The identification and sealing of a leak in the Ardnacrusha headrace canal containment embankment

C. FITZPATRICK, ESB International, Ireland
T. A. HAYES, ESB, Ireland
S. P. M^{c}EVOY, ESB, Ireland

SYNOPSIS. The 11.5km headrace canal servicing Ardnacrusha Hydro Station in Co. Clare, Ireland, was constructed during the period 1925-1929. The canal is partly through rock cut but is largely contained by earthen embankments. Over the lifetime of the headrace, seepage problems have been remedied through leakage route detection and grouting programmes. This paper discusses the recent development of a significant leak and the thermal leak detection procedure adopted to identify the route of the leak through the embankment. The steps taken to seal the leak using gravity cement grouting are also described.

BACKGROUND AND DESCRIPTION OF SHANNON SCHEME

The River Shannon, approximately 340km long, is the longest Irish river. Rising in the Cuilcagh mountains in Co. Cavan, it flows through Lough Allen, Lough Ree and Lough Derg, entering the Atlantic Ocean at Kilrush in Co. Clare on the West coast of Ireland. The Shannon is notably flat with the only significant fall (approximately 30m), occurring on the 24km stretch between Killaloe and Limerick. The total storage of the Shannon River and lakes is approximately 600 million cubic metres. The average flow of the river at Killaloe is 180 m^3/s but this can vary from 10 to 15 m^3/s in dry summers to in excess of $750m^3/s$ in a major flood. The conventional design of a large storage basin formed by a high dam with a power station at its foot was not possible due to the topography of the area. Instead, the design involved the construction of a smaller dam or weir on the river upstream of the village of O'Briensbridge, five kilometres south of the town of Killaloe.

A canal was then constructed from the weir to the site of the power station at Ardnacrusha approximately 11.5km away. The canal follows the fall of the terrain, minimising the amount of material that was required for construction of the embankments on either side. At Ardnacrusha, the canal terminates in a 30m high dam, through which four penstocks, 6m in

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diameter, feed the water to the turbines, in the power station, at the foot of the dam. The water emerging from the power station is then carried by way of a tailrace canal (2.4km long), back to the River Shannon, approximately 3km upstream of Limerick City.

