with w/c = 0.5. In addition, there are also some sets of parameters created by the combination of existing data to make more detail discussion.

(1) Sensitivity to saturated permeability k_s

A comparison of chloride ion concentration profiles resulting from different value of saturated permeability k_s (i.e. 3×10^{-22} m^2, 3×10^{-21} m^2 and 3×10^{-20} m^2) after 30 years is presented in Fig. 5-16. The diffusion process and convection process are presented separately to obtain the sensitivity in detail. The result shows that with the increase of saturated permeability, the convection depth increases obviously, while the influence in diffusion is negligible. It is found that the convection depth is around 10mm, 33mm,100mm under the effect of saturated permeability 3×10^{-22} m^2, 3×10^{-21} m^2 and 3×10^{-20} m^2, respectively, which means that with the saturation permeability increases by an order of magnitude, the convective zone depth increases by a factor of 2.

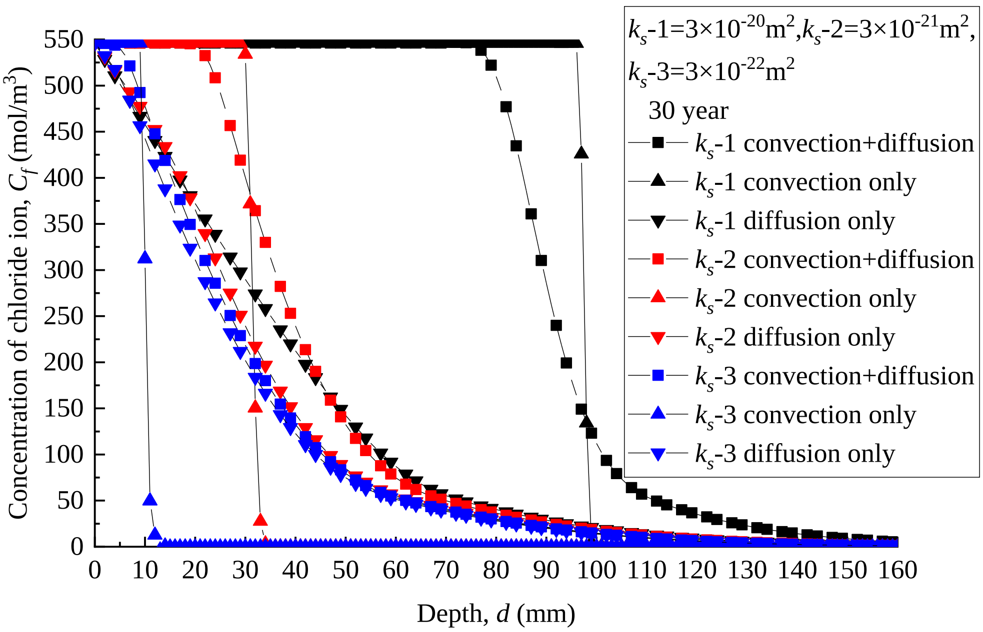


Fig. 5-16. Predicted chloride ion concentration profile with different k_s.

(2) Sensitivity to vG parameter and initial saturation S_{e0}

It is more sensitive for the initial saturation S_{e0} than vG parameters (a, m) in affecting the chloride ion transfer, as can be seen in Fig. 5-17. It may because saturation affects not only diffusion by effective diffusion coefficient D_e but also convection by permeability k. When investigate carefully at the distribution curve of S_{e0} = 0.8, it is recognizable that the difference of the gap between vG-1 to vG-4 is much larger than that between vG-2 to vG-4. It is identifiable that vG-1 and vG-4 share the same value of a, while vG-2 and vG-4 share the same value of m, it is not difficult to conclude that m is the dominant factor in vG parameters.

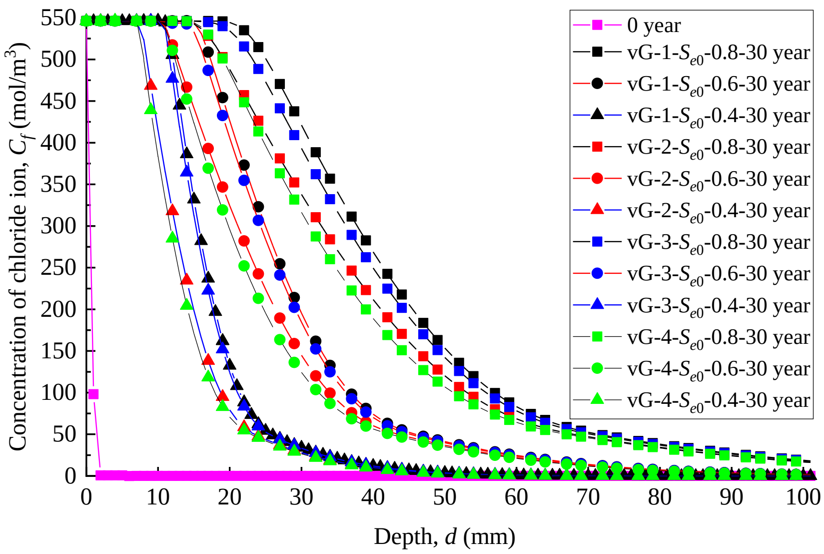


Fig. 5-17. Predicted chloride ion concentration profile with different vG parameters and S_{e0}.

