# LONG SUBMERGED TUNNEL INSPECTIONS: THE MANTARO HEADRACE TUNNEL CENTRAL ANDES MOUNTAINS, PERU

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## BACKGROUND

Located in the central Andes mountains in Peru, the 900 megawatt C.H. Antunez de Mayolo hydroelectric facility (Mantaro) generates approximately 70% of the region's power, which includes the capital city of Lima (population 7 million).

In a remote region approximately 350 kilometres east of Lima, at an altitude of over 2500 meters above sea level, the Mantaro facility (named after the river upon which it is situated) is a major engineering feat in itself. The headrace tunnel servicing the plant, 4.8 metres (15 feet) in diameter, has been bored through the Andes mountains and extends for an extraordinary distance of 19.8 kilometres (66,000 linear feet).

Since its construction in the early 1970's this facility has been unable to meet it's maximum generating capacity due to a gradual loss of head pressure. The purpose of the inspection is to determine the cause of this problem and to identify possible solutions.

Possible causes for loss of head pressure have been identified as follows:

**a) Catastrophic failure:** Various rock types and geophysical conditions were encountered during construction, so that materials and construction methods had to be adapted to suit local conditions. Three types of concrete were used, including a super-reinforced section in the area of a major fault, and a steel lined section at the downstream end of the tunnel where sand and till were present. The occurrence of a catastrophic failure such as a cave-in or occlusion due to misalignment from fault shift was considered to be remote, since the loss of head pressure was known to be gradual and no major seismic activity had occurred locally since construction. Another theory is that naturally occurring anhydrous calcium sulphate encountered during construction may have been converted to its hydrous form through contact with water leaking through joints or cracks in the walls of the tunnel. This would produce hydrous calcium sulphate, or gypsum, which expands tremendously and can cause structural damage by exerting pressure on the outside of the tunnel walls.

**b) Corrosion:** Major copper mining activity upstream has severely altered the electrolytic properties of the Mantaro River, resulting in a minimum conductivity of 34600mS/m (much higher than seawater, which only reaches a maximum of 20000 mS/m). Sulphates and other dissolved minerals may have corroded the inner surface of the concrete lining, increasing the effective surface area of the tunnel wall and thereby increasing drag. (The corresponding increase in internal diameter would presumably be offset by the greater drag coefficient). Water velocity is estimated to average over 3 metres/second, and the resultant cumulative drag over the 20 kilometres length could be a factor in head loss.

**c) Deposition:** The above factors pertaining to dissolved minerals could also produce the opposite effect, a crystallization of minerals along the tunnel walls as the warm supersaturated river water moves through the tunnel, cooled by the ambient subterranean temperatures. Resulting precipitates could gradually occlude the tunnel, producing both additional drag and reduction of effective internal diameter.

**d) Sedimentation:** The Mantaro river transports an incredible volume of solids due to the fact that much of the local terrain is not rock but sand and till. This is especially true during the rainy season, when most of the annual volume of over 4 million cubic meters of solids is flushed down the river, to accumulate in the reservoir basin at the dam. This sediment is routinely purged through conduits in the dam base. Water entering the tunnel must first pass through sand traps designed for the settling of suspended solids. In addition, purge piping is utilized to flush sand from the tunnel invert at two locations where accumulation is likely. Even so, there is still the possibility that sediment is accruing in the tunnel and reducing flow.

## INSPECTION PARAMETERS

The first and somewhat obvious consideration is the fact that the tunnel cannot be dewatered to facilitate inspection 'in the dry'. This is because the dewatering process must be accomplished relatively slowly, in order not to stress the tunnel walls due to the potential (in some locations) for immense hydrostatic pressure outside the tunnel. The dewatering process could take more than 15 days, too long for this vital facility to be shut down.

This means that the tunnel must be inspected under flooded conditions, and, due to the unknown nature of the head loss problem, must be inspected in its entirety. Dive support would have to be negligible due to the combination of altitude and water depth, which can reach over 100 meters at the downstream shaft access. Bottom time would therefore be extremely limited unless an ADS (Atmospheric Diving Suit) were utilized.

Not only is the tunnel 20 kilometres long, it also has numerous significant bends and incorporates changes in elevation at two points, presenting obvious difficulties for anything towing an umbilical.

In order to facilitate this inspection, Electroperu specified a shutdown window to coincide with a national holiday at the end of July. This will leave a total of 72 hours (intermittent) time to complete the entire inspection. Needless to say, there is not much room for error in terms of equipment readiness and capability.

