Aline Fernandes Heleno

BIM for information management in structural safety control of embankment dams

BIM A+ — European Master in Building Information Modelling

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Aline F. Heleno

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Aline Fernandes Heleno

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European Master in Building Information Modelling

Work conducted under supervision of:
Miguel Ângelo Dias Azenha
Laura Maria Mello Saraiva Caldeira

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STATEMENT OF INTEGRITY

I hereby declare having conducted this academic work with integrity. I confirm that I have not used plagiarism or any form of undue use of information or falsification of results along the process leading to its elaboration.

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RESUMO

A aplicação de modelos *Building Information Modelling* (BIM) para integração de grandes volumes de informação e análise de dados é uma prática corrente, e cada vez mais frequente, no setor da construção civil. No entanto, a aplicação da metodologia BIM em obras de infraestrutura, como é o caso de barragens, ainda não é prática difundida, principalmente em barragens de aterro.

A construção de barragens é essencial para diferentes usos, como abastecimento de água, geração de energia, exploração mineiras. Uma grande parte destas barragens são construídas com solo compactado e apresentam estruturas específicas que permitem garantir controlo do fluxo, estabilidade e compatibilização das deformações. Não obstante o referido, os impactos social, económico e ambiental gerados por possíveis ruturas destas estruturas são de maior importância e relevância para as comunidades, e, infelizmente, tem vindo a ocorrer. Os esforços que possam ser desenvolvidos para o controlo da segurança de uma barragem são sempre essenciais. O controle da segurança de uma barragem é realizado por meio de inspeções visuais e análise das medições da instrumentação instalada. Em algumas barragens as medições da instrumentação ainda são realizadas de forma manual, sem processos integradores das informações. Em decorrência disso o uso de modelos BIM integrados com um banco de dados, e ferramentas específicas para análise de dados, torna-se um procedimento interessante para a solução e resolução de alguns problemas decorrentes do processo de análise da segurança da barragem.

A utilização da metodologia BIM em barragens de aterro com foco na análise da segurança de barragens é o principal objetivo do presente trabalho. Os procedimentos desenvolvidos na presente dissertação em parceria com o Laboratório Nacional de Engenharia Civil (LNEC) visam estabelecer a conexão entre diversas informações existentes modo a gerar um modelo BIM, para visualização tridimensional dos dados obtidos da instrumentação colocada. Acresce ao referido que é também estabelecida a conexão entre o banco de dados (SQLite) e uma ferramenta de análise de dados (Power BI), sendo a metodologia testada para um tipo de instrumento (baterias de assentamento), permitindo o estabelecimento da conexão e integração dos dados entre o modelo BIM, o banco de dados e a ferramenta de análise de dados. A aplicação desenvolvida, permitiu concluir que a utilização da metodologia BIM para análise de informação é muito promissora, existindo, contudo, diversos desafios para implementação generalizada de uma solução.

Palavras chave: (BIM, Barragens, Banco de dados, Instrumentação, Análise da segurança)

ABSTRACT

The application of Building Information Modelling (BIM) for the integration of large volumes of information and data analysis is a current practice, and increasingly frequent, in the civil construction sector. However, the application of the BIM methodology in infrastructure works, such as in the case of dams, is still not a widespread practice, especially in embankment dams.

Dams' construction is essential for different uses, such as water supply, energy generation, mining exploration. A large part of these dams is built with compacted soil and have specific structures that ensure flow control, stability and compatibility of deformations. Notwithstanding the social, economic and environmental impacts generated by possible failures of these structures are of greater importance and relevance for the community, and, unfortunately, have been occurring. The efforts that can be made to control the safety of a dam are always essential. The safety control of a dam is carried out through visual inspections and analysis of the instrumentation measurement. In some dams, instrumentation measurements are still carried out manually, without processes integrating the information. As a result, the use of BIM models integrated with a database, and specific tools for data analysis, becomes an interesting procedure for the solution and resolution of some problems arising from the dam safety analysis process.

The use of the BIM methodology in embankment dams with a focus on the analysis of dam safety is the main objective of this work. The procedures developed in this dissertation in partnership with the Laboratório Nacional de Engenharia Civil (LNEC) aim to establish the connection between different existing information in order to generate a BIM model, for three-dimensional visualization of the data obtained from the placed instrumentation. Furthermore, the connection between the database (SQLite) and a data analysis tool (Power BI) is also established, the methodology being tested for a type of instrument (settlement batteries), allowing the establishment of the connection and data integration between the BIM model, the database and the data analysis tool. The developed application allowed us to conclude that the use of the BIM methodology for information analysis is very promising, there are, however, several challenges for the generalized implementation of a solution.

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1. INTRODUCTION

The BIM Model stands out for concentrating a large amount of detailed information in the same model (Lopes, 2017; Sari, Wahyuningrum and Kresnanto, 2020), being an excellent tool for information management about any infrastructure work, such as dams. Several works have been developed using the BIM methodology and monitoring analysis to improve the procedures in the different phase of the concrete dams (Fernandes, 2015; Wang *et al.*, 2015; Liu *et al.*, 2018), but no application was found for embankment dams.

There are different types of dam constructions (embankment and concrete structures for example) with several uses such as water supply, mining waste, electric energy generation.

The dam construction can generate potential damage to the surrounded populations and areas. A recent study based on a tailings dam failure database showed that since 1915 there have been 283 failures, leaving 2300 dead, and various environmental, social, and economic impacts. In addition, since 2000 approximately 500 deaths have occurred because of tailings dam failures, demonstrating that there is no reduction in dam failures. Ruptures were also recorded in dams of different uses, showing the importance of an integrated monitoring strategy with an understanding of the best geotechnical practices(Clarkson and Williams, 2020).

The best way to avoid an accident is to keep constant monitoring of dam's safety conditions throughout its life cycle, from conception, design, construction, operation and finally decommissioning. During the conception and design phases the monitoring is planned, the parameters are calculated, and criteria are established to guarantee dam stability. The monitoring consists of the instrumentation analysis and inspection realized during the construction, operation, and the decommissioning steps.

The safety conditions of the dams should be periodically reviewed considering any changes resulting from aging and structures deterioration.

The concentration of the information in the same model, by using the BIM methodologies, allows the evaluation of different types of data provided by instrumentation, visual inspection and eventual tests carried out on the dam in an integrated and automated way. Therefore, it is possible to predict anomalous behavior and remedy them to ensure the dam safety.

1.1. Objectives

The main objective of this dissertation is to develop a BIM model to help during the instrumentation for the data analysis of existing embankment dams. This process intends to automate some activities to solve some pitfalls identified during the manual data analysis process, such as (i) data available in different files, not allowing a concentrated and integrated analysis, (ii) lack of automated processes to connect information in different types of data analysis and visualization tools.

The secondary goals are listed below:

- Identify the necessary parameters for the development of a BIM model with application to existing embankment dams;
- Identify and understand the necessary procedures to establish the data connection with the BIM model;
- Develop procedures to establish the connection between existing data and new tools for concentrating information and visualizing the results;
- Establish connection between the different tools automatically, to facilitate the analysis of instrumentation data.
- Application of the procedures developed in a real case study in an embankment dam in operation phase;
- Identify improvements in the procedure developed in this work, proposing future improvements.

1.2. Activities and organization

The activities to develop this work start with the literature review and the acquaintance with software's tools (Dynamo, Revit). The Dynamo will be used to develop all the data analysis code and to link the information with Revit. For this work, all the data will be stored in Relational database.

The data to be incorporated in the dam models consist of monitoring data. The methodology developed will be applied to a real embankment dam, called Odelouca Dam. This dam is located Algarve region of Portugal, for water supply. The main result is a 3D BIM model with geometric information of the dam and data instrumentation.

For the development of this dissertation, the workflow shown in Figure 1 was created, which describes the main activities.

The first step corresponds to developing procedures (2, 3) that allow establishing a connection between the existing data format (1) to format need to generate the BIM model (4) and feed the database (5) with the instrumentation data information. The database receives information that already exists and from future surveys (6), however the goal of this dissertation involves only the existing data.

After the instrumentation information is entered into the database, it is connected to the BIM model (7) and to other tools for analyzing and visualizing the instrumentation data. This procedure aims to integrate the information into a single three-dimensional model.

This dissertation is organized into 6 chapters, the first corresponding to Introduction. Chapters 2 and 3 correspond to a literature review. Chapter 2 conceptualizes embankment dams, showing the general aspects of a dam, the three main premises for designing a dam and the respective structures that guarantee the premises. Moreover, the chapter shows a brief approach to inspections and some of the main instruments installed in an embankment dam to safety control, and the main pitfall and

opportunities in monitoring embankment dams. Chapter 3 gives some concepts about Facility Management (FM), databases, and business intelligence. Chapter 4 present all the computational workflow developed during this project, all the implementation. Finally, Chapter 5 corresponds to application of the methodology of Chapter 4, to an existing embankment dam.
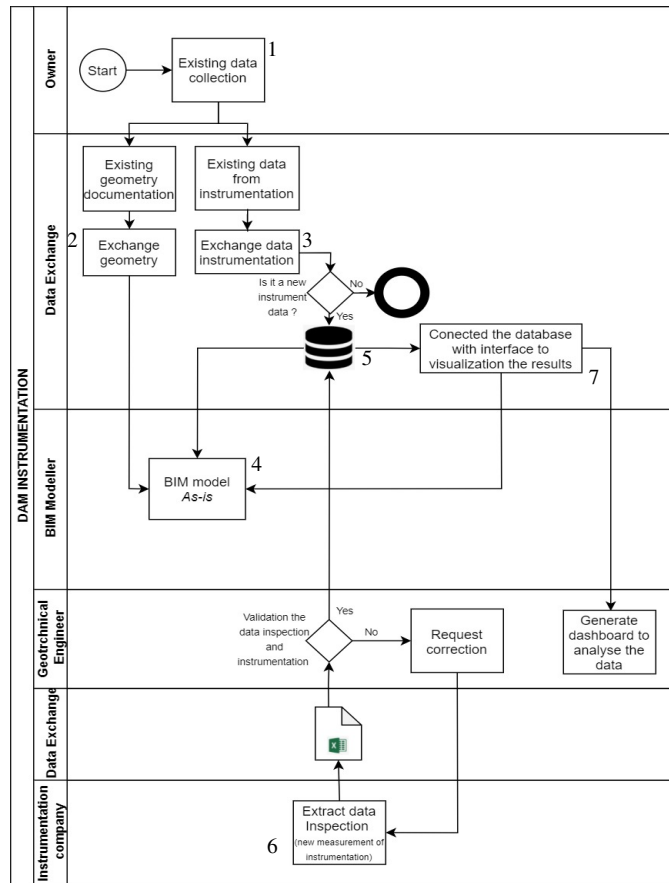

Figure 1 – Workflow proposal.

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2. SAFETY CONTROL OF EMBANKMENT DAM

Dams have been built since antiquity and construction techniques are still developing. Over the last few decades, the construction of dams has undergone great technical advances in the control of construction procedures and the materials used (Neves *et al.*, 2015).

The dam's construction could be associated with industrial and even subsistence activities, with different uses like: hydroelectric power, navigation, flood control, water source and others (Evans *et al.*, 2000). These structures are associated with development and, in many countries, they have been used as a booster of growth (Fusaro, 2007).

However, these kinds of structures can cause enormous environmental, social, and economic impacts during the construction, operation and decommissioning phases, even more in case of a dam failure resulting in flooding of vast areas downstream with losses of human life (Vallejo, 2016). According to Vallejo (2016) in the last 100 years, thousands of people died or lost their properties, because of dam failures.

Figure 2 shows the percentage of the failure that occurs around the world for each type of dams (Vallejo, 2016; Nasrat *et al.*, 2020). In a simplified way, dams can be divided into concrete dams and embankment dams. There are many kinds of concrete and embankment dams. Each of these types of dams has constructive characteristics, requests, foundation requirements, in short, different behaviors, which must be considered whenever a particular project is studied (Marques Filho and Geraldo, 1998).
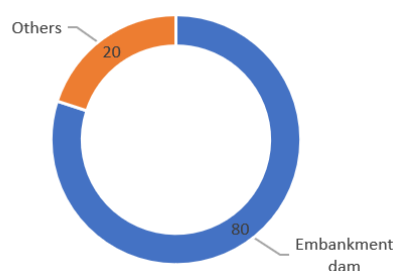

Figure 2 – Dam failure according to dam type around the world (modify from Vallejo, 2016).

Embankment dam engineering has evolved over many centuries, with the major developments occurring since the 1940s with the development of soil mechanics and geotechnical engineering. This kind of dam corresponds to the majority of existing dams, totaling 77% of all dams in the world, and it is the type of dam that most frequently fails (Foster *et al.*, 2000; Vallejo, 2016; Nasrat *et al.*, 2020).

In order to avoid the dam's failure, it is essential to establish the safety control of embankment dam during the construction and operational phases as a permanent process of monitoring and evaluation

of the behavior of such structures, with visual inspections and instrumentation measurement and analysis (Fell *et al.*, 1992; Fusaro, 2007).
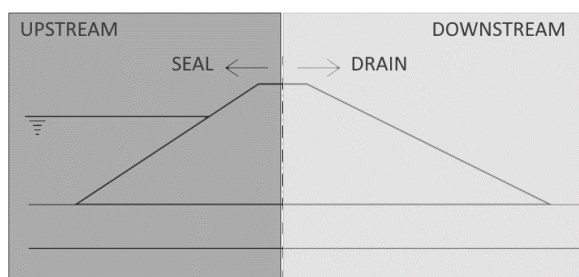
In this chapter, discussions are held in regard to issues related to general aspects of the embankment dam and their safety control, and to all the information necessary to understand the workflow development during this dissertation work.
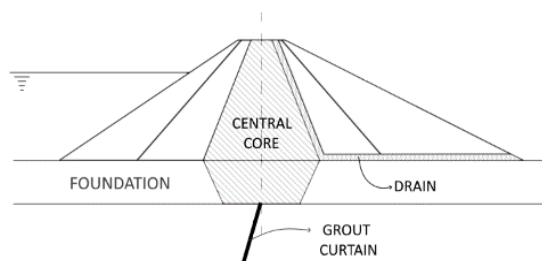
2.1. General aspects of embankment dams

There are different types of embankment dam, but in general there are three basic principles that must be obeyed in a dam design, they are: (i) flow control, (ii) internal (dam and foundation set) and external (general slope) stability and (iii) deformation compatibility.

The Figure 3a shows the upstream and downstream zones of a dam. The flow control is generally established by sealing the upstream zone of the dam (Figure 3a), as much as possible, by introducing waterproof systems for this, like a central core in the earth fill dam body and grout curtain in the foundation (Figure 3b). On the other hand, the outflow is facilitated at downstream zone of the dam (Figure 3a), as much as possible, by introducing drainage systems (Figure 3b) (Fell *et al.*, 1992; Cruz, 1996).

All structures indicated in Figure 3b are illustrative and there are several other types of structures. For example, the position of the core could be central or at the upstream zone, and the drains solution could include horizontal, chimney or toe drains. These configurations depended on the conditions of each project.

(a) Upstream and downstream zones of the dam and the respective principle for flow control.   (b) Example of structures arrangement to control the flow.

Figure 3 – Flow control structures (adapted from Cruz, 1996).

The stability of the dam is guaranteed by the external areas of the dam – upstream and downstream shells. The zone of the dam which provides strength is shown in Figure 4, by gray color, which must be made compatible with the foundation materials to ensure, in addition to the stability of the upstream and downstream slopes, the stability of the dam and its foundation, considering the various loading phases throughout the construction and operation phases.

Finally, the compressibility of the materials of the various zones of the dam (core, filters, drains and shells) and its foundation must be compatible, or some transition zones needs to be considered in order to reduce differential and total settlements. These displacements can affect the performance of

the impervious zones and drainage systems, by the occurrence of cracks. These cracks become features of concentrated flow that could generate the piping process through the embankment or even by the inversion of the flow gradients in the drainage system.
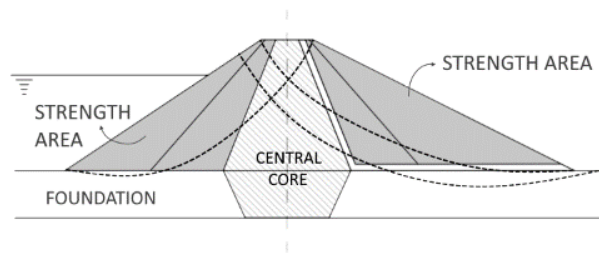

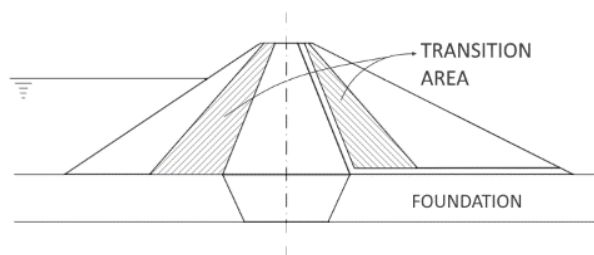**Figure 4 – Stability structures (adapted from Cruz, 1996).**

Figure 5 – Transition area (adapted from Cruz, 1996).

According to Foster *et al*. (2000), the structural modes of failure involving piping are the most common in large embankment dams. This study concludes that the incidence of piping through the embankment is two times higher than piping through the foundation, proving the importance of building adequate filter systems in embankment dams.

2.2. Safety control

The aim of the safety control of a dam is the observation, detection and characterization of eventual deteriorations that could be a potential risk to the conditions of the global safety. The safety control can be done by visual inspection, monitoring and analysis (Fonseca, 2003).

The visual inspections are a qualitative process, through periodic field inspections, and the monitoring is the process to obtain and analyze the measuring of each instrument installed in the embankment and in the foundation of the dam (FERC, 2003).These processes must be carried out together during the whole life of the dam (construction, operation, and decommissioning), to provide the necessary data for an eventual revision or adaptation of the procedures adopted in each phase (Fonseca, 2003).

One of the greatest benefits of instrumentation is to enable the assessment of the structural behavior of a dam, through comparison between quantities measured in situ and those provided by the mathematical analysis models, helping to validate design and construction quality, and to identify potential problems. During construction, instrumentation allows owners to verify the adequacy of constructive methods and eventually, to conclude on the need to change the adopted methods (Fusaro, 2007).

During the operational phase, the geotechnical instrumentation can be used to provide an alarm when the measurement exceeds the limits established as acceptable. In this case, instrumentation is a tool to identifying possible situations of risk, giving the opportunity to intervene in structures avoiding dam failure. Alternatively in situations of imminent risk, they provide the capacity to put into action the emergency plan in order to evacuate the areas that may be affected by the dam failure (Fusaro, 2007).

2.2.1. Visual inspection

Visual inspection is mandatory for all kind of dams. This is the way to detect anomalies. There are different kinds of visual inspections. Some examples are routine and periodic inspections.

The routine inspections are carried out regularly by operational staff, and the periodic inspections are carried out by a civil engineer specialized in dams (ICOLD, 2017a). In addition to planned inspections, the dam should have special inspections after unusual or extreme events like earthquakes, important floods, or other natural/induced events that could change the normal dam operations (CDA, 2007).

