In praise of monitoring and the Observational Method for increased dam safety

L'approche observationnelle de Ralph Peck pour assurer la sécurité des barrages

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ABSTRACT: The Observational Method has served the geotechnical profession well in most areas of practice, such as bridge foundations, culvert construction, tunnels and dams. This paper summarizes one case history where the Observational Method played a key role in helping make risk-informed decisions during the construction and operation of the Zelazny Most tailings dam in Poland. The Zelazny Most dam is the largest tailings dam in Europe. For this dam, the i*n situ* measurements followed (and continue to follow) the movements and pore pressure in the foundation during operation. The use of the Observational Method resulted in significant design changes, including moving the dam crest, the construction of stabilizing berms and the installation of relief wells in the foundation. The Observational Method, when correctly applied, can be a most useful tool for follow-up of a dam design. The paper describes the Observational Method, its advantages and its affinities with the statistical Bayesian updating approach. It also describes briefly the observations at the Zelazny Most sites and discusses how the Observational Method was a key instrument for "risk-informed" decisions.

RÉSUMÉ: L'approche observationnelle proposée les professeurs Terzaghi et Peck est un outil qui a bien servi tous les domaines de la pratique de l'ingénierie géotechnique, tels que les fondations de ponts, la construction de ponceaux, les tunnels et les barrages. Cet article résume une histoire de cas où la méthode d'observation ("Observational Method") a joué un rôle clé en aidant à prendre des décisions éclairées en fonction des risques pour l'exploitation future de grands barrages, y compris le barrage de résidus de Zelazny Most en Pologne, le plus grand barrage de résidus en Europe. Pour ce barrage, les mesures in situ ont suivi (et continuent de suivre) les mouvements et la pression interstitielle dans le sol pendant la construction et l'exploitation. L'utilisation de la méthode d'observation a entraîné d'importants changements dans la conception, notamment le déplacement de la crête du barrage, la construction de bermes de stabilisation et l'installation de puits de secours dans les fondations. La méthode d'observation, lorsqu'elle est correctement appliquée, peut être un outil très utile pour la gestion des barrages. Le document discute de la méthode d'observation et de ses avantages, et la compare avec la mise à jour bayésienne. La méthode d'observation est considérée comme un instrument clé pour "des décisions éclairées par le risque" ("risk-informed decision making").

1 INTRODUCTION

It is now (2019) 50 years since the Observational Method (OM) was first published as Professor Ralph B. Peck's Rankine Lecture (Peck 1969). Peck recognized the importance of field observations and performance monitoring for the practice of geotechnical engineering. Lord W.T. Kelvin (1824-1907) once wrote:

> *"When you measure what you are speaking about and express it in numbers, you know something about it. But when you cannot express it in numbers your knowledge about it is of a meagre and unsatisfactory kind."*

A recurring factor in geotechnical failures is that modifications made during construction and operation did not follow the original script. Examples include the Aznalcóllar (Spain) and the Mount Polley (Canada) tailings dams where, among several factors, the downstream slopes were significantly steeper than intended in design. These failures reinforce the need for the "Observational Method", a seminal deterministic method in geotechnics.

The paper discusses briefly the Observational Method and its advantages, and presents a case history following Ralph B. Peck's philosophy of monitoring and evaluating the performance, and implementing mitigation measures. This paper includes for project description, soil conditions, instrumentation, performance and concerns, iimplementation of the Observational Method and the benefits of the application of the method. The paper closes with a suggestion to complement the Observational Method with Bayesian updating to enable "risk-informed decisions" and the optimisation of the construction and rehabilitation.

2 THE OBSERVATIONAL METHOD

Karl Terzaghi (1961) wrote:

> *"Soil engineering projects […] require a vast amount of effort and labor securing only roughly approximate values for the physical constants that appear in the equations. The results of the computations are not more than working hypotheses, subject to confirmation or modification during construction. In the past, only two methods have been used for coping with the inevitable uncertainties: either adopt an excessively conservative factor of safety, or make assumptions in accordance with general, average experience. The first method is wasteful; the second is dangerous. A third method is provided that uses the experimental method. The elements of this method are 'learn-as-you-go:' Base the design on whatever information can be secured. Make a detailed inventory of all the possible differences between reality and the assumptions. Then compute, on the basis of the original assumptions, various quantities that can be measured in the field. On the basis of the results of such measurements, gradually close the gaps in knowledge, and if necessary modify the design during construction."*

Terzaghi's observation follows Terzaghi's 1929 warning about the important effect of minor geologic details on the safety of dams. The Observational Method, described by Professor Ralph B. Peck in his Rankine Lecture in 1969, is a formalisation of Terzaghi's philosophy. The Observational Method consists of:

1. Exploration sufficient to establish at least the general nature, pattern and properties of the deposits, but not necessarily in detail.
2. Assessment of the most probable conditions and the most unfavourable conceivable deviations from these conditions. In this assessment geology often plays a major role.
3. Establishment of the design based on a working hypothesis of behaviour anticipated under the most probable conditions.
4. Selection of quantities to be observed as construction proceeds and calculation of their anticipated values on the basis of the working hypothesis.