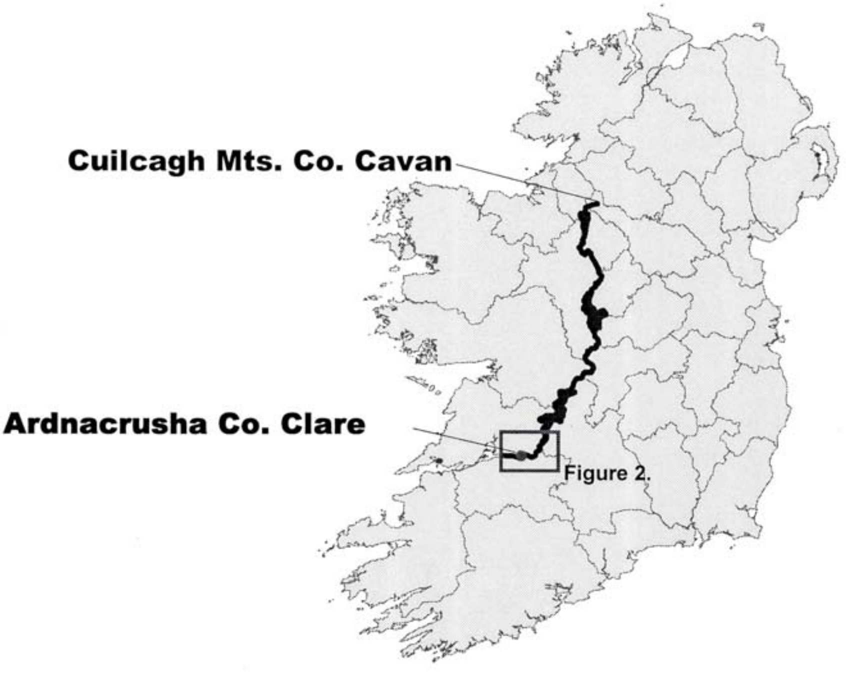

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Figure 1. River Shannon

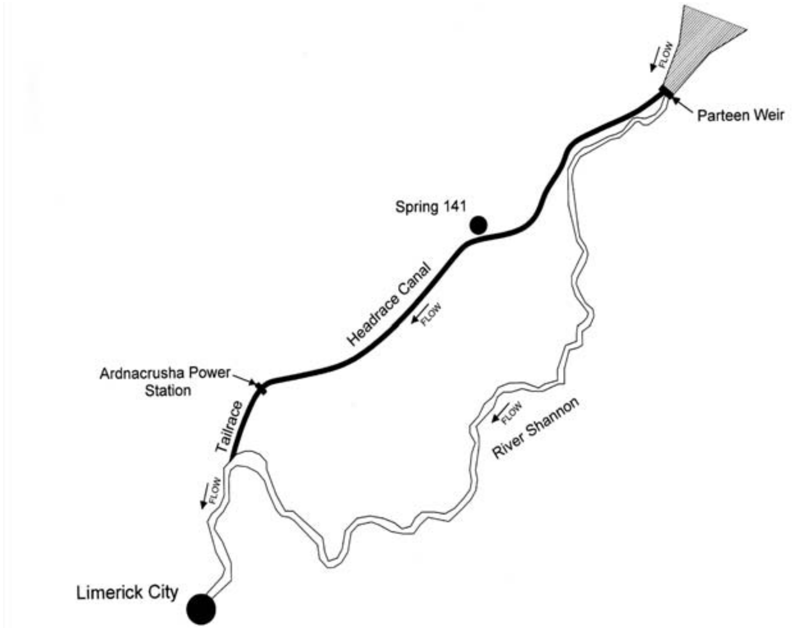

Figure 2. Layout of Shannon Hydroelectric Scheme

Headrace canal and seepage problems

The headrace canal is typically nine metres deep (Figure 3). In general the canal bed level is approximately 24.50m O.D. The minimum normal operating water level is 31.50m O.D. and the maximum normal operating level of the headrace is 33.50m O.D. The typical crest levels of both left and right embankments are 37.80m O.D. The canal bed and sides up to original ground level were given a 0.60m puddle lining on porous soils. Boulder clay and gravel for construction was drawn from several borrow pits and the embankment was tipped directly on original ground after the stripping of humus, roots and organic matter. The embankments were unlined; however, there is a concrete plating on the face of the embankments from 32.50m O.D. to 35.00m O.D. providing protection from wave action to the face of the embankment rather than to provide an impermeable seal.

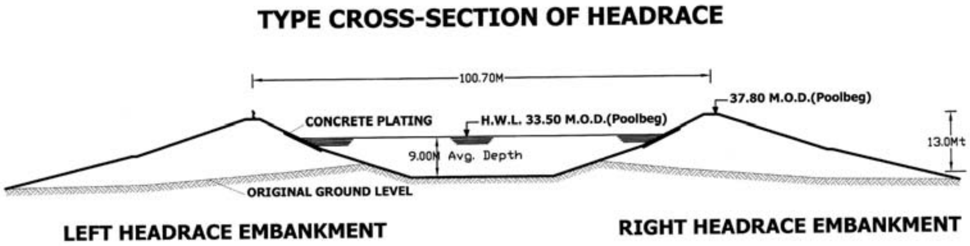

Figure 3. Typical Cross Section

Since the filling of the headrace, 142 occurrences of suspected seepage problems have been observed. In the past, a time consuming and sometimes fruitless method of seepage route detection was adopted, using water holding tests at intervals along the embankment in the vicinity of noted seepage locations. In many cases it was found that the seepage route was very concentrated and was only found through persistence or luck, requiring water holding tests at intervals as onerous as 0.1-0.2m. However, many leakage routes were identified using this method and were successfully sealed with grout. Over 20 grouting programmes have been completed on the headrace embankments since 1929.[1]

