A summary of the RAIU Investigation Report into the collapse of Malahide Viaduct on the 21st August 2009

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1. Accident events

On the 21st August 2009 as an Iarnród Éireann passenger service, travelling from Balbriggan to Pearse, passed over the Malahide Viaduct the driver witnessed a section of the viaduct beginning to collapse into Broadmeadow Estuary. Within minutes, Pier 4 of the Malahide Viaduct had collapsed into the Broadmeadow Estuary. Post accident emergency procedures were properly employed by the operating staff resulting in no fatalities or injuries to any members of the public or staff.

2. History of the Malahide Viaduct

The Dublin to Belfast railway line crosses the Broadmeadow Estuary, a tidal estuary, by means of embankment and the Malahide Viaduct, in summary, the history of the Malahide viaduct is as follows:

- Originally constructed in 1844 as an eleven span timber structure;
- By 1846, a 'virtual weir' was created as a result of stones being discharged along the viaduct to prevent scouring of the structure;
- In 1860, the timber structure was replaced by wrought iron lattice girder beams supported by eleven masonry piers founded on two stone fill foundation courses, constructed on the weir, see Figure 1;

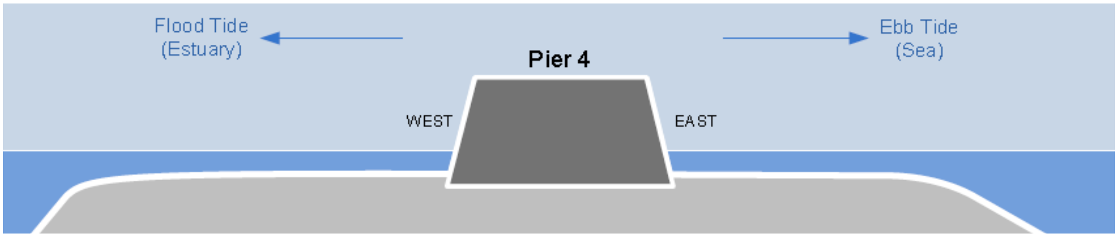


Figure 1 – Masonry pier constructed on weir

- In 1965, the girder beams were replaced by concrete beams, the new design specified removable handrailing which allowed for future discharges of stone along the weir,
- In 1967 – 1972, part of the weir was grouted to form a grouted rock apron, to prevent the continued damage as a result of persistent scouring at the piers, see Figure 2;

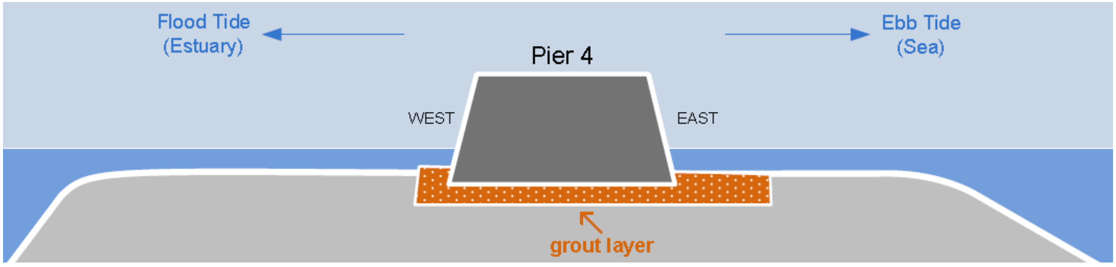


Figure 2 – Grout layer

- Despite the presence of the rock apron, stones continued to be discharged to maintain the profile of the weir, as erosion as a result of scouring was not rectified by the rock apron. There is no record of stones being discharged after 1996.

3. Mechanism of Failure

3.1 Introduction

To understand the mechanism of collapse it is important to consider the combination of the long, medium and short term events leading up to the date of the accident. To aid this understanding of events, physical models were created to determine the hydraulic and discharge characteristics of the weir, and to simulate the hydraulic mechanisms involved in the collapse.

