TSANKOV KAMAK DOUBLE CURVED CONCRETE ARCH DAM PRACTICAL CONSIDERATIONS TO IMPLEMENT AN INSTRUMENTATION PROGRAM

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ABSTRACT:

A new dam in Bulgaria, Tsankov Kamak HPP, was under construction between 2006 and 2011. The dam employs a double curved concrete arch construction, with a height above lowest foundation of 130.5m. The crest length is 480m and the reservoir will contain 110 million cu. meter of water. The main power plant is located some distance along the cascade valley, but a small generating station of 1.12 MW is contained inside the dam. The scope of the instrumentation was mostly developed from designer studies, which analysed the potential failure modes, defined the monitoring parameters and the measurement program. From these specifications, more than 300 instruments were identified for Tsankov Kamak, 200 of which were installed during the construction phase. The installation of such a large number of measurement sensors and their subsequent integration is not obvious in many ways but the advantages are numerous, particularly for a concrete dam whose geometry comes from an understanding of structural optimization.

The paper presents the challenges encountered, future practical considerations and perspectives from an integrators' standpoint when implementing such an instrumentation program from another country.

RÉSUMÉ:

Un nouveau barrage en Bulgarie, a appelé Tsankov Kamak HPP, a été construit entre 2006 et 2011. Ce barrage est de type double-courbure-voûte, avec une hauteur à sa fondation la plus basse de 130.5m. Sa longueur en crête est de 480m et le contenu du réservoir de 110 millions de m3. La principale centrale électrique est déportée à un autre niveau en cascade dans la vallée, néanmoins une petite centrale de 1.12MW est installée à l'intérieur du barrage. Les besoins en instrumentation proviennent généralement des études du concepteur qui analyse les modes de défaillance potentiels et défini les paramètres de surveillance et le programme de mesure en conséquence. A partir des spécifications établies pour l'ouvrage Tsankov Kamak, plus de 300 instruments sont nécessaires, et parmi eux, 200 ont été utilisés lors de la phase de construction. La mise en œuvre d'un tel nombre de capteurs de mesures à ce stade du projet n'est pas évidente à plusieurs égards, néanmoins, les avantages sont nombreux, en particulier pour un barrage en béton dont la géométrie est issue d'une optimisation structurelle profonde.

Le document présente les défis rencontrés, les considérations pratiques futures de la part d'un intégrateur en instrumentation géotechnique et structurale pour la mise en œuvre d'un programme d'instrumentation sur un projet outre-mer.

1 INTRODUCTION

Dam instrumentation plays a fundamental role providing an understanding of the foundation and structural behaviour both during construction and in operation in subsequent years. The monitoring program provides the information that is needed to develop a better understanding of the performance of the dam. Knowing that the dam is performing as expected is reassuring to dam owners, and the ability to detect a change in this performance is critical as the dam owner is generally directly responsible for any consequences of a dam failure. With performance information dam owners can improve their ability to responsibly operate and maintain their dams in a safe manner.

As part of the Tanskov Kamak dam construction, in December 2007, ALPINE Bau Gmbh appointed GKM Consultants Inc. for the entire instrumentation and monitoring required in the project; the responsibilities included:

- Providing engineering details of instrumentation schemes to designer;
- Procurement management of all instruments, hardware and monitoring systems;
- Testing and verification of the goods prior installation;
- Technical assistance to local sub-contractor and training for installation and measurement readings;
- Editing measurement forms for data reporting, validation, sensor nomenclature identification and baseline evaluation;
- Cable routing, wiring and connection, data acquisition systems configuration and programming;
- System commissioning;
- Data management implementation and visualization for remote monitoring;
- Owner handover to operating staff & training.

Instrument manufacturers selected in this project were GEOKON for the vibrating wire instruments, HUGGENBURGER for the pendulum systems and SYSCOM for the strong motion earthquake accelerometers. In addition to the GKM technical and management staff, services from START ENGINEERING JSCO of Sofia, Bulgaria were contracted to assist with the instrument installations during each construction phase, and to make measurements during implementation of the monitoring system.

The purpose of this paper is to present an overview of the instrumentation work conducted at Tanskov Kamak Dam, highlight the challenges encountered, and to present future practical considerations and perspectives from an integrators' standpoint when implementing such an instrumentation program from another country.

1.1 Project location

The Tsankov Kamak hydroelectricity project is located in the Rhodopes, a mountain range near the border with Greece, it is a part of the Vacha Cascade which has great potential for hydro energy in this region. The system of hydropower plants, currently in operation on the river, has over 400 MW of capacity including four turbine power plants and one pumped-storage power plant. The objective of Tsankov Kamak hydropower project is to utilize the hydropower potential of the non-developed section of the cascade, more particularly the 21.5-km-long Sredna Vacha section that stretches between the two main reservoirs.

The project comprises the construction of the 130.5-meters-high Tsankov Kamak Dam forming a reservoir with a total storage volume of 110 million cu. meter, and the Tsankov Kamak Power Plants which will provide an installed power capacity of 85+1 MW generating 188+10 GWh/a.