SPRING 141

In August 2006, a wet area was observed at the toe of the berm at C/s 251 and was labelled Spring 141. Spring 141 is located close to Errina syphon inlet in one of the natural valleys crossing the headrace. It was decided to construct a manhole at the base of the berm to collect the flow through the embankment. The flow was piped via a slotted land drainage pipe to a measuring point. The flow was measured daily and was observed to increase from approximately 0.3l/s to 0.6l/s in August 2007. The flow subsequently decreased substantially to approximately 0.1l/s in October

2007. When investigated it was discovered that the land drainage pipe had become blocked with a silty material. This provided evidence of a wash out of solids from the embankment with the flow. The land drainage pipe was replaced with a solid PVC pipe and the solids were collected at the measuring point and measured once weekly. The flow continued to be measured and was regularly observed to be flowing at a rate of approximately 0.9l/s. The total solids in the flow were estimated at 1 litre per week. When analysed against levels in the headrace, it could be determined that the flow in Spring 141 was influenced by levels in the headrace, increasing with high headrace levels and decreasing with low headrace levels (Figure 4).

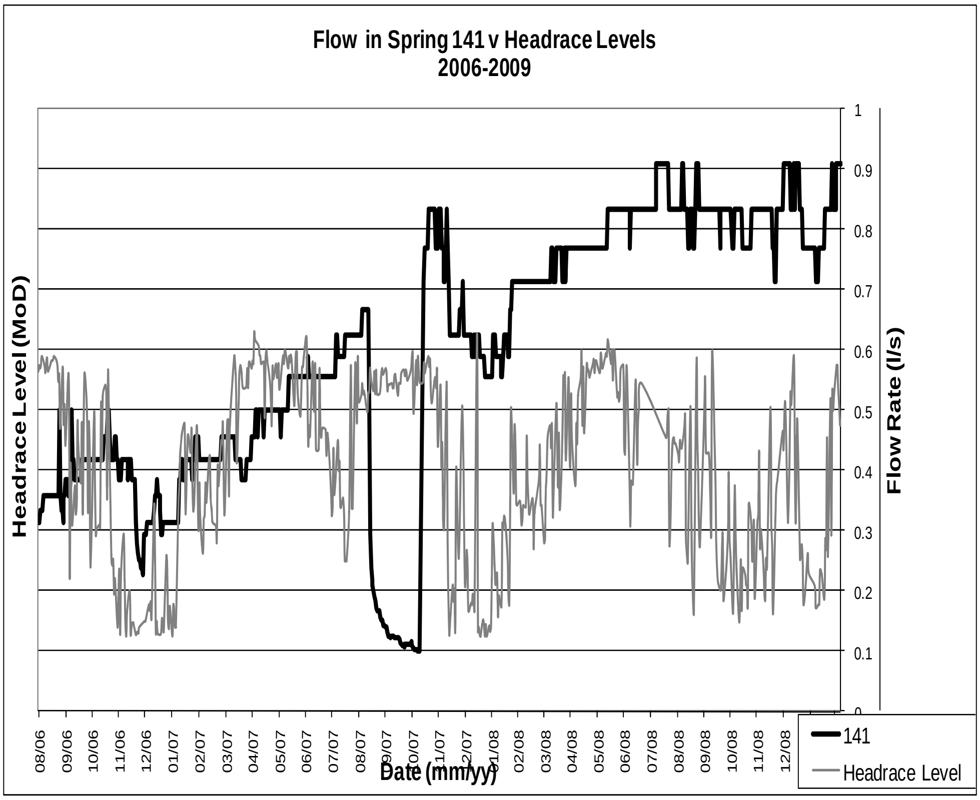

Figure 4. Plot of flow in Spring 141 against headrace levels

LEAK DETECTION

Preliminary Temperature Analysis

In January 2009, temperature measurements were taken of the flow in Spring 141, a nearby stream, air temperature, the headrace and a nearby groundwater spring (Spring 40). The results of these measurements are illustrated in Figure 5. From this preliminary analysis it was determined that the temperature of the water flowing in Spring 141 matched that of the headrace water. This provided evidence that Spring 141 was a leak from the headrace.