3.2 Long term events leading to the collapse

The physical models, using simulated stones, showed that the stones were unstable and moved even when slightly dislodged. This movement of stones, simulated over a period of many years, resulted in the material being eroded from the crest of the weir; this process is generally referred to as winnowing. This erosion resulted in the weir's profile changing over the years from the original weir profile, a more elongated weir on the eastern side, illustrated in Figure 3. This would have been magnified by the fact that there was more stones to be eroded as the weir crest was being replaced by IÉ, through the continued discharge of stones.

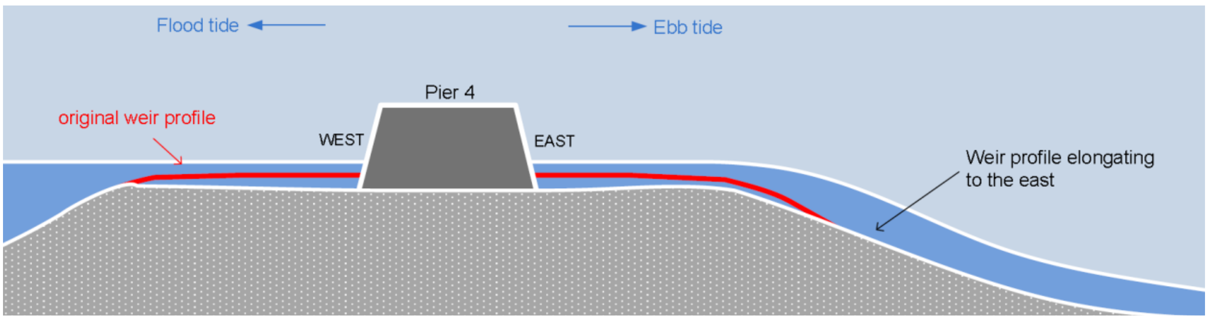


Figure 3 – Weir elongating to the east due to erosion

3.3 Medium term events leading to the collapse

3.3.1 Erosion – General

The stabilisation by the grouted rock armour was proved successful by the absence of observed scouring or potholing after the storms in February 1969, and the elongated profile on the east remained, (see Figure 4).

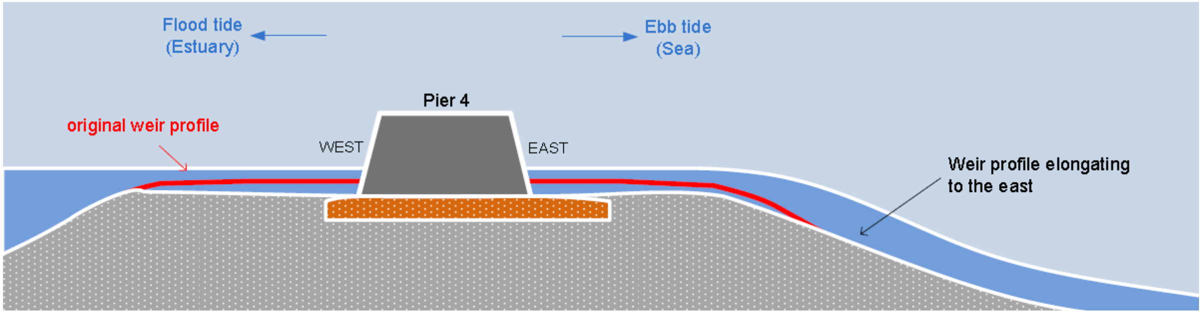


Figure 4 – Stabilising of weir profile as a result of grout

However, the grouted rock armour began to break down as a result of degradation of the grout (the grout on the west side remained semi-intact). This led to further transport of stone and grout from the weir crest. However, with the non-replacement of stones to the crest of the weir, since 1996, further erosion resulted under the eastern side of the pier, (see Figure 5).