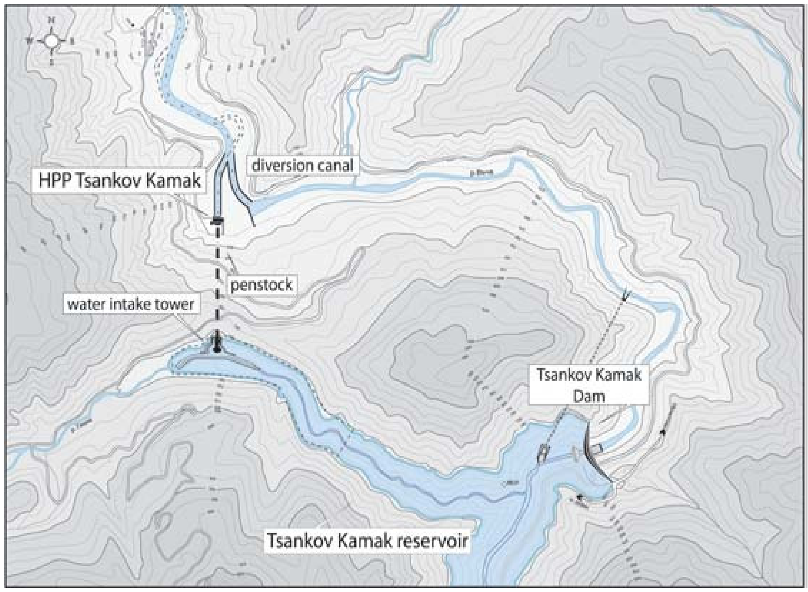

Figure 1: Dam project location overview

1.2 Dam construction details

The Tsankov Kamak Dam is designed as a double-curved concrete arch dam. The left and right banks end with gravity blocks and the dam arches are of parabolic shape. All arches are symmetrical to the dam axis. The dam length along the crest is 480 m (341 m thereof is the length of the arch dam) and the cord is 376 m. A road from the left to the right abutment is situated along the dam crest. The thickness at the base of the highest dam block is 27.6 m and at the crest is 8.8 m. Tanskov Kamak dam is classified as a thin arch dam with a width at the base of 2/10 of the height.

Excavation work and construction of the main dam required that the Vacha River be diverted around the construction site. The diversion comprised a tunnel with inlet and outlet structures, and an upstream and a downstream cofferdam. The hydraulic layout of the river diversion had to guarantee, during the construction period, against a 20-year flood with peak discharge of Q = 450 m^3/s with sufficient free board at the U/S cofferdam. The diversion tunnel is 493 m long. Before the concreting of the dam could start, ca. 410,000 m3 of rock were blasted for the dam foundation, and about 210,000 m3 for the plunge pool; an additional 200,000 m3 were removed for plant installations and roadways.

The dam is built up of vertical concrete sections interconnected in block joints with shear keys. In total there are four horizontal galleries and one base gallery (grouting) along the banks, connecting the horizontal galleries. A total of 315,000 m3 of concrete was poured and which had to be carefully cooled by means of cooling coils in order to reach the specified joint grouting temperature.

The dam was designed by POYRY, Switzerland, is owned by Natsionalna EleKtrichicheska Kompania (NEK), Bulgaria, and operated by CASCADES, a branch of NEK. The dam was constructed by ALPINE Bau Gmbh, supervised by ENERGOPROEKT HYDROPOWER LTD (co-designer) and ARNAUDDOV LTD, and managed by HYDRO ELECTROINVEST, a construction branch of NEK.

2 INSTRUMENTATION

The stability of arch dams is based on competence of the rock that forms the abutments. Arch dams require a comprehensive stress and force analysis in order to create the optimum design. The main force against an arch dam is the hydrostatic pressure provided by the reservoir behind it, uplift which is water pressure beneath the dam, the weight of the dam itself and finally all the forces combined. Other forces that can affect the dam include, but are not limited to, temperature, chemical reactions, settling, silt accumulation and earthquakes.

A mix of electrical instruments and mechanical devices were used (some in redundancy) to measure the parameters of interest. In the present concept, the instrumentation defined in the tender document resulted in over 300 instruments, of 19 different signal outputs, and 200 of which were embedded during the construction concreting phase. All the electrical instruments were to be automated through a central data acquisition system.

The instrumentation layout was divided between three principle cross-sections with left, center and right bank profiles. Figure 2 presents a general disposition of the instruments in the foundation, embedded inside the concrete mass, and at various locations in the galleries.

Implementation of such a number of sensors was a great challenge in view of the fast pace of the construction activities and the *just-in-time* procurement and site deployment objective.