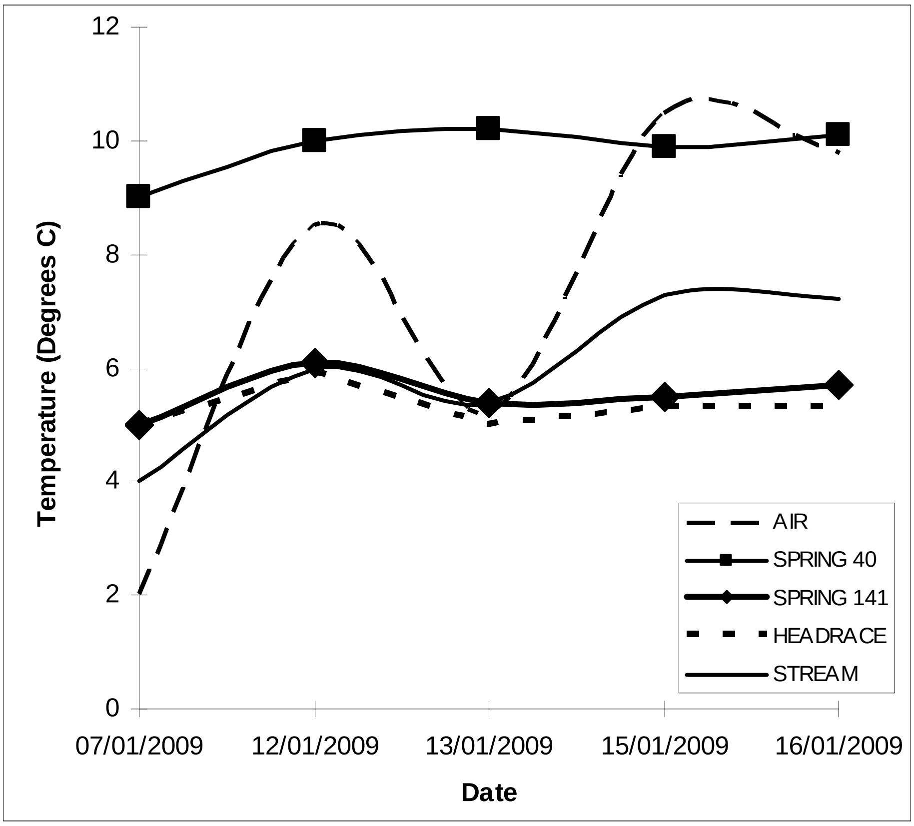

Figure 5. Plot of preliminary temperature analysis

Thermal leak detection

Following the initial evidence, provided from temperature analysis of the flow, GTC Kappelmeyer were contracted to perform ground temperature measurements to identify the path of the leak emerging at Spring 141.[2]

GTC Kappelmeyer developed and adopted a measurement technique that allows the measurement of temperatures to depths of up to 30m in embankment and dam structures. The data from these measurements is then used to track a flow of fluid through an embankment based on the following theory.

Temperature changes in surface waters and soil layers close to ground level (0-2m in depth) occur at approximately the same time as ambient temperatures. However, due to the low conductivity of the soil a phase shift between the occurrence of seasonal highs and lows in ambient temperatures and their occurrence within deeper ground layers takes place. Further, due to the heat capacity of soil, the seasonal temperature variations of the ground decrease with depth. During periods of cold ambient temperature a leak of reservoir water percolating through the embankment would be of a lower temperature than that of the soil through which it flows. However, the advective heat transport that is inevitably connected to the fluid flow leads to an adaption of the immediately surrounding soil temperature to the fluid temperature. Due to this adaption, seepage zones within an embankment are characterised by a negative temperature anomaly during the winter and a positive temperature anomaly during the summer. During spring and autumn, the difference between the temperature of the lower layers of the ground and the surface temperature is small; therefore the optimum time for use of thermal leak detection is during winter or summer months.[2]

