The British Dam Society

A Field Monitoring Data-Driven approach to Dams and Reservoirs: Risk Reduction Through Predictive Maintenance

D FORNELLI, Geotechnical Observations Limited

SYNOPSIS The challenges associated with reliable assessment of the conditions of geotechnical and structural elements of ageing dams and reservoirs are becoming more complex and critical, due to the combined effects of Climate Change and the need for optimised and sustainable maintenance (and construction) solutions. The paper focuses on how a quantitative understanding of the current behaviour of dams and reservoirs via field monitoring can help overcome such significant challenges. The paper presents a general approach to the monitoring of geotechnical and structural elements; it also discusses the use of specific technologies for the monitoring of some fundamental parameters of interest for dams and reservoirs. The use of field monitoring data for risk reduction and maintenance optimisation purposes revolves around meaningful and trustable field data (and metadata) as well as the robustness and durability of the monitoring system as a whole. The paper discusses the importance of high-quality field instrumentation, high-quality installation and high-quality data analysis, alongside the importance of the role and involvement of a Monitoring Specialist. Finally, the paper discusses the potential of using Digital Twins to help the interpretation of the field monitoring data and provide an assessment of the assets via numerical models (e.g. finite elements models, finite differences models, etc.) which, via Artificial Intelligence tools, can enhance predictions on the basis of field monitoring data.

INTRODUCTION

The use of monitoring data from instrumentation installed on existing dam and reservoir assets for asset assessment purposes is not new. During the course of the last fifty years, reservoirs have been recognised as strategical and complex assets to which is associated a high level of risk due to the potentially disastrous consequences of an incident. However, it should be noted that too often the attention (and the monitoring systems) is concentrated on the body of the dam (whatever its nature) rather than on all the potentially critical assets which constitute a dam and reservoir assets, e.g.:

- dam (arch, gravity, earth, rockfill, etc.),
- natural slopes enclosing the artificial water body,
- transitions between the dam and the surrounding natural features,
- penstocks,
- tunnels,
- M&E

Managing Risks for Dams and Reservoirs

The development of powerful numerical tools supported by Artificial Intelligence techniques can unlock significant benefits when combined with field monitoring data. In such a data-driven approach the field monitoring data are used to "train" the numerical model and continuously increase the reliability and the accuracy of the predictions. These in turn can provide a powerful tool for the optimisation of maintenance planning and maintenance interventions.

This approach is the so-called "predictive maintenance" and is currently being applied in Europe mainly to bridge structures. However, the aforementioned techniques and concepts are completely asset-agnostic. These can be applied to any asset, provided the numerical models are sound and the field monitoring data are reliable and of high-quality. The need for a data-driven approach had its roots in the following main factors, which cannot be captured by the current assessment approaches:

- ageing assets,
- effects of Climate Change,
- sustainability (through optimised maintenance strategies).

The first two present the challenge of the unknown, whilst the third one can only be faced effectively as the solution of an optimisation problem. As such, in all cases the solution must rely on data acquired from the field which can shed light on the current status and behaviour of an asset and its evolution under changing conditions. As such, it can be inferred that reliable and adequate field monitoring data are (or can be) a key component of the endeavour to overcome the aforementioned challenges.

There is obvious potential in using Instrumentation and Monitoring (I&M) data to improve the understanding of the behaviour of existing assets, especially when seeking optimisation in terms of asset maintenance.

However, in the very same way as any asset modelling technique (analytical, numerical or other) relies upon the reliability and quality of the input parameters, any data-driven approach relies upon the reliability and the quality of the monitoring data and of the associated metadata. The principal aim of this paper is to discuss the main concepts and challenges that should inform the definition ad the deployment of a monitoring system (and an associated data dissemination software) which is able to provide data (and metadata) which are a) reliable and b) of an adequate quality. As will become clear in the following sections, such targets can be achieved only if all the interested parties (asset owner, consultants, field monitoring specialist) recognise the highly technical and complex nature of all the field monitoring activities (definition, deployment, data management and validation, etc.) and are engaged in a cooperative effort.