(3) Sensitivity to chloride binding isotherm k_p

The Freundlich isotherm is adopted to describe the binding capacity. It is found that when the free chloride ion concentration is extremely small, the calculation will not converge, so here the 50mol/m^3 is set as threshold concentration, and if the concentration is lower than the threshold value, k_p will be taken as a very small constant. As shown in Fig. 5-18, in the saturated zone the bound chloride ion content and binding isotherm are constant. As the depth increases, the free chloride ion concentration decreases, which results in a decrease in bound chloride ion but an increase in k_p.

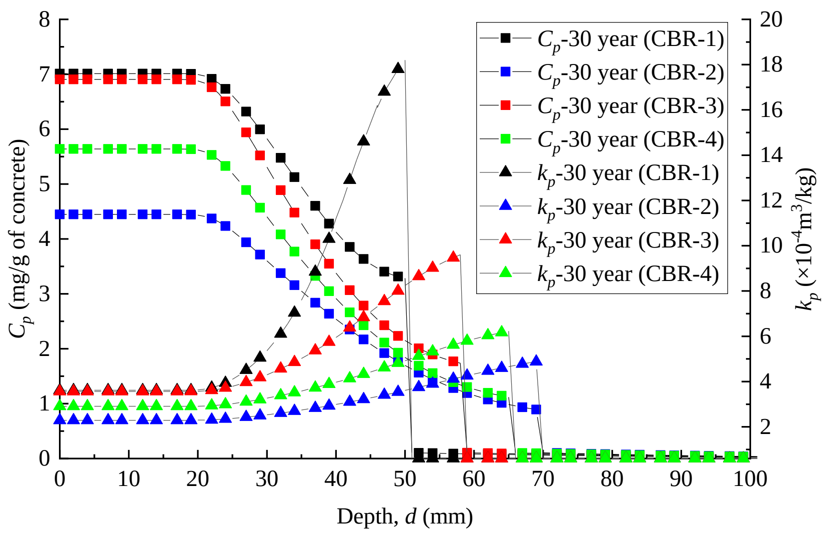


Fig. 5-18. The distribution and relationship of CBR to k_p.

As mentioned in Fig. 5-15, CBR-4 takes only different value of β to CBR-1 and CBR-4 takes only different value of α to CBR-2. Fig. 5-19 shows the predicted chloride ion distribution calculated by different binding parameters (α, β). it can be found from the profile that the diffusion process is affected by changes of binding parameters, but the influence is not extremely big in total. The distribution curve calculated by binding parameters of CBR-4 is closer to CBR-2 than to CBR-1. Then it can be carefully concluded that the β may be the dominant factor in the binding parameters.

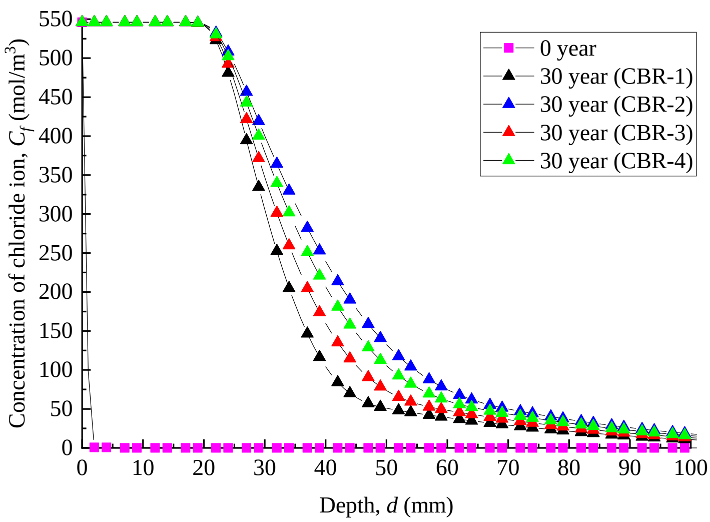


Fig. 5-19. Predicted chloride ion concentration profile with different CBR.

It can be concluded that the key sensitivity factor seems to be the parameters related to moisture transport (e.g. saturated permeability, initial saturation) while the factor of chloride binding isotherm shows less sensitive. At the same time, users also need to pay attention to the parameters that have a greater influence in each group (e.g. β may be the dominant factor in binding parameters (α, β)).

2) Sharing knowledge by network technology

Professional software is generally used to conduct the simulation process by experts, even in developing the open parameter application. Different analysis may use different software, which leads to a large number of software requirement. Non-experts (here it refers to maintenance manager) will not buy a lot of professional analysis software, from the perspective of economics and requirement of analysis depth. Now, network technology is booming. It is already common to share information on the internet through browser (shown in Fig. 5-20). In order to realize a more flexible access to the application for general users, remote access technology via web browser is optimal choice to eliminate the limitations of professional software.

A local computer with professional software installed is worked as server computer, which connects to the Internet and supports physical data interaction with other devices connected to the Internet. And then the server computer address is distributed to the network in form of URL (uniform resource locator) for client access. This article uses the Hyper Test Transfer Protocol (HTTP) as network transfer protocol. HTTP designed for information transfer between web browsers and servers is an application-layer protocol for transmitting hypermedia documents. The syntax of HTTP URL is:

http://<host>:<port>/<path>?<searchpart>

where <host> is IP address or host name; <port> is the service port; <path> is an HTTP selector, and <searchpart> is a query string; <path>, <searchpart> and the "?" in front of it are all optional. If there are no <path> and <searchpart> parts, "/" can also be omitted.

In this research the URL is adopted as: http:// IP address for server computer:2036. The client computer can remotely access to server computer.