The frequency of each visual inspection depends upon the up-to-date need for information. Therefore the routine inspection are generally performed daily or weekly, and the periodic inspections occur once a year (ICOLD, 2017a). However, the frequency of the visual inspection depend on the size of the dam (maximum height of the dam and the capacity of the reservoir) and the hazard rating, associated with environmental, social, and economic impacts in case of dam failure (Fell *et al.*, 1992). The inspection is carried out using a checklist that includes de following items:

- Condition of the vegetation on dam: verify if the dam shows overgrowth, incomplete vegetation or even wet terrain vegetation. In case of overgrowth, for dam surveillance it is required to cut the vegetation and to eliminate weeds. It also may indicate seepage or excessive capillarity. In case of incomplete vegetation, it is required to repair the vegetation to avoid external erosion. In the local of the wet terrain vegetation, it is important to look for sand boils and deltas (Fell *et al.*, 1992).
- Condition of the drainage ditches: verify if the dam has some obstruction by vegetation/soil, damp, the quality/quantity of flowing water, boils, misalignment and silt accumulation, deltas, cones (Fell *et al.*, 1992).
- General condition of the embankment: verify if the crest has some cracking, subsidence, the axis misalignment, and holes caused by animals, termite mounds and anthills. Observe if the upstream slope has cracking, surface erosion, gullying, wave erosion, deficiency of material protection (riprap), and holes caused by animals, termite mounds and anthills. Observe if the downstream slope has cracking, subsidence, bulging, erosion, moisture on dry days, damp areas, boils, seeps, and holes caused by animals, termite mounds and anthills. Observe if the berms have erosion, gullies, damp areas, boils, seeps and holes caused by animals, termite mounds and anthills (Fell *et al.*, 1992; Maranaha das Neves *et al.*, 2015).
- General condition of the spillways: verify the discharge conduit condition, the seepage or damp areas around conduit, erosion below the conduit and boils in the

      vicinity of the conduit, verify the spillway slabs for uplift, subsidence, and cracking (Fell *et al.*, 1992).

- General condition of the reservoir: the main anomalies to observe are the instability of the bank slopes due to the erosive action of the ripple of the reservoir waters and the presence of debris or other floating materials that can obstruct the discharge system (Maranha das Neves *et al.*, 2015)

- General condition of the dam toe: verify at upstream the existence of concentrated flow, and the colour of the water flow, which may indicate dragging of material and the accumulation of water/swamps (Neves *et al.*, 2015).

- General condition of the contact between different materials: verify the existence of springs, water outlets or wetlands, erosions in contact between different materials and cracks (Maranha das Neves *et al.*, 2015).

2.2.2. Geotechnical instrumentation

For proper monitoring of an embankment dam, several parameters must be measured and analyzed throughout all phases of the dam life to control its performance during construction, first filling, rapid drawdown and long-term operation (ASCE, 1995). For example, the physical quantities to be measured are pore water pressure, displacements, total stress, temperature, water flow emerging downstream, and seismic accelerations. This dissertation will focus on the instrumentation to measure the pore water pressure and internal displacements of the dam body and at its foundation. These are the most common instrumentation in embankment dams, to provide the stability analyses of the embankment.

The pore water pressure is commonly measured in the foundation and dam body. The device mostly used for this parameter is the piezometer. There are different types of piezometers: open standpipe, twin-tube hydraulic, pneumatic, vibration wire, electrical resistance piezometers (Silveira, 2006).

Figure 6 shows a typical installation scheme for an open standpipe piezometer. For this type of piezometer, there are some variations such as the LNEC type piezometer (Figure 7), which aims to reduce the time delay in the measurement of the local pore water pressures in soils with a low permeability.

The time for the liquid column in the piezometer to stabilize after a pressure variation represents the sensitivity of the instrument. This time is directly proportional to the cross section of the pipe and inversely to the permeability of the soil in the vicinity (Silveira, 2006).

The instruments for measuring deformation can be grouped in different categories, but to simplify, the surveying methods are used to monitor the magnitude and rate of horizontal and vertical deformation of structures on ground surface and subsurface (Dunnicliff, 1988).

According to Silveira (2006), one of the oldest and simplest methods for observing the displacements of an embankment dam is the installation of the Surface Settlement (Figure 8), along the berm and crest, to observe the surface settlements and horizontal displacements. To measure these displacements of the surface settlement, it is necessary to install the benchmark in the outcrop rock of natural terrain, to have a fixed reference.
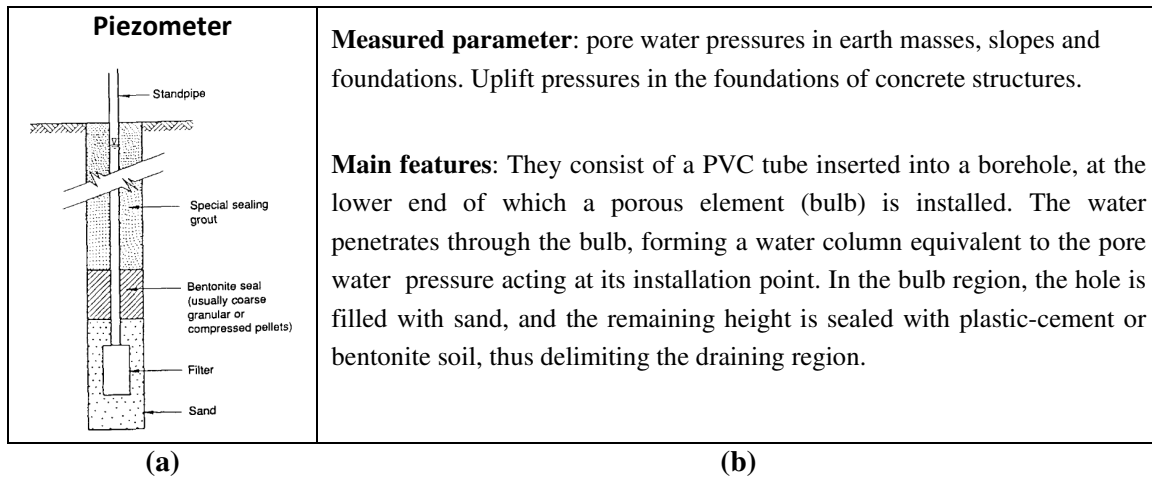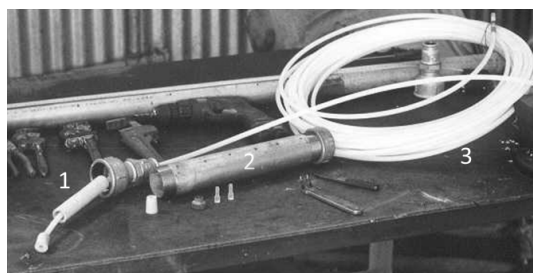
Piezometer	**Measured parameter**: pore water pressures in earth masses, slopes and foundations. Uplift pressures in the foundations of concrete structures. **Main features**: They consist of a PVC tube inserted into a borehole, at the lower end of which a porous element (bulb) is installed. The water penetrates through the bulb, forming a water column equivalent to the pore water pressure acting at its installation point. In the bulb region, the hole is filled with sand, and the remaining height is sealed with plastic-cement or bentonite soil, thus delimiting the draining region.
(a)	**(b)**

Figure 6 – (a) Piezometer schema(Dunnicliff, 1988); (b) General comments (Fusaro, 2007).

1-Filtering element, to avoid clogging, ceramic or synthetic.

2- Perforated galvanized pipe.

3- Piezometric lifting tube in polyurethane or polyamide, with a diameter of 6.0 mm and 2.0 mm.

Figure 7 – Piezometer LNEC (Maranha das Neves et al., 2015).

One of the instruments used to monitor the internal settlements at the dam and its foundation is the settlement platforms/gauges. Figure 9 shows the schematic drawing of settlement platforms with a brief description of the equipment and measurement.
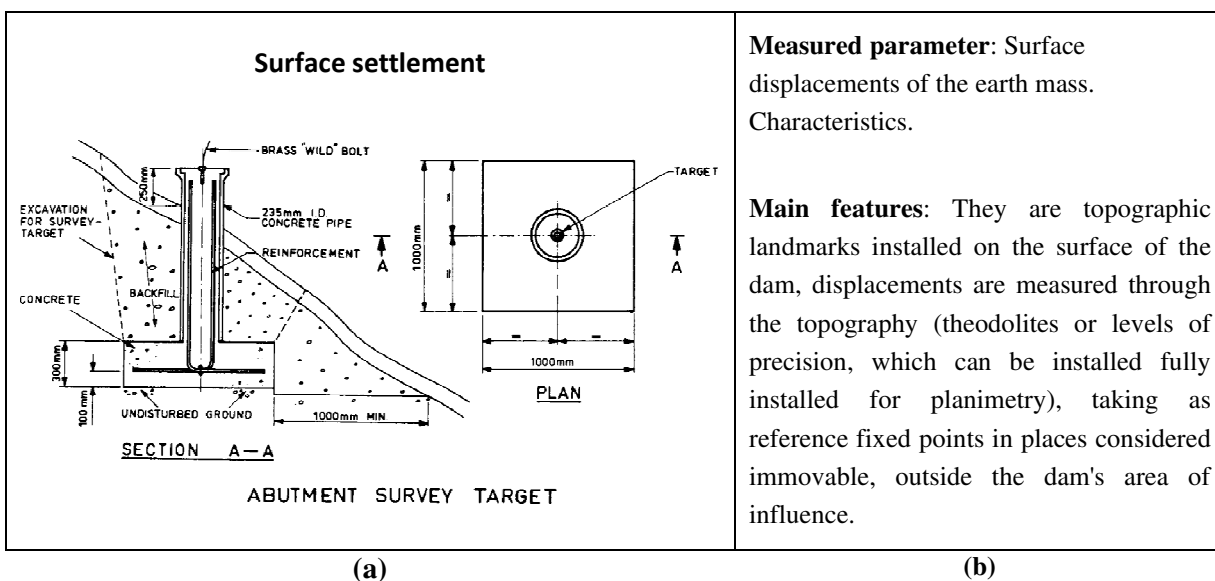
Surface settlement	**Measured parameter**: Surface displacements of the earth mass. Characteristics. **Main features**: They are topographic landmarks installed on the surface of the dam, displacements are measured through the topography (theodolites or levels of precision, which can be installed fully installed for planimetry), taking as reference fixed points in places considered immovable, outside the dam's area of influence.
(a)	**(b)**

Figure 8 – (a)Surface settlement platforms schema (Fell et al., 1992); (b) General comments (Fusaro, 2007).
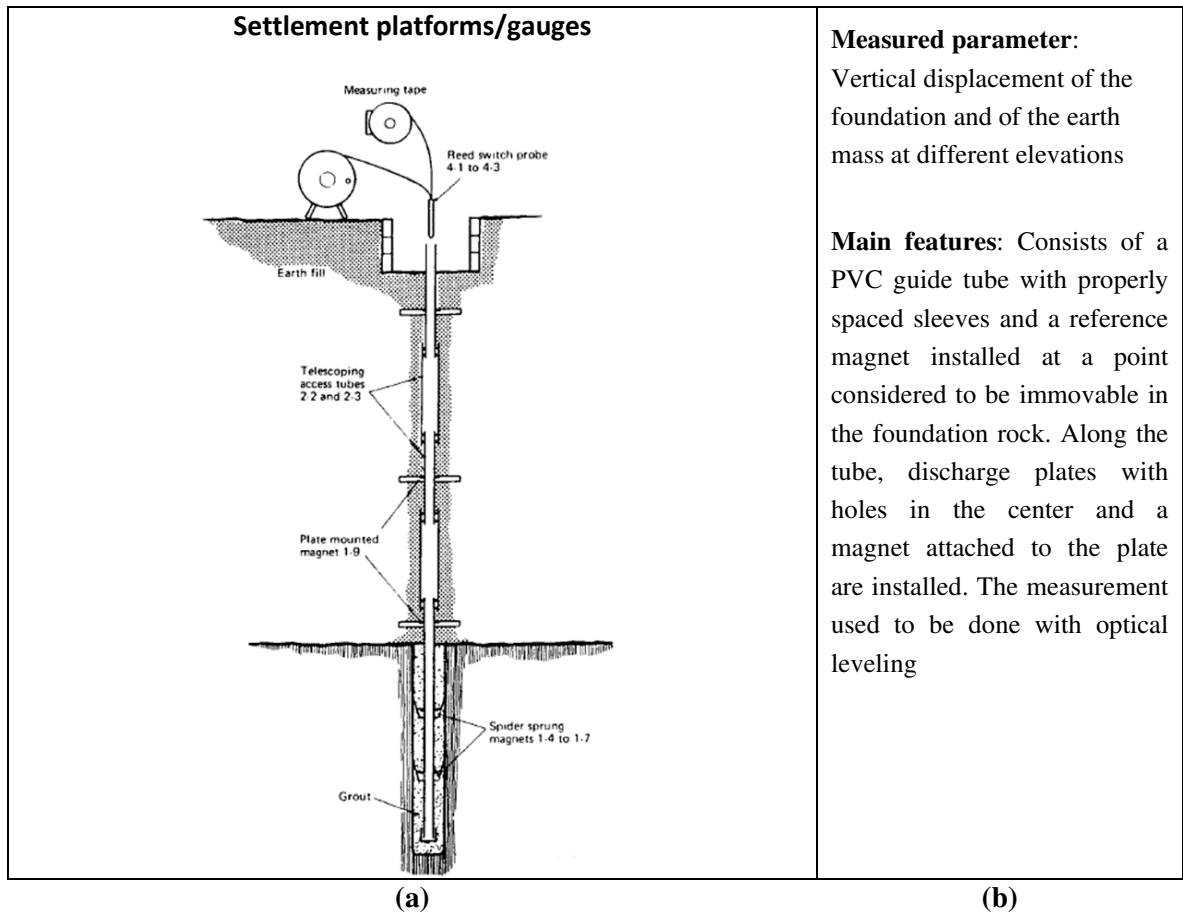
(a)   **(b)**

Figure 9 – (a) Settlement platforms/gauges schema (Fell *et al.*, 1992); (b) General comments (ASCE, 1995; Fusaro, 2007).

The inclinometer is another instrument to measurement in internal displacements, that are define as devices for monitoring displacements normal to the axis of a flexible pipe (ASCE, 1995). Figure 10 shows the main principle of inclinometer operation and some features about the equipment.
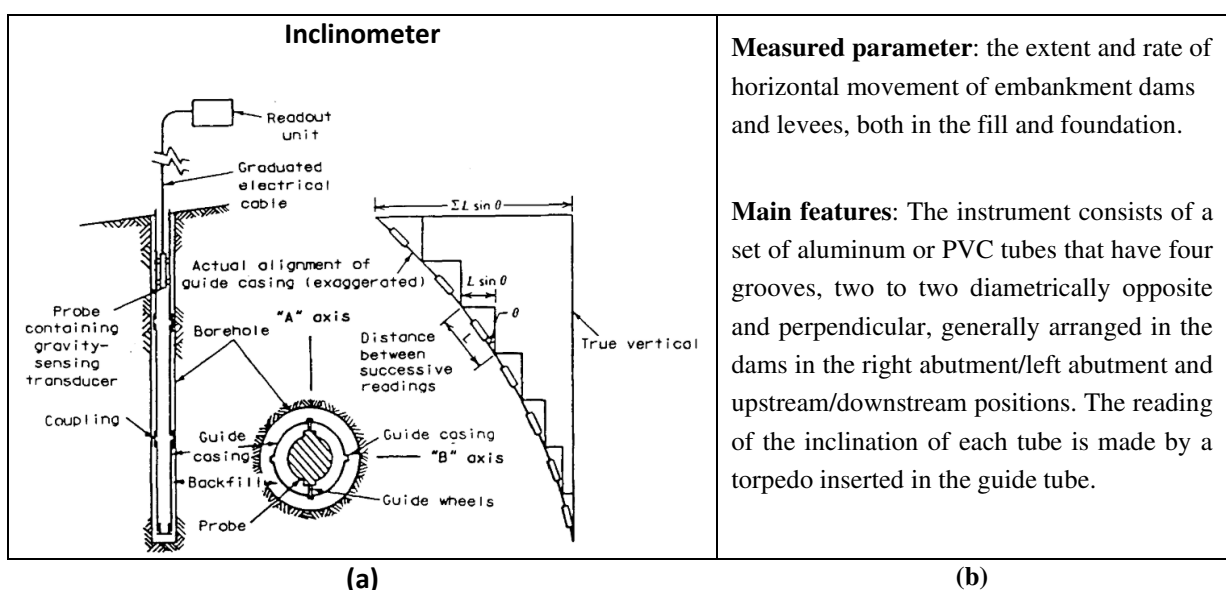

(a)   **(b)**

Figure 10 – (a) Inclinometer schema (Dunnicliff, 1988);. (b) General comments (Fusaro, 2007).

Other parameters, like seepage flow, water quality (turbidity measurement) and atmospheric precipitation are very important during the dam safety condition analysis.

2.2.3. Model analysis

The evaluation of the structural behavior of a dam and its foundation is fundamentally based on visual inspections and on the results of monitoring data analysis, such as displacements, settlements, seepage flow volumes, pore water pressures, uplift pressures and total and effective stresses. Monitoring data analysis involves correlating the measured values with the loads, determining trends in variation, and carefully comparing the measured values with those predicted theoretically or experimentally (Fusaro, 2007).

Monitoring data must be analyzed from two perspectives: first, as a function of time, to identify changes in trends, and second, within the context of expected behavior in relation to design criteria. From either of these two perspectives, to carry out this analysis, the following aspects should be considered (ICOLD, 1989):

- the interpretation of results must be carried out immediately after data collection;
- there is a time-lag between a physical phenomenon, such as a change in the water level in the reservoir, for example, and the response given by the instrument;
- distorted scales for the graphical representation of collected data can lead to distorted interpretations and conclusions;
- sudden and/or unexpected variations must be carefully correlated with information relating to the construction and operation of the dam, in order to provide logical interpretations for these collected records;
- conclusions should be based on trends established over a reasonable period of time from the observations;
- correlations with different types of data must be established in order to ensure reliability of the monitoring processes;
- the limitations inherent to each instrument must be known in advance, in order to avoid unproductive attempts to evaluate data whose magnitude is within the margin of error of the instrument used;
- acceptable limits for instrumentation data should be established in the design phase, before the start of reservoir filling (structures and foundations being able to withstand certain magnitudes of displacement, pressure, etc.), avoiding such based propositions in the later records indicated by the instrumentation;
- the occurrence of instrumentation data in disagreement with the predicted values does not necessarily imply the existence of a problem; on the other hand, it is also true that even data entered within the allowable ranges of the instruments do not necessarily imply that there are no problems.

For the analysis of dam instrumentation data, Fusaro (2007) recommends the following steps described in Figure 11.
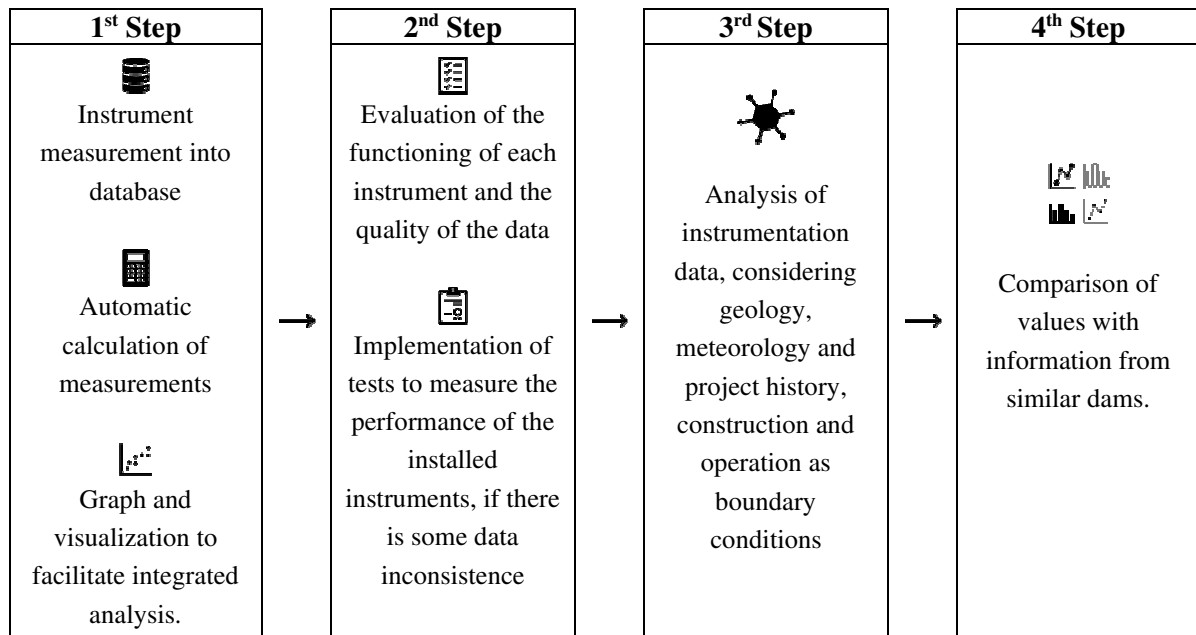
1ˢᵗ Step	2ⁿᵈ Step	3ʳᵈ Step	4ᵗʰ Step
Instrument measurement into database	Evaluation of the functioning of each instrument and the quality of the data	Analysis of instrumentation data, considering geology, meteorology and project history, construction and operation as boundary conditions	Comparison of values with information from similar dams.
Automatic calculation of measurements	Implementation of tests to measure the performance of the installed instruments, if there is some data inconsistence		
Graph and visualization to facilitate integrated analysis.			