5. Calculation of values of the same quantities under the most unfavourable conditions compatible with the available data concerning the subsurface conditions.
6. Selection in advance of a course of action or modification of design for every foreseeable significant deviation of the observational findings from those predicted on the basis of the working hypothesis.
7. Measurement of quantities to be observed and evaluation of actual conditions.
8. Modification of design to suit actual conditions.

The Observational Method (OM) is particularly useful for the design of dam foundations, tunnels, cuts, deep excavations and large foundations. In many cases, the results of the early design computations are not more than working hypotheses, subject to confirmation or modification during construction, with the help of the OM.

The degree to which each step is followed depends on the nature and complexity of the project. Geotechnical engineers work in both a theoretical dimension and a practical dimension. Both have aleatoric and epistemic uncertainties[1], which can be reduced, but never completely eliminated. Because of the uncertainties, there is always a finite, even if very small, probability that a failure may occur.

The Observational Method has many advantages, but requires a robust set of procedures throughout a project: the method adopts the "most probable" design parameters, as opposed to conservative parameters; it assesses a range of probable behaviour; it sets out modifications in construction to be implemented if the parameters or the behaviour turn out to be less favourable than assumed in the design; it monitors the behaviour of the structure and soil, providing indication of whether mitigation measures are required or not; and it analyses the data and triggers the implementation of contingency plans.

Costly overdesign can be avoided without compromising on safety or the environment. One key aspect is the advance selection of a course of action for every foreseeable significant deviation of the observational findings from those predicted on the basis of the working hypothesis.

3 THE ZELAZNY MOST TAILINGS CONTAINMENT FACILITY IN POLAND

3.1 *Project Description*

The Zelazny Most tailings storage facility (TSF) in southwest Poland is a ring-shaped dam with a perimeter of about 14 km and area of 20 km^2 (Figs 1 and 2). It is the largest tailings dam in Europe. Approximately 18 million m^3 of copper mining waste are transported hydraulically to the facility every day. Deposition of the tailings started in 1975, and by 2019, the maximum dam height is 71 m. The crest elevation of the dam is at 185 m. The original ground surface at the facility was saddle-shaped, as a river has crossed the site, and the eastern and western portions of the ring dam are higher than those to the north and south.

The dam was raised by the upstream method of construction (Fig. 3). Circumferential drains were installed as the dam was being raised. The drains were placed at El. 147, 153, 162 and 175 m asl (Fig. 4). The dam crest was raised at a rate of about 1 to 1.4 m/year, with an average downstream slope of 3.5 horizontal to 1 vertical. The operations are planned to continue until 2042.

3.2 *Complex Geology and Soil Conditions*

The Zelazny Most tailings storage facility is located in a complex geological environment (Jamiolkowski 2014). From the ground surface, the foundation soils consist of Pleistocene deposits, including silty lake clays and outwash sands, few sandy gravel inclusions and silty sands. These

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[1] *Aleatoric* uncertainty (also known as statistical uncertainty) is the natural randomness of a property or a load, e.g., soil strength and ocean wave height. The aleatoric uncertainty cannot be reduced.

Epistemic uncertainty (also known as systematic uncertainty) is the uncertainty due to lack of knowledge, e.g., measurement uncertainty and model uncertainty. The epistemic uncertainty can be reduced by, for example, increasing the number of tests, improving the measurement method and/or verifying the calculation procedure with model tests.

are underlain by thick layers of freshwater Pliocene clays of medium to high-plasticity. The Pliocene deposits overlie Triassic strata, below which the copper ore body is encountered.

Figure 1. Zelazny Most copper tailings disposal location in Poland.

Figure 2. Tailings disposal, aerial view.

Figure 1. Zelazny Most copper tailings dam in Poland and areal view of dam (Jamiolkowski *et al* 2010).

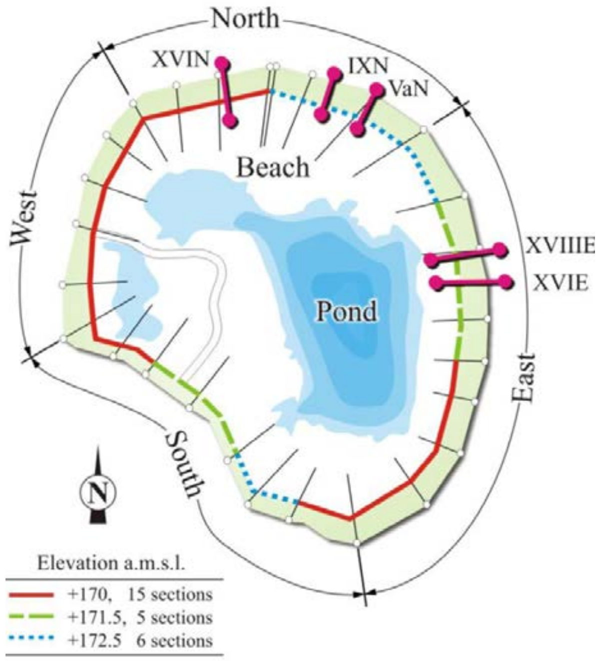

Figure 2. Bird's eye view of Zelazny Most Dam and elevations in 2010 (after Jamiolkowski *et al* 2010).