GTC Kappelmeyer carried out their investigation from 10 - 14 February 2009, during a period of cold weather (-2°C to 5°C air temperatures). During the investigation a total number of 45 probes were rammed from the crest, berm, toe or top of plating level into the original ground level at the base of the embankment. These probes consisted of 22mm diameter hollow pipes containing a chain of temperature sensors spaced at 1m intervals, enabling measurement of the ground at these depths. The total depth of the probes varied from 5m to a maximum depth of 20m below ground level. The subsurface embankment material encountered by GTC was mainly boulder clay with occasional boulders. Previous investigations carried out by SWECO in the 1980s in this location also indicated the presence of gravel layers. The water temperature in the headrace varied during the investigation between 3.9°C and 4.2°C while the water temperature at Spring 141 was 4.4°C to 4.6°C.

The investigation revealed temperature anomalies in probes located on the crest, berm, toe and at the top of the concrete plating. On the crest, the anomalies were found at soundings at c/s 250+65m and c/s 250+70m with the maximum disturbance at c/s 250+65m at 9m depth below the crest (Figure 6). The berm profile showed temperature disturbances at soundings c/s 250+55m, c/s 250+57.5m and c/s 250+60m, with the maximum at c/s 250+57.5m in 6-7m depth below ground level. The temperatures at the toe of the embankment were anomalous at the soundings c/s 250+50m and c/s 250+52.5m with the maximum disturbance at c/s 250+50m at 2 to 3m in depth. The fourth profile, above the concrete plating, has disturbed temperatures at the soundings c/s 250+67.5m, c/s 250+70m and c/s 250+72.5m, with the biggest anomaly at c/s 250+70m in 5-6m depth below the top of the plating level. All other temperature disturbances within the investigated embankment sections were considered insignificant.