When the browser needs a file hosted on a server computer, the browser requests the file via HTTP. When the request reaches the correct server computer through internet, the HTTP server receives the request, finds the requested document (if the document does not exist, it will return a 404 response), and passes the document to the browser via HTTP.

People who get the permission can login website, input the URL address and run the apps remotely via web browser in their own computer. These calculations can all be done on the server computer(s) and the feedback can be checked through brewers. In that case, for users, there is no necessary to install professional software in their own computer or mobile device.

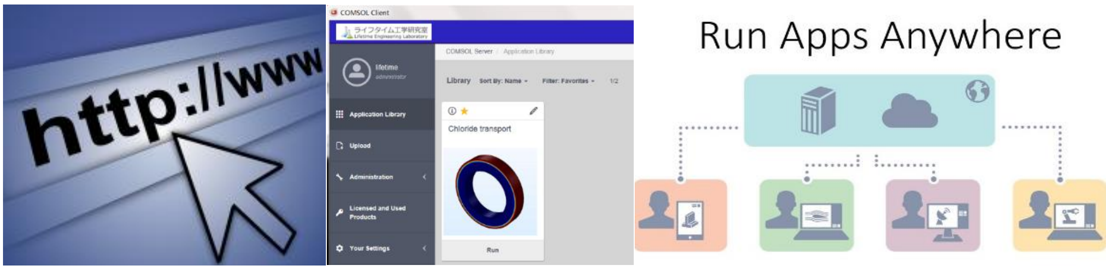


Fig. 5-20. Sharing professional analysis by network technology.

5.2 INTEGRATED INFORMATION PLATFORM

In this paper, the software for maintenance information management of civil infrastructure is developed. The maintenance management focuses on a highway system, Yakang Expressway, which is located from Ya'an City, Sichuan Province to Ganzi Tibetan Autonomous Prefecture, China (shown in Fig. 5-21). The whole system consisting of Erlang mountain concrete tunnel, interchange, Luding concrete tunnel, and Daduhe concrete bridge. The altitude difference across the line reaches 1900 meters. Terrain and geological conditions are extremely complex: perennial ice, snow, heavy rain, dense fog, mudslides, landslides. From December 31, 2018, the expressway has been put into use.

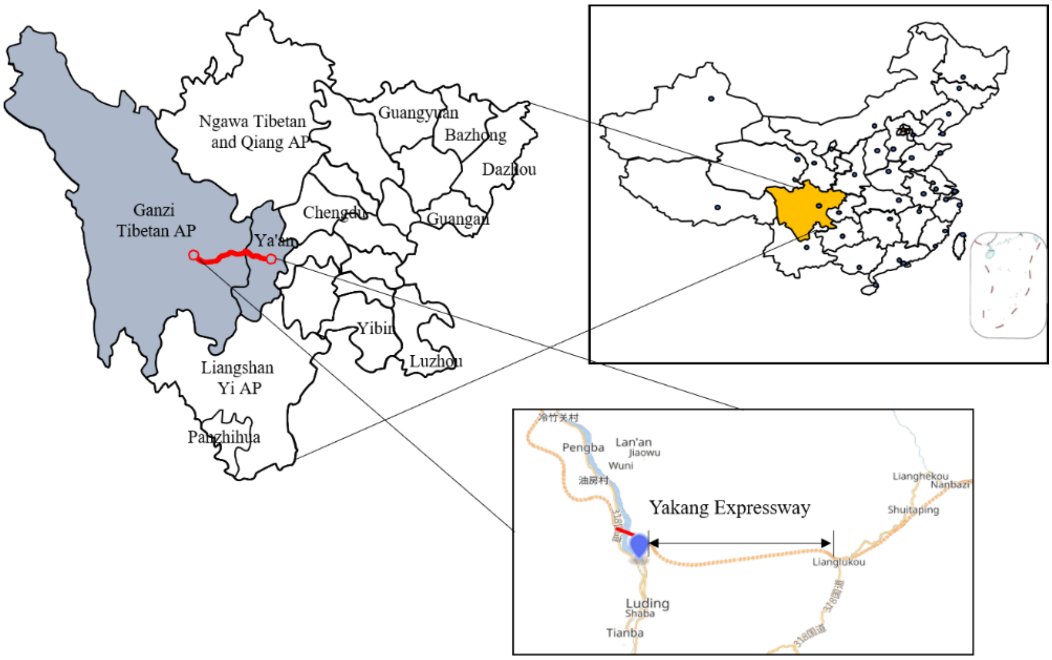


Fig. 5-21. location of the project.

In order to respond to the requirements of informatization in civil engineering, the project proposes to build digital visualization model environment by using BIM and GIS.

From design, construction to operation phase, it lasted up to 5 years. During the design and construction phase, a large number of documents were recorded and delivered for maintenance management.

Due to the complex geographic environment and long lines, it is difficult to implement on-site inspection. A structural health monitoring system was installed on-site in advance to collect monitoring data in real time and monitor the project status remotely.

Moreover, the project proposes to reserve the scientific research results module to allow users conduct the degradation analysis and obtain other research results via internet during maintenance management.

5.2.1 Software development tools and design

Software development involved many tools:

(1) Autodesk Revit 2017 provides digital 3D highway models on behalf of BIM. SuperMap iDesktop 9D provides geographic information on behalf of GIS and also serves as the basis for the final integrated platform. (2) System architecture is C/S architecture. The client system provides visualization and operation user interface. The server system undertakes the tasks of data storage, access and management. (3) This system uses relational database MySQL (SQL queries) for the basic information management.

