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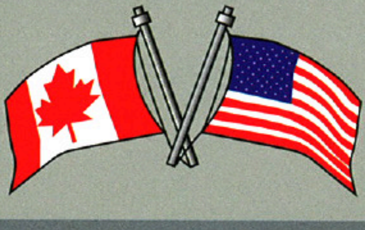

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HYDRO AND PUMPED STORAGE IN NORTH AMERICA ~ DAM SURVEILLANCE
HYDROLOGICAL DATA MANAGEMENT ~ ELECTRICAL ENGINEERING

Wolf Creek dam foundation remediation an innovative solution

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A complex and innovative remediation programme is currently being undertaken by USACE at the Wolf Creek multipurpose dam in the USA, where problems had been caused by the karstic foundations. After an evaluation of several alternatives to deal with seepage, it was decided to construct a concrete diaphragm wall.

Wolf Creek dam is located on the Cumberland river in south central Kentucky, USA. It provides hydropower, flood control, a water supply, and water quality benefits for the Cumberland river system and the surrounding region. The lake is a source of recreation that has attracted more visitors (4.89 million) than Yellowstone National Park (2.87 million).

Designed and constructed between 1938 and 1952, the 1748 m-long dam is a composite rolled earthfill and concrete gravity structure. It has a maximum height of 79 m above its foundation level.

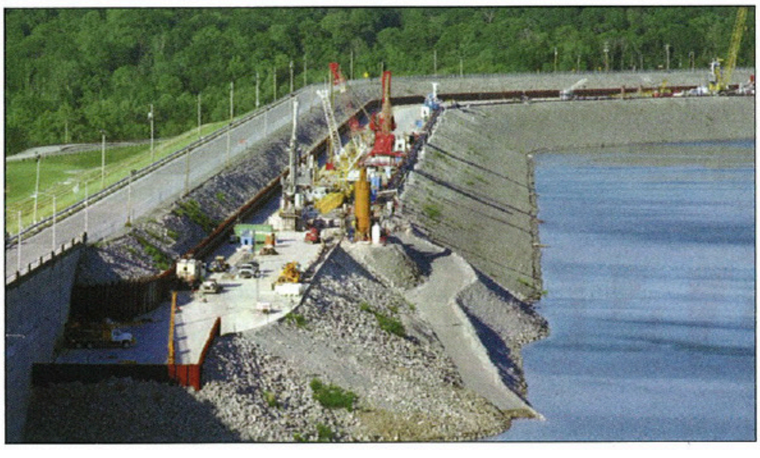
A six generator unit powerplant, with a capacity of 270 MW, is located immediately downstream. US Highway 127 crosses the top of the dam. Lake Cumberland, created by the dam, impounds 7.5×10 m^3 at its maximum pool elevation of 232 m. It is the largest reservoir east of the Mississippi and the ninth largest in the USA.

1. The challenge

The dam and its adjacent reservoir are founded on a heavily karstic bedrock foundation. Karst formations are large void spaces lying beneath seemly solid species of limestone bedrock.

In 1968, muddy flows in the tailrace, and two sinkholes near the downstream toe of the embankment, indicated serious reservoir seepage problems. Investigations indicated that the problems were caused by the Karst geology of the site, characterized by an extensive interconnected network of solution channels in the limestone foundation. The piping of filling materials into these features, and the collapse of overburden and embankment into the voids caused the problems.

(a) View of the dam from the dam from the left abutment.



(b) General view of the Wolf Creek dam.

To address the seepage problems, the USACE Nashville District has prepared a 'Major Rehabilitation Report'. It evaluated several alternatives to improve the long-term reliability of the dam. From this analysis, the recommended alternative was a new concrete diaphragm wall, constructed using modern technology, which will reinforce the original wall. The new wall will begin immediately upstream of the furthest right concrete monoliths, and will extend the length of the embankment into the right abutment, which will take it 503 m beyond the existing wall. It will be constructed to a depth extending beyond the deepest sections of the original wall, and as much as 23 m deeper than the majority of the original wall.