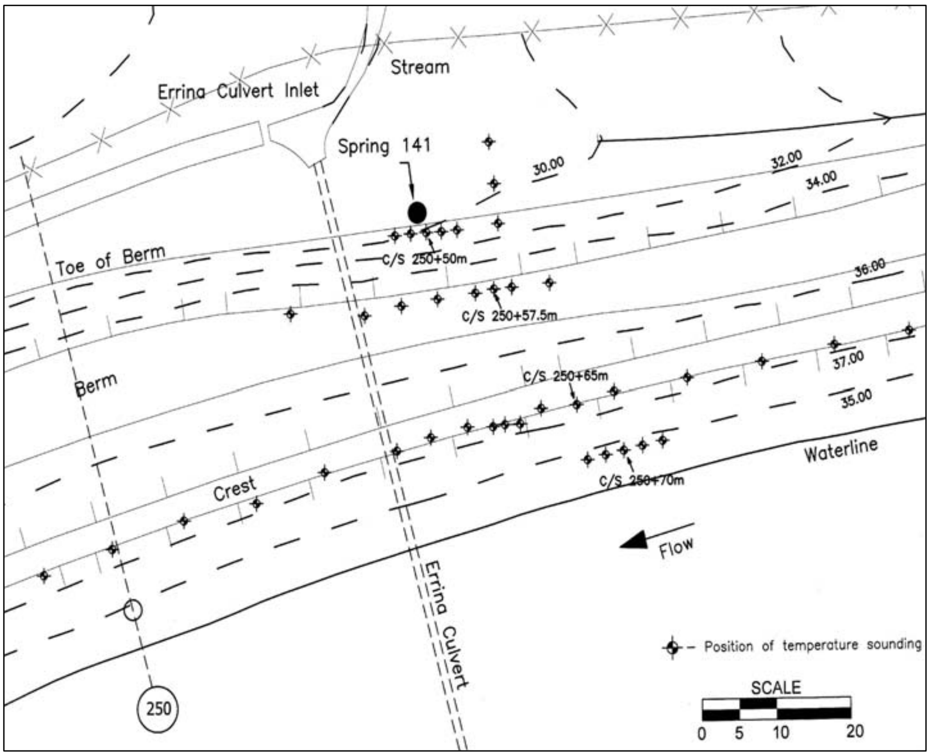

Figure 6. Temperature sounding locations

GTC Kappelmeyer concluded from the results of the investigation that the anomalies observed confirmed the presence of a leak through the headrace. Further, that due to the small lateral extent of the anomalies it could be assumed that the leak was fairly localised. Due to the very clayey nature of the embankment material in the vicinity of the leak, leakage water along its flow path was confined to a small area resulting in “piping”. The route of the leak was envisaged as water entering the embankment at approximately c/s 250+70m at a depth of 5m to 6m, directly above the original ground level and flowing on top of the original ground level in a fairly straight line and within a radially confined space to the area of “Spring 141”, where it emerged at the original measuring point, located in the manhole.

Water holding tests

In order to identify the optimum location to commence grouting of the leak it was decided to carry out water holding tests to establish a location with a strong connection to the leak. In early March 2009 a total number of 15 steel pipes (70mm internal diameter) were driven to 8.0m in depth from the top of the plating, on the waterside slope of the embankment. The first pipe was driven at c/s 250+70m, the cross section identified as the origin of the leak by the thermal investigation. A further six grout pipes were driven spaced at 500mm intervals, three upstream and three downstream of c/s 250+70m. The steel toe of each pipe, in situ for the purpose of driving, was knocked out and the pipes were subjected to constant head tests at 0.6m depth intervals and none displayed a drop in water level. It was decided to reduce the intervals to 250mm and tests were carried out at c/s 250+68.75m, c/s 250+68.25m, c/s 250+69.25m, c/s 250+69.75m, c/s 250+70.25m. When withdrawn, to a depth of 6.2m below ground level, the water level in the pipe at c/s 250+69.25m dropped. A further three grout pipes were driven at c/s 250+69.125m, c/s 250+69.375m and c/s 250+69.315m. When subjected to constant head tests, at depths between 6.2 and 7.1m, the water in all three pipes dropped at a steady rate. However, the response rate of the pipes located at c/s 250+69.375m and c/s 250+69.315m appeared to be faster, indicating a stronger connection to Spring 141.

The quality of the connection with the Spring was determined by adding fluorescent dye to the water in the grout pipe and timing the appearance of the dye at the manhole at the toe of the berm, where Spring 141 emerged. The pipe located at C/s 250+69.315m took the fluorescent dye and the dye appeared within seven minutes, faster than the response of any of the other connecting pipes (varying from 9 to 11 minutes). It was decided to use this pipe to commence grouting.

SEALING OF SPRING 141

It was decided to seal the leak with cement grout starting with pipe located at c/s 250+69.315m. Preparations were undertaken to carry out the grouting as follows:

- A working platform was constructed on headrace bank.
- An adequate supply of cement was secured.
- A staff rota was organised to ensure availability of staff for continuous work while grouting was in progress.
- A plant contractor was available.

At 08.00 on 12 March 2009 grouting commenced at a rate of 0.4 tons of cement per hour and a water to cement ratio of 3:1. Grouting continued for the following 31 hours at cement to water ratios and rates of input as detailed in Table 1 below. The flow observed in Spring 141 reduced significantly in the first five hours of grouting, reducing from 0.9l/s at 08.00 to 0.4l/s at 13.00 (Figure 6).

Table 1. Grouting sequence

Date	Time	Mix Ratio by Weight Water: Cement	Rate Tons/hr
12/03/2009	09:00 – 19:00	3:1	0.4
12/03/2009	19:00 – 24:00	3:1	0.2
13/03/2009	24:00 - 08:30	3:1	0.2
13/03/2009	08:30 – 11:30	3:1	0.1
13/03/2009	11:30 – 12:30	2:1	0.3
13/03/2009	12:30 – 13:30	1.5:1	0.4
13/03/2009	13:30 – 15:00	1.2:1	0.75

At 19:00 a decision was taken to slow down the rate of grouting. Again, at 08:30 the following morning it was decided to slow down the rate of grout input further. At this point, there were signs that the pipe upstream of the Spring 141 outlet was beginning to block up at times, but freeing itself every so often (Figure 6.).