Because the maintenance management information contains a large amount of unstructured information, such as pictures and videos, and the information will be continuously updated over time, MongoDB (NoSQL) is adopted to achieve the expansion of information. (4) The development environment is Microsoft Visual Studio 2017, .Net Framework 4.5 and development language is C#.

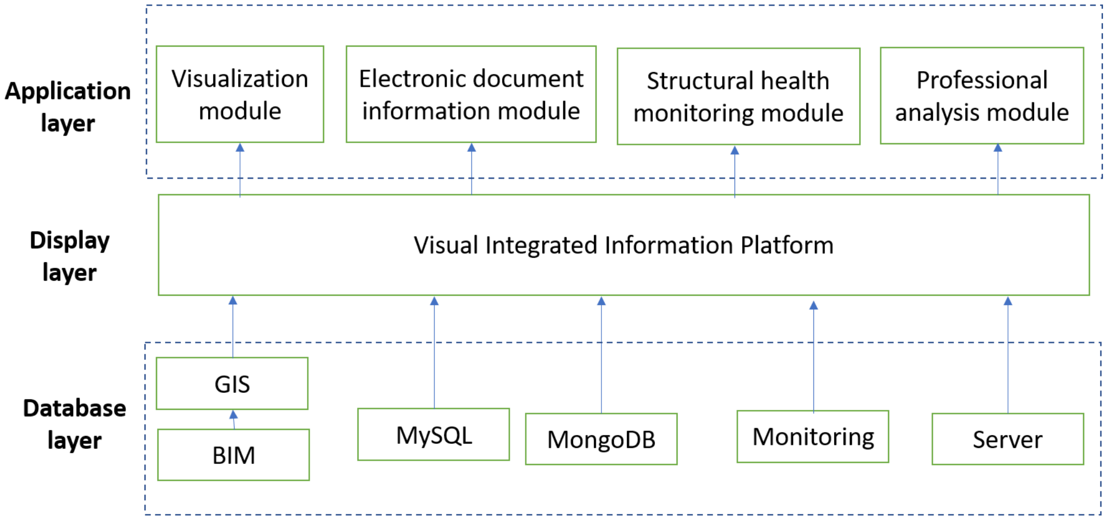


Fig. 5-22. Visual integration information platform.

The function was divided into four layers as shown in Fig. 5-22. Database is from different sources: the visualization module is by combining BIM data with GIS data; the electronic document information module is by adding MySQL database and MongoDB database; the structural health monitoring module is from monitoring data onsite, and the professional analysis module is from server computer.

5.2.2 Function module implementation

This is an independently developed information platform, and its security has been set since login. At login, it is required to verify the user's permissions. Users such as maintenance managers and engineers must put the correct ID and password to log in successfully (shown in Fig. 5-23). After login the user is lead directly to the main interface of information platform with module menu and view window to be given immediate overview about the information system. Users can switch to different information modules through the module menu.

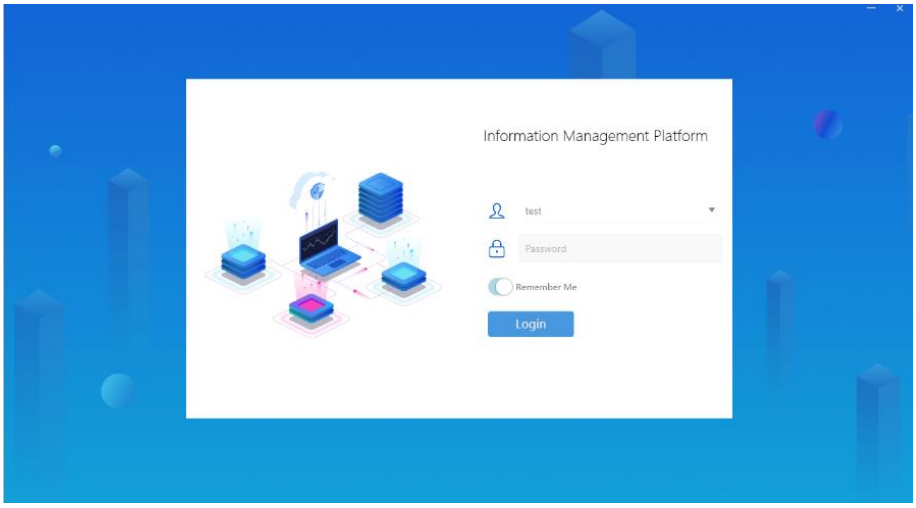


Fig. 5-23. login interface of the information platform.

1) Visualization module

The convert method of the external data exchange mode was used to use BIM data and GIS data to export data from BIM and match the format of BIM data with GIS model, and then merge them into one system through programming. The programming software was used to read information such as geometry, attributes, and coordinates of the model created by Revit, and then convert and write to data format used in SuperMap Idesktop 9D by programming. Visualization is implemented with multi-scale, multi-precision (Fig. 5-24). The first level is an overview map of the road, showing the terrain location and direction of the road. The second level is a fine BIM model, which can view the geometric information, attribute information, etc. The third level is the detailed model, which uses roaming, list positioning and other methods to check the status of facilities and equipment on the road.

This module provides two types of unique functions: 3D visualization and controller roaming. Users are allowed to view 3D model of the whole road system provided by Revit as well as 3D maps provided by SuperMap iDesktop 9D. The model can be zoomed locally to check the detail according to requirements. Controller roaming function allows users to browse the road system along the scheduled route. Users can quickly understand the overall layout of the project through video animation.