It should be recognised that a monitoring system fit for asset management and maintenance purposes should not be seen only as a system able to "ring alarm bells" in emergency conditions. The main purpose of such system should actually be to provide:

a) an accurate understanding of the evolution of the parameters of interest for an asset far before any adverse effect produces visible damage and

b) a significant amount of time and quantitative information (i.e. data and metadata)

so that:

i. measures can be taken early on to avoid reaching an emergency condition;

ii. asset maintenance schedule can be optimised;

iii. asset maintenance solutions can be optimised and their sustainability increased.

These concepts are presented graphically in Figure 1, where the exemplar evolution in time of a generic parameter of interest is compared with an exemplar associated curve which presents the increase in risks and associated maintenance/remediation costs as the value of the parameter of interest evolves toward a "critical value". In the figure, the "critical value" is reached at time TC. If the damage becomes visible at time TB, then the difference TC-TB represents the amount of time available for maintenance/remediation if no adequate monitoring system is in place. If TA is the time when an adequate monitoring system becomes operational, the amount of time available for maintenance/remediation is represented by the difference TC-TA. As such, the scope of an adequate monitoring system should be to provide reliable and meaningful data within the amount of time represented by the difference TB-TA. It should be stressed that TB and TA are influenced by the actions (or the lack of action) from time TA, so that an adequate use of the field monitoring data can be an effective way to prolong the operational life of an asset (e.g. a reservoir) while minimising the risks and allow the optimisation of a maintenance schedule and maintenance interventions while optimising costs/resources and maximising sustainability.

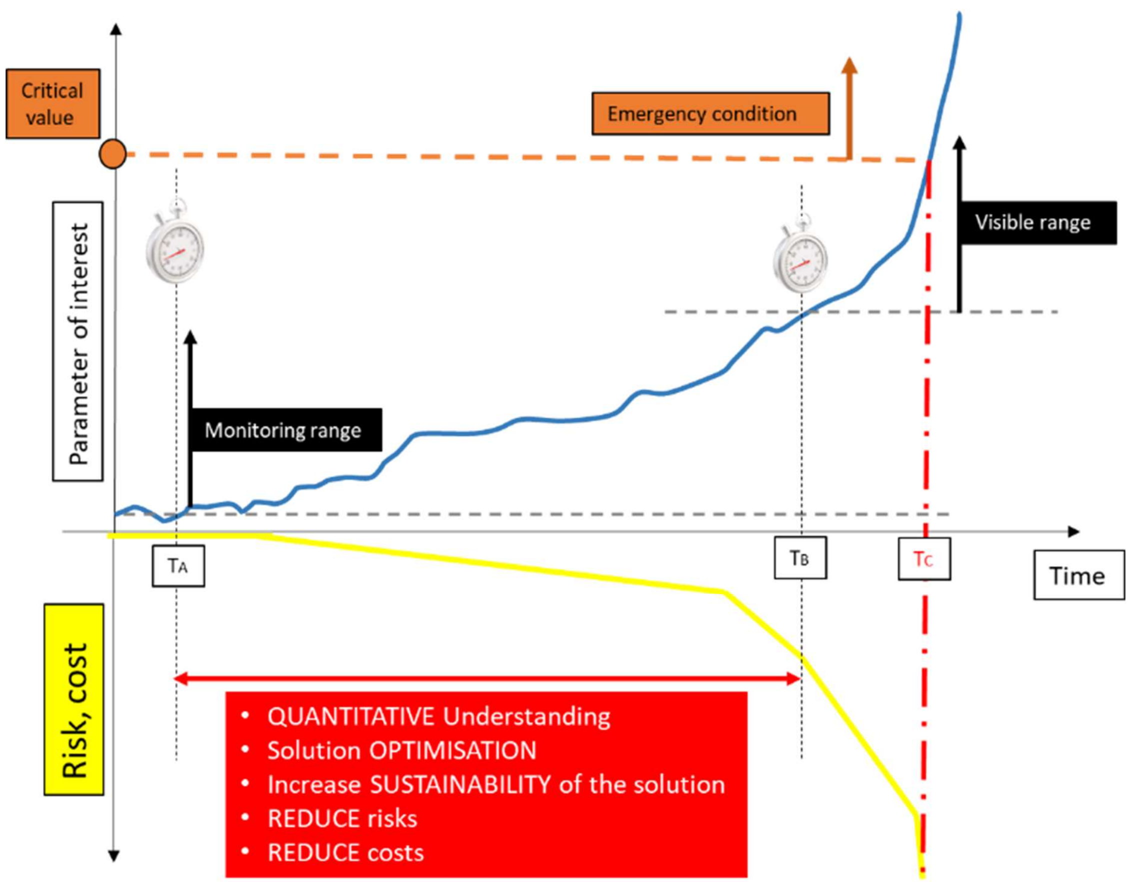

Figure 1: schematic representation of the evolution of a parameter of interest, the associated risks and costs and the benefits of the installation of an adequate field monitoring system.