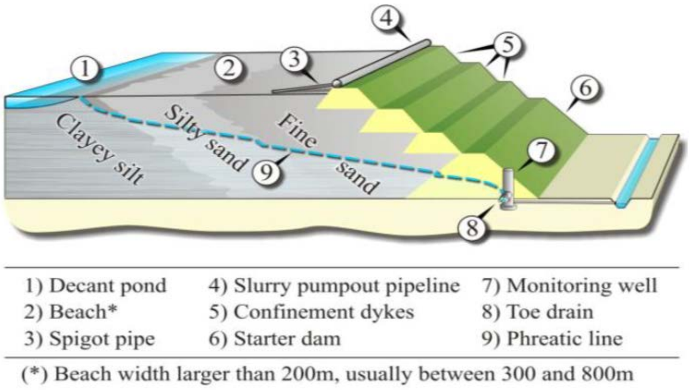

Figure 3. Schematic cross-section and phreatic line (after Jamiolkowski *et al* 2010).

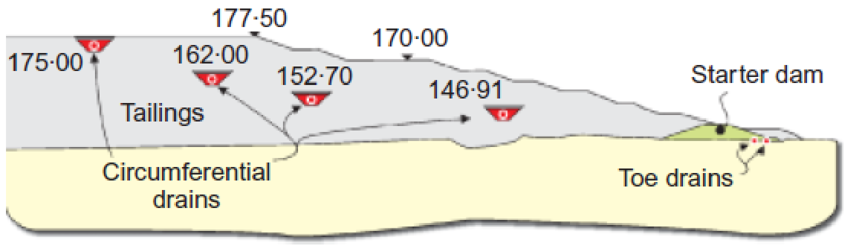

Figure 4. Circumferential drains in Zelazny Most ring dam (after Jamiolkowski, 2014).

The complexity of the deposit is due to a Pleistocene succession of ice sheets moving from north to south over central Europe. At least six major ice advances occurred in south Poland, whereof no less than three passed over the Zelazny Most area. The ice sheets, believed to have been at least 1000 m thick, have induced widespread glacio-tectonic features extending to depths of about 100 m which greatly affected the Pliocene clays. As a consequence, the soils have been intensely sheared, folded and generally disturbed. In places, the initially horizontally bedded freshwater Pliocene sediments have Pleistocene deposits thrusts within them.

The glacio-tectonic phenomena left a permanent imprint on the Zelazny Most geotechnical environment, especially extended shearing and folding of the Pliocene deposits. The ice sheets are believed to have imposed a stress field resembling that of simple shear, generating several shear surfaces. Laboratory tests showed that the shear surfaces are found mainly in high plasticity clay and have a drained shear strength close to the residual. The horizons containing the glacio-tectonic shear planes are probably thin 'zones' of high-plasticity slickensided clay (Jamiolkowski 2014).

For stability analysis and modelling, the soil profile was set to have an upper 10 m consisting of mainly sandy deposits. The Pliocene deposits below consist of mainly freshwater medium to very high-plasticity clay. The shear strength of the slickensided high plasticity clay is close to its residual friction angle of 6.5 to 8º (Jamiolkowski 2014). The sub-planar shear surfaces forming slickensides in the clay have variable shear strength.

The presence of the shear surfaces was established through the application of the Observational Method.

3.3 *Instrumentation*

The monitoring program includes seismographs and biaxial accelerometers for monitoring mining-induced seismicity, open standpipe piezometers and over 300 vibrating-wire piezometers in boreholes. Over 450 benchmarks for geodetic and GPS measurements plus an automatic Total Station were installed. Fifty-six inclinometers, many of them more than 100 m deep, were installed to monitor subsurface displacements (dam and foundation).

Because the tailings dam was built by the upstream construction method (Fig. 3), the initial concern was instability due to potential liquefaction of the tailings. The first inclinometer installations through the dam into the foundation were therefore fairly shallow and did not penetrate deep into the foundation. Deeper inclinometers were installed when the rate of horizontal dam displacement started to increase (DiBiagio, 2013)[2].