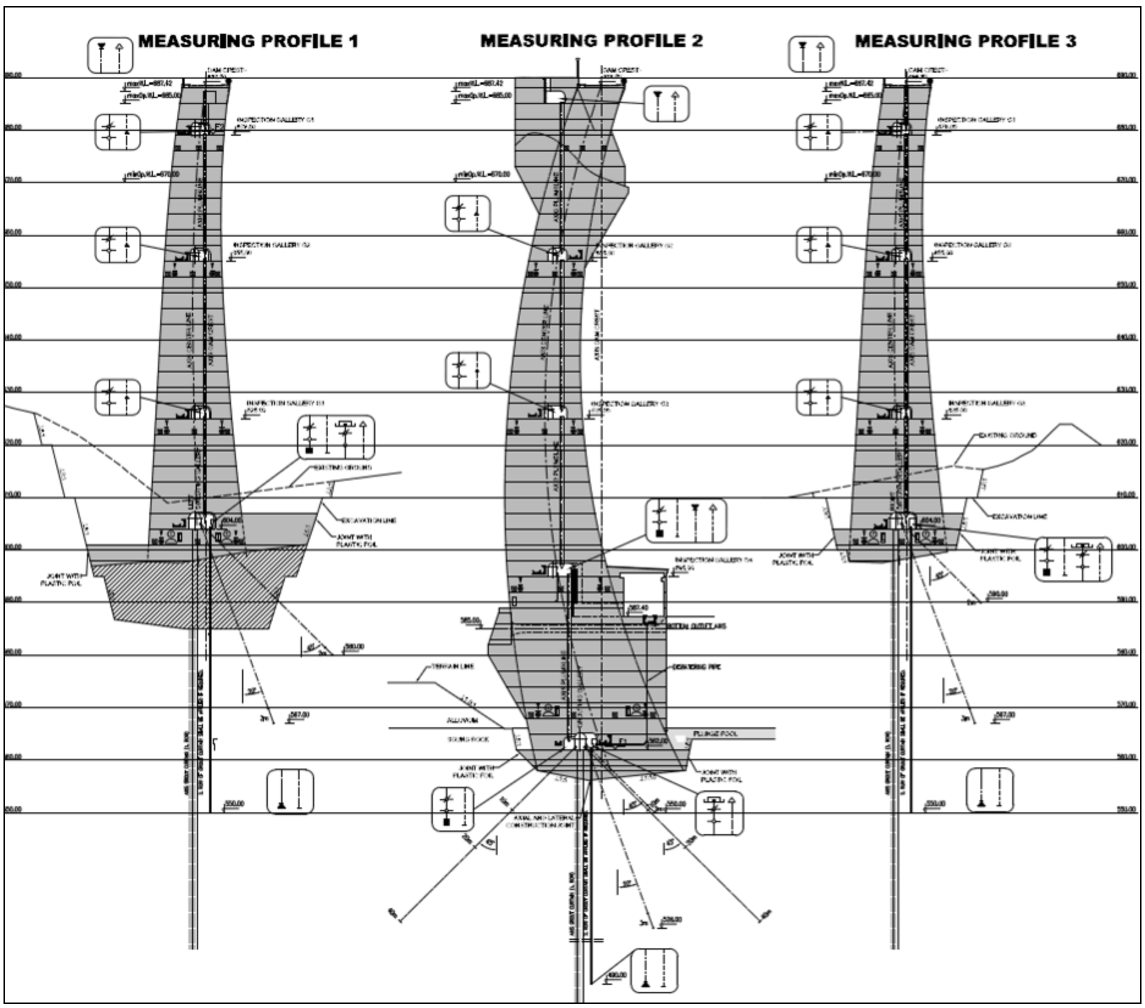

Figure 2: Typical Instrumentation profiles

The following sub-sections present an overview of the instrumentation proposed and installed in this project.

2.1 Strain Gauge (Tensiometer)

A total of 30 strain gauges were embedded at 5 locations in key concreting mass blocks. Working under the vibrating wire principle, each gauge contains an integral thermistor for temperature measurement and temperature correction.

Each gauge has a base length of 250mm with 51mm diameter flanges suitable for a coarse aggregate concrete matrix (60mm) and to withstand the rigors of concrete placement. The measuring range of the Geokon Model 4210 is 3000 microstrain with an accuracy of ±0.1% full scale.

The strain gages were mounted in a 6-gage rosette fixture, for 3D strain orientation measurements (45 degrees in each plane), and each recess (130x110x50cm) also included a no stress-strain gage assembly.

Figure 3: recess with strain gages, No stress gage

2.2 Total pressure cell (Telepressmeter)

Twenty (20) Geokon Model 3500 Total Pressure Cells were cast inside concrete blocks for stress variation measurements. The specifications required the total pressure cells to be capable of dynamic measurements, and therefore semiconductor (4-20mA) pressure transducers were selected. Consisting of an oil-filled pad, 230mm in diameter, any external pressure squeezes the two plates of the cell together creating an equal pressure in the internal oil which is, in turn, exerted on the pressure transducer diaphragm and consequently measured. The pressure transducer range was 10 MPa with ±0.25% F.S. accuracy.

It is important to mention this hydraulic/electrical instrument is subject to mechanical expansion as the concrete in which it is embedded hydrates and its temperature increases, therefore the cells were fitted with a re-pressurisation feature for post-stressing after installation and curing of the concrete.

Due to some unusual behaviour of the telepressmeters installed in first concrete block at the lowest elevation it was decided to test both precast (briquette) and recessed methods (same as strain gage rosette recess) side by side to determine the optimum method for the remaining installations.