PARAMETERS OF INTEREST

The parameters of interest of an asset (or part of it) are those quantities which are deemed critical to understand its current status, its behaviour and to predict future evolutions. Such parameters can or cannot be directly measurable, and it should always be assumed that they are asset-specific (and as such, it must be assumed that the development and deployment of a meaningful monitoring system is asset-specific too). Asking for a monitoring solution for "a dam", "a slope", or "a penstock" should not be regarded as a meaningful requirement.

Although similarities and previous experiences can always be beneficial, each existing asset has its own location, its own history (including construction history), its own boundary conditions, its own materials, crack patterns, specific risks, etc. As such, the definition of the parameters of interest for each asset should be the result of a dedicated analysis. This in generally true for all types of assets, and is particularly critical for reservoirs. The idea of monitoring reservoirs can often be confused with the concept of monitoring the dam. However, the reservoir should be always seen as a complex system which involves not only the dam itself but also the natural slopes surrounding the retained water body (which are for instance subject to significant and periodical changes of the hydraulic boundary conditions), as well as the influent watercourses (where applicable), the penstocks, the transition between natural slopes and the dam, the tunnels, the galleries, etc. All of these components have their own parameters of interest, which should be assessed on a case-by-case basis if an adequate field monitoring system is to be developed.

One of the fundamental aspects from an I&M perspective is that the result of the monitoring of a parameter of interest is a "discrete" time-series of (scalar) values which are measured by a real instrument at the location where it is installed. Therefore, the very first step towards a meaningful set of data must be a very clear definition not only of the parameter itself, but also of a number of other requirements associated with the "discrete" and "real" nature of the results provided by the monitoring system. It will be shown in the following sections that such information is a fundamental initial step towards the definition of the constituents of an optimal I&M system, i.e. the right instruments, the right installation methodology, the right communication system, the right software and the right maintenance arrangements. The requirements include (but are not limited to, depending on the specific application):

a) which parameters are to be monitored (e.g. strain, crack width, displacements, displacements, groundwater pressure, water pressure within penstocks, temperature, tilt, surface water velocity for open channels, vibrations, water levels, vertical and horizontal displacement, etc.).

b) where are the above parameters to be measured (e.g. in which location along the slope or the dam, at which depth underground, etc.).

c) what is the expected range of the parameter value (e.g. the expected displacement of the slope, the expected range of water pressure, the expected deformation of the dam, etc.).

d) what are the specific regulatory (or acceptable) limits/alert values for the parameters of interest.

e) what is the required acquisition frequency (e.g. 1 reading per hour, 1 reading per day, 1 reading per month, how many Hz in case of dynamic measures, etc.).

f) what are the requirements around the in-situ precision and accuracy.

g) the duration of the baseline monitoring period.

h) what kind of redundancy is required, if any.

i) the expected duration of the monitoring (e.g. a few months, several years, etc.).

j) the required metadata to facilitate data analysis and interpretation.

In respect of point f) above, the in-situ precision can be defined on the basis of a semi-probabilistic approach framework (Fornelli, 2022). One of the fundamental features of such a framework is the definition of two different sets:

I. the set of parameters of interest (X_T) for a specific project, and

II. the set of measurable parameters (X_M), that is, the set of parameters that can be directly measured with appropriate instrumentation.

In general, the elements of the set X_T are functions of the elements of the set X_M, where the functional relationship depends on the choice of the instruments and the monitoring set up.