3.4 *Performance and Concerns*

The East Dam, with the highest crest elevation and with significant horizontal displacements, is discussed herein[3]. At the end of 1995, when the dam reached the height of 40 m, the rate of horizontal displacement increased. The maximum displacement (about 650 mm) between 2003 and 2013 occurred at cross-section XVIE (shown in Fig. 1). Between 2001 and 2009, the rate of horizontal displacement was 40 to 50 mm/year. The deeper inclinometers quickly disclosed zones

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[2] DiBiagio (2013) published 24 examples of the implementation of instrumentation, monitoring and the OM for a variety of geotechnical engineering problems, including dams, retaining structures, braced excavations, slurry trenches, large scale model tests, avalanche hazards and offshore structures.

[3] Jamiolkowski (2014) presented also results for other parts of the dam.

of concentrated displacements at large depths below the dam, at El. 40 beyond the East Dam toe, and at El. 80 for the North Dam.

As mentioned, the main instability concern was initially the tailings dam itself and not the foundation. The early inclinometers installed through the dam and into the foundation of the East Dam turned out to be too shallow to detect the development of significant shear displacements at large depths. The deep inclinometers installed after 2003 clearly demonstrated movements on a sub-horizontal shear zone in the foundation of cross-section XVIE at about 40 m asl, about 75 m beneath the original ground surface. Figure 5 shows the inclinometer measurements in that cross-section. An interpretation of the results from this and the neighboring inclinometers in sections North (up to cross-section XVIIIE) and South (to cross-section XIVE) of cross-section XVIE indicates that a shear zone at 40–50 m asl extends at least 600 m along the dam axis and at least 150 m from the toe under the dam (Jamiolkowski *et al* 2010). To better define the zone of concentrated shear strain, additional inclinometers were installed. Between 2003-2007, the measured horizontal displacement rates at 40 m asl were about the same as the maximum measured horizontal dam displacement recorded on the crest of the starter dam at cross-section XVIE.

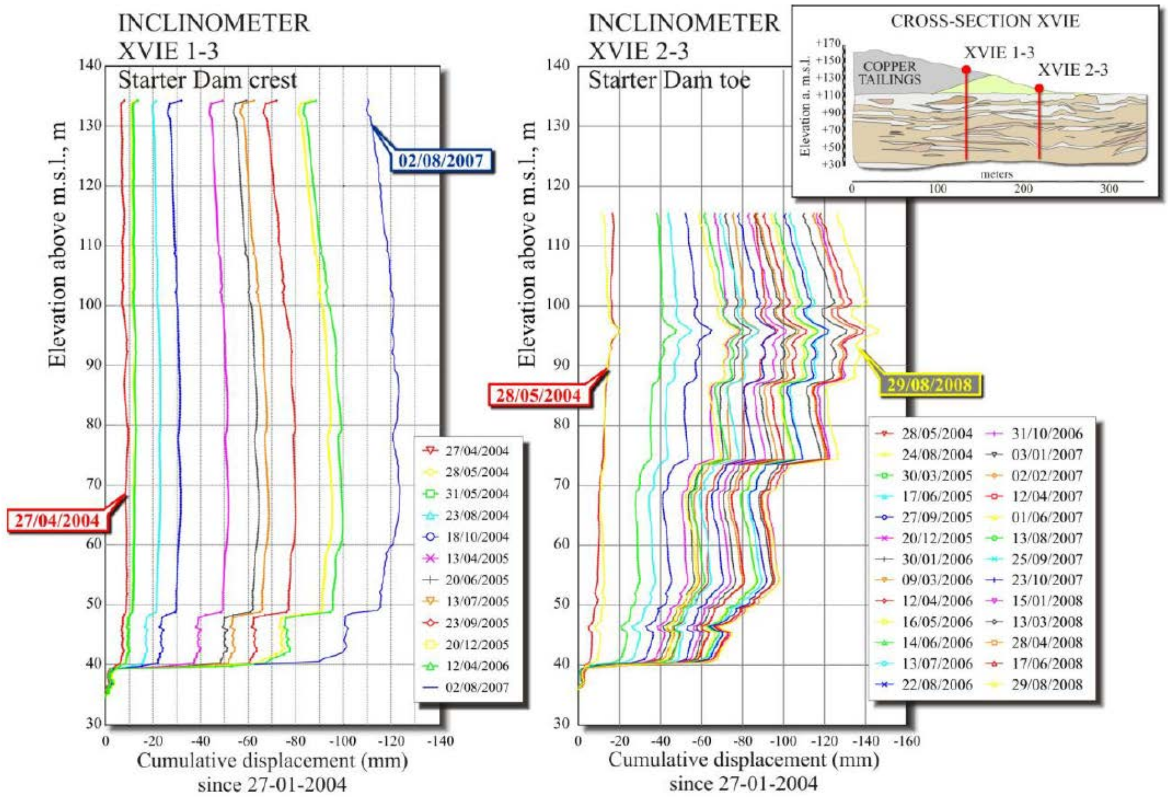

Figure 4. Horizontal displacements measured in deep inclinometers on East Dam (Jamiolkowski *et al* 2010).