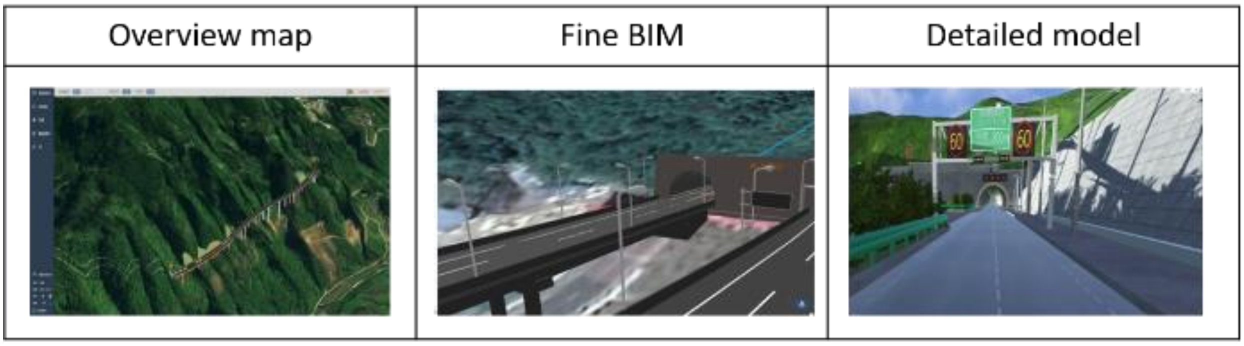


Fig. 5-24. Three-level visualization.

2) Electronic documented information module

Maintenance information is stored in the database in the form of electronic documents. Electronic document information contains a variety of information from design information to maintenance information and is aggregated according to document type that can be updated over time. The electronic document information is linked in the visualization platform based on their locations and categories, thereby making the information retrieval more accurate and efficient as shown in Fig. 5-25. This module provides storage function and four types of inquiry functions:

- Document storage: document is stored in an independent database. This function allows the user to link the database of document with the 3D model component described in the document by adding marks to the components in the visual model. As mentioned before. This road system is consisted by four sections. For every section, documents can be stored in different categories: technical documents, research documents, design documents, construction documents, delivery documents, maintenance documents, and each type of document can be marked differently in the model. Different formats of information also can be stored together such as document in word file, pdf file, txt file.
- Document retrieval: document can be retrieved according to the location. The menu on left of user interface lists the sections of the road system. By clicking them, visualization window will shift to the corresponding position and marks can be seen in the graphical user interface. When you click the mark, a list of documents will be shown in the right menu.
- Document viewing: document can be directly opened in a new window in the platform by click the title of document in the right menu. Therefore, users can obtain the information in the document immediately to help them make maintenance decisions.
- Document download: this function provides users to keep important document anytime in their local computer for further use.
- Document print: this function allows users to send printing instructions to the printer directly on the platform.

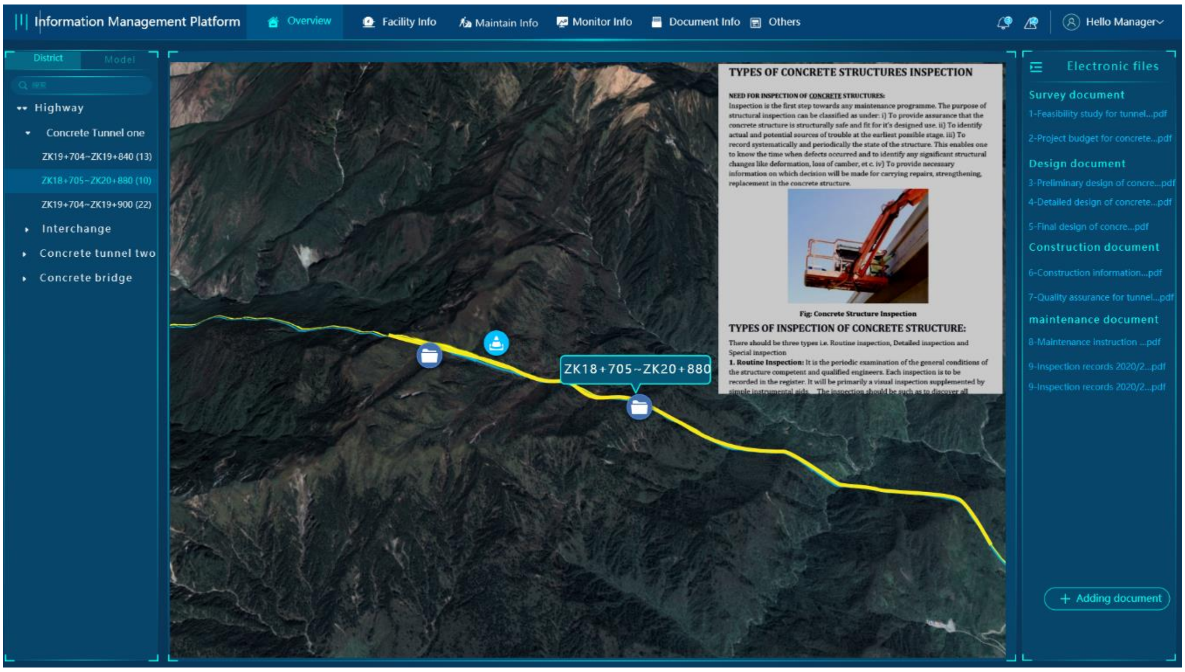


Fig. 5-25. Electronic documented information.