Figure 11 – Steps to analyze dam instrumentation (adapted from Fusaro, 2007).

In the first step, the database must automatically calculate the measurements and allow them to be listed in tables and/or plotted in graphs, to facilitate their visualization and integrated analysis. The second step is the validation of instrumentation data and instrument life testing if necessary. In the third step, geological/geotechnical aspects include foundation and abutment conditions, nature of construction materials, topographical and geomorphological features of the dam site, regional seismicity conditions and groundwater regime. Meteorological aspects include atmospheric precipitation, barometric pressures, wind velocity and direction, and temperature variations. Historical factors include design assumptions, design concepts, construction techniques, and operation and maintenance data. Finally, the fourth step consists of comparing the values with information from similar dams, when deemed pertinent (Fusaro, 2007).

2.2.4. Reporting

After all the speciality inspections the final report are preperad. This provides supporting information on, whether the dam is safe or not, and whether specialized investigations, rehabilitation, or intervention measures are necessary (ICOLD, 2017b). For that, in general, the inspection report includes the follow information:

- photographic records;
- description of unusual circumstances;
- analysis of checklist of routine inspection;
- analysis of the instrumentation data for the period;
- definition of responsibility.

The definition of responsibility should be in place for evaluating data and observations to confirm structural and operational safety and to identify areas requiring deficiency investigations (ICOLD, 2017b).

Usually, a dam safety report is prepared by the dam owner. This report summarizes the findings of the instrumentation monitoring and visual inspection of the last period (ICOLD, 2017a).

2.2.5. Pitfalls and opportunities

Table 1 shows some pitfalls and opportunities identified in current inspection and instrumentation data acquisition processes in embankment dams.

Table 1 – Pitfalls x Opportunities

Pitfalls	Opportunities
Manual processes for measurement of the instrumentation parameter, in some cases using paper forms. This procedure can generate typing errors. High time between measuring the parameters in the field and digitizing the information.	The real-time of the instrumentation measurement, by using IoT and database, solves the problems typing errors and reduces the time it takes to send the data to the technical responsible for analyzing the instrumentation. IoT connects the physical and cyber world to capture real-time data for modeling and analyzing, and data mining methods incorporated in the virtual model aim to discover hidden knowledge in collected data.(Pan and Zhang, 2021).
Presence of several files and/or spreadsheets for analyzing the instrumentation, not allowing the integrated analysis of the data.	Use of a database that can integrate all instrumentation and connection data with tools that assist in data visualization and analysis. These can help predict the behavior of the dam and even an automatic system for issuing an alert, which does not exempts the presence of experts to validate the analyzes and the alert.
Measurement of instrumentation parameters and safety inspection performed periodically, but not daily in some cases.	Use of automatic inspection methods that can complement the inspection carried out, such as the use of Unmanned Aerial Vehicle (UAV) associated to BIM models for visual inspections, or even the use of geophysical methods in constant operation to determine areas of saturation in the dam. Associated with this, the use of Artificial Intelligence (AI) to process all information and identify possible anomalies in aerial images

The use of the technologies identified in Table 3 does not exclude the visual inspection carried out by specialist technicians in landfill dams, nor even the instrumentation analysis by specialists. However, automation helps and speeds up data transfer, on the other hand it helps in data analysis making security systems more efficient.

3. BIM APPLIED TO DAMS IN OPERATION

In this chapter, discussions are held in regard to integration between BIM with the FM to improve the workflow of a dam's operation phase. Furthermore, their application in dam operation, database support in operation, business intelligence are presented.

3.1. BIM and facility management

The BS EN ISO 41001:2018 defines FM as an integration of "*multiple disciplines in order to have an influence on the efficiency and productivity of economies of societies, communities and organizations, as well as the manner in which individuals interact with the built environment. FM affects the health, well-being and quality of life of much of the world's societies and population through the services it manages and delivers*".

In other words, FM allows users to improve the performance of an organization optimizing time and reducing costs. Moreover, the use of FM allows several applications in several areas such as operational and maintenance phase, risk management, and project/construction management of an asset (Trabulci, 2020).

The operation and maintenance phases of buildings and civil infrastructures can reach more than 50 years of the whole lifecycle. So, it is essential to ensure an actual and efficient management of buildings during these phases, ensuring the continuous and reliable information of asset inventory, condition and performance, during the entire lifecycle (Trabulci, 2020; Seghezzi *et al.*, 2021)

In this way the BIM model could deliver so many advantages with the integration with the FM system, such as better validation, access, and update of the building data during all the lifecycle of the building (Eastman *et al.*, 2018). A general example of applications of BIM with FM is the optimization of facility management and maintenance, by integrating the as-built building model and equipment information to the systems used over the facility lifecycle (Eastman *et al.*, 2018; Altohami *et al.*, 2021).

The BIM-FM is used to solve many different problems such as the location of existing mechanical, electrical and plumbing (MEP) system installations during maintenance services, using the Augmented Reality (AR) technique to assist in the visualization and location of the systems (Sun *et al.*, 2021). Another application is the use of Internet of Things (IoT) devices to integrated building information to live data, which can be beneficial for different kind of user for the facility management industry, such as different kind of monitoring, health and safety of a structure. (Pourzolfaghar *et al.*, 2017; Altohami *et al.*, 2021). This kind of application could be used to create alert systems into BIM model for monitoring several parameters such as the thermal comfort. The system measures the humidity and temperature levels of the room, and the sensors data is transferred to a remote database via internet. Thereafter BIM is used to visualize the monitored thermal comfort level of the room remotely through wireless-connected devices, as well as effective space and facility management(Valinejadshoubi *et al.*, 2021).

Besides the application in operation and maintenance, there are many potential aspects for BIM contributions in FM applications during project/construction management, such as facilitates collaboration between project participants, errors reduction and field changes and leading to a more efficient and reliable process delivery that reduces project time and cost (Eastman *et al.*, 2018).

According to Seghezzi *et al.* (2021) other promising fields in building management include security, safety, cleanness, and space management. These aspects have an important significance, especially during the sanitary emergencies related to the COVID-19 pandemic: space monitoring is one of the parameters to guarantee health safety in existing buildings (Capolongo *et al.*, 2020; Pavón, Arcos Alvarez and Alberti, 2020). In this case the BIM has an interface with IoT, that permits a large amount of real-time data available for analysis with FM concepts.

Although, there are several discussions on applications in the integration between BIM and FM in building design, construction, and operation/maintenance, it is still necessary to resort to some adaptation to use BIM methodology in infrastructure projects. Recently, there has been an increasing interest on the application of BIM to infrastructure, which has its own complexities and particularities(Correa and Santos, 2021).

There are diverse kinds of infrastructure works like tunnels, dams, airports, highways, among others, each potentially requiring a different BIM-based approach, that create challenge for integration of BIM to FM (Correa and Santos, 2021).

In the case of highways and airport the BIM model have been used to evaluated the functional and structural pavement parameters during lifecycle (Lopes, 2017; Manico, 2018). In the case of railways and tunnels, BIM models have also been developed for design and data sharing and check information of the entire infrastructure facility, to optimize costs and timing of design and construction work (Rebeca and Carmali, 2018; Sorge *et al.*, 2019).

Another interesting application is the use of BIM programming technologies and data sharing methodologies to improve the way geotechnical data is used and preserved. This data is essential for the development of geotechnical projects that consist of an important part of infrastructure projects. Sibaii (2020) developed an application based in visual program that uses geotechnical data from boreholes to model the boreholes and the subsurface layer elements. This automation in geotechnical profile generation advanced could help in visualization during the infrastructure design and provide an excellent subsurface database.

3.2. Application in dams' operation

The use of the BIM technology applied to different phases of a dam is an innovation. It has been used the 3D digital technology to carry data parameters and complete model construction could improves the dam construction and maintenance (Shi and Gu, 2020).

One of the topics that has been studied is the use of BIM methodology to control some dam parameters in real time. Ji and Hu (2019) used BIM technology combined with a simulation of the finite element method to analysis the temperature influence in the stress of concrete during construction phase. In this work, thermometers and strain gauges were used to monitor the

temperature and deformation of concrete throughout the process. BIM model was used to analysis the finite element result and measurement values (temperature and stress). This methodology allowed to reduce the cracks occurrence during the construction period (Ji and Hu, 2019).

Fernandes (2015) also developed a BIM model in an integrated framework for a concrete dam to connect the modeling, the thermal calculation and constructive phasing. This methodology allows improvements during the design phase, for which different scenarios could be quickly investigated, and helps on decisions during the preliminary stages of the project.

Another application that has been carried out in concrete dams is the use of UAV associated to BIM models for visual inspections during the construction and maintenance phase. The UAV provides qualitative information, with the aim of recognizing the materials conditions and quantitative information, for modelling the structure by geo-referenced dense point cloud (Buffi *et al.*, 2018; Coetzee, 2018).

Buffi *et al.* (2018) compared the results of a traditional topographic instrument and the results of UAV technique for a concrete dam, to evaluate the dam conditions during the operational phase. The UAV methods is faster than the traditional methods, although, the traditional topographic tool are still necessary for georeferencing and validate model. The possibility to have a photographic record of every detail of structures allows for the monitoring of the evolution of the conservation status of the structure. The aim is the creation of whole dam system 4D model, that is used to evaluate the dam condition during the time (Buffi *et al.*, 2018).

Coetzee (2018) used the UAV and BIM model to monitor and quantify activities during the construction phase of a roller compacted concrete (RCC) dam. This approach constitutes a reliable and validated tool for engineers who require high-resolution modelling and monitoring of construction sites. The use of UAV photogrammetry solutions for monthly surveys was used for payment certificates and the 3D models generated monthly improved the quality of works, especially in the case of bulk earthworks.

Another application during the construction phase is the use of BIM and the Web Geographic Information System (WebGIS). This solution can decrease the complexity management of construction site and structures of a hydropower projects, that involves extensive areas and different kind of subjects. For this Zhang and Jiang (2021) developed an extended IFC export method based on data exchange from to batched 3D Tiles. The batched 3D Tiles is regarded as an efficient data format to solve the problems of rendering speed and loading efficiency. This methodology was applied to a RCC dam to information integration and publishing problem, ensuring the convenient management under BIM and GIS platforms. However, the interoperability between the various BIM tools for use in infrastructures such as dams is still limited and needs to be expanded.

As seen in the examples above there are already some applications of the use of the BIM methodology for concrete dams. However, it still needs significant advances to incorporate into the BIM tools the full application for all phases of dam (design, construction, and operation), especially when it comes to embankment dams. In this application, the BIM methodology is more restricted, and there are practically no scientific works about it. For this kind of dam, the application is limited

to the design phase. Even so, the BIM application is still considered an innovation and missing legal guidelines and application roadmap for dam's design and application (Shi and Gu, 2020; Tran *et al.*, 2020).
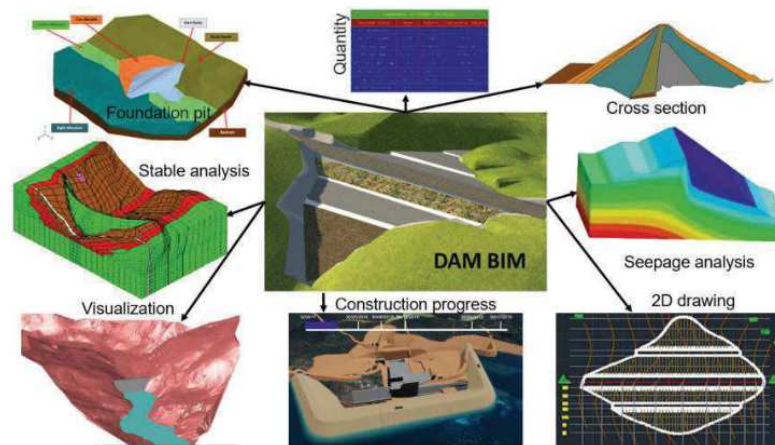

Figure 12 – BIM technology for dam design (Tran *et al.*, 2020).

BIM application for dam design is complex and carried out according to the procedure shown in Figure 12, which follow the sequence:

- Simulate 3D terrain and 3D geology;
- Calculate dam top elevation; select dam type;
- Select dam cross section parameters;
- 3D dam details, seepage analysis, stable analysis, 3D foundation pit;
- Design 3D measurement and monitoring system,
- design 3D electromechanical systems (if necessary), select 3D solution of divert water flow;
- Select 3D solutions and construction sequence;
- Simulate 3D water compartment and drainage works;
- Export volumes and 2D drawings;
- Set 3D construction progress, arrange 3D construction sites; estimate costs;
- Illustrate project by film and 3D images.

After each design step, the parameters of the dam cross section can be adjusted to be reasonable (Tran *et al.*, 2020).

For the operating embankment dams, where the dam is already built, no articles were found that indicated the treatment and analysis of instrumentation data with the use of BIM methodology.

3.3. Database support in operation

Database management system (DBMS) is a collection of programs that allows the process of defining, building, manipulating and sharing data among different users and applications. Defining a database involves specifying the types, structures and restrictions of the data to be stored. Sharing a

database allows multiple users and programs to access it simultaneously (Elmasri and Navathe, 2011). There are several types of database management systems, each database stores a particular collection of data for a specific purpose (Panwar, 2021). There are different methods to classify databases, such as by the number of users supported (single or multiuser database), where the data is located (centralized, distributes or cloud database), and how the data is structured (Carlos *et al.*, 2018). For the last kind of classification, database could be divided in several categories, an example is following:

- Relational model, uses a collection of tables to represent the relationships between the data. Each column of a table represents an attribute and each row in a table represents a record. Each field in a table represents a data value. It is the most widely used data model. Example of applications: Oracle, SQL Server, MySQL, SQLite, and IBM DB2.(Korth and Silberschatz, 1991; Panwar, 2021)
- Semi-structured model, permits the specification of data where individual data items of the same type may have different sets of attributes. Example of application: JSON and Extensible Markup Language (XML) are widely used semi-structured data representations (Korth and Silberschatz, 1991).
- Object-Based model, it provides full-featured database programming capabilities while containing native language compatibility. Example of applications: TORNADO, Gemstone, ObjectStore, GBase, VBase, InterSystems Cache, Versant Object Database, ODABA, ZODB, Poet. JADE, and Informix (Panwar, 2021)
- NoSQL, means not only SQL. It is a new generation of DBMS that is no base in relational database model, that could accept a variety kind of type and different structure of data. Example of applications: Cosmos DB, ArangoDB, Couchbase Server, CouchDB, Amazon DocumentDB, MongoDB, CouchBase, Elasticsearch, Informix, SAP HANA, Neo4j (Carlos *et al.*, 2018; Panwar, 2021)

In general for all databases, the main features of the approach are as follows: (i) self-describing nature of a database system, (ii) isolation between programs and data, (iii) support of multiple views of data, (iv) data sharing and processing with multiple users (Elmasri and Navathe, 2011).

And, some of the advantages of using the DBMS are: (i) redundancy control, (ii) data access restrictions, (iii) persistent storage (information can be retrieved by other systems), (iv) efficiently performs queries and updates, (v) offers backup and recovery, (vi) complex data relationships, (vii) integrity constraints and user interface (Elmasri and Navathe, 2011). These are the main reasons why a Microsoft Excel spreadsheet does not correspond to a database, although it allows the manipulation of data in a tabular format, it does not support self-documentation through metadata, ensure consistency of data in a column by application of data types or domains to data, or defined relationships between tables(Korth and Silberschatz, 1991).

As seen in items 3.1 and 3.2 of this dissertation, the connection between BIM models and database has been used for different applications, an example is connection with monitoring data to analyze the performance of a structure, thermal comfort or occupation of environments.

An important application for relational database using is the system for the safety control of concrete dams called GESTBARRAGENS, which supports: (i) the process of instrumentation installed in the dams; (ii) the process about visual inspections; (iii) the management process; (iv) and the process of detecting anomaly situations in the observed data. According to Silva *et al.* (2005) " *the technical architecture of GESTBARRAGENS also adopts a multi-instance, distributed and federated model whenever convenient, and adopts modern software development technologies, in particular technologies linked to the Internet, geographic information systems and mobile computing*".

Trabulci (2020) used the SQLite database to connect BIM model, and demonstrated an automated extraction of data from Revit model into the SQL database, "*giving facility managers access to work on a complete structured database that interacts with the original Revit model, in addition to that the data analytics is powerful for both prediction of future maintenance and analysis of the asset's performance metrics, assisting on decisions for improvements on energy consumptions of lighting fixtures on the building*".

The SQLite is a kind of relational DBMS with multiple tables, indices, triggers, and views, contained in a single disk file, that means this database reads and writes directly to ordinary disk files, it does not have a separate server process like another database (SQLite, no date). This database establishes a connection in a simplified way with the BIM model, as there is no need to establish a connection with servers as with other relational databases. Also, SQLite is available for free, it has no restrictions on database creation and permanence.

Relational database is similar to a table of values, in which a row is called as tuple, a column header is called an attribute, and the table is called a relation. The value of each cell is called attribute value (Elmasri and Navathe, 2011).

The data type of each attribute (column) describes the types of values that can appear in each column is represented by a domain of possible values. All values in a column are of the same data type and the domain is a set of indivisible values that an attribute can have. This define the variable, name, value (text with character number definition, integer or float values, Boolean) and if the variable could be null or not (Elmasri and Navathe, 2011).

Another important point to define an attribute (columns) is that multivalued or composite attributes are not allowed. Multivalued attributes must be represented in separate relations (tables).

There are three restrictions that must be respected to create a relational database (Elmasri and Navathe, 2011).:

- Key restriction: By definition, all elements of a set are distinct. Thus, two tuples cannot have the same combination of values for all their attributes. To guarantee the uniqueness between the tuples, an attribute (column) is defined that has unique values for each tuple. It can be a sequential value, the registration number of a device, but it must ensure that this value does not repeat throughout the entire relationship. This attribute (column) is called the Primary Key.

- Entity Integrity Restrictions: The primary key of a relationship cannot have a NULL value. If this was allowed, then we would be assuming that there are tuples that do not differ, violating the basic rule of the primary key.
- Referential Integrity Restrictions: It is classified between two relationships and used to maintain consistency between the tuples of the two relations (tables). A tuple in a relation, which references another relation, must refer to an existing tuple in this relation. The concept of foreign key (foreign key) is used to define the referential integrity constraints. The foreign key of a relation must be the primary key of the other relation, in this sense it is possible to establish the connection between the different relations. Therefore, Referential integrity states that every foreign key value in a relation must match a primary key value of a second relation or must be null.

In addition to establishing a connection with the BIM model, another important point is to establish a connection between the database with some tool for data analysis as performed in the work of Trabulci (2020). In this work this connection was established to show the potential to procedure data analysis with data from BIM model.

3.4. Business Intelligence

Business intelligence (BI) is a term for the technology that enables data preparation, data mining, data management, and data visualization, by integrating a set of tools and process. BI tools and processes allow identifying information from data, and supporting decision for organizations in several subjects (IBM, no date). "*This intelligence is based on learning and understanding the facts about the business environment. BI is a framework that allows a business to transform data into information, information into knowledge, and knowledge into wisdom*"(Carlos *et al.*, 2018).