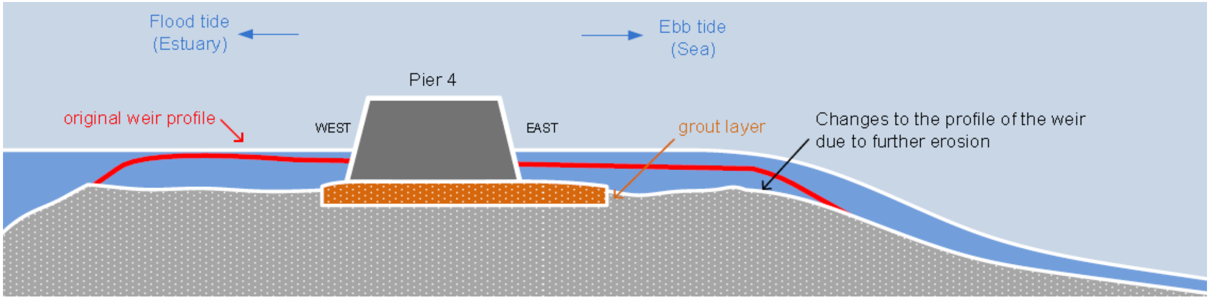


Figure 5 – Erosion of the weir

3.3.2 Erosion – Hydraulic jump

For water travelling over a weir, the flows of the water alter as a result of pressure changes, altering the velocity and energies of the water flow. For water to travel over a weir, the flow begins at sub-critical flow on one side of the weir and must return to sub-critical on the other side of the weir; in order to achieve this the flows become critical and super-critical over the weir crest. The change from super-critical to sub-critical is not smooth and which causes a vigorous turbulent mixing action, know as hydraulic jump (see Figure 6).

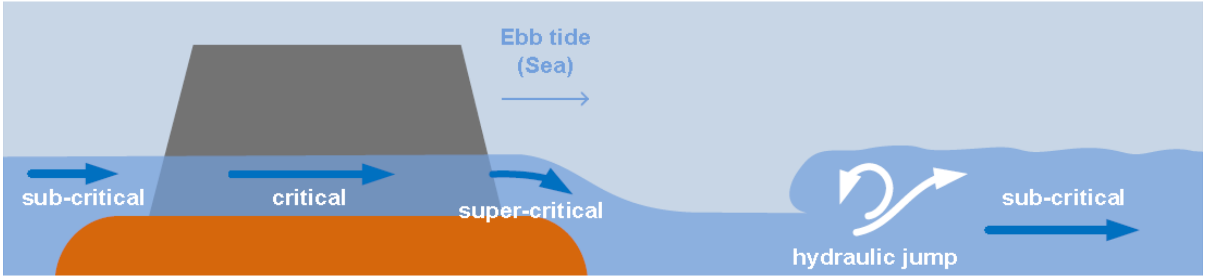


Figure 6 – Critical flows and hydraulic jump

However, the models, simulating the high spring ebb tide flow rate, showed that when the tide reached certain critical levels on the eastern side, a hydraulic jump formed between Pier 4 and Pier 5, the location of the collapsed pier, see Figure 7.