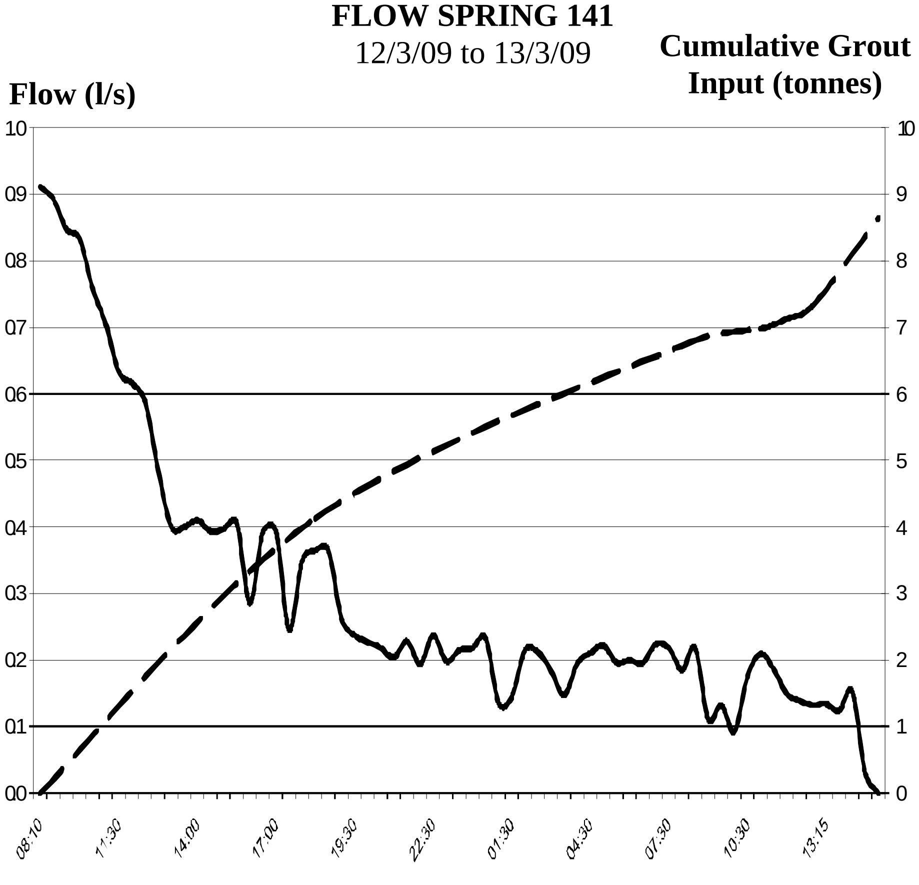

Figure 6. Plot of flow in Spring 141 against grout input

Because the slow-down in rate of grout input was not sealing the leak completely it was decided to thicken up grout at 11:30 and again at 13:30. The leak was completely sealed by 15:00. The total quantity of cement used up to this point was 8.64 tons.

Following sealing of the leak, pipe and manhole upstream of the leak, the other three pipes that had originally made contact with the leak were sealed using the thickest grout mixture, 1.2:1, and approximately 0.5 tons of cement were used to do this.

Spring 141 and area of headrace and berm in the vicinity of the spring have been observed closely since the leak was sealed, a period of almost eleven months. There is no longer any evidence of leakage at Spring 141.

CONCLUSION

Temperature measurements proved to be most advantageous in giving an early positive indication that the flow in Spring 141 was more than likely a leak from the headrace. The detailed thermal survey undertaken by GTC Kappelmeyer successfully identified the leakage flow path. Following the thermal survey, water holding tests could be undertaken in a localised area to determine the optimum position to commence grouting of the leak. The number of water holding tests required was considerably reduced and cement grouting was minimised resulting in a very cost efficient outcome.

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1. SWECO (1982), *Shannon Embankments Investigation Volume*. Commissioned report to ESB.
2. GTC KAPPELMEYER Gmbh (2009), *Ground Temperature Measurements for Leakage Detection, Ardnacrusha – Right Headrace Embankment*. Commissioned report to ESB.