A "trigger value" T_{XT} can be defined as a specific value of one of the parameters within the set XT. It is assumed that the monitoring data (elements of X_M) are normally distributed. For each adequate set of measurements, a mean value (μ) and a standard deviation value (σ) can be calculated (Taylor, 1982). It is then possible to define the required in situ precision on the basis of the in situ standard deviation σ_{XM1} of an adequate set of measurements associated with X_{M1}, in the sense that a higher precision corresponds to a lower σ_{XM1}. In particular, the in situ standard deviation is defined as the standard deviation of an adequate set of measures taken at some point in time during the baseline monitoring (see point g) above). It is then required that the probability of a measure X_{M1} to be within the interval $[\mu-\beta\cdot\sigma_{XM1} ;\mu+\beta\cdot\sigma_{XM1}]$ is larger than a given probability value P.

$$Pr(\mu-\beta\cdot\sigma_{XM1} \leq X_{M1} \leq \mu+\beta\cdot\sigma_{XM1}) \geq P$$

In a situation where the mean value of the assumed normal distribution coincides with the trigger value T_{XT}, it makes sense to ask the product ⍰(P) ·⍰XM1 to be not larger than a given fraction of the trigger value T_{XT}, that is:

$$\beta(P) \cdot\sigma_{XM1} \leq \alpha \cdot T_{XT}$$

Where α is a non-dimensional positive real coefficient restrained by:

$$0 \leq \alpha << 1$$

The choice to refer to "trigger values" is deliberate, as this is currently a common approach across the industry; however, the proposed approach is applicable to most probable values or otherwise defined values of the parameters of interest.

The previous inequality can be rearranged as follows:

$$\sigma_{XM1} (P, \alpha, T_{XT}) \leq (\alpha \cdot T_{XT})/(\beta(P)),$$

which provides the maximum value of the in situ standard deviation which verifies the condition:

$$Pr(\mu-\beta\cdot\sigma_{XM1} \leq T_{XT} \leq \mu+\beta\cdot\sigma_{XM1}) \geq P ,$$

for some chosen value of P, a and TXT.

The above is applicable regardless of any specific significance of the value T_{XT}, as it is effectively a way to define a minimum requirement on σ_{XM1}. The values of P (and hence of $\beta(P)$) and α can be chosen for each trigger value and should be selected on the basis of an assessment specific to such trigger value and to the parameter of interest X_T.

Further details are included in Fornelli (2022) which extends the framework to the case of multiple "trigger values", as well as to the more general case where the parameter of interest (to which the triggers are applied) does not coincides with a single chosen measurable parameter, but is instead a function of one or more measurable parameters. In fact, in this case the previously proposed inequality $Pr(\mu-\beta\cdot\sigma_{XM1} \leq T_{XT} \leq \mu+\beta\cdot\sigma X_{M1}) \geq P$ does not hold, because X_T and X_M do not coincide. In fact, the previous condition should be changed to

$$Pr(\mu-\beta\cdot\sigma_{XT} \leq T_{XT} \leq \mu+\beta\cdot\sigma_{XT}) \geq P .$$

The above represents just one of the many factors that should be taken into account when selecting the instruments for a monitoring project. In fact, all the points from a) to j) above should be taken in due consideration. From a point of view of long-term monitoring, which is often associated with reservoir assets performance monitoring and maintenance, special attention should be given to the robustness and durability of the hardware (instruments, cabling, acquisition and communication systems, etc.) and to the redundancy of the system.

Data interpretation should be one of the main goals of any monitoring exercises; as such, it seems important to stress here the (often forgotten) importance of the metadata (point j) above). In this context, this term indicates all the data which are not directly associated to the monitoring of any parameter of interest, but rather to help establish a causality relationship between the evolution (in time) of the parameters of interest and the "actions" on the asset which are responsible for such evolution. Examples of metadata (just to quote a few) are of course the application of loads (either static or dynamic) on the asset, the change in atmospheric conditions, rainfall events, works on the asset or on nearby assets. A correct monitoring data interpretation crucially relies on adequate qualitative and quantitative metadata. As such, adequate means for metadata recording (instruments, scans, reports, etc.) should be an integral part of any monitoring system.

In the author's experience, the involvement of an I&M specialist from this very first stage, where parameters of interest and associated requirements are defined, can provide a significant contribution to a successful outcome. An understanding of the capabilities, limitations and durability of different instrument types (and hardware in general), of the associated installation procedures and of the specific requirements and constraints of the asset are extremely useful to keep a holistic view of the scheme.

CHOOSING THE RIGHT INSTRUMENTS

As discussed in the previous section, the choice of the optimal instrument depends on a number of considerations around the parameter of interest that it needs to measure (or contribute to measure). There are numerous producers on the I&M market; there are several ways to measure the same parameter and of course there are several instruments with their specific range, precision, durability, etc.