## THE INSPECTION VEHICLE

No off-the-shelf ROV is capable of such a task, so various means of inspection were considered. These included the use of a specialized pull-through trolley with sensors mounted on an articulating arm and a tethered float-through vehicle which would also have controllable surfaces for manoeuvrability. One advantage of the float-through vehicle would be the potential to inspect during operation of the plant, as flow would be required to propel the vehicle, possibly with the use of a sea anchor or some other chute-like device.

It was later decided that a more traditional approach using a purpose built *new generation* ROV would be used, as float-through technology is unproven for this application and a pull through vehicle would require insertion of a tag line into the tunnel. Experience has shown that tag line insertion in long pipelines and tunnels is a dubious exercise at the best of times. In addition, almost any obstacle encountered would incapacitate a towed vehicle and bring the project to an abrupt halt.

A self propelled ROV would, by virtue of its payload size and increased mobility, provide more data and could also perform tasks such as concrete coring and NDT of the steel lined section.

Long tunnel inspections are a relatively new phenomenon in the ROV world, and technological advances have greatly affected inspection methodology. The applications of sonar and fibre optics to tunnel inspection techniques are probably the most significant as regards the Mantaro project.

The ASI Pipeliner, built by Deep Ocean Engineering, has been in operation for about five years and has more than proven itself in the harshest tunnel and pipeline environments. Deep Ocean Engineering were eager to approach the Mantaro challenge as a means of moving forward from the Phantom line of controller systems to a more advanced, fibre optic based system, called Phoenix..

In the case of sonar, fast scan, colour imaging systems which produce easily interpreted data have made this technology an integral part of inspections where tunnel diameters are large enough to warrant their use. Obvious advantages are associated with data which can also be stored digitally for post inspection manipulation. Due to the relatively low visibility (optimal during winter months at an average of 0.5 meters), combined with the tunnel's large diameter, sonar is essential both for object avoidance and structural deficiency location.

This means that the first 'front' of data is derived from two sonar systems, one forward looking and one profiling. The forward looking sonar is intended to provide early warning to the ROV pilot of obstructions in front of the vehicle to a 'safe' distance (relative to vehicle speed). The profiling sonar serves two functions: it scans areas 360 degrees around the vehicle not currently within video range for obstacles which might represent a threat to the vehicle/umbilical, while simultaneously highlighting areas of interest which warrant video investigation.

Without the relatively recent advances in fibre optic technology, it would be impossible to conduct an internal inspection of 10 kilometres penetration (assuming both upstream and downstream access and dividing the total length by two) with a free swimming, surface powered ROV. The key (and interdependent) factors are umbilical weight and the resultant diameter when a compensating floatation jacket is added for neutral buoyancy.

A heavier umbilical means a thicker floatation jacket, which in turn increases drag. This immediately rules out hardwire telemetry, which in any event poses problems over this distance when incorporated with power leads, creating a mains power condition resulting in signal interference and video noise. Using light as the mode of telemetry overcomes this problem, permitting clean, uninterrupted signal transmission at a high rate of speed. With the use of low density, small diameter fibre optics, floatation and overall diameter can be kept to a minimum.

This new vehicle, suitably named 'Mantaro', would follow the basic design principle incorporated into the ASI (Phantom) Pipeliner already in use for shorter (6000 ft.) tunnels and pipelines: high torque horizontal (rear) thrust, effective hull design and adaptable data gathering sensors. Initially, Ground Penetrating Radar (GPR) was also specified as a potential data gathering technology for concrete analysis, but it's use was precluded by the fact that, as mentioned, the conductivity factor in the river water is far too high.

As stated, the basic difference between the Phantom and Pheonix systems is the use of multiplexed fibre optic control telemetry and subsea power distribution as opposed to the multiple conductor system, allowing greater penetration distance.

The ASI Mantaro, from the Phoenix family of ROV systems by Deep Ocean Engineering incorporates an application designed sensor package, multiple camera suite, dual sonar, NDT probe, five function manipulator and a concrete coring drill.

Powered by eight independent high torque rear thrusters, plus two vertical and two lateral thrusters, the vehicle is designed for over 300 lbs. horizontal bollard pull. It weighs about 1200 lbs and is approximately 6 feet long by 4 feet wide by 3 feet high. This permits payload capabilities for a wide variety of tooling packages as well as a stable sonar platform.

## HANDLING SYSTEMS

The vehicle will be deployed from two locations. The upstream (dam) access is a vertical shaft with relatively convenient access for cranes and equipment. The downstream access is more difficult, as the vehicle must be deployed down a 100 meter equalization 'chimney' (see photo). This shaft is meant to provide for equalization of water pressure in the tunnel, with the result that water levels in the 'chimney' fluctuate and occasionally overflow. To contain this overflow, a 10 meter concrete wall surrounds the chimney area, making access to the top of the shaft difficult and, in the event of an overflow, dangerous for anyone caught inside. Experience with the ASI Pipeliner has taught that proper cable management is as critical to a successful inspection as vehicle performance is. For these reasons, it was decided that tether management systems, along with topside operations, would be located outside the chimney enclosure, and that a boom crane be used to deploy the vehicle.