In late January 2007, the USACE placed the dam under a 'high risk of failure' designation and launched a major, and ambitious US$ 584 million remediation programme to bring the dam to full operating condition. In the meantime, and until the remediation programme is complete, the USACE maintains the pool elevation at 207 m, 24 m below its maximum capacity, with huge impacts to the local economy

2. The solution

The main contract, for US$ 341 million, was awarded in 2008 to Treviicos-Soletanche JV (TSJV), a joint venture formed by the following companies:

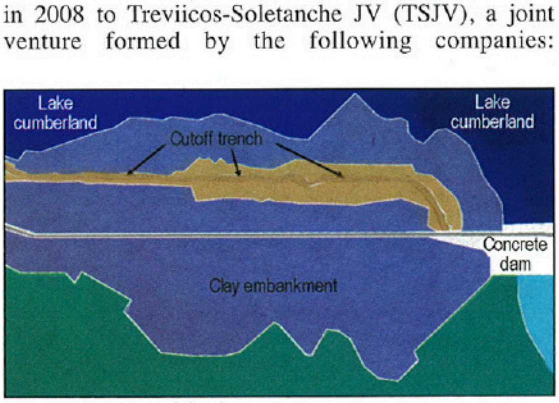


Fig. 1. Plan view of the dam.

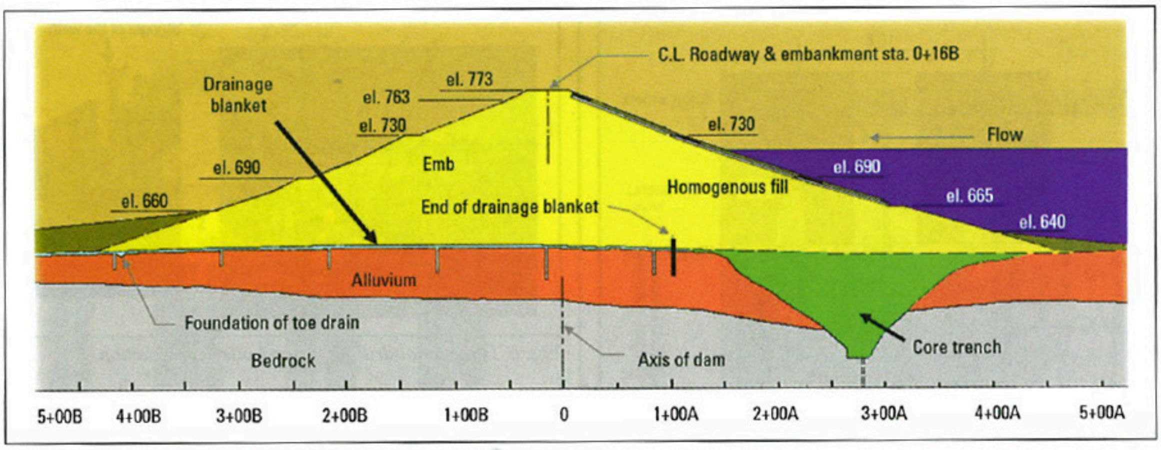


Fig. 2. Typical cross section of the dam.

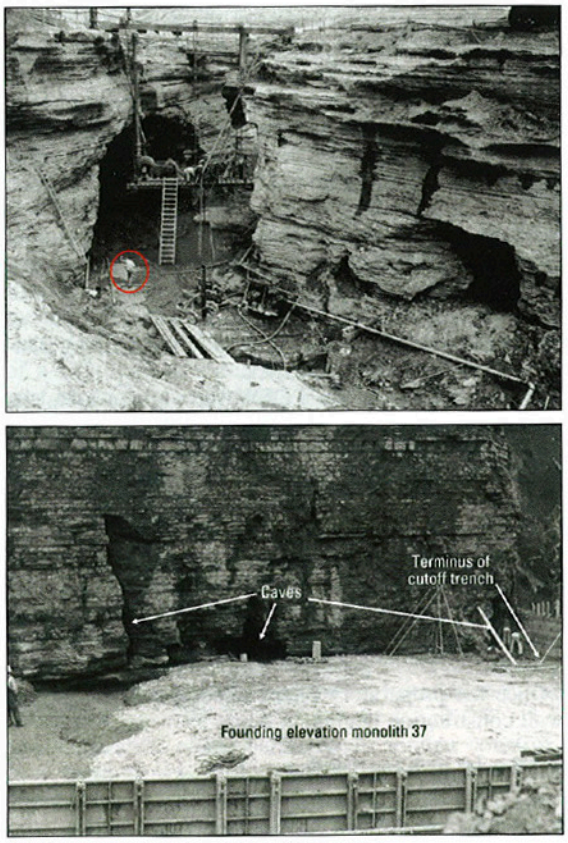
Treviicos, an American company based in Boston, Massachusetts, which is part of the Trevi group, one of the largest foundation contractors in the world; and, Solétanche-Bachy, which is part of the Vinci Group, one of the largest main contractors in the world.