A list of instruments and their capabilities and applicability limits is well beyond the scope of this paper, and, taking into account the wide spectrum of potential parameters of interest on dam and reservoir assets, it would be a very arduous task. What is of interest here is to stress that choosing the right instrument for a specific application, i.e. to reliably and meaningfully monitor a parameter of interest, takes much more than to browse a catalogue or to type a few keywords on an Internet search engine. One of the fundamental factors in choosing an instrument for an asset performance monitoring system is its durability. It is worth stressing again that each instrument is a physical device which reacts to the surrounding environment and is subject to external factors as much as the asset on which is installed. As such, the presence of an aggressive environment (both above-ground and under-ground) is fundamental information (as in the case of a piezometer installed within an aggressive aquifer). Also significant is the exact location of where an instrument will be installed and which kind of actions are likely to be exerted on the instrument, such as in the case of a joint meter that could be subject to torsion as a consequence of the movement of the joint.

The expected range of the parameter of interest can significantly influence the choice of the instruments; for instance, with reference to the monitoring of the underground displacements of a slope (or an embankment), there are several recorded cases where the deformation is highly localised around a "slipping surface". As such, the instrument (e.g. an inclinometer or a ShapeAccelArray) has to be adequate to withstand significant localised movements without loss of functionality. Another significant example in the same "geotechnical" context is the choice of piezometer sensors: these have to be selected taking into account, amongst other things, the permeability of the soil layer where the sensor will be installed, as well as the required response time and the likelihood of the development of negative pore pressure (suction) around the sensor, which can make standard Vibrating Wire piezometer sensors provide unreliable readings (Nader and Ridley, 2022).

Exemplars in this sense can be drawn from the point of view of the monitoring of the underground displacements of the (artificial) slopes of an earth dam and of the natural slopes enclosing the retained water body. In both cases, the monitoring of the underground displacements and of the evolution of the pore water pressures is of paramount importance to understand and predict the long-term behaviour of the assets, especially in relation to the creep behaviour, the ageing/damage propagation of the materials and the effects of the climate change. It has been stressed in the previous section that "to monitor a slope" or "to monitor a dam" should not be regarded as meaningful requirements; "procure a strain gauge" or "procure a piezometer" are not meaningful requirements either.

The choice between a system in which the data are collected manually and one which is instead provided with an automated data collection system is also a fundamental one. The optimal solution in terms of data acquisition strongly depends on the specific site needs and constraints (e.g. data acquisition frequency), as well as Health and Safety considerations. Within the framework of maintenance (long-term) monitoring schemes, it is usually convenient to choose a robust automated system, due to considerations around the difficulty of access and the remoteness of the assets across the country. However, it should always be taken into account that no automated system can reliably run (especially for long-term applications) without maintenance. This can be associated to the instruments and the cabling or the communication systems in general. Adequate choices in terms of redundancy, type of hardware and robustness of the I&M system as a whole can help in minimising (although not remove entirely) maintenance-related activities.

In summary, choosing instruments for a field monitoring data-driven approach to the maintenance of dam and reservoir assets should be the result of a careful consideration of the requirements (see previous Section, points a) to j)) and their significance for the specific situation at hand. In fact, such choices should be based as much as possible on a rational approach to the more general goal of obtaining reliable and adequate high-quality data, such as the one which has been presented in the previous section with reference to the requirements around the in-situ precision. In this context, the help of a specialist I&M consultant is obviously beneficial.

THE CRITICAL ROLE OF INSTALLATION AND SOME PROCUREMENT CHALLENGES

All field data produced by an asset monitoring system come from instruments installed on the asset. Although this may sound obvious, it is easy enough to forget that such data are basically a measure of how each instrument reacts to the changes it experiences. As such, if the instrument is not properly installed, if it is not "comfortable" in the way it has been "connected" to the to the structure, to the ground or to the asset in general, it cannot be expected to provide data which are an actual representation of the behaviour of the asset (at the location of the instrument). Therefore, the critical role that the installation procedures (and materials) play in achieving reliable and high-quality monitoring data cannot be stressed enough.