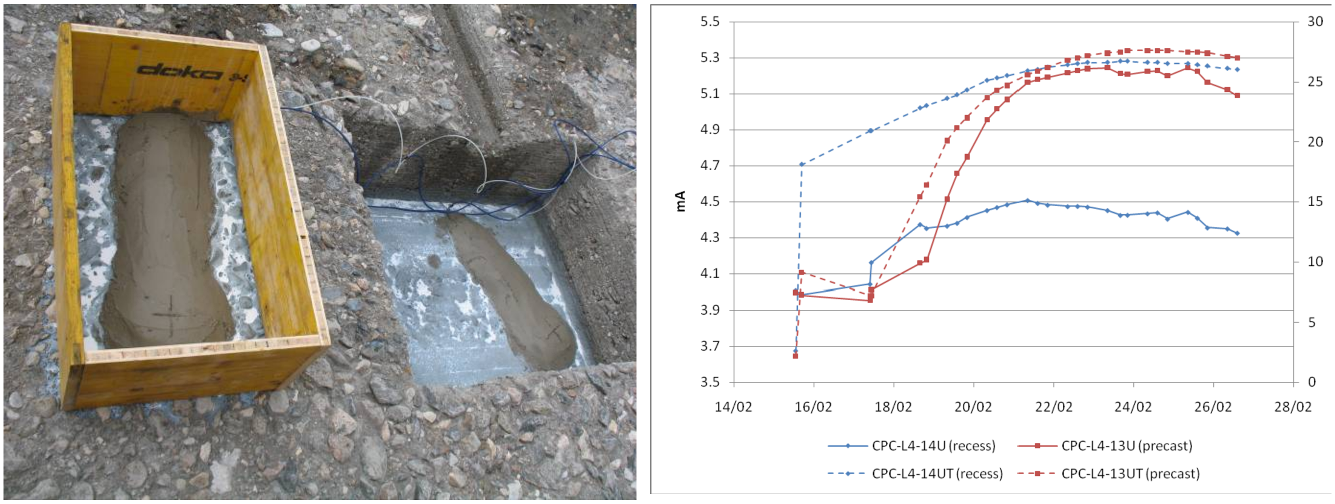

Figure 4: View and graph of precast and recessed total pressure cell installation methods test.

From the results presented in figure 4, the following observations were concluded:

1) Initial temperature in precast concrete is about 10°C lower than into the recesses. Therefore, the instruments in the formwork experience less expansion and consequently re-pressurization is much easier to achieve and which, in turn, ensures a better contact; and,

2) In the second stage, when the temperature is increasing due to the concrete in block L4-13 curing, pressure builds up much faster in the precast cells than in those in the recesses; which infers that the precast cells have little or no room for expansion.

2.3 Thermometer (Telethermometers)

In addition to the thermistors contained in each strain gage and total pressure cell, 40 additional temperature sensors were installed inside concrete for long term monitoring measurements and to complement thermocouples supplied by the general contractor for concrete curing monitoring.

The instrument selected was the Geokon Model 3800, which comprises a 3kΩ thermistor embedded inside a stainless steel enclosure 50mm length by 12mm diameter. The operating temperature range is from -50°C to 150°C with an accuracy of ±0.2°C.

2.4 Joint Meter

To monitor the effectiveness of the joint grouting Joint Meters were installed at every monolith joint (concrete block) in each of four (4) inspection and grouting gallery levels. Over 66 Geokon Model 4400 Vibrating Wire Joint Meters were employed each with a 25mm measuring range and ±0.1%F.S. accuracy.

2.5 Borehole Multi-point Extensometer (Extensiometer)

Extensometers measure rock deformation under the dam utilizing a combination of anchors and rods installed at various depths inside a borehole below the foundation. A total of (18) Geokon Model A-3 extensometers were installed in 76mm diameter boreholes drilled into the dam foundation. Anchors, located at 10m, 20m and 40m depths convey movement to displacement transducers in the extensometer head assembly which is located in the grouting gallery.

Each extensometer head included three (3) vibrating wire displacement transducers with 50mm range and ±0.1% F.S. accuracy, The design of the head assembly also provided for manual readings with depth micrometer, for redundancy and for QC/QA checks.

2.6 Piezometer

2.6.1 Uplift (Piezometers in Dam)

A total of 10 uplift piezometers were drilled and installed in foundation underneath the grouting gallery. For QA/QC redundancy and verification, each assembly employed a manifold for dual measurements with a vibrating wire pressure transducer and a bourdon gage manometer. The Geokon Model 4500H Pressure Transducers used had a measuring range of 1MPa and an accuracy of ±0.1% F.S.

2.6.2 Ground water pressure (Piezometers outside the Dam)

Initially, the open standpipe piezometers installed on each side of Ghanya reservoir slopes (10) and around the whirlpool area, downstream of the dam (13), were specified to be read manually. However it was decided, near the end of the construction project, to retrofit such that automatic measurements could be made.