There are different kind of BI tools available on the market, most of these tools has offers comprehensive reporting, analysis, and interactive data visualization, but for different goals, such as SAP Business Objects, that focus on customer experience and digital supply chain.

Most BI tools connect to a database, such as Microsoft Power BI, Looker, Tableau (Haije, 2019). The connection between database with information from social media and BI allow companies to understand their customers better, improve marketing technology, make personalization possible and identify real-time problems and opportunities(Niu *et al.*, 2021).

For the construction area a lot of different BI tools available in market have been used such as the software Accept System, IBM SPSS, Matlab, MS Clustering, Pentaho, Power BI, Primavera, Qlik, Rapid Miner, SAP, Statsoft Statistica Weka and Wordstat. In another hand, Lopes and Boscarioli (2020) shows in his study that more than 64% of the software used in construction sector were not commercial and had been specifically developed for each company. These the large number of developed specifically solution is because of the characteristics inherent to the construction sector, and for the different uses that have been applied to construction sector (Lopes and Boscarioli, 2020).

There are different applications to construction sector by utilization the BI and analytics technologies, such as: management support were preparation of budgets, cost management of works in progress and in the area of occupational safety. In addition to these, there were also uses in the areas of knowledge management, risk management, strategic management, schedule management, productivity management, inventory management, waste management and structural design (Lopes and Boscarioli, 2020).

Although many of the systems available in market were primarily developed to support business (financial) analytics, they also seem perfectly suited to handling engineering issues. Szelka and Wrona (2010) studied several BI and analytics tools to support decision making in structural projects, concluding the most appropriate application is data warehouse, because of the use multidimensional structures in the processes of data gathering, handling and distribution. The data warehouse is a kind of database that stores data in a format optimized for decision support. These tools could be considered a kind of BI and analytics tools, that contain data from the operational databases as well as data from other external sources (Carlos *et al.*, 2018).

Another type of application already carried out was the use of BI tools for performance and energy efficiency analysis. For this, the BIM model was connected to a BI tool (Trabulci, 2020). This methodology can be applied to the analysis of instrumentation in dams by connecting the dam instrumentation database and BIM model with BI tools.

One of the BI tools that allows this kind analysis is the Microsoft PowerBI, which can connect with database and with the BIM model through an application that make this connection. An example of this kind of tool is the Tracer. This is a standalone toolkit for visualizing interactive 2D or 3D geometry created for BIM model to visualize in Microsoft PowerBI. This helps to visualize the unique information. Figure 13 show an example of connection between BIM model and BI tool.
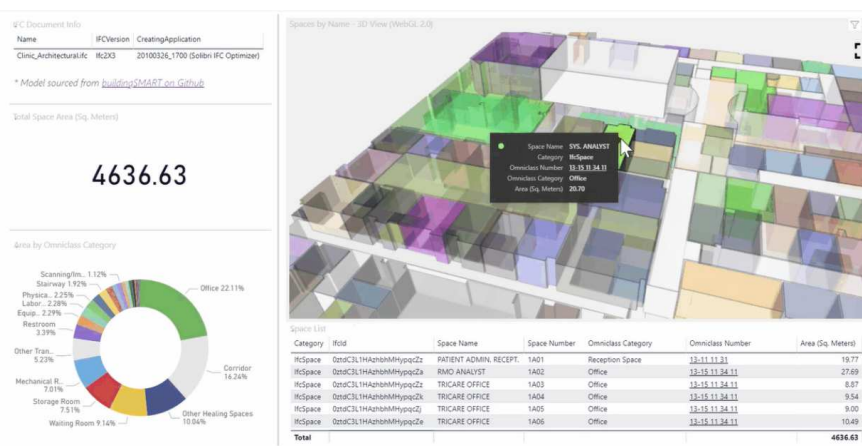

Figure 13 – BIM model connected to BI tool (https://apps.provingground.io/tracer/)

4. INTEGRATED FRAMEWORK FOR SAFETY CONTROL OF EMBANKMENT DAMS

This chapter describes the procedure to develop the BIM *As-is* model focusing on safety control for embankment dams during the operation phase.

The current procedure for the flow of information between the parameter's measurement of instrumentation and data analysis is carried out according to the workflow shown in Figure 14. The activities start with field measurement of the *n* instruments as shown in column *A* of Figure 14. For each instrument, a text file with the measurement data is issued, column *B* of Figure 14. For each of the instruments there is a spreadsheet for data analysis, column *C*.

Figure 14 – Current workflow to measurement and data analysis.

To improve the current workflow of activities, this work proposes the workflow shown in Figure 1, where data from existing and new measures will be stored in database that will provide information to the BIM model. Therefore, all the information will be concentrated in the same place (database), allowing an integrated analysis of the data by using the visualization in BIM model and the tools for data analysis.

Figure 15 shows the computational workflow used for implementation of the procedures. In this workflow the procedure for implementation was divided into four activities listed between 4.1 and 4.4, which correspond to the sub-items in this chapter.
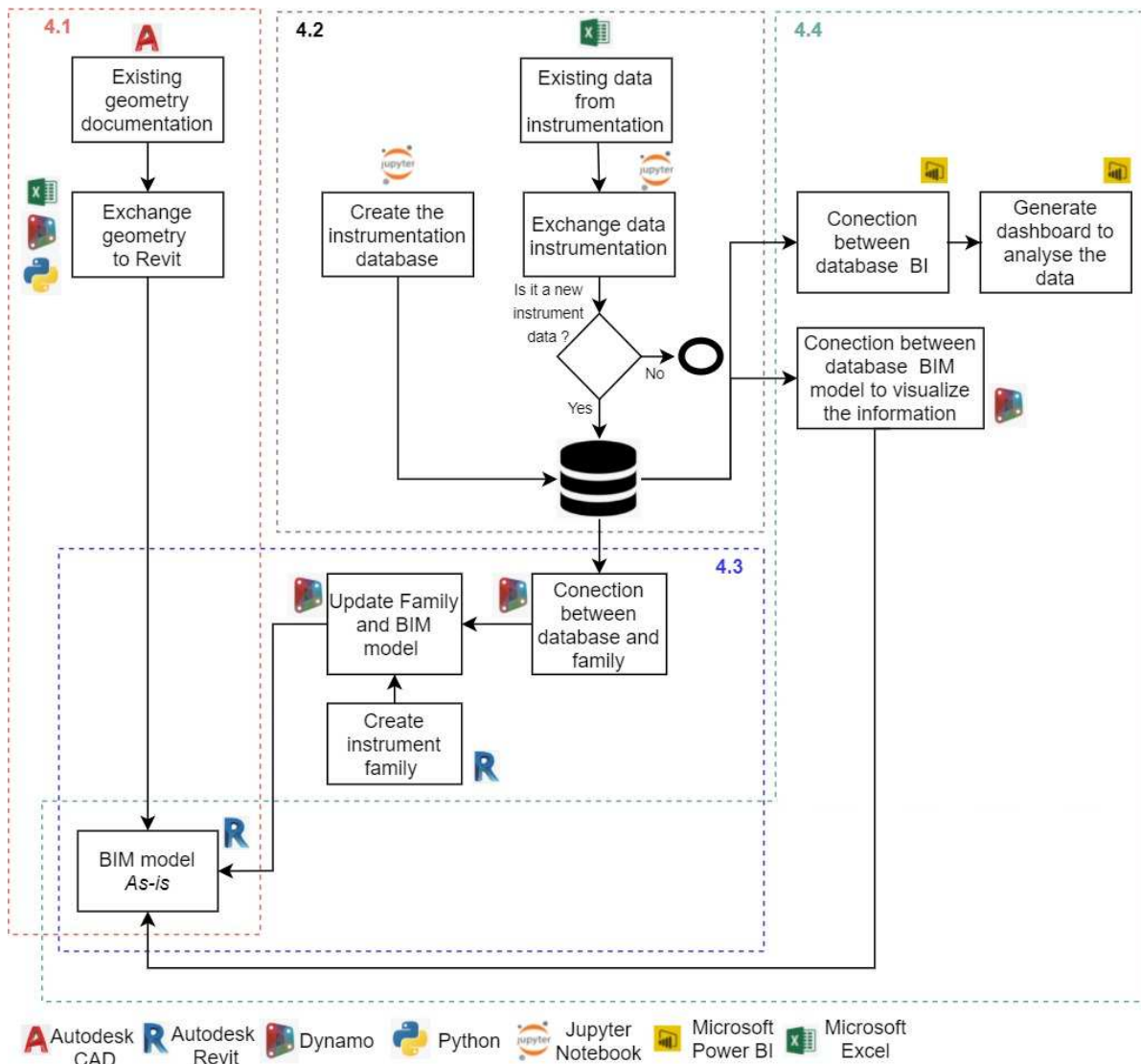
Figure 15 – Computational workflow.

This workflow allows you to visualize that practically all the information is arriving in the BIM As-is model as a final product. The information that feeds the procedures to establish the connection with the BIM As-is model is focused on the database.

The activities numbered in 4.1 consists of the exchange of geometry, between AutoCAD and Revit. For this the information was transformed into Microsoft Excel sheets and visual programming and Python language were used to establish the exchange of information. The result is the BIM *As-is* model of the dam geometry.

The activities numbered in item 4.2 consist of the creation of the BIM object instrumentation, by connecting the database and the BIM *As-is* model, using for that the visual programing.

The activities numbered 4.3 consist of the creation of the instrumentation database and verification of the existence of data that already exists in the database and consequently the writing of non-existent data. For this, programming in python language was used in the develop open-source software *Jupyter Notebook*. For the database, DBMS SQLite was used.

Activities 4.4 correspond to business intelligence, establishing the connection between the database and the BI tool (Microsoft Power BI) and with the BIM As-is model through the visual programming language.

Details of the activities listed above and shown in Figure 15 are found in the sub-items of this chapter, numbered as shown in Figure 15.

4.1. Modelling geometry in BIM model platform

To facilitate the creation of the geometry of existing dams, a code was developed based on visual programming language. This code generated some parts of the dam such as upstream and downstream embankment, core and drain of the dam (Figure 16). As shown in item 2.1, in general and simple way, these are the three structures that help to ensure the three principles of dam design: stability (embankment), deformation compatibility (core) and flow control (drain).

Embankment   Core   Drain

Figure 16 – Geometry automatic generated.

Geometry is generated by provided the cross sections points of each structure (embankment, core and drain). Data entry is performed using Excel spreadsheets, with each of the structures corresponding to a different excel spreadsheet. The points must be inserted sequentially, but it does not depend on the direction, they can be inserted clockwise or counterclockwise. Figure 17, Figure 18(a) and Figure 18(b) show an example of the spreadsheet.

In addition to the points referring to the cross sections, the dam axis is also provided, this information is obtained directly from BIM platform, by using visual language for that. In this case, the axis can be drawn directly in BIM platform or imported from AutoCAD.
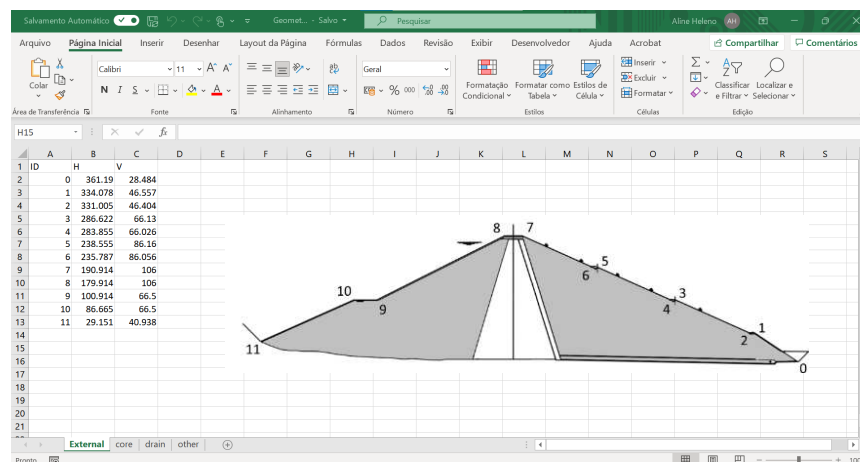

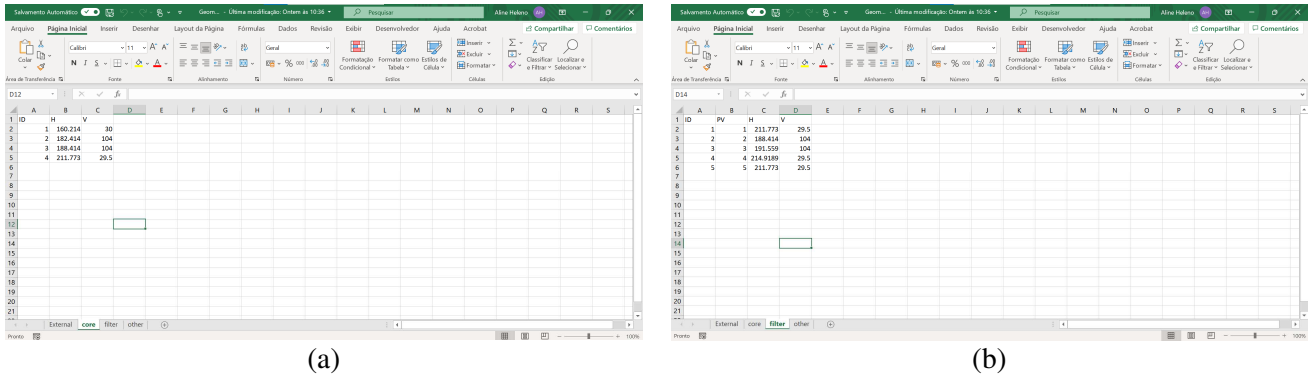**Figure 17 – Excel spreadsheet with geometry information – embankment.**

Figure 18 – Excel spreadsheet with geometry information – (a)core; (b)drain.

From the points of each structure, a polygon is generated. These polygons are extruded in relation to the axis of the dam, generating three independent solids. This procedure is performed for the three types of structure (embankment, core and drain). The solid corresponding to the embankment dam is cut according to the geometries corresponding to the core and drain. Figure 19 shows the process to generate the dam geometry.

It was not the focus of this dissertation to add the non-geometric data of the dam structures. The reason for inserting the geometry was the visualization of each structural components by the cross sections that can contribute during the instrumentation data analysis. However, this point corresponds to an improvement for future work, since the integrated analysis, considering construction data, such as test data that indicate the technological control of the compaction of the landfill layers, can be an important source of information for possible problem identified during the instrumentation analysis.
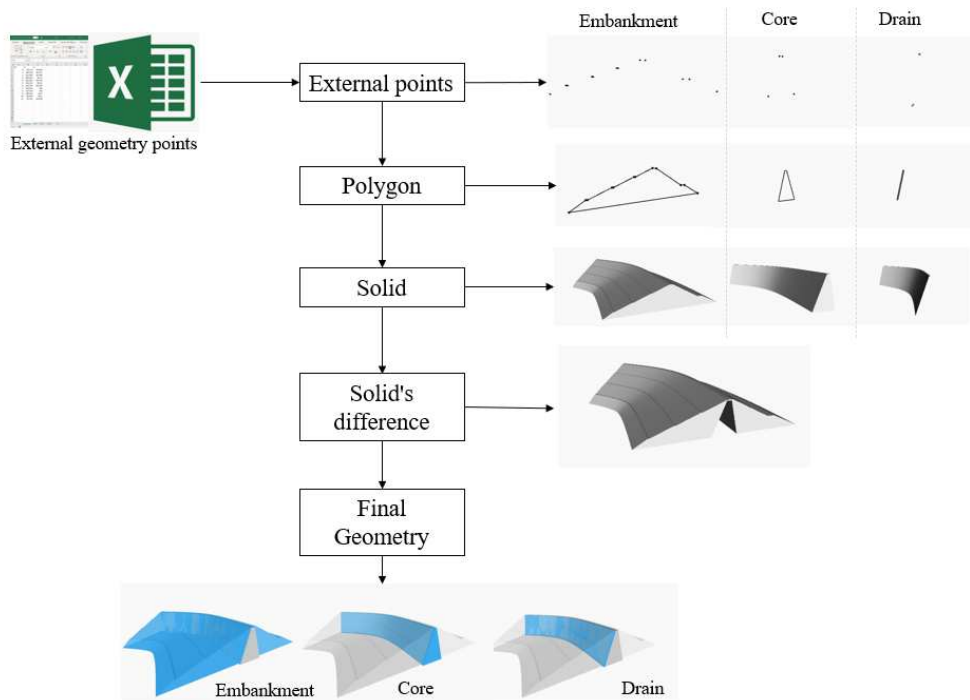

Figure 19 – Geometry process generation.

Figure 20 shows the code developed in dynamo. The code was divided into three steps namely (i) importing the data, (ii) creating the geometry, and (iii) exporting the geometry to BIM platform. For these three steps, the set of codes used for each of them were grouped and defined by three different colors as shown in Figure 20. Details can be better seen in Appendix 1 of this dissertation.
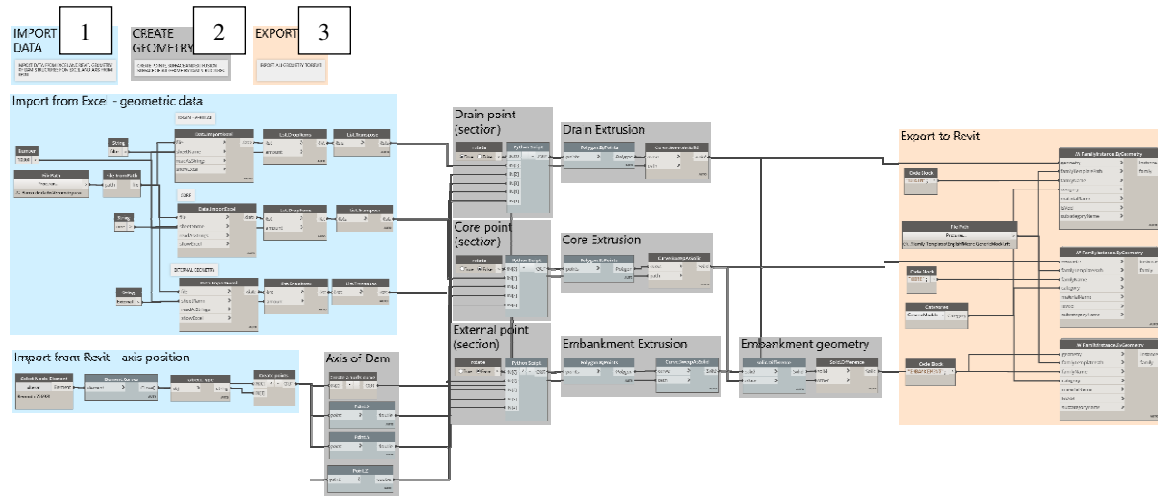

Figure 20 – Dynamo script to create dam geometry.

The first part of the code is import from Excel the geometry points of each of the structures (embankment, core and drain) and from the BIM platform the dam axis.

The second part of the code corresponds to the creation of the geometry. It starts with the creation of the axis dams, then the line imported from BIM plataform is discretized, and the *nurbscurve* is generated. The cross section of each structure is created by a python code showed in Appendix 1. The whole cross section is extruded along the *nurbscurve*, by using the *Sweep.AsSolid* component. To define the embankment structure, the solid created is extruded by using the *Solid.Diferrence* component. Finally, the geometry created is exported to BIM platform as a family instance.

4.2. Database

As shown Figure 15 one of the activities consists of creating a database of the instrumentation of an embankment dam already built and in operation. The data is currently in Excel spreadsheets. Each instrument corresponds to a different excel spreadsheet.

As discussed in item 3.3 of this dissertation, there are several types of DBMS available for processing, manipulating, and sharing different types of data. As instrumentation data are found in Excel spreadsheets, they correspond to structured data, that are like the date structure of Relational DBMS.