## SURFACE SYSTEMS

All video data will be recorded onto SVHS video tape with simultaneous VHS backup. Collision avoidance sonar will also be recorded and displayed in video format, and profiling sonar data will be digitally encoded on SVHS (DAT). This allows for future manipulation of data being displayed such as magnification (zoom but not resolution) and dimensioning. This also means that edited video documents can incorporate and synchronize both sonar and video images on the same screen with vehicle sensor data, making future correlation and interpretation of information much more efficient.

## INSPECTION PROTOCOL

The tentative order of operations is as follows:

1) Preliminary shaft inspections at both ends (by DOE's HD2) to provide general reconnaissance and, in particular, to determine if debris is located at the base of either shaft which may hinder access to the tunnel proper.

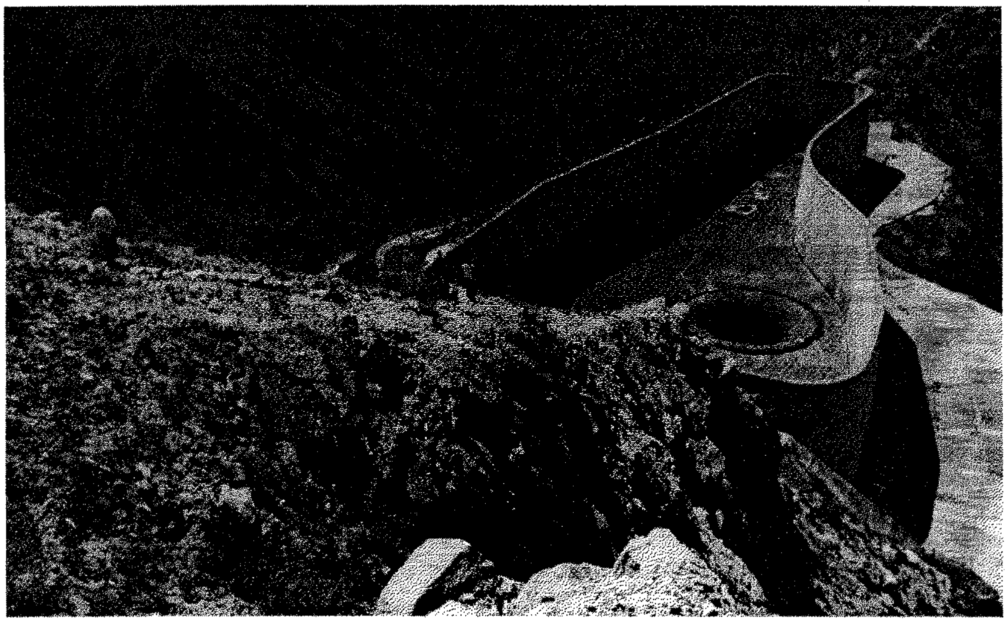
2) Downstream (chimney) access - penetration, 10 kilometres, plus cores at or near the 2 kilometre mark.

3) Upstream (dam) access - penetration, 10 kilometres.

It is estimated that the average speed of the vehicle, aside from stoppage for points of interest and sample collection, should be approximately 1 km/hr. This is because profiling sonar data is of little value past a given rate of travel since, even at the highest scan rate, a large percentage of the tunnel's inside surface would be missed.

Since retrieval of a severely fouled vehicle is not considered to be an option, the pilots will have to exercise extreme care, especially in low visibility conditions, to ensure that fouling does not occur. As umbilical strength has, to some degree, been sacrificed to keep the diameter small, there is not much (aside from the expensive process of dewatering) that can be done if the ASI Mantaro becomes badly stuck 10 kilometres deep inside a tunnel high in the Central Andes.

*This is the first of two articles about this project, which is unprecedented in the history of long tunnel inspections both in terms of scope and difficulty. The headrace tunnel inspection comprises the main part of a larger contract, which includes inspections of the reservoir dam, purge conduits, and aeration tubes, all of which are to be completed in the summer of 1995. This article will focus on the tunnel only, and is intended to provide background information and some insight into the problems associated with this undertaking. The second article, scheduled for the fall issue, will concentrate on project execution and inspection findings.* *The author wishes to thank Ian Griffith, ROV pilot and technician with ASI, for his assistance in the preparation of this article.*



Equalization 'Chimney' at down stream end of Headrace Tunnel, Mantaro Hydroelectric Facility