Figure 5 presents the 2005 to 2014 measurements at cross-section XVII E5-A on the east side of the dam. At El. 44, this is a plane where the horizontal displacements are larger than anywhere else. Most of the horizontal movement is concentrated along this sub-horizontal glacio-tectonic shear plane. The explanation for the large displacement at elevation 44 m is the presence of a shear plane in the Pliocene clay which was pre-sheared during at least three periods of glaciation. The concern for the critical failure body is illustrated in Figure 6.

3.5 *Implementation of Observational Method*

Tailings deposition started in 1975. In 1993, a four-member International Board of Experts (IBE) was appointed by the operating mining company to give advice on the safe development of the facility. The decision was made to apply as closely as possible and rely on the Observational Method.

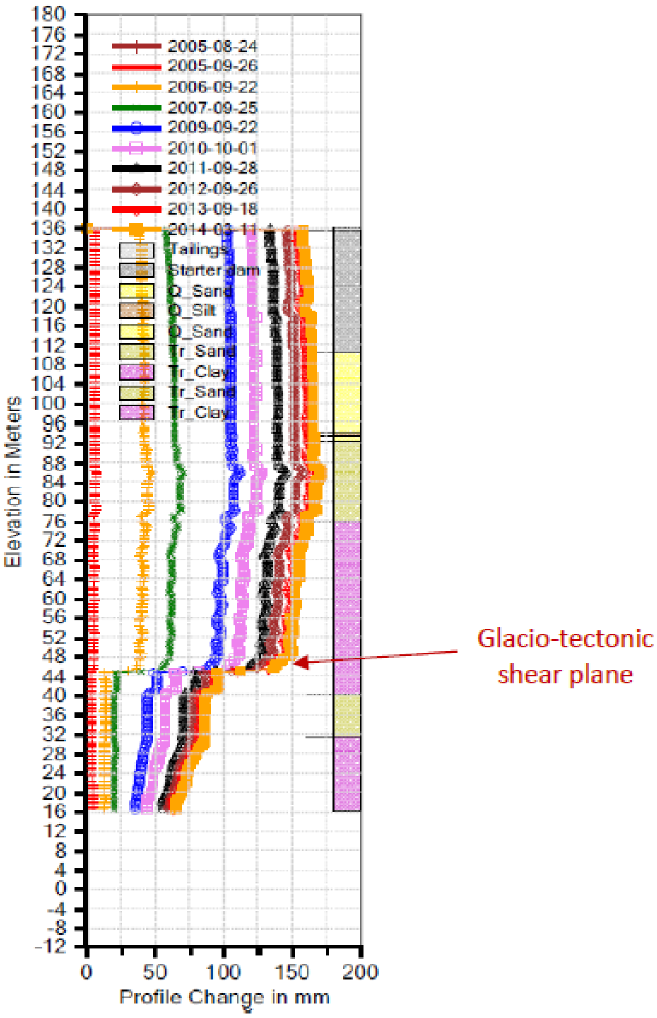

Figure 5. Horizontal displacements from deep inclinometers at cross-section XVII E5-A (project files).

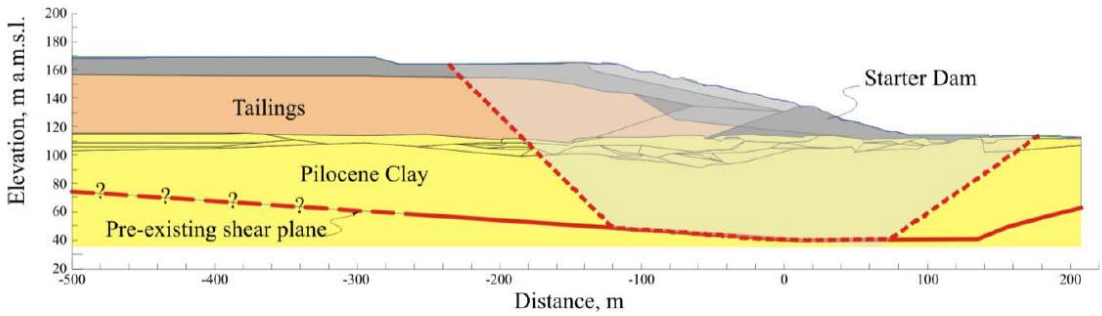

Figure 6. Illustration of stability concern for cross-section XVI-E ((Jamiolkowski *et al* 2010).

3.5.1 *Course of action*

At cross-section XVIE, the following stabilization measures were implemented in the period 2007-2009: (1) construction of a stabilization berm at the toe of the dam; (2) shifting of the dam crest 150 m closer to the pond (Fig. 1); (3) drilling of 20 relief wells, some as far down as 150 m; and (4) extensive, state-of-the-art finite element analyses of the dam under current conditions and with different mitigation measures implemented (Jamiolkowski 2014; NGI 2010, 2011, 2013 a, b; Rocchi and Da Prat 2014).