3) Structural health monitoring module

The structural health monitoring information comes from the data detected by the on-site sensors. Sensors are scattered in different parts of the structure, such as planted into concrete, steel cable or pasted on the structure surface, etc. The sensors are correctly installed and debugged to ensure continuous monitoring work and data collection.

Monitoring data is stored in an independent database to reduce the load on the platform. To make monitoring data easy to read, pre-treatment should be done in advance such as reducing the length of data, calculating the corresponding degradation indicators, etc. The information platform helps display the legible monitoring information. This module provides visual display of monitoring data to help maintenance managers quickly grasp the on-site situation. A series of operations need to be carried out in the platform: first mark the position of the sensor in the 3D model in the graphical user interfaces, then link the mark to the database, and finally display the monitoring data of the corresponding label in the right information box in time (shown in Fig. 5-26).

The mark on the graphical user interface can help the managers to track the rough location of the monitoring system in the real world. In the display interface on the right, the cross-sectional view is used to accurately position the monitoring data. The data in the display interface is dynamically changing, responding to on-site monitoring in real time.

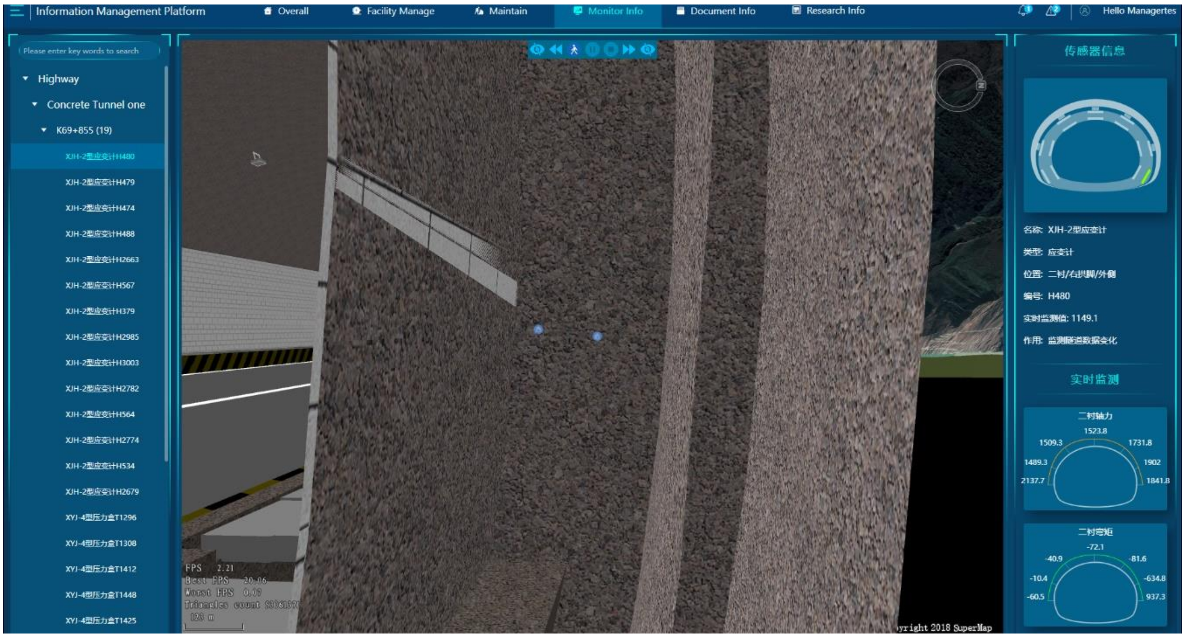


Fig. 5-26. Structural health monitoring module.

4) Professional analysis module

During the service period of road system, it is necessary to conduct a variety of dynamic analyses such as deterioration analysis, bearing capacity analysis to grasp the status of the structure so that to provide evidence for maintenance decisions. Moreover, different analysis involves different professional software. Real-time communication tool such as network technology can be used to remove professional knowledge and professional software restrictions in sharing of professional analysis among different groups.

Professional analysis module provides the window for professional analysis sharing through cooperation with other software. In this module, A browser (chromium browser, which is a free and open-source software project from Google) interface is installed in the platform. URL (uniform resource locator listed in the righthand menu. URL is a reference to a web resource that specifies its location on a computer network and a mechanism for retrieving it. A typical URL takes the form as: http://www.example.com/index.html, which indicates a protocol (http), a hostname (www.example.com), and a file name (index.html).). When click the URL link, the browser interface will appear and jump to the web page the same as using google browser to surf with internet.

Here we link to the address of simulation app for chloride ion penetration into concrete from the case above (http:// IP address for server computer:2036). The professional software is installed in server computer while the client computer with installation of integrated information platform only. Managers (as non-experts) input parameters into the open parameter model app released by experts to perform the same chloride ion simulation analysis in the browser interface on the platform. The simulation results can be quickly calculated and displayed in the browser as shown in Fig. 5-27. This is the principle of a B/S framework, the client computer sends instructions to the browser, the browser consults to the server computer, and the server computer calculates the simulation with professional software and finally transmits the calculation result back to the browser for the client computer to view. Through this method, managers can independently conduct professional analysis on this platform without restriction of professional knowledge and professional software.