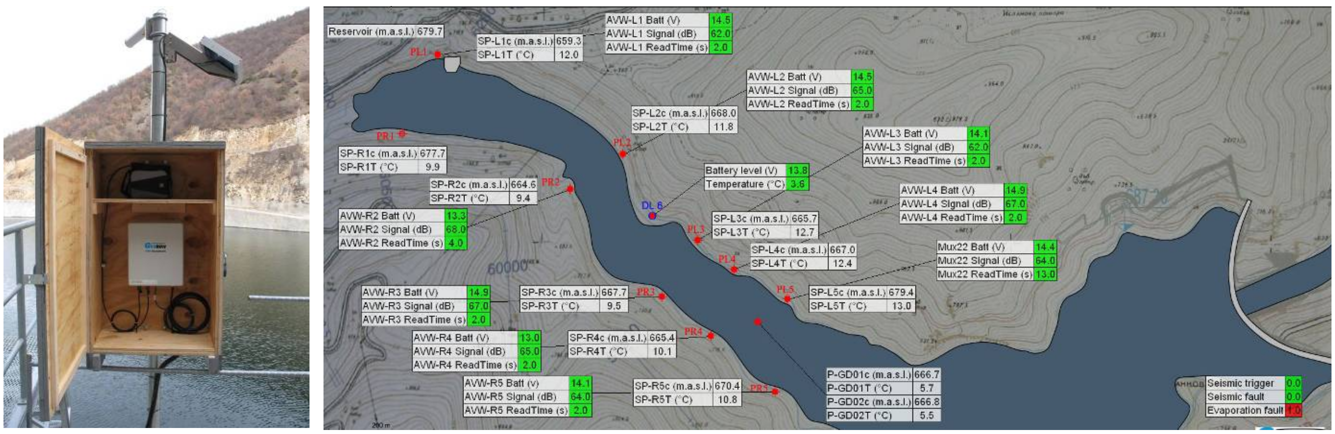

Figure 5: Remote open standpipe monitoring

To merge readings into same monitoring platform and data base management, Geokon Model 4500S vibrating wire piezometers with 350kPa or 700 kPa range with ±0.1% F.S accuracy were selected and installed inside each observation well and connected to an addressable wireless interface at the surface. Each system was self-powered and capable of communicating to the central measuring system located in the administrative building.

2.7 Plumblines, Telependulums & Invar Extensometers

The pendulum determines horizontal deformation of the dam which occurs between its top and its base. Plumb lines, located in vertical shafts in the dam, were 1mm diameter stainless steel for 55m lengths and shorter, and 2mm diameter for lengths greater than 55m. Access to the plumb lines, for measurements, was provided at 12 stations in the galleries. The left and right bank profiles had one inverted pendulum at 55m with a 300N uplift weight vessel, and the center profile was 75m depth with 1000N uplift.

Huggenberger reading tables, Model Telelot VDD allowed for both manual reading with a co-ordiscope and electronic readings for automatic monitoring. The reading tables provided for 150mm x 60mm measurements in the x & y -axis respectively, and 20mm in the z-axis (for the inverted stations).

At each plumbline installation, an invar wire extensometer was provided to measure the vertical deformation of the dam. This measurement was taken manually with a counter-weight and depth gage of 25 mm range and ±0.1 mm accuracy.

2.8 Clinometer (Inclinometer)

Stainless steel reference points were installed for tilt measurements at each telependulum for QC/QA redundancy checks. The instrument (Huggenberger Model ECS1000VD) consists of a 1 meter base length stainless steel bar with special conical seats which provide for inclination measurements in 2 directions between the reference points.

2.9 Remote level measuring gauge of the water reservoir

A remote level measuring gauge was installed at inspection gallery G4 elevation adjacent to dam intake. This custom-made apparatus consisted of a stainless steel water inlet and damping/filter vessel, to which was connected a ParoScientific high precision water level transmitter (with a digital display) and a bourdon gage manometer, for QA/QC redundancy and verification. The precision required for this system was ±10 mm in 100m of water. Vented to atmosphere and protected by desiccant cartridges, the transducer automatically compensates for any changes in barometric pressure.

2.10 Staff gauge

Staff gauge or limnimeters were installed in the upstream reservoir slopes on concrete stair case and stainless steel mounting channel. The gauges used were the Style M from Stevens, comprising graduated ceramics plates, 65mm wide x 1m length spanning a total distance of 110m.

2.11 Seepage weir monitor (Waterflow gauge station)

A total of 6 seepage measuring weirs with V-notch graduated plates were designed and installed in the grouting gallery. The measuring device proposed consisted of a Geokon Model 4675LV vibrating wire weir monitor (0.1mm accuracy) which exhibits zero drift and a very small response to temperature changes. Vented to atmosphere and protected by desiccant cartridges, the transducer is automatically compensates for any changes in barometric pressure. Drainage system designed with 45degree x 500 mm height of water and 30 l/s flow.

2.12 Seismic monitoring system (Earthquake stations)

Three (3) seismic strong motion systems were supplied and installed in a network for peak particle velocity analysis and to trigger the whole instrumentation to a faster recording mode in the event of an earthquake.

Each station comprises a +/- 2G tri-axial MEMS accelerometer (Model MS2005+ from Syscom) connected, via cable to a Model MR2002-SM24 strong motion recorder complete with over-voltage protection. Each station is interconnected, via fiber optic cable, to a central Station network control center (NCC) located in the administrative building. In case of a seismic event the NCC will trigger the special gateway logger to call all the other data loggers in, and outside, the dam to change their logging frequency.

Figure 6 : Seismic tri-axial MEMS accelerometer and recorder

2.13 Weather Station

A complete weather station with 10m mast and containing a barometer, relative temperature & humidity gages, wind speed and direction and evaporation gauges was erected on left abutment.