The contract is for the construction of a 91 045 m^2 concrete barrier wall. Most of this concrete barrier wall, which will be a minimum 0.6 m wide, is being built to depths reaching 84 m, using innovative construction techniques to be utilized in variable conditions, such as rock strength varying from 89.6 MPa to 248.2 MPa, and in mixed rock/soil conditions with non-rock intervals of up to 12.2 m.

The construction of the barrier wall involves the use of five different foundation techniques, including: drilling and grouting; hydromill excavation both in embankment and in rock; directional drilling; auger drilling; and, reverse circulation drilling. All of these activities run simultaneously, following stringent requirements in terms of verticality, distance between open elements, strength and, dimensions that control the installation sequence of each barrier wall element. Unprecedented levels of quality control are required, to ensure that the quality of the barrier wall meets the design requirements, with the minimum need for remediation work.

Table 1: Main barrier wall performance requirements

Description	Unit	Specification requirements
Barrier wall thickness (min.)	ft	2
Overlap between elements (min.)	ft	0.5
Concrete strength	psi	2000
Permeability	cm/sec (1 Lugeon = 1.3×10^{-5} cm/s)	1.3E-05



(c) Caves and features along critical areas.

The main performance requirements of the barrier wall are reported in Table 1.

In addition to these stringent requirements, the barrier wall has to reach a maximum depth of 84 m with a verticality tolerance that must be within 0.15 per cent from the vertical.

In terms of installation sequence, before any barrier wall work can proceed, grout curtains installed in the rock mass from 1.5 m below the top of the rock to 15 m below the bottom of the cutoff wall must be completed, reaching a closure criterion between 3 and 10 lugeon, at a distance of at least 161 m ahead of barrier wall work. In addition, simultaneous excavation of barrier wall elements cannot occur closer than 27 m if:

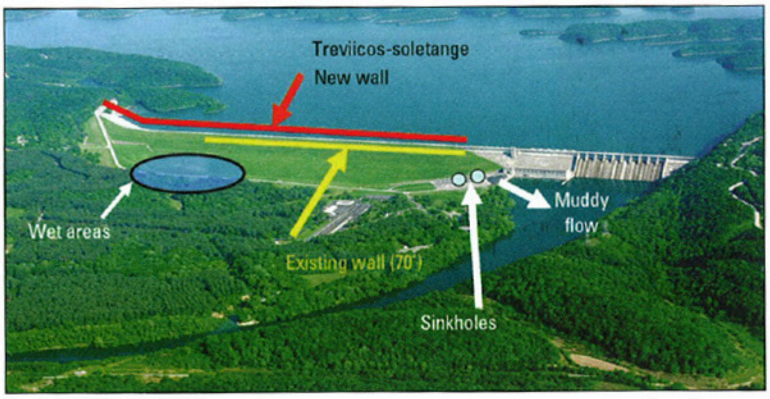


Fig. 3. New barrier wall.

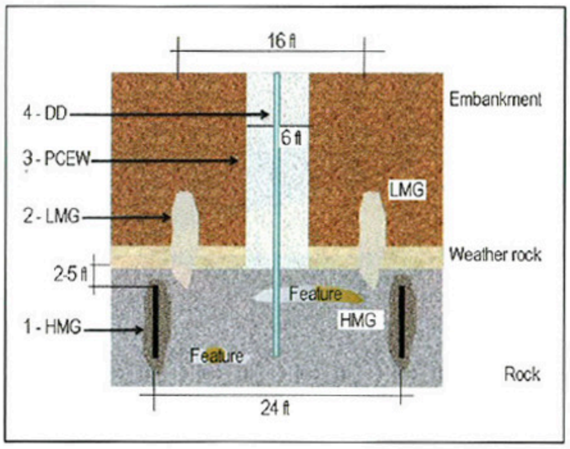


Fig. 4. Preparatory phase before construction of the barrier wall began.

the elements are located in four areas (274 m) of the dam-denominated 'critical areas', which as a result of their geology, are at a higher risk during barrier wall construction; and, not closer than 12 m if the elements are located in the rest of the dam in 'non-critical' areas. Despite the definition of the areas where the barrier wall is being installed, extreme care is required to ensure the dam is never at risk of damage during the construction of the barrier wall.