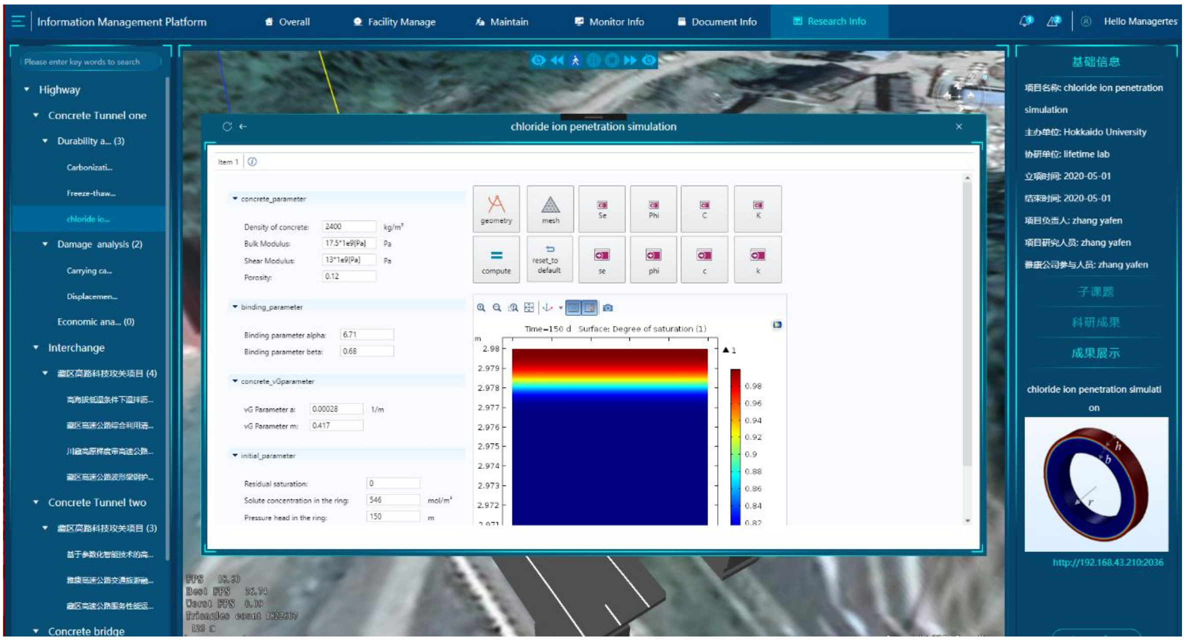


Fig. 5-27. Professional analysis module.

5.3 CONCLUSION

This approach enables people from different backgrounds to enter the knowledge sharing system, in which experts share their method in professional analysis to non-experts. Knowledge management is adopted to illustrate the process of expertise sharing in professional analysis. First, experts use their knowledge to create prototype model by professional software, then the complex prototype model is packaged and simplified into applications, and finally the applications loaded with knowledge are distributed to the internet. Non-experts thus can access the application through browsers with internet and complete the corresponding analysis and calculation process through simple operation. The form of knowledge is very flexible because the explicitness degree and the simplification degree of knowledge can be customized to meet user needs. The knowledge management process for the analysis of chloride penetration into concrete is shown in Fig. 5-28.

Knowledge externalization by numerical software

Knowledge simplification by second-development method

Knowledge transfer by internet technology

Fig. 5-28. Knowledge acquisition, simplifying and transferring process for chloride ion penetration simulation.

This chloride ion simulation application is finally integrated into the self-developed information platform (shown in Fig. 5-29) to allow maintenance managers to access it in a visual manner and long period.

This platform acts as the information carrier and knowledge repository to integrated different kind and form of information or knowledge generated during the life of project. This information platform is based on actual projects (Yakang Expressway in China) and is developed to meet the needs of project maintenance management. Information is linked to corresponding position in the 3D visual model， a complete multi-scale 3D visualization environment integrating model from BIM and GIS. This platform integrates information of different sources including electronic documents, structural health monitoring data, and professional analysis.

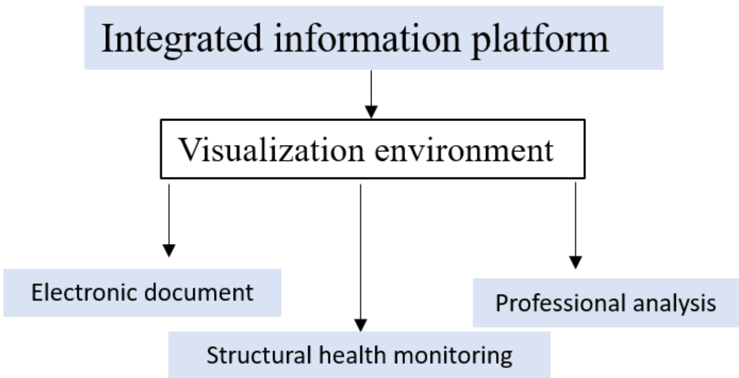


Fig. 5-29. Self-developed integrated information platform.

For electronic document module and structural health monitoring module, information is integrated and displayed on this platform, When the information is retrieved, the graphical interface will locate to the accurate place the 3D visual model. In addition, the professional analysis module and knowledge management are combined to realize the sharing of analysis application for chloride ion simulation in the platform. It realizes the knowledge sharing from experts to non-experts (maintenance managers). This allows managers to conduct professional analysis independently and obtain analysis results in a time. Thence, managers do maintenance management efficiently.