The evaluation work resulted in a temporary (over 3 to 5 years) idle period for mining waste disposal in the Zelazny Most tailings containment facility. The tailings were deposited in a nearby auxiliary pond.

3.5.2 *Preparedness.*

Additional ongoing measures include (Jamiolkowski 2014): (1) continuous enhancement of the monitoring network, the communication system between monitoring groups and end-users, with the adherence to a strict application of the Observational Method; (2) addition of circumferential drains as the dam was raised further; (3) further geotechnical analyses of the observed displacements of the dam to predict its evolution with increasing dam height; (4) modification of the plans for design and construction in light of the monitoring results and constantly updated stability analyses; (5) development of options as more information become available from the instrumentation; and (6) study of the stabilization potential of large diameter structural shafts and shear keys downstream of the dam toe.

An understanding of the complex geology was and continues to be crucial to conceive and be prepared to implement measures capable of mitigating the horizontal dam displacements. This involves considering the already-known active shear planes, as well as dormant shear planes existing in the foundation clay that may be reactivated by further dam raising.

In light of the presence of shear zones, the continuing horizontal displacements and the construction generated pore pressures, the current plan includes trying to improve tailings deposition and consolidation technology to reduce the volume of tailings already stored and planned to be stored in the facility.

3.6 *Benefit of the Observational Method for Zelazny Most tailings dam.*

The design and on-going operation of the Zelazny Most tailings dam is an excellent example of the use of the Observational Method in geotechnical engineering: after a few years of operation, geodetic data and inclinometer measurements suggested that the East starter dam and foundation soil were moving more or less as a semi-rigid body. After the implementation of the measures to improve the stability in the period of 2007-2009, the East Dam was more stable, with a reduction of the movements of the starter dam by two-thirds. The relief wells were believed to be the most effective of the three measures, and the circumferential drains (Fig. 4) proved to be very efficient in lowering the phreatic surface.

The application of the Observational Method and the ensuing stabilization measures taken helped reduce considerably the risk of instability of the Zelazny Most tailings facility. The measurements and engineering of the tailings containment facility during operation resulted in design changes and rehabilitation measures including: moving the dam crest upstream to flatten the average downstream slope; constructing stabilizing berms at the dam toe; and installing relief wells in the foundation to reduce pore water pressures.

It is appropriate to cite Hutchinson (1995): "In any stability problem the most important question is generally whether or not pre-existing discontinuities, especially shears, are present". The behaviour of the Zelazny Most dam confirms the wisdom in this statement (Jamiolkowski 2014).

4 EXAMPLES OF BENEFITS OF OBSERVATIONAL METHOD

Peck himself used the Observational Method on several embankment dams, but the method has found applications in most of geotechnical engineering works. Fourteen such applications were presented by Geotechnique (1996). In this publication, Peck commented on why he published the Observational Method in 1969: *"My real interest* [with the Rankine Lecture], *instead* [of theoretical research] *was in the ways our existing knowledge could be applied more effectively."*

Dunnicliff and Deere (1991) published a number of works by Ralph Peck where the use of the Observational Method is illustrated. In the section on embankment dams in Dunnicliff and Deere, Peck points out the following provoking thoughts:

- Influence of non-technical factors on the quality of embankment dams.
- "Let's get it straight" about embankment dams (a series of statements organised in a True/False query).
- Where has all the judgment gone?

Peck also wrote a paper on the advantages and limitations of the Observational Method, also included in Dunnicliff and Deere (1991). DiBiagio (2013) presented case histories of embankment dams where instrumentation and monitoring considerably helped making decisions on the next steps. Examples of the additional knowledge and benefits of the monitoring and the Observational Method are presented in Table 1 for three Norwegian dams.

Another example where the OM approach is desirable, or even required, is the design of seepage control and drainage treatment in a dam foundation. Information gained during foundation excavation and further investigations may significantly modify and improve the original design used as a working hypothesis (ICOLD 1993).

Table 1. Benefits of monitoring program for three dams in Norway (compiled from DiBiagio 2013)

Type of dam Dam height Name Year completed	Benefits of monitoring program
Rockfill dam 77-m Moravatn Moraine core 1968	Confirmed need for rehabilitation from the high pore pressure in the dam foundation: - Drove a drainage gallery into the downstream foundation. - Installed a system of drainage and observation holes. Checked that the drainage was efficient. Checked the drop in pore pressures. Pore pressures have remained stable ever since
Rockfill dam 129m Svartevann Zoned dam Moraine core 1976	Documented satisfactory behaviour during construction and operation - Total settlement was somewhat larger than predicted. - Pore pressures in the core were measured during early construction to check stability. Pore pressures were low and allowed construction with a steeper upstream slope than originally designed. - Small leakage.
Rockfill 90 m Storvatn Inclined asphalt core 1987	Documented the deformation behaviour of asphaltic core Used the observations to calibrate the analytical models Provided useful information for future dams of this type