Figure 7: Weather Station

2.14 Automatic Data acquisition system (Tele-Measuring System)

The automatic data acquisition system provided for monitoring all the instruments at the dam site including the open standpipes at Ghasnya is based on a reliable platform able to function in a harsh environment, and combining flexible instrument interfaces and multiple means of communication. The heart of the system is the CR-1000 Measurement and Control System from Campbell Scientific which is, in turn, coupled to a series of multiplexers to which all instruments to be automated are connected.

The network is composed of six (6) secondary stations, two (2) units for remote open standpipe monitoring, one (1) for the weather station, and three (3) for the instruments inside the dam.

Each secondary station (CR1000) is equipped with an appropriate battery back-up (gel-cell rechargeable battery), allowing autonomous operation, from a few hours to as long as a couple of months, depending on the schedule of measurements. Instrument interfaces are also provided in each secondary station depending on the type of sensor being monitored. All items were factory tested and then assembled in a Nema 4x polyester enclosure (IP66) with appropriate voltage protection. All enclosures are also equipped with a heating element to control excessive humidity.

Figure 8: Typical secondary station and multiplexer installation

The system is fully programmable, and reading intervals for each instrument can be adjusted directly from the Central measuring station or by using a portable laptop connected to any secondary station.

Each instrument is connected to the secondary station via cabled multiplexers or wireless radio multiplexers and commutators to allow QA/QC manual reading redundancy checks. Secondary stations are connected in a network arrangement by means of an Ethernet interface NL-115 with fibre optic converter. The communication link is brought to the Central measuring station on the fibre optic backbone and so to the administrative building.

The central measuring station is a server-type computer based on the HP proliant series, and meeting all requirements of the tender document. It has all the resources required to easily manage all the instruments installed in (and around) the dam. On this server is installed the Vista Data Vision Data Management Software, that will allow automatic reporting, database management, alarms management, graphing, and the production of WEB-based pages, etc. Vista Data Vision automatically builds and maintains a database for storing and editing data originating from secondary stations, based on a MySQL database.

The contract specifications originally called for the supply and installed a mimic board (old relay annunciator screen) as a means of visualization; instead we provided a virtual digital display by means of the *db.web.browser* included in the Vista Data Vision software. This feature allows operators to view data and/or the state of each sensor on a two large LCD monitors in the administrative building at the dam site or 400 km away at the NEK corporate office in Sofia, Bulgaria.

Various views can also be programmed in the visualization software, depending on the user access control level. Even with no additional hardware, it is possible to display new sensors installed on the dam at a later time should the need arise. Threshold and alarm values and cross-channel calculations were also implemented.

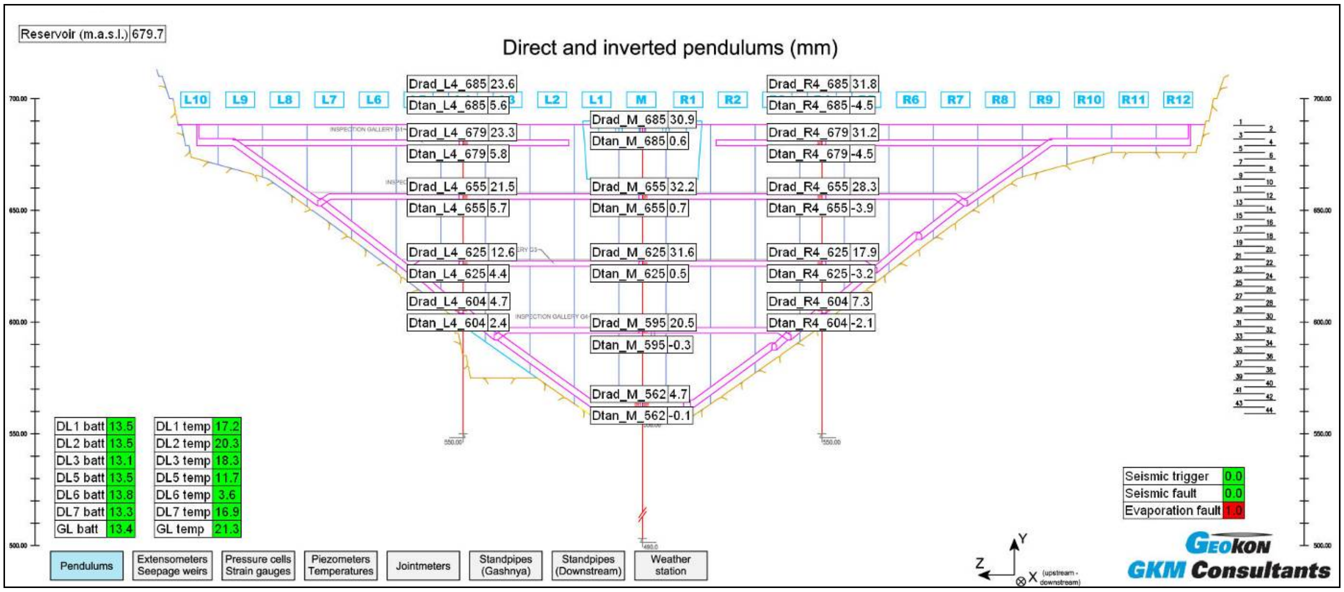

Figure 9: Virtual Mimic screen showing Pendulum measurements and location

Figure 10: Large LCD monitors for graphical visualisation

3 CHALLENGES AND FUTURE CONSIDERATIONS

The following sections describe the challenges and issues encountered prior to contract signing, during the construction, and the adaptations made at various phases of the contract-project advancement through to the final handover and client acceptance at the end of the contract.