There are some Relational DBMS tools available on the market. The DBMS chosen to develop the database was SQLite because it is a tool available for free, it does not offer restrictions or limit of attributes and data permanence. It is also easy to automate and manipulate the database creation, by textual programming. In addition, the connection between the BIM model and the database becomes easy using the visual programming language, the connection doesn't need a server because this

database reads and writes directly form the disk file. This kind of database have also had successful application with BIM model, and item 3.3 shows some of these applications and the main characteristics of the Relational database.

Figure 21 shows the conceptual schema of the database created. The relations (tables) were numbered to facilitate the explanation. For each attribute the following are defined: the variable, name, value type, and if it can accept null value or not. The three-value types defined in Figure 21 are: (i) char, text variable; (ii) int, integer value; (iii) real, float value.

The relationship between each database table is defined for a row with one point and three points, that means from one to many respectively. The primary and foreign key are defined by the letter PK and FK, before the variable, some of relation has more than one FK, in this case they are enumerated.

The relation defined as 1 and named as "*GeneralInformation*" contains the general information about the project, such as name, location, type of dam (zoned, rockfill, among others), the use declaration (water supply, energy generation, mining waste containment, among others), the maximum height and dam classification. The PK is defined as sequential integer number and unique, named as "*ProjectNumber*".

This database table establishes a one-to-many relationship with the database table number 2, named "*Instrument*" this connection is made by the attribute called "*ProjectNumber*". This parameter is PK in relation (table) 1 and FK in relation (table) 2. The relation 2 contains the general information about the instrument like instrument name, geographic position and foundation level. The PK is a sequential integer number and unique, named as "*Inst_ID*", and establish the connection with two relations (tables) numbered as 3 and 5a and named as "*DI_General*" and "*SP_Ring*", respectively. The relation 3 contains data information, about the date of instrumentation measurement, the ID of the technical team responsible for the measurement. This information is an FK that comes from the relation number 4, named "*Persons*". Relation (tables) numbered with 5 (a and b), 6(a and b), 7 and 8 are tables of instruments measurement, such as: settlement platform/gage, inclinometer, surface settlement and piezometer, respectively.

For each settlement platform/gage instrument, there are *n* rings, that are numbered as is shown in Figure 22. Information like name of each magnetic ring, installation date and geometric dimension of each ring does not change, in addition for each ring there are many measurements that depends on the measurement date, therefore two relations (tables) were created for this instrument, 5a and 5b. Relation 5a correspond to the Ring information relation (table) and the 5b corresponds to the measurements relation (table) for this instrument, that has two FK one correspond to "*DataInformation*" relation and the another the "*SP_Ring*" (ring information).

For the inclinometer instrument there are two relations, 6a and 6b, but just to separate the measurement form the calculation, as shown in Figure 21. For the other two instruments, surface settlement and piezometer, there is just one relation, 7 and 8, respectively, with the final result for each one (Figure 21).

Figure 21 – The conceptual schema of the database in class diagram notation.
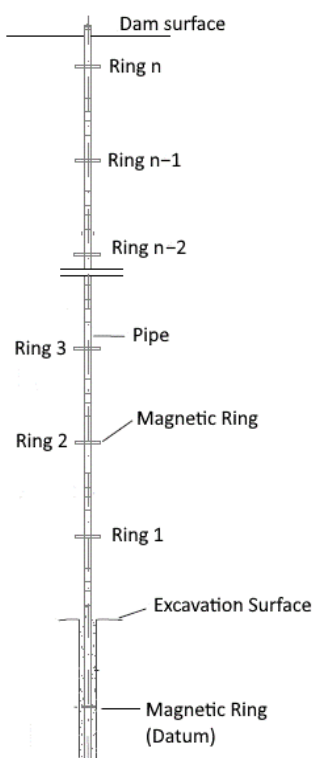
Figure 22 – Settlement gage.

The code implementation was developed using python language and Jupyter Notebook application. The implementation of the database proposed in Figure 21 was not complete, only the relations within the red polygon was implemented, which consist of settlement platform/gage measurement. Appendix 2 shows the code to create the database.

To facilitate and automate the data writing process in the database, a code was created for automatic reading of the data in the Excel spreadsheet provided by LNEC the institute involved in the study. These tables were prepared by LNEC and contain instrumentation data, calculations, and data analysis.

After this step, a code was created to verify the existence of data already existing in the database, to ensure that no data duplication occurs. If the data does not exist in the database, this information is written and recorded. The code, to write and verify the existence of the data, is shown in Appendix 2 of this dissertation.

The connection between the database and the BIM model is done by comparing a set of parameters: *DamName, InstName, SG_RingName*. These parameters are checked during the insertion of new instruments, both in the database and in the BIM model, so that there is no duplication of information in the database and in the model.

4.3. Classes of objects for geotechnical instrumentation

The first step in creating a new BIM object is to define one of the standards or procedures, such as Open BIM Object Standard (OBOS), which contributes to interoperability in BIM models. The second step is identifying the existence of objects and modify and insert the information need for the

project (Trabulci, 2020). However, there are not existing geotechnical instrumentation libraries available, also there are not templates that could help the construction of the object.

Therefore, to create the instrumentation object, it was decided to start developing the Product Data Template (PDT) of one instrument, the settlement gauges. The NBS BIM Object Standard rules and procedures was followed for this.

The level of information need was defined according to the conditions of an already built dam, the instruments have been installed and are in the operation phase. The development of the BIM model is a way to contribute to the analysis and visualization of instrumentation results. In this context a minimum definition of the level of information need was considered as anything beyond that would be considered a waste.

The most important information defined for settlement gauge instrument are: i) the name and location of the instrument, ii) the name and depth installation of each ring, iii) the measurement date, and iv) the visualization of measurement. Some geometric parameters were also added.

For the instrument parameters, an attempt was made to fit the rules defined in the NBS BIM Object rules, as showed in the Table 2. This table represents the PDT. The PDT shows the information for new industrial products and consists in a spreadsheet divided in different categories of information, the parameters name with each property. Figure 23 shows the geometric data and the settlement gage instrument 3D visualization.

Table 2 – Settlement Instrument PDT

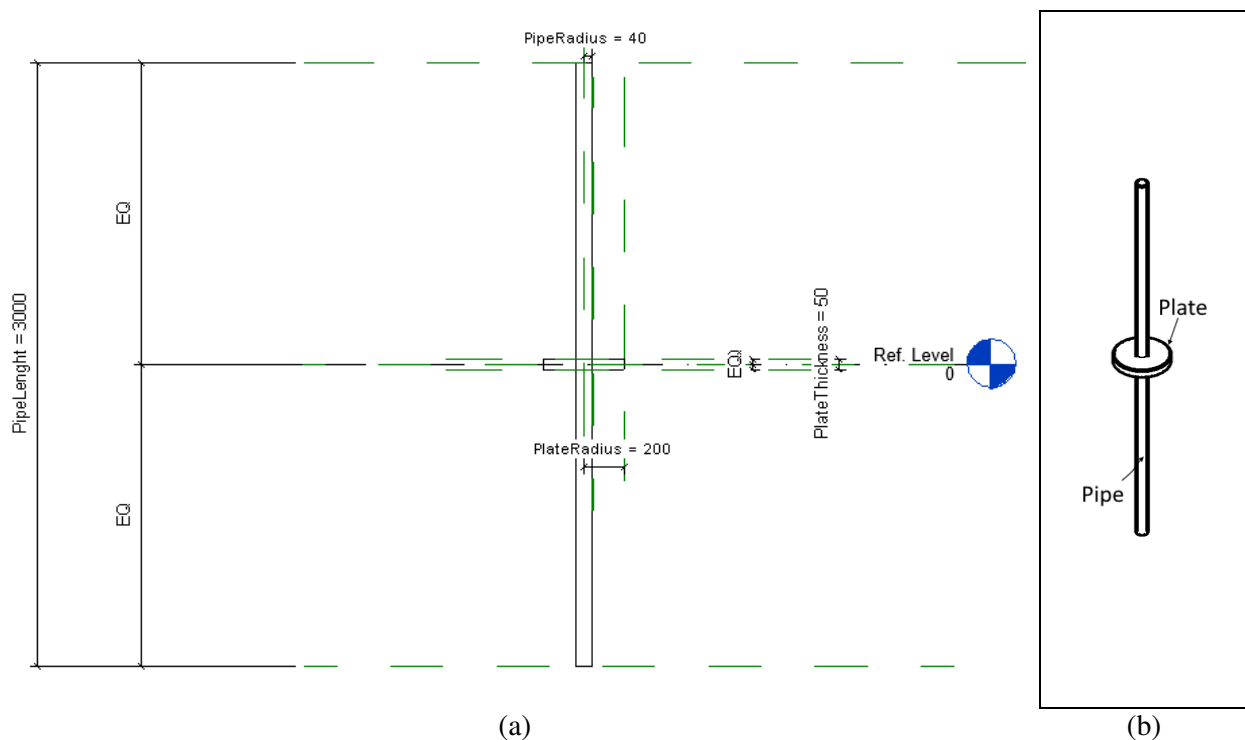| Group Parameter	Parameter name	Units	Data Type	Example
Geometric Data	PipeLenght	mm	Numeric	1
	PipeRadius	mm	Numeric	40
	PlateRadius	mm	Numeric	500
	PlateThickness	mm	Numeric	50
Others	DamName	text	Alphanumeric	Odelouca
	InstrumentName	text	Alphanumeric	BA5-1
	RingName	text	Alphanumeric	R1
	InstLocationX		Numeric	2222222.25
	InstLocationY		Numeric	2222222.25
	RingLevel	m	Numeric	20
	MeasurementDate		Alphanumeric	1900-12-31T23:59:59
	InstallationDate		Alphanumeric	1900-12-31T23:59:59
	Settlement	mm	Numeric	200

Figure 23 – Settlement gage object (a) Geometry information; (b)3D visualization.

The position of each of the elements referring to the instruments is based on the information available in the database.

The procedure for plotting the instrument on the BIM model is described in Figure 24. Information such as dam name, instrument name and ring name are extracted from the BIM Model and the instruments database. Based on this information, the existence of the object is checked. If the object does not exist in the BIM model, it is plotted from the coordinates available in the database, but with correction regarding on the project based point of the BIM model.

For this, a code in visual language was created to define this position. Python code was developed to establish the connection with the database and read the information corresponding to the location of each instrument in BIM model. Python code and the visual code are available in Appendix 3. This application also connects to the database to fill in the metadata information in each of the instruments.
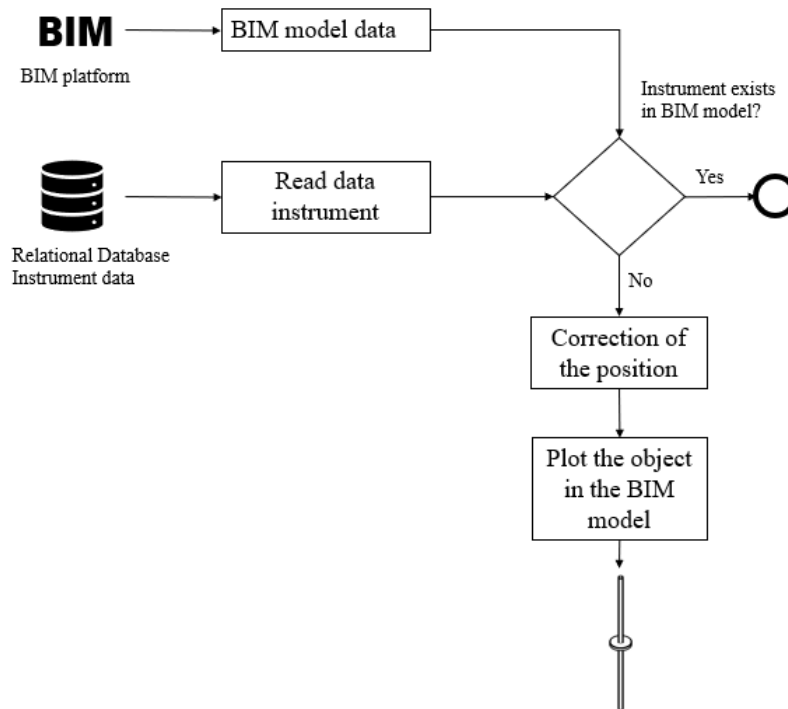
Figure 24 – Plot instrument object in BIM model.

4.4. Interact dashboard and visualization data

The last step of the workflow shown in Figure 15 corresponds to the connection between the database and a tool for graphic visualization and analysis. The connection with the BIM model was also established for the spatial visualization of the results. Appendix 4 shows the connection made between the database and the BIM model As-is, for data visualization.

The implemented instrument provides vertical displacement values along the depth as presented in item 2.2.2 of this dissertation.

Data visualization in the BIM model is done through a cylindrical object, which are plotted in the position of each one of the rings. For that, it was created a BIM object as shows Figure 25.The height of the cylinders corresponds to the vertical displacement value, and the color scale also provides a preview of the same parameter. The user can change the viewing radius of the rings as well as the color scale. The values of the color scale were obtained from the normalization displacement, the warmer colors correspond to the unit value and cooler colors to values less than 1, with the white color corresponding to the lowest value of the normalized series. The measuring plate of the instrument named in the Figure 25(a) *PlateRadius* was also kept in the object, just to facilitate the visualization of the initial measurement position. Figure 25(b) shows the 3D element with the instrument and visualization data objects.
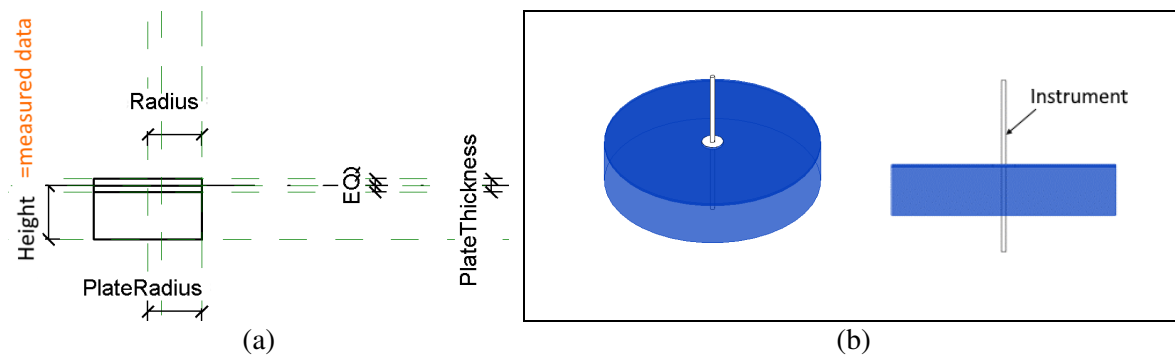
Figure 25 – Visualization data object (a)Geometric information; (b)3D Visualization.

The database was connected with Power BI to develop data preparation, data mining, data management, and data visualization, to the created dashboards and analyses of the instrumentation data, which is commonly called business intelligence. Item 3.4 describes this subject and presents some available tools in the market. This type of tool has been widely used and presents a promising field in connection with BIM model.

The application of this type of tool in the civil construction industry has been increasingly used, due to the need for processing and analyzing the data produced, especially with the integration between BIM, IoT, and data mining (DM) techniques (Pan and Zhang, 2021).

5. CASE STUDY – ODELOUCA DAM

This chapter shows the application of the entire process developed and described in item 4 of this dissertation. The process was applied in an existing embankment dam in operation phase. The main objective is to demonstrate the applicability of the BIM model as a tool to assist in dam safety analysis.

5.1. Description

Odelouca dam is an embankment dam located at north of Silves, on the Ribeira de Odelouca, the main tributary of the River Arade. The dam use is water supply and has a crowning level at 106 m and a maximum height above the foundation of 76 m. The crest is 11 m wide and about 415 m long, with two straight stretches connected by a curved stretch on the right bank. Figure 26 and Figure 27 show the Odelouca Dam in plan and the cross section respectively.

In the cross section (Figure 27) it is possible to visualize the zoned section, with the core that performs the watertight function, the upstream stabilizer mass incorporating the cofferdam. The separation between the core and the downstream stabilizer mass is made by a filter, 3 m wide, which will extend as a drainage, 0.5 m thick, under the downstream stabilizer mass (LNEC, 2007).
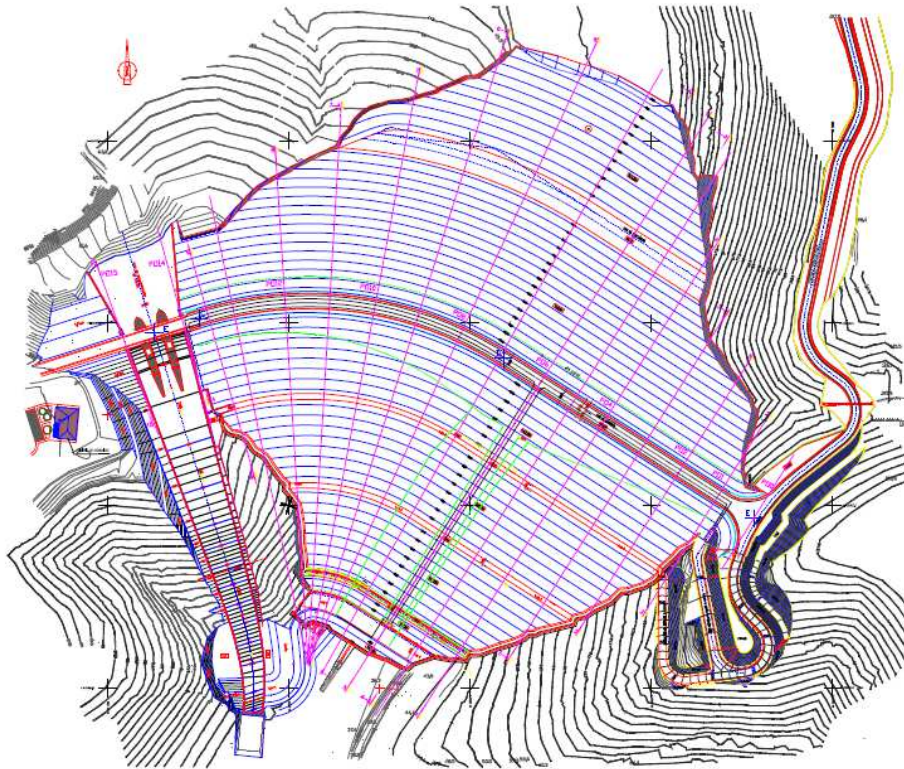

Figure 26 – Odelouca dam plan (AQUALOGOS, 2005 apud. LNEC, 2007).

The flow percolated through the core and part of the flow coming from the foundation will be collected in a drainage ditch located immediately downstream of the core, in contact with the foundation. This ditch will have an exit to the outside in the central area of the valley, materialized by its extension towards the downstream foot. The entire flow that will access this belt will then be collected in the transversal drainage gallery or in the pumping well. The exterior geometry of the dam, the upstream slope will be inclined at 1:2.25 (V:H), below the berm at an elevation of 66.5 m, and at 1:2 (V:H), above of that berm. Downstream, the slope will be inclined at 1:2.25 (V:H), above the foot berm in rockfill at an elevation of 46 m, and at 1:1.5 (V:H), below this berm. On this slope there will be two other berms, at 86 m and 66 m, all 3 m wide.
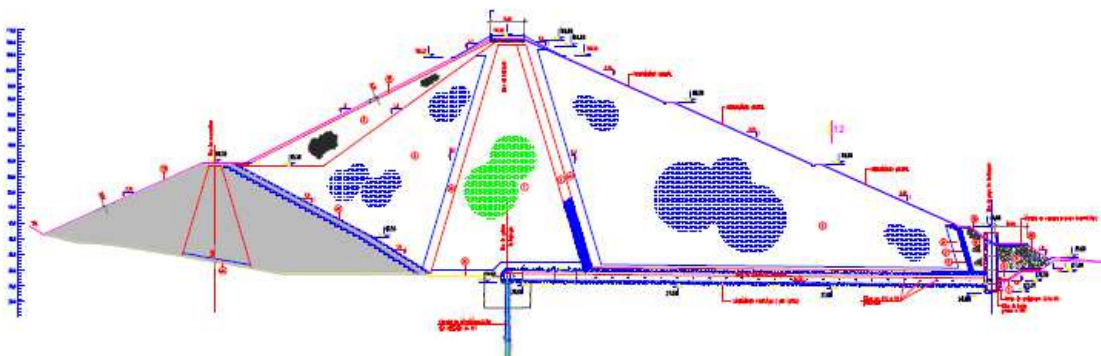

Figure 27 – Odelouca dam section (AQUALOGOS, 2005 apud. LNEC, 2007).