5 BAYESIAN UPDATING AND THE OBSERVATIONAL METHOD

There is a potential for combining the Observational Method (OM) with the Bayesian updating approach. The OM is a practical way to deal with uncertainty. Bayes' theorem provides a framework that enables updates of first estimates with new information. Bayes' theorem is the essential means of adjusting one's opinion in the light of new evidence. In fact, it is a tool made for geotechnics, as most of what geotechnical engineers do is Bayesian! Most often, the estimates of soil profiles, soil properties, model uncertainties and predictions are based on both measurements and earlier experience and engineering judgment. Bayesian thinking was, for instance, used by Alan Turing in solving the German *Enigma* code during WWII (the movie *The Imitation Game*).

Two sets of data (or predictions), in this case the mean value and the standard deviation, can be combined by Bayes theorem, assuming both datasets are normally distributed, to yield an updated estimate:

$$\mu_{updated} = (\mu_1/\sigma_1^2 + \mu_2/\sigma_2^2)/(1/\sigma_1^2 + 1/\sigma_2^2) \quad \text{(Eq. 1)}$$

$$\sigma_{updated} = (\sigma_1^2 \cdot \sigma_2^2)/(\sigma_1^2 + \sigma_2^2) \quad \text{(Eq. 2)}$$

where μ_1 and σ_1 are the mean and standard deviation of the first estimate (the prior), μ_2 and σ_2 are the mean and standard deviation of the measurements (the likelihood, the new knowledge), and $\mu_{updated}$ and $\sigma_{updated}$ are the updated (posterior) estimates of the mean and the standard deviation. The result is an updated average weighted by the inverse of the standard deviations.

The Observational Method and the field monitoring during dam operation could be "complemented" with a Bayesian updating formulation in the assessments. In this way, one could associate uncertainties and outcomes with probabilistic estimates (probability of occurrence and consequences) and quantify the scenarios for making decisions. A dynamic updating of the risk picture (means and standard deviations) with the help of continuous real-time measurements and prepared response scenarios would be an easy way to make designs safer and provide support for "risk-informed" decision-making.

Bayesian updating[4] has been applied to continuously update the latest knowledge of the unknown parameters with the knowledge of new observations. For dams, two examples of successful applications of the Bayesian updating approach are: (1) in an uncertainty analysis of overtopping of a flood mitigation dam, Michailidi & Bacchi (2017) improved information on the flood peaks from historical observations by incorporating supplementary knowledge from different sources, including their associated uncertainty and errors; (2) Andreini *et al* (2019) developed probabilistic models to predict the internal erosion rate in embankment dams. They did reliability analysis of earth dams in terms of the critical shear stress and a coefficient of internal erosion. The Bayesian updating approach was used to quantify the uncertainty of the uncertain model parameters on the basis of observations in situ jet erosion tests[5].

Folayan *et al* (1970) were the first to introduce the application of Bayes' theorem to geotechnical engineering. They used Bayesian updating to predict the settlements of a marshland development analysed the associated economic consequences. The approach was also used to illustrate the optimal number of samples to improve the reliability of the prediction. Figure 7 illustrates the overconfidence that can occur in prior subjective estimates of probability distributions, in this case for the compressibility of San Francisco Bay mud.

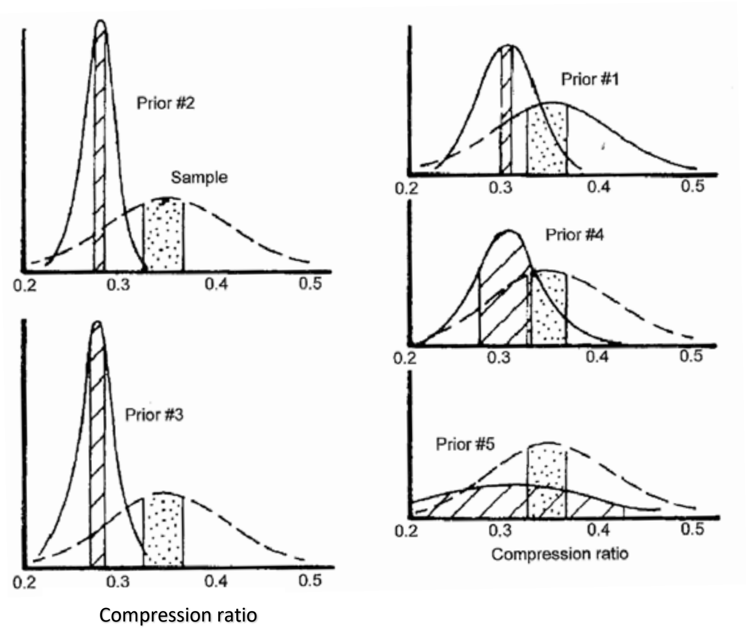

Figure 7. Subjective estimates of the compressibility of San Francisco Bay mud compared to test results (after Folayan et al 1970; Baecher 1972; Hartford and Baecher 2004).