3.1 Tender & design phase

3.1.1 Definition & specification interpretation

From an integrator's or manufacturer's standpoint, one of the biggest difficulties in the early stages is to gather as much information as possible for a complete understanding of the scope of the instrumentation project. In most cases, instrumentation is a very small fraction of a large scale civil engineering project and it often only receives minimal documentation and drawings, and omits procedures, such as type of materials, method of construction, construction schedule, etc., that are required for the execution of the monitoring system

Another important consideration is to have a full understanding of the requirements. Specification interpretation and definitions can be very general and generic which require clarification from the designer as to his real intentions and needs. For example, in the case of Tsankov Kamak dam, the Telepressmeter better has known as

Total Pressure Cell for stress variation measurements in concrete, or Telethermometer defined as a temperature sensor brought some confusion at time of tender. Instrument names as designated in the tender document are presented (in parenthesis) in the previous subsection 2 titles.

3.1.2 Monitoring topology

Instrumentation and monitoring programs are generally well defined in tender documents and instrument quantities are normally indicated in the bill of quantity. The designer knows precisely what the parameters to be measured are, and where to measure them, along with the reading frequencies. However the same is not always true where automatic data acquisition systems (the backbone of the dam safety monitoring program) are concerned. Just as with the sensors, instrument cables, and commutation or terminal boxes, it is important that the data acquisition system be detailed as much as possible in the requirements document.

Further information as to how the instrument and telecommunication cables are, or can be, routed inside the structure also helps the integrator to properly design the optimum system topology and telemetry system. Similarly, in large scale projects such as dams, it is beneficial if the monitoring system can be validated and tested onsite to experience actual site conditions, especially when wireless telemetry is involved.

We realize the scope of the monitoring system is often adjusted and modified, either because new instruments are added or removed, or due to false assumptions or last minute changes in site conditions. Accordingly, a preliminary visit is invaluable (and highly recommended) as it has the potential to eliminate many of such uncertainties.

Once the system structure is designed, the detailed engineering work (with respect to the dam maintenance and operating staff) can begin; i.e. listing the multiplexer network, detailing the wiring schematic for each (including instrument nomenclature/identification) etc.

3.1.3 Commercial consideration

With projects of this scale and importance there is no other choice but to choose first-class, high quality products from reputable manufacturers/suppliers. Similarly, deployment should be carried out by reliable and qualified teams with an on-site presence to perform accurate installations and to make timely measurements.

Of course, each contract has its own legal engagements and terms of responsibility. Nonetheless, working in a foreign country with suppliers and subcontractors in other countries adds another complexity with respect to the management of the various currencies and taxation systems involved. For example, at the time of the contract signature, there was no tax treaty between the USA and Bulgaria to address double taxation issues. Then, in January 2009 a new tax treaty came into force which compounded the administrative work required to ensure exemption and avoid paying unexpected taxes.

3.2 Construction phase

3.2.1 Scheduling (concreting)

As many of the instruments were to be embedded into concrete blocks (temperature probes, pressure cells, strain gauges) and it was mandatory to deliver according to the project concreting schedule. Therefore it was essential for all the commercial documentation be complete and accurate to avoid any troubles with customs, and to use transport companies capable of making timely deliveries in such a remote location as the Rhodopean Mountains. Similarly, it is important to maintain excellent coordination between the local subcontractor and the main contractor to prevent any delay with dam construction works throughout the construction phase.

3.2.2 Instrument location (time frame, orientation)

Instrument locations were determined on 2D drawings, which resulted in some confusion at times, and which were only resolved directly on site at a later date. Careful consideration also had to be made to the coordinate system specified (left handed with Y axis as vertical axis) along with dam curvature (tangential and radial axis) especially where sensor orientations were concerned. For example, rosettes of strain gauges had to be set up with care as they give stress through principal axis. This was difficult to ensure on site as they were installed in 50cm deep recesses located upstream and downstream of foundation concrete blocks, however the use of surveyors and detailed drawings solved the issue. Orientation difficulties were also encountered with the direct pendulum readout installations, which happened late in the project, once the whole dam is completed. Every wall inside the dam is curved, and the units have to be installed along tangential and radial axis. With no other reference than the walls of pendulum room, the alignment of the readout units was challenging. Axes at these locations must be identified during concreting with optical survey techniques while reference targets are still line of sight.

3.2.3 Instrument adaptation (remote)

It is not unusual in such project to make minor changes to the instrumentation system to fit with unexpected site conditions encountered during the construction stage. At Tsankov Kamak the most challenging adaptation involved the water level system that measures height of water in the reservoir. In spite of many visits in the galleries, pictures and design revisions, the equipment had to be modified (at the suppliers factory) to conform with reality (inlet pipe tilted, width of gallery ditch, etc).

3.2.4 Installation conditions (cables, recess, access, damage)

Installing sensors and routing cables inside a dam during the construction phase is challenging: it is important to ensure the instrument and cable integrity until they are secured; embedded into concrete, protected from machinery or falling objects, or placed in cable trays and connected to the data acquisition system.