There are a number of activities that need to be carefully planned and undertaken (both in controlled environments and on site) to perform a successful installation. The handling of the instruments is obviously important to avoid damaging the hardware, and there is a significant amount of detail to be considered when installing field instrumentation which depends on the instrument of choice as well as on the specific local details of the asset. For all instrumentation, it is obviously essential that the bonding between the instrument and the asset is such that the changes experienced by the asset at the location of the instrument are transferred to the instrument minimising the disturbances due to the installation; for instance in terms of displacement/deformation and temperature effects.

A typical example is the installation of crack-meters or joint-meters on structures, where the details of the connection between the instrument and the structure shall be defined to minimise the differential displacement due to the connection, which may involve drilling and grouting (on concrete and masonry structures) or welding (on metal structures). A similar situation arises when connecting fibre optics to structures, where appropriate solutions in the form of clips or epoxy resin need to be selected and potentially tested for ensuring data reliability as well as limiting the impact on the asset. The criticality of the installation process is even more evident when installing field instruments underground, as may be the case for inclinometers, extensometers, piezometers, etc. In this case the continuity between the asset (ground, groundwater) and the instrument is removed during the installation process due to the drilling operations. Therefore, such continuity needs to be restored as much as possible and taking into account the local conditions of the asset and the nature of the parameter of interest that the instrument is intended to monitor. Furthermore, the installation at depth requires a number of details to be carefully considered and checked, such as the torsion of the inclinometer casing during the lowering operations and the installation of the Vibrating Wire piezometers with the filters facing upwards to allow any residual air to leave the instrument.

These examples represent just an extremely limited selection of the considerations that are required to provide reliable field monitoring data. However, in the author's opinion, they are useful to clarify the fundamental role of the installation process (and of the amount of detail associated with it). The efforts and resources required to identify the parameters of interest, the associated requirements and to define and procure the optimal instruments, can be entirely wasted if the data are made unreliable by an inadequate installation.

As such, it is essential that the installation of each instrument and, more in general, of every component of the I&M system, must carefully defined, planned and carried out by experienced personnel and under the constant supervision of an I&M specialist.

One of the main challenges to the above is the current common procurement model for I&M activities. In most instances, it is based on a Bill of Quantities with instruments and installation rates. The main effect of this kind of procurement model is that the "perceived value" of an I&M system is associated with the procurement of the instruments rather than with obtaining reliable, high quality useful data. Also, it makes it very difficult for the I&M specialist to be engaged at an early stage to provide support and useful insight for the optimisation of the field monitoring scheme. As per previous considerations, the overall risk is that, if the data reliability and quality are not identified as the true benefit of an I&M system, then the possibility to apply a data-driven approach to dam and reservoir asset maintenance is jeopardised. On the basis of the considerations developed in this and previous sections, it should be recognised instead that the I&M would be better procured as a service, and should be focussed on the quality of the data rather than on the cost of the instruments.

DIGITAL TWINS

The idea of using field monitoring data to inform and optimise the construction process dates back at least to Terzaghi's and Peck's works around the use of Observational Method in Geotechnical Engineering. The recent huge development of numerical analysis techniques and software, associated with the increasing capabilities of Artificial Intelligence (AI) algorithms nowadays allows the use of the field monitoring data from real assets as part of complex digital models. The numerical modelling (of the asset) and the field monitoring data (from the instruments installed on the asset) are integrated within a framework which allows the predictions of the former to increase in their accuracy on the basis of the latter. The numerical models are "trained" via AI algorithms on the basis of the evolution of the monitored parameters of interest and metadata. Such an approach is quite new, and the associated nomenclature still somehow undefined. It is easy enough to find "trainable" models (numerical solver + AI) referred to as "Digital Twins". The idea is that the trained numerical model becomes a digital "replica" of the real asset, so that it can provide an accurate understanding the current behaviour of the whole asset (e.g. in terms of the evolution of the displacement field, strain field, pore water pressure field, etc.), as well as provide an accurate prediction of the future behaviour of the asset under given boundary conditions. The general concept is further explained in Figure 2: the monitoring data from a general dam and reservoir asset are used to train the numerical models and provide predictions; these are subsequently interpreted to assess the need for (and, if needed, optimise) adequate maintenance intervention. It should be noted that the possibility of optimising maintenance interventions is connected to the quantitative nature of the outputs of the model, as opposed to the mostly qualitative nature of standard visual inspections. The reliability of the predictions increases in time as more field monitoring data become available (i.e. the "training" increases).