To allow for the excavation of new elements close to elements that have already been concreted, the concreted elements should have reached an unconfined compressive strength of at least 6.9 MPa. Before excavation of an element adjacent to a concreted element can proceed, the concreted element should have reached an unconfined compressive strength of 13.8 MPa.

Finally, a large verification coring campaign takes place to verify the quality of the barrier wall. This campaign includes: coring in the centre of the elements and in the joints; water tests, to determine barrier wall permeability; use of a televiewer, to determine the presence of weak zones; and, determination of concrete strength. At least 25 per cent of the elements and/or joints of the barrier wall will be cored to confirm that the performance requirements of the barrier wall have been met.

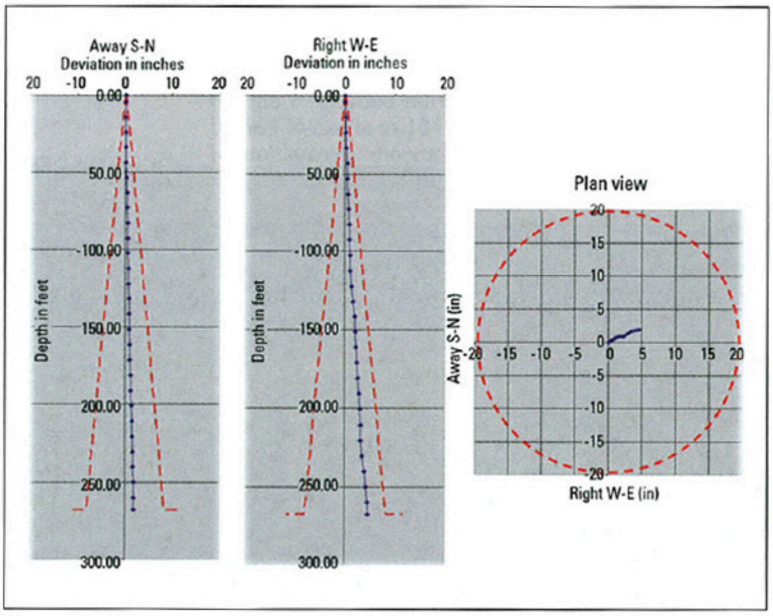


Fig. 5. Directional drilling deviation charts.

Fig. 6. Directional drilling rig and piles construction.

3. The construction sequence

To accomplish the demanding requirements of the specifications, which first take into account dam safety, TSJV developed, in its bid proposal, an innovative construction concept, which can be summarized in two main phases: a preparatory phase; and, a barrier wall construction phase.

The techniques proposed by TSJV for the construction of the barrier wall were successfully tested, before the barrier wall construction began, in two technique areas. The testing of the techniques beforehand provided added value to the TSJV and to the District because it allowed for the development of a learning curve, required in any project in a controlled environment, which facilitated the District's understanding of, and increased confidence in, the techniques to be used in this sensitive DSAC 1 project.

3.1 Preparatory phase

The preparatory phase comprises a three-stage process to minimize the potential for damaging the embankment during the construction of the barrier wall. This three-stage process begins with a grouting campaign, which is a combination of high mobility foundation drilling and grouting work specified in the contract to treat the rock 1.5 m below the top of the rock, and the execution of a focalized low mobility grouting campaign, which is designed to treat the interface between the bottom of the embankment and the top of the rock and, the top of the foundation drilling and grouting work. When this first stage is complete, the installation of a 1.8 m-wide protective concrete embankment wall (PCEW) follows, which is built with the use of hydromill equipment from the top of the working platform and to the top of the rock.