Cable routing is not always obvious from 2D drawings and in spite of adding 15% extra length, many cables were short by a few meters, especially where sensor cables had to cross galleries and where cable trays were routed along gallery ceiling.

For embedded instruments, cables were to be routed vertically upward to reach future horizontal galleries approximately 5m above the sensors. Needless to say, 20 rolls of cable and tubing is a considerable weight, and as there was no rebar cage in the concrete blocks to support the cables or pipes, a plastic pipe reinforced with steel rods was improvised to hold rolls of cable while concrete was poured.

During curing, access to cables for recording readings was either impossible or very difficult. Cable routing, temporarily access to cable terminations and secure access are topics that should not be ignored during the instrumentation system design.

Figure 11: Team at work erecting cables

3.2.5 Measurement program during construction (data validation, remote)

The instrument system is intended to be used during the four most important phases of an arch dam's life: during construction, joint grouting, reservoir impounding and production. Measurements during the two first phases can be difficult to achieve as the whole system is not completed (for example, the power supply may be missing, and communication cables may not be available until just before reservoir impounding). Therefore, only manual or semi-automatic readings are possible at these times.

At Tsankov Kamak most of the instruments were accessible from dam galleries. Identification tags were kept clean of dirt and excess cables were rolled to prevent damage during concrete pouring or machinery moves. However, where cables from embedded sensors were routed to upper galleries, it was not always possible to connect to commutation panels and take readings. These situations created some discontinuities in measurements. Similarly, due to construction activities, many readings may change suddenly (such as concrete strains) so care should be taken to record any work or activity that could affect readings for correlation purposes.

3.2.6 Instruments add-on (impact on monitoring design system)

The design of an instrumentation system should provide flexibility in order to accommodate any sensors that may be added at a later date. For example, at Tsankov Kamak measurements recorded during the early stages of construction pointed out some issues with local concrete curing and further analysis was required. As a result it was required to install additional jointmeters, which would then become part of the final instrumentation system. Also, wherever possible, it can be helpful to keep one or two spare locations on multiplexers in case of defective channels.

System expansion is also important as demonstrated in this project where at the Ghanya reservoir slopes, a whole secondary station, equipped with more than 20 piezometers, was integrated into the dam instrumentation system using the same technology and communication (radio network, fiber optic links).

3.3 Commissioning & handover phase

The final stage of the project and likely the most critical, is the commissioning and handover to client. It requires synchronisation between all parties, and perfect timing. The Contractor, who is likely stretched by its legal and contractual responsibilities wants to handover and be released from its commitment, as does the instrumentation integrator who wants the same with the Designer, who needs all instrumentation to behave within the specifications agreed at the initial design stage.

The challenges now are to establish a protocol of tests for each instrument loop to prove its correct functioning. "Loop" in this case refers to the signal path coming from the instrument and all obstacles it may encounter; starting from the instrument (which in many cases is not accessible anymore) to the cable, to any junction boxes or splices and then to the switch box where manual readings are taken. At Tsankov Kamak, each instrument "loop" is also automated which adds to the complexity of the testing protocol both technically and logistically. Not only does it require to include multiplexers to interface multiple instruments (at the same time), but also the data logging system and corresponding signal interfaces.

When the automated instrument loop is closed, information generated by the data logging system has to reach its final destination in the control room located a few kilometers away. The measurement reading produced will be displayed on a screen and eventually stored on a server for further evaluation. Each measurement at this stage needs to be validated against its manual measurement and at the same time wherever possible. If there is a too long a gap between the manual reading and the automatic, the parameter being measured may have been changed, in such cases more than one person is needed to conduct the manual and automatic loop test.

In present project, where there are more than 300 instruments loops, a great deal of time is required for testing and so efficiency becomes extremely important. As mentioned previously, at this stage the Contractor is anxious to leave and the site is almost empty with fewer facilities to help the integrator performing his tests. As such, it becomes obvious that all previous steps related to the instrument loop (pre-design, executive design, construction phase, implementation and installation, pre-commissioning, etc.) have a major influence on the final commissioning, and the more that can be accomplished as you go will result in less pressure at the end.

Training, not mentioned so far, is extremely important and should form an integral part of the monitoring system particularly for parties who have vested interests in the success of the instrumentation program.

Figure 12: Training sessions are essential for proper transfer

Transfer of information is essential to ensure longevity of the instrumentation and proper comprehension of the instrument behaviour. Therefore, to avoid loss of information, it is essential to provide training sessions at numerous phases during project not only at its conclusion. This said, training at the commissioning phase is probably the most appropriate to synthesize all previous information in a practical way.

4 CONCLUSION

In brief, the key points to ensure the successful implementation of a monitoring program on such large project such as this are the following:

- at the onset of the project create a good complicity with the contractor and the client,
- ensure good communication channels and use them (communicate more than needed!)
- remain flexible
- leave nothing in a "grey zone" as it will likely come back to haunt you
- organize more meetings, roundtable, conference calls, etc..(this may sound costly but in reality it is not and at the end it pays dividends)

With the variety of instrumentation and different technologies that are available today, the role of the specialized integrator, with his knowledge of the same and his expertise in the field, becomes essential and should be exploited early in a project among all players. The result will be a successful project.

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