Figure 28 shows the installation locations of the instruments: surface marks, settlement batteries, inclinometers, and piezometers. This drawing is part of the observation plan planning prepared by LNEC. These instrumentations were installed and distributed along 15 observation cross sections, some important information about each instruments is describes as following:

- Surface settlement installed along six longitudinal alignments located on the upstream face, on the crown, upstream and downstream, and on the berms;
- Piezometers, installed from the crown inserted in the core, upstream and downstream, in transverse profiles equally spaced along the development of the dam, with different heights and foundation conditions;
- Settlement gauges, installed during the construction of the embankment in upstream and downstream crowning alignments, at first filling and exploration phases, located in the central area of the dam, where the embankments reach the greatest height, six settlement batteries in profiles displaced about 2.5 m to the right bank;
- Inclinometers, necessary for reading the internal displacements in the horizontal plane installed after construction, in the same position of the settlement gauges.

The observation plan defined by LNEC also includes other instruments for seismological monitoring and pressure cells at the interface between concrete structures and landfill.
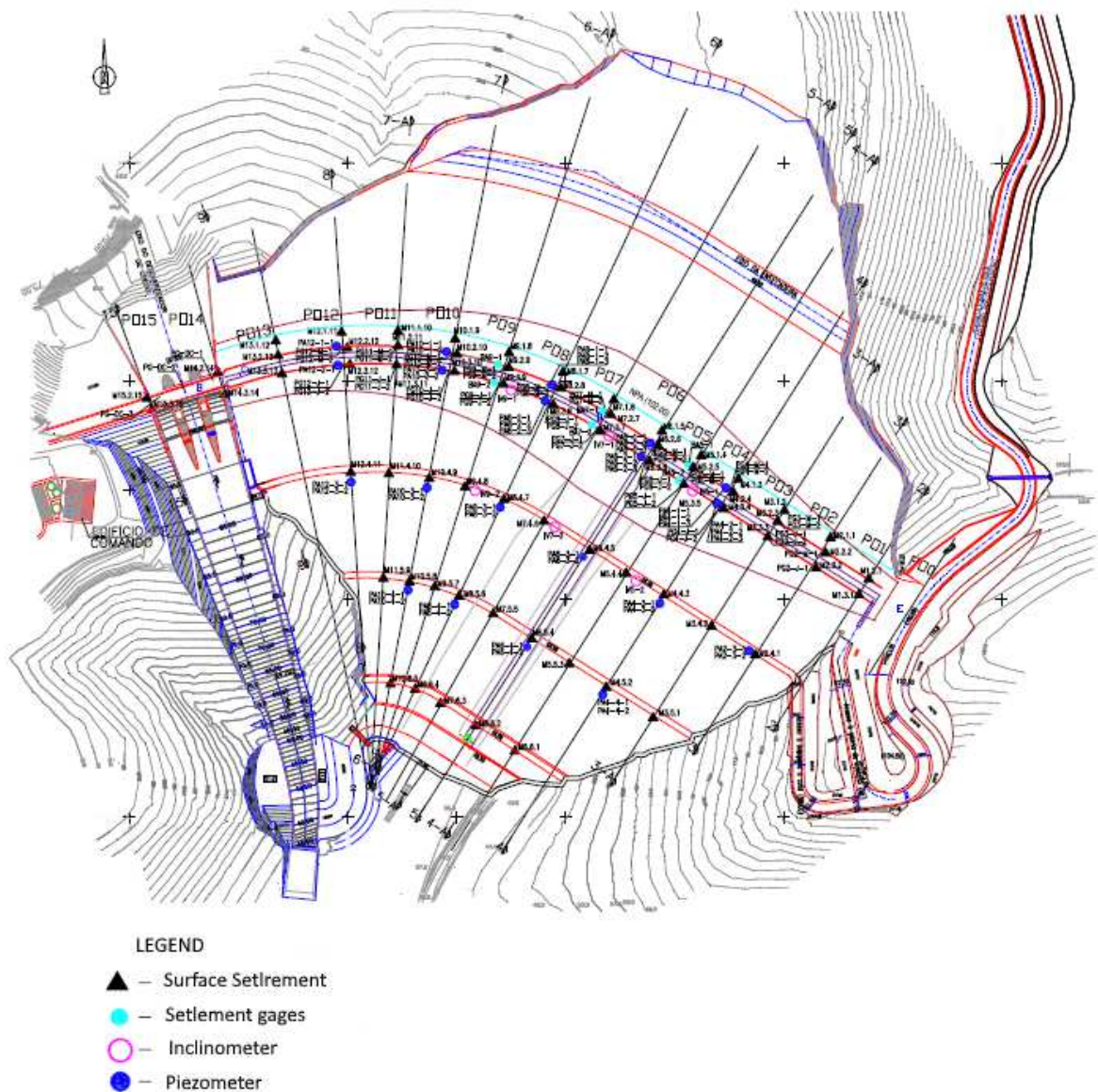
LEGEND

▲ — Surface Setlrement

● — Setlement gages

○ — Inclinometer

● — Piezometer

Figure 28 – Instrument location (modified from LNEC, 2007).

Monitoring plans provide installation details and sample measurement tables. The detailing of these properties is essential to guarantee the safety of the dam structure.

5.2. BIM model developed and results

The instruments at the Odelouca dam, as in most dams around the world, do not have connected instruments, with real-time transmission. Parameter measurements are often still performed with paper forms that are later digitized and sent to the technical responsible for instrumentation evaluation. In the case of the Odelouca dam, there is a different spreadsheet in Excel for each of the instruments, which makes an integrated analysis of the results difficult, with the analysis being carried out essentially two-dimensional and individualized for each instrument. In most cases the analysis is carried out on each of the cross sections defined in the observation plan.

Given the above, it is interesting to concentrate the instrumentation data in the same database and visualize the results in an integrated and three-dimensional way. In addition, some data analysis tools allow a differentiated evaluation of data, based on statistical models of correlation of information and data.

The following item presents, in a simplified way and just for one instrument, an example of application of the connection between different tools in order to integrate information, concentrate in the same database and visualize it in a different way, either through visualization three-dimensional or even by dashboard.

According to the workflow shown in Figure 29, the process starts with defining the three-dimensional geometry.

The geometry developed in this project was simplified and limited to the upstream and downstream embankment, core and the vertical filter. Figure 15 shows a view of the created three-dimensional model.
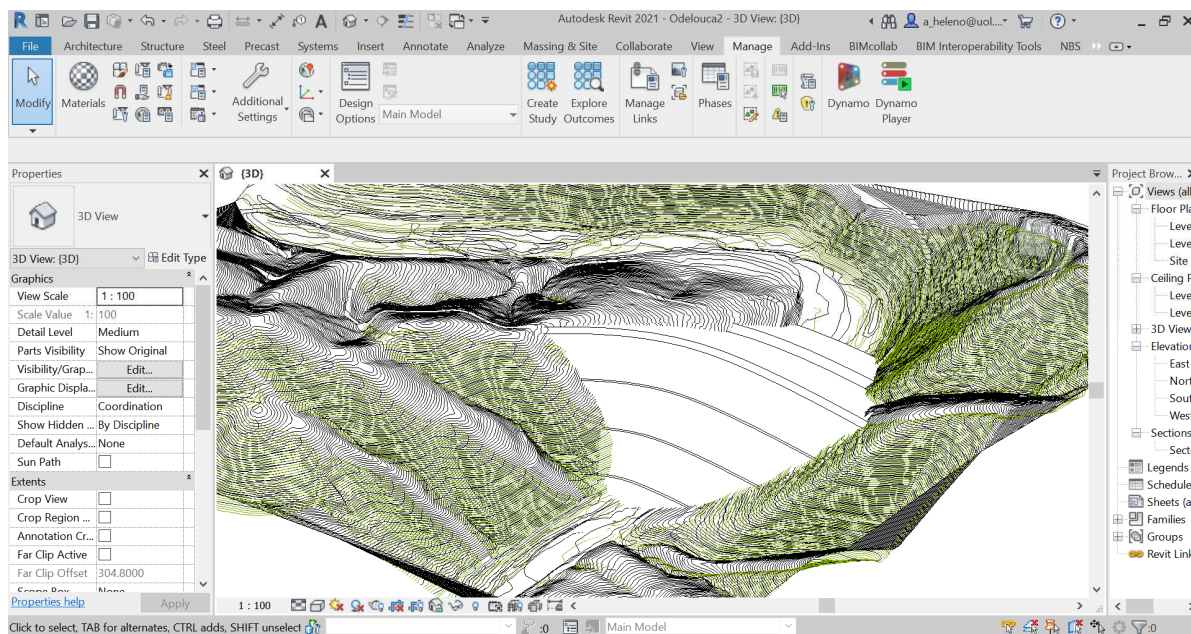

Figure 29 – Dam BIM model.

From the creation of the relational database with all the data measurement and information from the instruments referring to the settlement battery, it was possible to establish a connection with the BIM model. This connection allowed automatic plotting of the position of the instruments, the data measurement, and additional information for each instrument. Figure 30 shows the 3D visualization of the instrumentation data at BIM model. It was also possible to establish the database connection with tools for creating a dashboard, facilitating the integrated analysis of the data, as show in Figure 31.
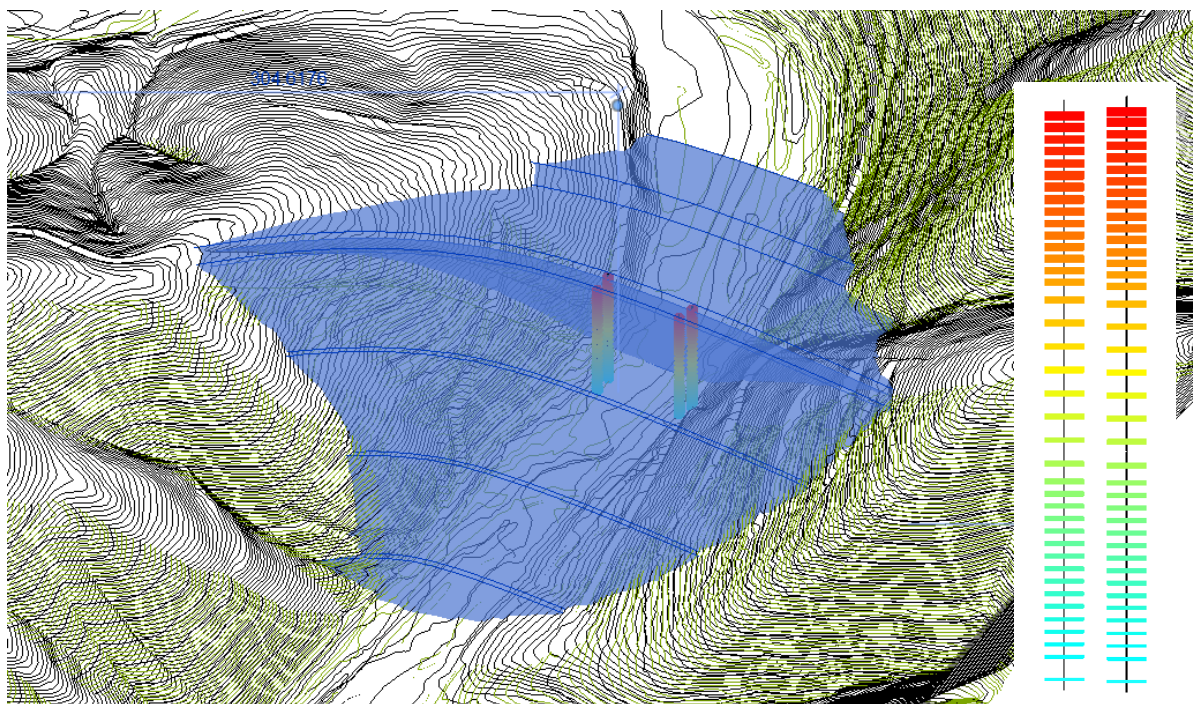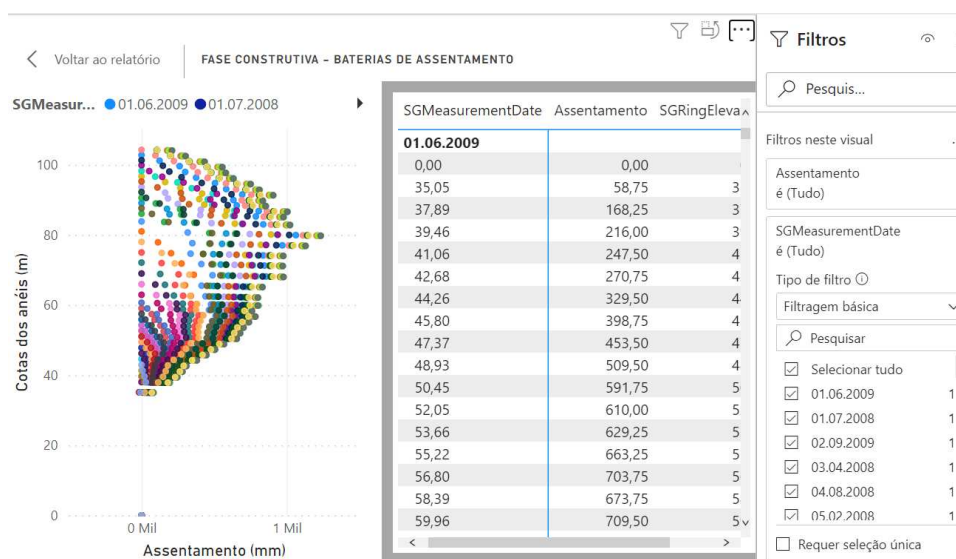
Figure 30 – 3D visualization BIM model.

Figure 31 – Instrument data dashboard.

This is just an example of visualization of instrumentation results, it is possible to improve the visualization. As well as add all the other instruments for a proper dam safety analysis. However, this study showed that the field of application is promising and allows the visualization and analysis of instrumentation in a three-dimensional way. The connection with the database allows the collection off all the data in same place. Also, if the instruments relate to real-time acquisition and connected with a database, it reduces the time for collecting, processing and the data analyses. Another good potential is associated with different data analysis to predict the behavior of the dam structure, from the existing instrumentation data, making it possible to anticipate bad behavior and prevent dam failure.

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6. CONCLUSION AND FUTURE DEVELOPMENTS

This dissertation objective was the use BIM model to improve the data analysis of instrumentation records in embankment dams. The motivation results from the identification of some pitfalls of manual data analysis acquisition procedure that still carried out in some embankment dams, namely: (i) data available in different files formats, not allowing a concentrated and integrated analysis and (ii) lack of automated processes to connect information in different types of data analysis and visualization tools.

The application of BIM model in infrastructure works to solve similar problems has been widely studied, mainly with the introduction of other technologies such as UAV, IoT, and AI. However, this application for dams is still limited, with some works being found for concrete dams. The application for embankment dams is still quite limited.

The work developed intended to show some potential applications of BIM model for existing embankment dams, focusing on the data analysis of instrumentation in dams during the operation phase. The main conclusions of this dissertation can be summarized as:

- From the As-is analysis it was possible to identify the main oportunities of instrumentation measurements that are still performed manually such as: establishment of the connection between the existing instrumentation data sheets with the relational database automatically, being possible to record data efficiently and quickly;
- Establishment of the database connection with the BIM model in order to guarantee the concentration of information (instrumentation and geometry) in a single model. The connection between the BIM model and the database was established through the connection of the BIM object of the setlement gage instrument;
- For data visualization, it was verified that there are resources to perform this type of visualization in the BIM model, being a promising tool. However, it still needs great advances for data analysis, requiring the development of more advanced codes for visualization or even for data analysis. In this sense, the integration with existing tools that allow data analysis and visualization becomes efficient, and this is one of the possibilities tested during this work, which showed that this connection between database and data analysis tools is also possible;
- The application of the processes developed in the Odelouca embankment dam, showed that the use of the BIM model for instrumentation analysis is promising, although the example shown is simplified and restricted to only one instrument.

6.1. Future developments

The application of BIM models to analyze the safety of embankment dams is promising, but there are still great challenges for the integrated analysis of all dam information to be carried out in an

integrated manner. One of the most interesting points is add all the instrumentation data and information into a BIM model for a proper dam safety analysis, and integrated analyses. For this, here are some points for future study work to integrated data for safety embankment dams analysis:

- Create a PDT of all geotecnical instrumentation;
- Structure the database with information of the other geotechnical instrumentation, field tests, and information from visual inspection;
- Incorporate at BIM model data from the dam construction, construction phases, zoning and mapping of the materials used;
- Establish procedures to connect the BIM model with tools for numerical analysis of stress x strain, flow network to verify dam stability;
- Establish procedures for data analysis, using existing tools or creating codes to predict the behavior of the dam based on data from instrumentation, construction and material behavior, and AI can be used;
- Establish connection with devices for automated instrument reading and real-time connection with the database, in order to ensure continuous monitoring and analysis of results.

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LIST OF ACRONYMS AND ABBREVIATIONS

AI	Artificial Intelligence
AR	Augmented Reality
BIM	Building Information Modelling
BS	Business Intelligence
CX	Customer Experience
DBMS	Database management system
DM	Data mining
FK	Foreign key
FM	Facility Management
IDMS	Integrated Database Management System
IDS	Integrated Data Store
IFC	Industry Foundation Classes
IoT	Internet of Tings
MEP	Mechanical, Electrical and Plumbing
PDT	Product Data Template
PK	Primary Key
RCC	Roller Compacted Concrete
UAV	Unmanned Aerial Vehicle
WebGIS	Web Geographic Information System

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APPENDIX 1: DYNAMO AND PYTHON SCRIPT FOR GEOMETRY DAM CREATION

The images below show the visual programming and the python code in greater detail, to create geometry. All python codes are enumerated, making it possible to visualize in the visual programming the location of each code in python.

Figure 32 show the visual code for importing information from the spreadsheet into Excel and the axis from BIM model.