On completion of the PCEW for a given area, the installation of 20 cm directional drilled pilot holes (DD) follows from the top of the platform through the PCEW and into the rock, reaching depths of up to 86 m. The pilot holes are installed to: allow an additional investigation of the rock/soil conditions below the top of rock, which permits additional treatment of conflictive areas before barrier construction begins; and, guide, with limited and controlled deviation, the installation of the secant piles, which form most of the barrier wall.

Once the preparatory phase is complete, the barrier wall construction begins.

3.2 Barrier wall construction

Directional drilled pilot holes are a fundamental part of both the barrier wall preparatory phase, and the construction of the barrier wall.

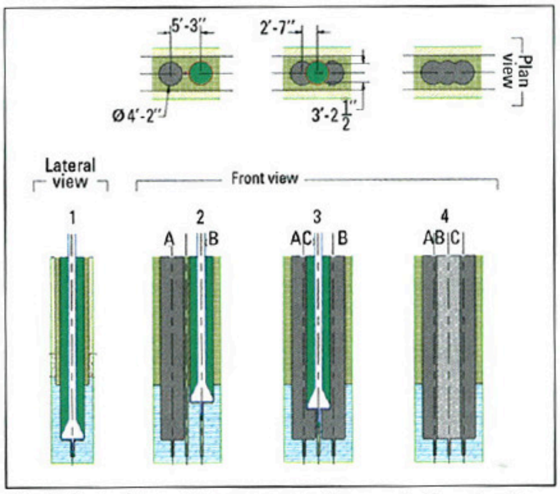


Fig. 7. Typical installation sequence for secant piles, showing: (1) reverse circulation drilling dia. 50' in (1270 mm) down to specified depth; (2) installation of primary shafts; (3) installation of secondary shafts; and (4) a completed portion.

The execution of the DD pilot holes evolved during the project from the original target maximum deviation of 21 cm at 86 m, to a significantly improved 5-7 cm at the same depth for more than 60 per cent of the elements installed. This achievement is unprecedented for this scenario.

The direct consequence of this achievement is the elimination of the need for remedial work resulting from verticality issues. TSJV has installed more than 70 per cent of the elements (almost 900) of the barrier wall with only two remedial piles required, both of them at the beginning of the project during the development of the techniques in the areas of concern.

Once the DD holes are complete in a certain area, pre-drilling (PD) of the piles begins. Immediately after the execution of the 127 cm piles with reverse circulation drilling (RCD), follows the previously drilled pilot hole by an instrument known as a stinger. The advantage of this system is that as a result of the certainty that the RCD will follow the DD holes, once the DD holes are complete it is possible to determine the final location of the pile and with this, the compliance of the elements to be installed with the geometrical performance requirements of the barrier wall, even before excavation of the piles begins. Therefore, if after the completion of a DD hole, it is determined that the geometrical performance requirements will not be met, a new DD hole can be installed without incurring the cost and time of installing a complete secant pile. There are a few cases in which the deviation of the DD has exceeded the tolerance of a contract in the last 20 to 30 m. In those cases, TSJV has developed RCD alternative drilling techniques, which have allowed for completion of the piles, well within the tolerance.

On completion of the excavation of the piles with the RCD, concrete operations start. A typical primary-secondary sequence is followed for the installation of the piles.

In some areas of the barrier wall, another construction method was utilized. This method is called Combined Barrier Wall Method (CBWM) and involves the combination of RCD piles and hydromill excavated panels.