The estimated means in each prior were lower than the measured values (sample), but more significantly, over-confidence (the prior estimates) produced distributions too narrow to encompass the measured data (Baecher 1972; Hartford and Baecher 2004).

With updated means and standard deviations, probabilistic calculations of hazards and risk can be carried out. With today's computer and modelling techniques and real-time access to display data and probabilistic evaluations, the field monitoring program would reflect the geotechnical

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[4] Using Bayes' theorem, the unknown parameters can be estimated from $p(\theta \mid y) = \kappa L(y \mid \theta) p(\theta)$, where $p(\theta)$ is the prior density distribution of parameter θ; $p(\theta|y)$ is the posterior distribution with the observed information y; $L(y|\theta)$ is the likelihood function that reflects the information from n observations $y=(y_1,y_2,\cdots, y_n)$; κ is a normalizing factor.

[5] Jet Erosion tests (Hanson & Cook 2004 and Hole Erosion tests (Wan & Fell 2004) are experimental procedures to determine critical shear stress and coefficient of erosion. They have been successful in a number of soils.

engineer's ambition: a coherent combination of observations, analysis, judgment and risk-informed decision-making for optimising from both cost and safety points of view.

Folayan *et al* (1970) also concluded that application of theory of probability provides improved rationality in the evaluation of the meaning of safety factor. The Bayesian approach was also used to show that the probability of success of an engineering analysis depends on the amount and nature of the engineer's previous experience with similar problems (Fig. 7). Several areas of application of the Bayesian approach were exemplified, including applying decision theory to select a course of action. Already in 1970, Folayan *et al* concluded that a probabilistic approach provides a framework that can assist the engineer to organize, accumulate, interpret and evaluate experience, and provide complementary information for analyses under uncertainty.

6 CONCLUSIONS

The Observational Method, very early in our profession, included the aspects of uncertainty and risk in geotechnical design, by looking at the mean and the uncertainty (*"assessment of the most probable conditions and the most unfavourable conceivable deviations from these conditions"*)[6], evaluating the hazards *("calculation of values of the same quantities under the most unfavourable conditions*") and looking at potential mitigation measures *("selection in advance of a course of action or modification of design for every foreseeable significant deviation of the observational findings from those predicted on the basis of the working hypothesis"* and *"modification of design to suit actual conditions"*).

At the very start of the project, the Zelazny Most tailings dam did not have a plan following the principles and all the steps of the Observational Method. The planning with corrective actions, if unexpected behaviour should occur, was not done from the very start in 1975. However, as unexpected behaviour became more and more apparent in the 1990's, thanks to the instrumentation, the need for the Observational Method emerged.

One advantage of the application of the Observational Method is the planned course of action if and when unexpected behaviour, which helps solve the difficulties because the mitigation measures would have been explored and even put in place to some extent.

For the Zelazny Most ring dam, the use of the Observational Method and the stabilization measures implemented helped reduce considerably the risk of instability. The application of the Observational Method resulted in design changes and rehabilitation measures including moving the dam crest upstream to flatten the average downstream slope; constructing stabilizing berms at the dam toe; and installing relief wells in the foundation to reduce pore water pressures.

Field measurements and monitoring, coupled with Bayesian updating, together can focus on risk on the basis of observations and scenarios. A risk management strategy should integrate all aspects, with focus on communication and "lessons learned". Instrumentation and remote sensing techniques can identify and quantify geohazards and interconnectivity will allow for rapid update of hazard, vulnerability, and risk. New challenges reside in integrating remote sensing, geotechnical engineering and risk assessment and management into innovative and practical risk management tools to reduce risk associated with natural and man-made geo-hazards. The result would be a risk reduction strategy, with robust, documented and practical risk assessment and management tools.

Science and engineering help predict hazards. Knowing the hazards and the risk helps make "risk-informed" decisions, and the effectiveness can be improved with recent innovative information technology and interconnectivity.

This paper is an homage to the late Professor Ralph B. Peck and his seminal "Observational Method". Professor Peck has had a unique influence on the development of our profession and reducing the uncertainty in our predictions.

In closing, the authors wish to tell an anecdote about Professor Ralph B. Peck. When student Elmo Dibiagio discussed his PhD topic (early 1060's) with Advisor Ralph B. Peck, there was at the time rising interest in advanced numerical analysis tools. Student DiBiagio elected "numerical modelling of an unbraced open-cut excavation" as PhD dissertation topic. When the thesis was

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6 The parenthetical statement refers to the wording of the Observational Method presented at the start of the paper.

approved, Professor Peck politely told him: "No theory or mathematical model can be considered satisfactory until it has been checked by actual observations".

7 ACKNOWLEDGMENT

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