Figure 33 shows the python code to generated the points along the axis, to create the *nurbscurve*.
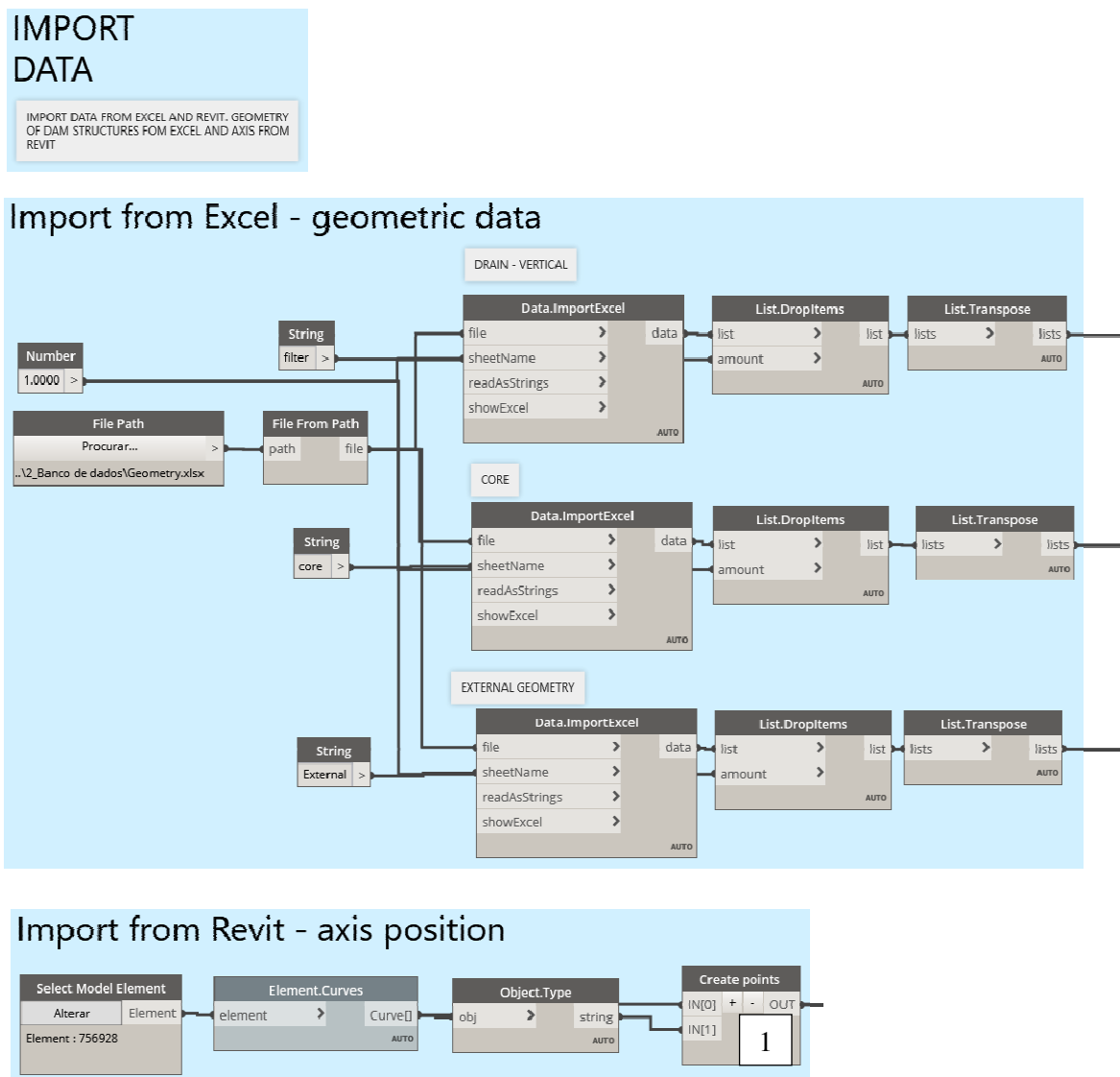

Figure 32 – Dynamo script to create import Excel data to BIM platform.

```python
# Carregar as bibliotecas DesignScript e padrão do Python
import sys
import clr
clr.AddReference('ProtoGeometry')
from Autodesk.DesignScript.Geometry import *

# As entradas para este nó serão armazenadas como uma lista nas variáveis
IN.
dataEnteringNode = IN
curve_list=IN[0]
CurveStartPoint=[]
CurveEndPoint=[]
x_ini=[]
y_ini=[]
z_ini=[]
x_end=[]
y_end=[]
z_end=[]
x_center=[]
y_center=[]
typeline=IN[1]


# Insira o código abaixo desta linha
def dist_linear(x1, y1, x2, y2):return ((x2 - x1)**2 + (y2 - y1)**2)**0.5
for i in range(len(curve_list)):
    CurveStartPoint.append(curve_list[i].StartPoint)
    CurveEndPoint.append(curve_list[i].EndPoint)


x_list=[]
for pt in CurveStartPoint: x_list.append(pt.X)

point_Ord=[]
pt_min= CurveStartPoint[x_list.index(min(x_list))]

dist=[]
for pt in CurveStartPoint:
    dist.append(dist_linear(pt.X, pt.Y, pt_min.X, pt_min.Y))

for j in range(len(dist)):
    for k in range(len(dist)):
        if (dist[j] < dist[k]):
            temp1 = CurveStartPoint[j]
            temp2 = CurveEndPoint[j]
            temp3= typeline[j]
            temp4= curve_list[j]
            temp5= dist[j]
            CurveStartPoint[j]= CurveStartPoint[k]
            CurveStartPoint[k]= temp1
            CurveEndPoint[j]= CurveEndPoint[k]
            CurveEndPoint[k]= temp2
            typeline[j]= typeline[k]
            typeline[k]= temp3
            curve_list[j]= curve_list[k]
            curve_list[k]= temp4
            dist[j]= dist[k]
            dist[k]= temp5


for i in range(len(curve_list)):
    x_ini.append(CurveStartPoint[i].X)
    y_ini.append(CurveStartPoint[i].Y)
    z_ini.append(CurveStartPoint[i].Z)
    x_end.append(CurveEndPoint[i].X)
    y_end.append(CurveEndPoint[i].Y)
    z_end.append(CurveEndPoint[i].Z)
    if typeline[i]=='Autodesk.DesignScript.Geometry.Line':
        x_center.append((0))
        y_center.append((0))
    else:
        x_center.append((curve_list[i].CenterPoint).X)
        y_center.append((curve_list[i].CenterPoint).Y)
div_seg=[]
line=[]
arc=[]
point=[]
pointc=[]

count=0

for i in range(len(x_ini)):
    P1=Point.ByCoordinates(x_ini[i], y_ini[i], z_ini[i])
    P2=Point.ByCoordinates(x_end[i], y_end[i], z_end[i])
    point.append(P1)
    if typeline[i]=='Autodesk.DesignScript.Geometry.Line': line.append
    (Line.ByStartPointEndPoint(P1,P2))
    else:
        z=(z_ini[i]+z_end[i])/2
        P3=Point.ByCoordinates(x_center[i], y_center[i], z)
        Arc=Arc.ByCenterPointStartPointEndPoint(P3,P2,P1)
        arc.append(Arc.ByCenterPointStartPointEndPoint(P3,P1,P2))
        div=1
        pointc.append(Curve.PointsAtEqualChordLength(Arc,div))
        for i in range(div):
            point.append(pointc[count][div-(i+1)])
        count+=1

point.append(P2)


# Atribua a sua saída para a variável OUT.
OUT = point
```

Figure 33 – Python code to create axis points.

Figure 34 show the visual code to generate the geometry, which involves creating the polygon, extruding it along the axis (solid), and cutting the solid to generate the geometry corresponding to the embankment dam.

Figure 35, Figure 36 and Figure 37 shows, respectively, the python code to define the polygon points for drain, core and embankment structures of dam.
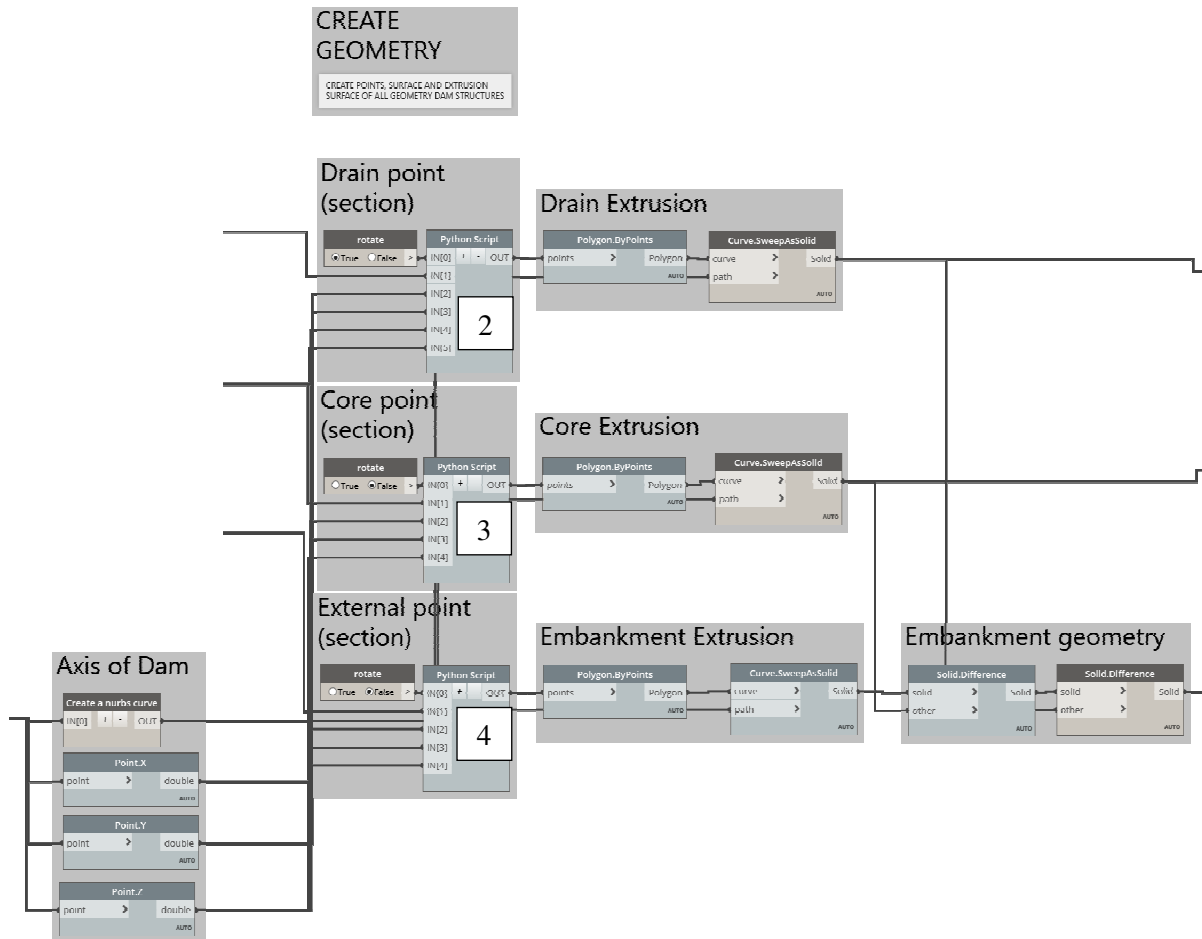

Figure 34 – Dynamo script to create dam geometry.

```python
1  # Carregar as bibliotecas DesignScript e padrão do Python
2  import sys
3  import clr
4  import math
5  clr.AddReference('ProtoGeometry')
6  from Autodesk.DesignScript.Geometry import *
7
8  # As entradas para este nó serão armazenadas como uma lista nas variáveis
   IN.
9  dataEnteringNode = IN
10
11
12
13 PN=IN[1][1]
14 H=IN[1][2]
15 V=IN[1][3]
16
17 x_coord=IN[2]
18 y_coord=IN[3]
19 z_coord=IN[4]
20 rotate=IN[0]
21 Hc=IN[5][1]
22 Vc=IN[5][2]
23
24
25 max_index=[]
26 top_point=[]
27 top_point_core=[]
28 out_points1=[]
29
30 x=[]
31 y=[]
32 z=[]
33 points=[]
34 point_test=[]
35 lin=[]
36 index1=[]
37
38 # Insira o código abaixo desta linha
39 def coef_ang(x1,y1,x2,y2): return (y2-y1)/(x2-x1)
40
41
42
43
44 #ordena em relaçao a distancia horizontal
45
46
47
48 for i in range(len(Vc)):
49     if Vc[i]==max(Vc):top_point_core.append(Hc[i])
50
51 #encontra o eixo
52 d1=(max(top_point_core)-min(top_point_core))/2
53
54 for i in range(len(V)):
55     if V[i]==max(V):
56         max_index.append(i)
57         top_point.append(H[i])
58
59
60 #encontra o eixo
61 top_midle_H=(max(top_point)+min(top_point))/2
62 d2=(max(top_point)-min(top_point))/2
63
64 x1=x_coord[0]
65 y1=y_coord[0]
66 x2=x_coord[1]
67 y2=y_coord[1]
68 ang=math.atan(coef_ang(x1,y1,x2,y2))
69
70 for i in range(len(H)):
71     d=(H[i]-(top_midle_H)+d1+d2)
72     if rotate==1:d=-d
73     z.append(V[i])
74     dx=d*math.sin(ang)
75     dy=d*math.cos(ang)
76     x.append(x1-dx)
77     y.append(y1+dy)
78     out_points1.append(Point.ByCoordinates(x[i],y[i],z[i]))
79
80 # Atribua a sua saída para a variável OUT.
81 OUT = out_points1
82
83
84
```

Figure 35 – Python code to create drain points geometry.

```
1 # Carregar as bibliotecas DesignScript e padrão do Python
2 import sys
3 import clr
4 import math
5 clr.AddReference('ProtoGeometry')
6 from Autodesk.DesignScript.Geometry import *
7
8 # As entradas para este nó serão armazenadas como uma lista nas variáveis
  IN.
9 dataEnteringNode = IN
10
11 H=IN[1][1]
12 V=IN[1][2]
13 x_coord=IN[2]
14 y_coord=IN[3]
15 z_coord=IN[4]
16 rotate=IN[0]
17 max_index=[]
18 top_point=[]
19 IM=[]
20 IM_aux=[]
21 IJ=[]
22 IJ_aux=[]
23 x=[]
24 y=[]
25 z=[]
26 points=[]
27
28
29 # Insira o código abaixo desta linha
30 def coef_ang(x1,y1,x2,y2): return (y2-y1)/(x2-x1)
31
32 #ordena em relaçao a distancia horizontal
33 rot=1
34 if rotate==1: rot=-1
35 for j in range(len(H)):
36     for k in range(len(H)):
37         if (H[j] > H[k]):
38             temp1 = H[j]
39             temp2 = V[j]
40             H[j]= H[k]
41             H[k]= temp1
42             V[j]= V[k]
43             V[k]= temp2
44
45 for i in range(len(V)):
46     if V[i]==max(V):
47         max_index.append(i)
48         top_point.append(H[i])
49
50
51 #encontra o eixo
52 top_midle_H=(max(top_point)+min(top_point))/2
53
54 x1=x_coord[0]
55 y1=y_coord[0]
56 x2=x_coord[1]
57 y2=y_coord[1]
58 ang=math.atan(coef_ang(x1,y1,x2,y2))
59 for i in range(len(H)):
60     if H[i]>top_midle_H:
61         IJ.append(i)
62         IJ_aux.append(i)
63     else:
64         IM.append(i)
65         IM_aux.append(i)
66
67 aux_i=0
68
69 for i in range(len(IM)):
70     aux_i=IM[i]
71     if H[aux_i]==top_midle_H:
72         x.append=x_coord[0]
73         y.append=y_coord[0]
74     else:
75         d=math.fabs(H[aux_i]-top_midle_H)
76         dx=d*math.sin(ang)
77         dy=d*math.cos(ang)
78         x.append(x_coord[0]-dx*rot)
79         y.append(y_coord[0]+dy*rot)
80     z.append(V[aux_i])
81     points.append(Point.ByCoordinates(x[len(x)-1],y[len(x)-1],V[aux_i]))
82
83 for i in range(len(IJ)):
84     aux_i=IJ[i]
85     if H[aux_i]==top_midle_H:
86         x.append(x_coord[0])
87         y.append(y_coord[0])
88     else:
89         d=math.fabs(H[aux_i]-top_midle_H)
90         dx=d*math.sin(ang)
91         dy=d*math.cos(ang)
92         x.append(x_coord[0]+dx*rot)
93         y.append(y_coord[0]-dy*rot)
94     z.append(V[aux_i])
95     points.append(Point.ByCoordinates(x[len(x)-1],y[len(x)-1],V[aux_i]))
96
97
98 # Atribua a sua saída para a variável OUT.
99 OUT = points
```

Figure 36 – Python code to create core points geometry.

```python
1  # Carregar as bibliotecas DesignScript e padrão do Python
2  import sys
3  import clr
4  import math
5  clr.AddReference('ProtoGeometry')
6  from Autodesk.DesignScript.Geometry import *
7
8  # As entradas para este nó serão armazenadas como uma lista nas variáveis IN.
9  dataEnteringNode = IN
10
11 H=IN[1][1]
12 V=IN[1][2]
13 x_coord=IN[2]
14 y_coord=IN[3]
15 z_coord=IN[4]
16 rotate=IN[0]
17 max_index=[]
18 top_point=[]
19 IM=[]
20 IM_aux=[]
21 IJ=[]
22 IJ_aux=[]
23 x=[]
24 y=[]
25 z=[]
26 points=[]
27
28
29 # Insira o código abaixo desta linha
30 def coef_ang(x1,y1,x2,y2): return (y2-y1)/(x2-x1)
31
32 #ordena em relaçao a distancia horizontal
33 rot=1
34 if rotate==1: rot=-1
35 for j in range(len(H)):
36     for k in range(len(H)):
37         if (H[j] > H[k]):
38             temp1 = H[j]
39             temp2 = V[j]
40             H[j]= H[k]
41             H[k]= temp1
42             V[j]= V[k]
43             V[k]= temp2
44
45 for i in range(len(V)):
46     if V[i]==max(V):
47         max_index.append(i)
48         top_point.append(H[i])
49
50
51 #encontra o eixo
52 top_midle_H=(max(top_point)+min(top_point))/2
53
54 x1=x_coord[0]
55 y1=y_coord[0]
56 x2=x_coord[1]
57 y2=y_coord[1]
58 ang=math.atan(coef_ang(x1,y1,x2,y2))
59 for i in range(len(H)):
60     if H[i]>top_midle_H:
61         IJ.append(i)
62         IJ_aux.append(i)
63     else:
64         IM.append(i)
65         IM_aux.append(i)
66
67 aux_i=0
68
69 for i in range(len(IM)):
70     aux_i=IM[i]
71     if H[aux_i]==top_midle_H:
72         x.append=x_coord[0]
73         y.append=y_coord[0]
74     else:
75         d=math.fabs(H[aux_i]-top_midle_H)
76         dx=d*math.sin(ang)
77         dy=d*math.cos(ang)
78         x.append(x_coord[0]-dx*rot)
79         y.append(y_coord[0]+dy*rot)
80     z.append(V[aux_i])
81     points.append(Point.ByCoordinates(x[len(x)-1],y[len(x)-1],V[aux_i]))
82
83 for i in range(len(IJ)):
84     aux_i=IJ[i]
85     if H[aux_i]==top_midle_H:
86         x.append(x_coord[0])
87         y.append(y_coord[0])
88     else:
89         d=math.fabs(H[aux_i]-top_midle_H)
90         dx=d*math.sin(ang)
91         dy=d*math.cos(ang)
92         x.append(x_coord[0]+dx*rot)
93         y.append(y_coord[0]-dy*rot)
94     z.append(V[aux_i])
95     points.append(Point.ByCoordinates(x[len(x)-1],y[len(x)-1],V[aux_i]))
96
97
98 # Atribua a sua saída para a variável OUT.
99 OUT = points
100
101
```

Figure 37 – Python code to create external points geometry.