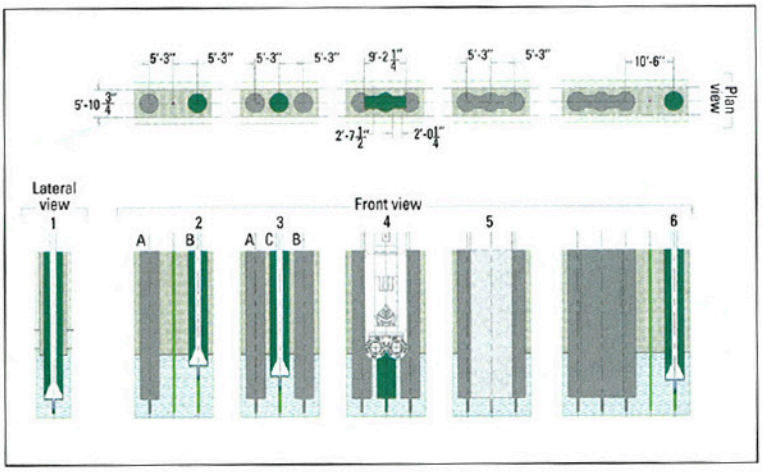


Fig. 8. Typical installation sequence for the combined barrier wall method, showing: (1) reverse circulation drilling dia. 50' in (1270 mm) down to specified depth; (2) after concrete maturity of Shaft A, execute Shaft B; (3) after maturity of Shaft B, drill Shaft C and pout concrete into shaft if required; (4) excavate with Hydromill a middle-connecting element, 2.62 in (800 mm) wide, down to design depths; (5) pour concrete into open excavation using the tremie method; and, (6) continue production of the compound wall with the same sequence.

The advantage of this method is that the footprint of five secant piles can be covered with two 127 cm RCD piles and one 2.8 m hydromill panel, thus using less material and building fewer joints between elements. Where the strength of the rock surpasses 206.8 MPa, and the depth of the panels exceeds 61 m, the utilization of this method would be successful but has to be weighed against time and cost considerations.

(d) Hydromill set up to work on the CBWM.

(e) The disposal area.

In addition, the disposal of waste and water constitutes a project within the project. TSJV has been able to set up a system, which allows the treatment and disposal of 1.1 × 10^6 litres of water per week and 2293 m^3 of solid waste.

4. Quality control

To overcome the challenges of the project, such as contract requirements, the construction sequence and a short schedule, TSJV developed an extensive and comprehensive quality control programme, which permits detailed control at each stage of the construction sequence of the barrier wall. The level of detail is such that TSJV is carrying out more than 350 quality control tasks per day.

To execute, document, compile, control and update such a large number of tasks efficiently, increases the significance of the Quality Control (QC) department becomes significantly important when measured against the entire structure. Th cost of this QC structure is repaid, when high quality is provided from the commencement of the project and, as a consequence, no remediation work is required.

(f) Three directional drilling rigs installing pilot holes in non-critical areas.

Table 2: Betterment of barrier wall performance requirements

Description	Unit	Specification requirements	Arrival on site	Improvement
Barrier wall thickness in embankment (min.)	ft	2	6	300 per cent
Barrier wall thickness in rock (min.)	ft	2	3.15	158 per cent
Overlap between elements (min.)	ft	0.5	1.5	300 per cent
Concrete strength	psi	2000	5200	250 per cent
Permeability	cm/s (1 Lugeon = 1.5 × 10^{-5} cm/s)	1.3E-05	1.0E-07	10000 per cent

The permanent interaction between the TSJV QC team and the District QA team has become a distinctive feature of this project.

Another distinctive feature of the QC/QA system in place at Wolf Creek, is the implementation and utilization of a 3D data management system, which allows for the processing of huge amounts of information on a daily basis, and also simplifies the final evaluation of the quality of the barrier wall, before its final acceptance.

As a result of the exhaustive QC system in place at this project, TSJV is able to exceed considerably and consistently the performance requirements of the barrier, as shown in Table 2.

5. Conclusion

At 78 per cent completion, the Wolf Creek dam foundation remediation is one of the most extensive and complex dam foundation remediation project to be undertaken, to the authors' knowledge. In addition, the joint effort of TSJV and the district are setting new industry standards in terms of construction techniques, quality control/quality assurance procedures and verification and final acceptance of the work carried out. ◊

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Fabio Santillan graduated from Universidad Nacional del Sur, Argentina, with a degree in Civil Engineering. He began his career as a teaching assisyant at the same university, and subsequently became a Project Engineer for the joint venture which included Trevi Argentina, This company carried out repairs to the Paso de las Piedras dam in Argentina. In 2002 he moved to the USA, where he worked as Project manager for Treviicos, and in the following years was involved in a number of projects involving jet grouting and cutoff walls. In 2006 he assisted with the construction of the Tuttle Creek dam foundation remediation project, heading the on-site team. He is currently Project Manager of the Treviicos-Soletanche JV, constructing the cutoff wall for the remedial project at Wolf Creek.

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