However, it should be noted that the reliability of the current and future behaviour obtained by such models depends directly on the reliability (quality) of the field data used to "train" the model. In effect, the usefulness, and more widely the adequate functioning, of the digital predictive framework output is based (and strongly depends) on the field monitoring data availability, reliability and quality. As such, it is the author's opinion that a "Digital Twin" should indicate an integrated framework including the (validated) field monitoring data as well as the numerical models "trained" using such data.

It is worth stressing that the use of "Digital Twins" for asset maintenance/management is currently in phase of deployment in Italy.

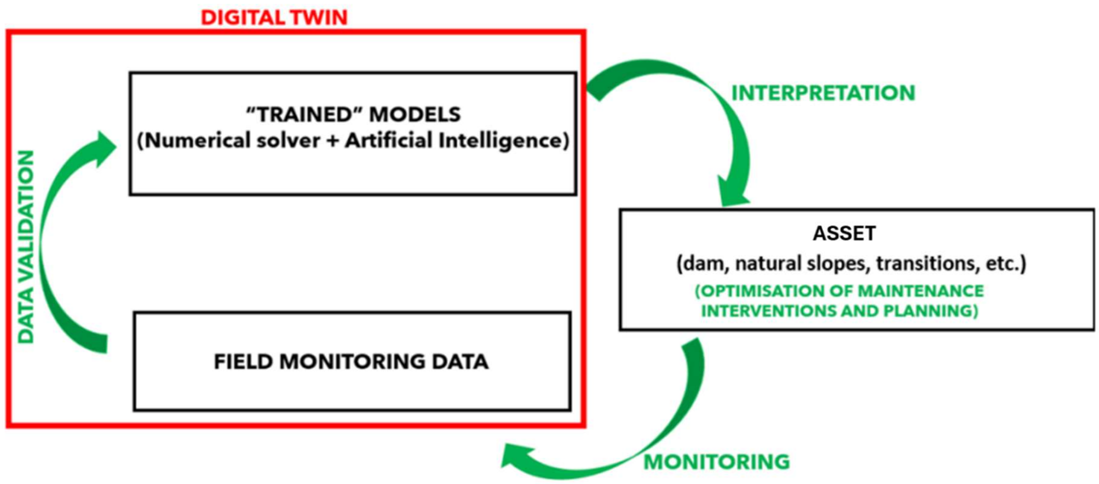

Figure 2: scheme of the constituents of a "Digital Twin" and general concept of data-driven predictive maintenance for dam and reservoir assets.

CONCLUSIONS

The paper has highlighted the fundamental importance of reliable, high-quality field monitoring data in the context of challenges posed by the UK's ageing dam and reservoir assets, together with the uncertainties associated with climate change and the needed optimisation (towards an increase in sustainability) of maintenance programmes and interventions.

The definition of a monitoring scheme able to provide adequate data relies on several steps and a significant amount of theoretical and practical experience, as well as cooperation throughout several different disciplines. Also, the deployment of a robust, reliable monitoring system able to provide high quality data requires a careful choice of instruments and an extreme attention to detail in the installation phase.

The early engagement of an I&M specialist alongside other parties has been recognised to be of paramount importance for a successful deployment. The challenges associated with the current common procurement models for I&M have been discussed, and in particular the need for recognising that the value of such system should be associated to the quality of the data rather than to the cost of the instruments, as well as recognising that, due to its transversal and highly technical nature, the I&M should be procured as a service.

There is potential for significant opportunities associated with the implementation of Digital Twins for dam and reservoir assets, in relation to the optimisation of maintenance planning and interventions; however, these rely strongly on the recognition of the fundamental importance of the reliability and high quality of the monitoring data, and of all the contributing factors discussed within the previous sections. To this end, it is the author's opinion that Instrumentation and Monitoring should be considered an Engineering discipline in its own right by the Construction Industry bodies and at Academic level.

REFERENCES

Fornelli D (2022). A semi-probabilistic approach for the definition of field precision requirements in Instrumentation and Monitoring design – *11th International Symposium on Field Monitoring and Geomechanics*, International Society for Soil Mechanics and Geotechnical Engineering, London, UK.

Taylor J R (1982). *An Introduction to Error Analysis.* University Science Books, California, USA.