6 CONCLUSIONS AND RECOMMENDATIONS

This thesis focuses on the improvement of maintenance management for civil infrastructure with the supports of information technology. An integrated information platform is designed in the domain of maintenance information management of civil infrastructure. The information is designed into modules according to different forms, and then integrated into a BIM collaboration platform: (1) electronic documents, such as design drawing, construction recording, past maintenance records and specifications; (2) structural health monitoring data obtained by continuously monitoring the civil infrastructure; (3) professional analyses such as deterioration analyses and safety analyses, which need to be carried out in maintenance management with theoretically bases. This professional analysis module is also known as a knowledge-base or an expert system. The innovation of this platform is the integration of information from different information sources, which can enable managers to more effectively obtain comprehensive information and help maintenance decisions. Another innovation is that the platform (called BIM collaboration platform) was built up based on a visual model environment using the BIM and GIS models. Information is linked to the corresponding position in the 3D model. The visualization helps managers retrieval and view information efficiently. This BIM collaboration platform was developed as a software system product based on the usage of different methods and techniques, as well as software tools. The development is centered around the representation and manipulation of different kinds of information from different sources and forms. The information technologies applied correspond to BIM, GIS, database, sensor, internet and browser, as well as procedural programming language and software development.

Knowledge management in maintenance management is another research interest, which is based on the in-depth study of professional analysis module in the information platform. Experts usually share the professional analysis results with non-experts. The approach presented in this thesis gives useful instruction in the professional knowledge sharing between experts and non-experts (maintenance managers), which breaks the knowledge sharing barriers in expertise and constraints in professional software. Non-experts can conduct professional analysis independently. Simulation is a powerful analytical method in deterioration analysis. This research combines knowledge management concepts and information technology to build the possibility of sharing simulation from experts to non-experts (maintenance managers). Experts first build simulation prototypes in professional software, then develop an application to carry simplified simulation prototype (here is in the form of open parameter model), and finally release the open parameter model to the network. Non-experts (maintenance managers) can operate the open parameter model in order to carry out the same simulation in the professional analysis through the browser embedded in the information platform. The managers can benefit from the power of simulation analysis without commissioning to a simulation expert. Through this method, managers can make different kinds of simulation analysis during maintenance management alone to make timely decisions supported by the analysis results, which enables to ultimately improve the efficiency of maintenance management.

This study demonstrates the process of knowledge management through a case study of deterioration analysis caused by chloride ion. Chloride ion penetration into tunnel concrete over time under external hydrostatic pressure was simulated to form a simulation prototype. In this simulation, a relatively complete simulation model was established, taking into account the following factors: (1) unsaturated moisture transport in the concrete; (2) chloride ion transfer including bound, diffusion and convection mechanisms, and (3) the fluid-solid coupling effect. A numerical model of unsaturated concrete is built to simulate the coupled process. Based on this model, the classic expression of effective diffusion coefficient is modified by considering constrictivity factor, and the sensitivity analysis was carried out on five sets of parameters (i.e. effective diffusion coefficient, saturated permeability, van Genuchten parameters, initial saturation, and binding capacity parameters) aiming at evaluating the robustness of the model. The simulation results show that the multi-mechanism penetration model is computationally feasible, and the multiphysics coupling model can well reproduce the chloride ion transfer process in a microscopic perspective. Furthermore, the sensitivity analysis results indicate that the parameters governing moisture transport process are more sensitive to the prediction of the chloride ion penetration into undersea tunnel concrete. This simulation model shows high value in the research of chloride ion penetration into concrete structures under hydrostatic pressure. Finally, this simulation prototype was simplified and integrated into the information platform, and knowledge sharing was successfully achieved.

This research mainly gives outstanding contributions in the aspect of information management in maintenance management, developed a visual multi-module information platform, and realized the sharing of professional knowledge among experts and non-experts. This information platform is expected to become a real product in maintenance management in an enterprise. Moreover, the efficient information communication approach can be implemented by using the knowledge management to disseminate knowledge to groups in need and increase the reusability of knowledge. The information platform has a great breakthrough in the visual management for maintenance information. In the future, more infrastructures such as existing or newly built project can be integrated into this platform, which can finally realize the development of smart city.

This research also has deficiencies. For example, the information contained in the information platform is mostly focused on the information supporting for maintenance decision-making, and it does not include information of maintenance implementation and post-maintenance evaluation. Prioritizing and scheduling maintenance work in advance makes sure the sufficient workloads assigned, which increases productivity and ensures critical work orders complete first. Maintenance schedule gives a clear and detailed instructions for performing maintenance so that new personnel can understand the tasks required and experienced personnel can verify that they have completed the work properly. The conventional method to create a maintenance schedule is to make work instruction documents, which is the list or table of recommended maintenance activities addressing the proverbial “who, what where, when, why, and how” of maintenance activities. Shortcomings in conventional method are obvious including the discretization of information and the impossibility of visually and accurately locating maintenance activities. The BIM collaboration platform should help to solve the problem of visualization management well during maintenance implementation and post-maintenance evaluation and integrate more BIM and GIS information in the platform, such as environmental parameters provided by GIS. Another deficiency is mainly in knowledge management; that is, it is necessary for experts to not only point out the sensitivity of open parameters, but also to provide the ranges of some parameters and suggestions in the development of applications and more professional analysis cases that would be required in maintenance management in the platform should be developed. Moreover, professional analysis here mainly considers simulation analysis method, and does not consider experiments or experienced estimation. Therefore, to fully implement maintenance information management, more information function modules need to be developed in the integrated information platform. It is also necessary to conduct user trial investigation before the platform is widely used to improve the usability of the software.

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