Finally, Figure 38 show the visual code to export the geometry to BIM model.
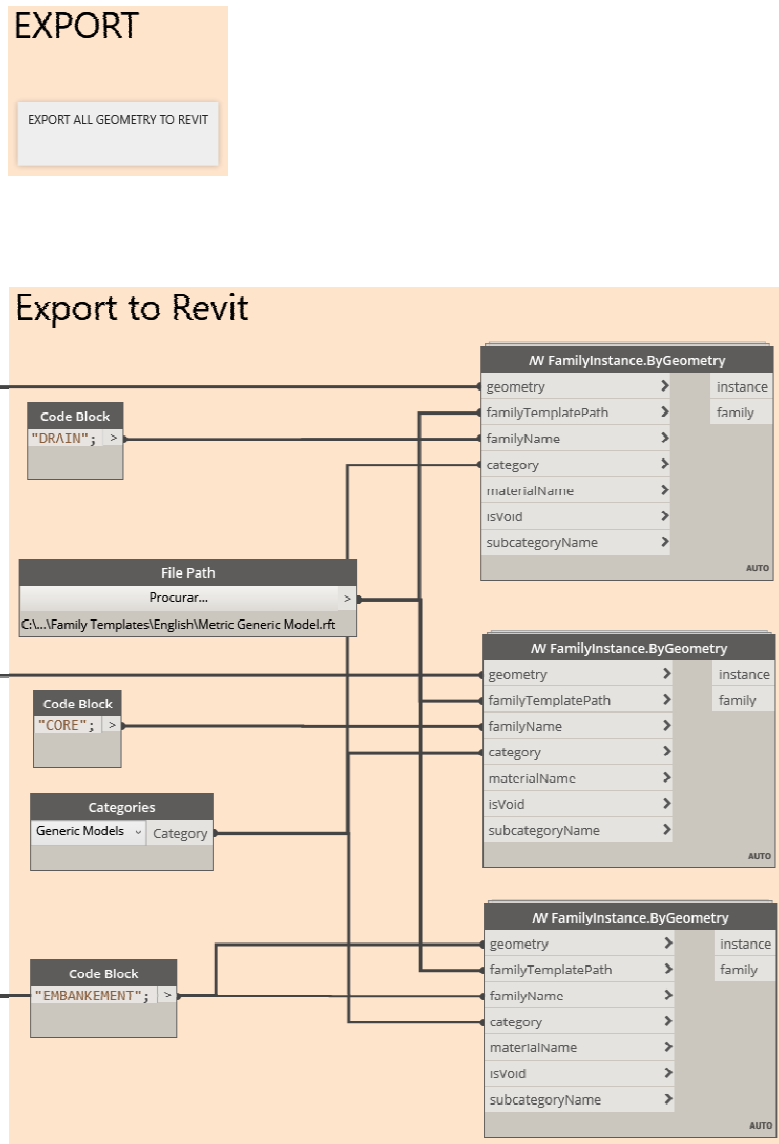

Figure 38 – Dynamo script to export dam geometry.

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APPENDIX 2: DATABASE CODE

Figure 39 show the python code to connect Jupyter Notebook to SQLite and create the database. Figure 40 shows python code to check if the information exists and write to the database if it is not an existing information.

```python
# import access to the database
import sqlite3

# Creates a connection to the database.
# If the database does not exist, it is created at this point.
con = sqlite3.connect('Odelouca.db')
c = con.cursor()
# Creating a cursor - allows you to scroll through all the records in a data set
cur = con.cursor()

# Function to create table
def create_table(x):
    c.execute(x)
```

```python
# Create a sql statement

sql_create=[]

sql_create.append('CREATE TABLE IF NOT EXISTS "GeneralInformation" \
("ProjectNumber" INTEGER NOT NULL UNIQUE,\
"DamName" TEXT NOT NULL,\
"DamLocation" TEXT,\
"DamType" TEXT,\
"DamUse" TEXT,\
"DamHeight" REAL,\
"DamClassification" TEXT,\
"DamDPA" TEXT,\
PRIMARY KEY("ProjectNumber" AUTOINCREMENT))')

sql_create.append('CREATE TABLE IF NOT EXISTS "Instrument" \
("Inst_ID" INTEGER NOT NULL UNIQUE,\
"ProjectNumber" INTEGER NOT NULL, \
"InstName" TEXT NOT NULL, \
"InstCoordWE" REAL NOT NULL,\
"InstCoordNS" REAL NOT NULL,\
"InstGeoCoordSist" Text,\
"Datum" INTEGER,\
"InstFoundationLevel" REAL NOT NULL,\
PRIMARY KEY("Inst_ID" AUTOINCREMENT),\
FOREIGN KEY("ProjectNumber") REFERENCES "GeneralInformation"("ProjectNumber"))')

sql_create.append('CREATE TABLE IF NOT EXISTS "Person" \
("Person_ID" INTEGER NOT NULL UNIQUE,\
"Name" TEXT NOT NULL,\
"TelNumber" TEXT,\
"Mail" TEXT,\
"Function" TEXT,\
PRIMARY KEY("Person_ID" AUTOINCREMENT))')

sql_create.append('CREATE TABLE IF NOT EXISTS "SG_General" \
("SG_ID" INTEGER NOT NULL UNIQUE,\
"Inst_ID" INTEGER NOT NULL,\
"SGMeasurementDate" TEXT NOT NULL,\
"SGDamCrestElevation" REAL NOT NULL,\
"SGPipeTopElevationM" REAL NOT NULL,\
"SGPipeTopElevationC" REAL NOT NULL,\
"DamWaterLevel" REAL NOT NULL,\
"DamObservatorID" INTEGER NOT NULL,\
"DamTRE_ID" INTEGER NOT NULL,\
FOREIGN KEY("Inst_ID") REFERENCES "Instrument"("Inst_ID"),\
FOREIGN KEY("DamObservatorID") REFERENCES "Person"("Person_ID"),\
FOREIGN KEY("DamTRE_ID") REFERENCES "Person"("Person_ID"),\
PRIMARY KEY("SG_ID" AUTOINCREMENT))')

sql_create.append('CREATE TABLE IF NOT EXISTS "SG_Ring" \
("SG_RingID" INTEGER NOT NULL UNIQUE,\
"Inst_ID" INTEGER NOT NULL,\
"SGRingName" TEXT NOT NULL,\
"SGRingRadius" REAL NOT NULL,\
"SGInstalationDate" TEXT NOT NULL,\
"SGInitialLevel" REAL NOT NULL,\
PRIMARY KEY("SG_RingID" AUTOINCREMENT),\
FOREIGN KEY("Inst_ID") REFERENCES "Instrument"("Inst_ID"))')

sql_create.append('CREATE TABLE IF NOT EXISTS "SG_Measurement" \
("SGM_ID" INTEGER NOT NULL UNIQUE,\
"SG_ID"=INTEGER NOT NULL,\
"SG_RingID" INTEGER NOT NULL,\
"SGDownM1" REAL NOT NULL,\
"SGDownM2" REAL NOT NULL,\
"SGUpM1" REAL NOT NULL,\
"SGUpM2" REAL NOT NULL,\
"SGAverage" REAL NOT NULL,\
"SGRingElevation" REAL NOT NULL,\
"Assentamento" REAL NOT NULL,\
FOREIGN KEY("SG_ID") REFERENCES "SG_General"("SG_ID"),\
FOREIGN KEY("SG_RingID") REFERENCES "SG_Ring"("SG_RingID"),\
PRIMARY KEY("SGM_ID" AUTOINCREMENT))')
```

Figure 39 – Code create database.

```
1  # insert data in database
2  def insert_GeneralInformation():
3      x=[]
4      c.execute("SELECT * FROM GeneralInformation")
5      for linha in c.fetchall():x.append(linha[1])
6      if DamName not in x:
7          c.execute("INSERT INTO GeneralInformation (DamName, DamLocation, DamType, DamUse, DamHeight,\
8              DamClassification, DamDPA) VALUES (?, ?, ?, ?, ?, ?, ?)",\
9              (DamName, DamLocation, DamType, DamUse, DamHeight, DamClassification, DamDPA))
10         con.commit()
11
12 def insert_Instrument():
13     y=[]
14     c.execute("SELECT * FROM Instrument")
15     for linha in c.fetchall():y.append(linha[2])
16     if InstName not in y:
17         x=[]
18         c.execute("SELECT * FROM GeneralInformation WHERE DamName = 'BARRAGEM DE ODELOUCA'")
19         for linha in c.fetchall():x.append(linha[0])
20         c.execute("INSERT INTO Instrument (ProjectNumber, InstName, InstCoordWE, InstCoordNS,\
21             InstGeoCoordSist, Datum, InstFoundationLevel) VALUES (?, ?, ?, ?, ?, ?,?)",\
22             (x[0],InstName,Coordm,Coordp,GeoCoordSist,Datum,InstFoundationLevel))
23         con.commit()
24
25 def insert_Person():
26     y=[]
27     c.execute("SELECT * FROM Person")
28     for linha in c.fetchall():y.append(linha[1])
29     for i in range(len(PersonName)):
30         if PersonName[i] not in y:
31             c.execute("INSERT INTO Person (Name, TelNumber, Mail, Function) VALUES (?, ?, ?, ?)",\
32                 (PersonName[i], TelNumber[i], Mail[i], Function[i]))
33             con.commit()
34
35 def insert_Ring():
36     y=[]
37     y2=[]
38     c.execute("SELECT * FROM Instrument")
39     for linha in c.fetchall():
40         y.append(linha[2])
41         y2.append(linha[0])
42     for i in range(len(y)):
43         if InstName==y[i]:Inst_ID=y2[i]
44     x=[]
45     c.execute("SELECT * FROM SG_Ring")
46     for linha in c.fetchall():x.append(linha[1])
47     if Inst_ID not in x:
48         for i in range(len(RingName)):
49             c.execute("INSERT INTO SG_Ring (Inst_ID, SGRingName, SGRingRadius, SGInstalationDate, SGInitialLevel)VALUES
50                 (Inst_ID,RingName[i], Radius[i], RDate[i], InitialLevel[i]))
51             con.commit()
52
53 def insert_SG_General():
54     y=[]
55     y2=[]
56     c.execute("SELECT * FROM Instrument")
57     for linha in c.fetchall():
58         y.append(linha[2])
59         y2.append(linha[0])
60     for i in range(len(y)):
61         if InstName==y[i]:Inst_ID=y2[i]
62     x=[]
63     x2=[]
64     Obs_index=[]
65     c.execute("SELECT * FROM Person")
66     for linha in c.fetchall():
67         x.append(linha[1])
68         x2.append(linha[0])
69     for i in range(len(DamObs)):
70         index=x.index(DamObs[i])
71         Obs_index.append(x2[index])
72
73     for i in range(len(MDate)):
74         c.execute("INSERT INTO SG_General (Inst_ID, SGMeasurementDate, SGDamCrestElevation, SGPipeTopElevationM, SGPipeT
75             DamWaterLevel, DamObservatorID, DamTRE_ID) VALUES (?, ?, ?, ?, ?, ?, ?,?)",\
76             (Inst_ID,MDate[i],CrestElevation[i],TopElevationM[i],TopElevationC[i],WaterLevel[i],Obs_index[i],Obs_i
77         con.commit()
78
79 def insert_Measurement():
80     z=[]
81     z2=[]
82     c.execute("SELECT * FROM Instrument")
83     for linha in c.fetchall():
84         z.append(linha[2])
85         z2.append(linha[0])
86     for i in range(len(z)):
87         if InstName==z[i]:Inst_ID=z2[i]
88
89
90     ID_Ring=[]
91     x=[]
92     x1=[]
93     x2=[]
94     c.execute("SELECT * FROM SG_Ring")
95     for linha in c.fetchall():
96         x.append(linha[0])
97         x1.append(linha[1])
98         x2.append(linha[2])
99     for i in range(len(MRingName)):
100        for j in range(len(x)):
101            if Inst_ID==x1[j] and MRingName[i]==x2[j]:ID_Ring.append(x[j])
102
103    ID_General=[]
104    y=[]
105    y1=[]
106    c.execute("SELECT * FROM SG_General")
107    for linha in c.fetchall():
108        y.append(linha[0])
109        y1.append(linha[1])
110    for i in range(len(y)):
111        for j in range(len(RingName)):
112            if Inst_ID==y1[i]:ID_General.append(y[i])
113
114
115
116    for i in range(len(DownM1)):
117        c.execute("INSERT INTO SG_Measurement (SG_ID, SG_RingID, SGDownM1, SGDownM2, SGUpM1,\
118            SGUpM2, SGAverage, SGRingElevation, Assentamento) VALUES (?, ?, ?, ?, ?, ?, ? , ?, ?)",\
119            (ID_General[i], ID_Ring[i], DownM1[i], DownM2[i], UpM1[i], UpM2[i], Average[i], RingElevation[i], Asser
120        con.commit()
121
122 insert_GeneralInformation()
123 insert_Instrument()
124 insert_Person()
125 insert_Ring()
126 insert_SG_General()
127 insert_Measurement()
```

Figure 40 – Code write and verify duplicated data.

APPENDIX 3: DATABASE AND BIM MODEL CONECTION

Figure 41 shows the visual programming that connects the database and assigns the information to the BIM object. Figure 42 shows the python code to connect Dynamo to SQLite.
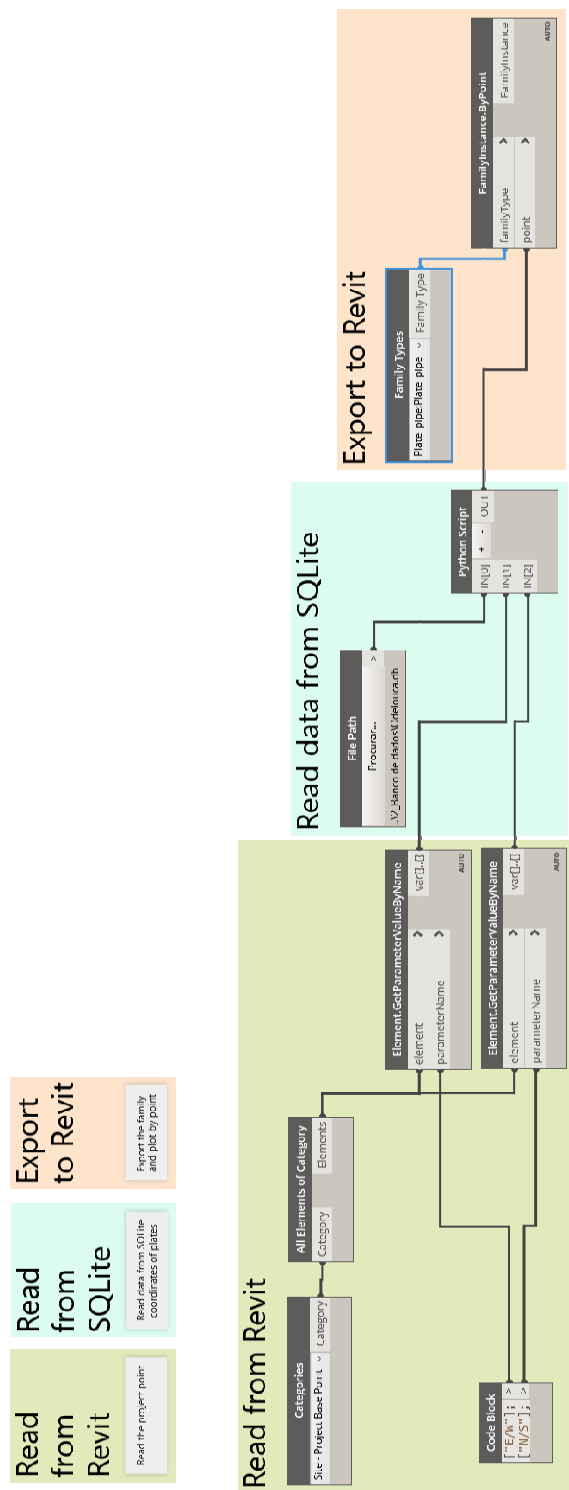

Figure 41 – Connection between database and BIM model to position elements.

```python
1  # Carregar as bibliotecas DesignScript e padrão do Python
2  import sys
3  import clr
4  import sqlite3
5  clr.AddReference('ProtoGeometry')
6  from Autodesk.DesignScript.Geometry import *
7
8  # As entradas para este nó serão armazenadas como uma lista nas variáveis
   IN.
9  dataEnteringNode = IN
10 file=IN[0]
11 EW=IN[1]
12 NS=IN[2]
13
14
15 point=[]
16 # Insira o código abaixo desta linha
17 con = sqlite3.connect(file)
18 c = con.cursor()
19
20 ID_ring=[]
21 z=[]
22 ID_coord=[]
23 x=[]
24 y=[]
25 point=[]
26
27 ew=float(EW[0])
28 ns=float(NS[0])
29
30 c.execute("SELECT * FROM SG_Ring")
31 for linha in c.fetchall():
32     ID_ring.append(linha[1])
33     z.append(linha[5])
34 c.execute("SELECT * FROM Instrument")
35 for linha in c.fetchall():
36     ID_coord.append(linha[0])
37     x.append(linha[3])
38     y.append(linha[4])
39
40 for i in range(len(ID_coord)):
41     for j in range(len(ID_ring)):
42         if ID_coord[i]==ID_ring[j]:point.append(Point.ByCoordinates(x[i]-
           ew,y[i]-ns,z[j]))
43         #if ID_coord[i]==ID_ring[j]:point.append(Point.ByCoordinates(0,0,z
           [j]))
44
45 # Close the conection
46 con.close()
47
48 #for i in range(len(x)):point.append(Point.ByCoordinates(x[i],y[i],z[i]))
49
50 # Atribua a sua saída para a variável OUT.
51 OUT = point
```

Figure 42 – Python code to read data from SQLite.

APPENDIX 4: DATA VISUALIZATION

This code is similar to the code show in appendix 3, the difference is the colour scale that change the and the dimension of the objects that reflect the value of the displacement.
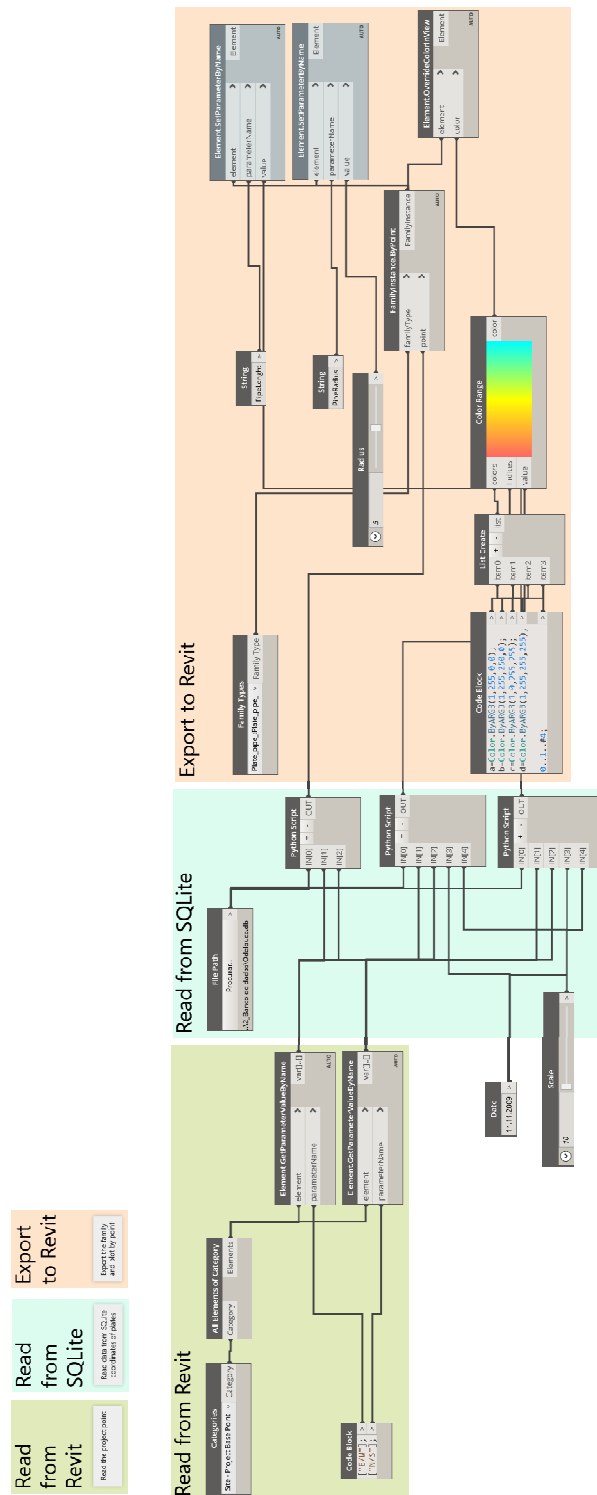

Figure 43 – Data visualization code to visualize the measurement data in BIM model.