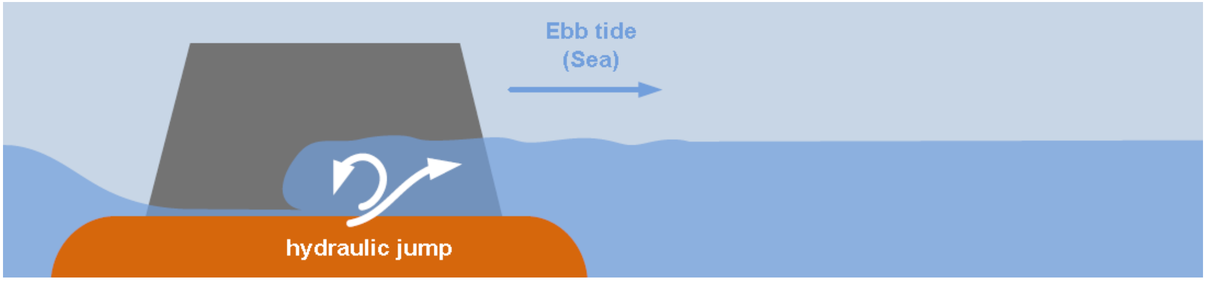
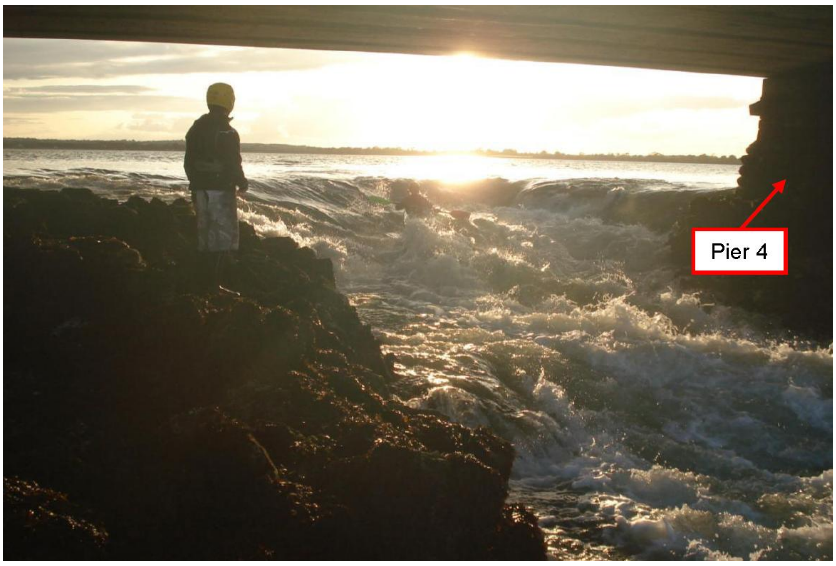


Figure 7 – New position of hydraulic jump, between piers 4 and 5

The turbulence from the hydraulic jump at the mid-point of Pier 4 would have meant that the stones were being eroded from the crest of the weir, with the stones being deposited on the eastern side of the weir, further elongating the weir profile. This erosion caused the area between piers 4 and 5 to deepen forming a channel, (see Photograph 1).

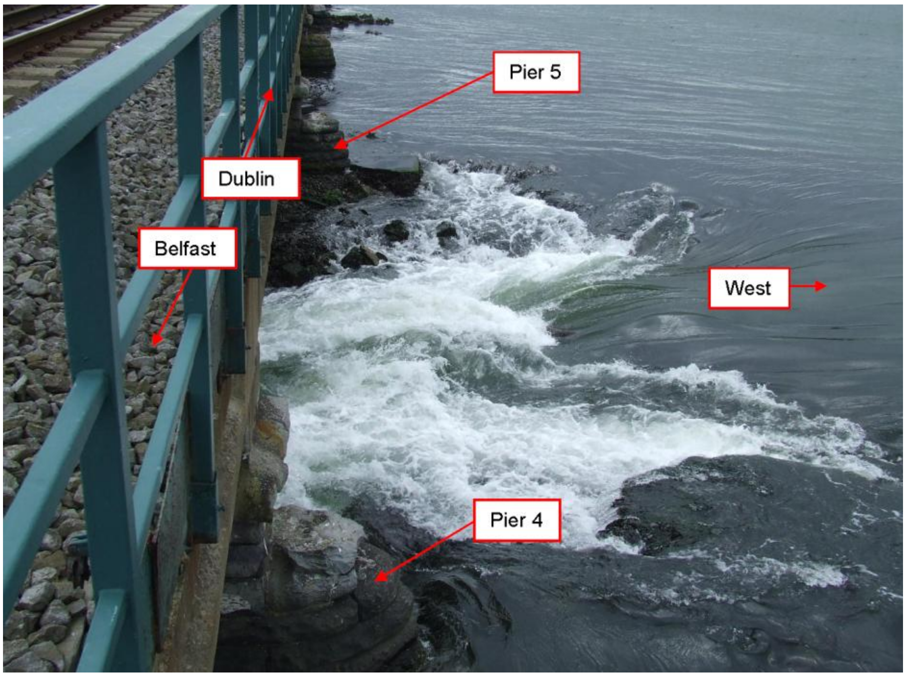


Photograph 1 – Deepened channel through Piers 4 and 5

This resulted in the majority of the water was flowing through this channel during the latter part of the ebb tide cycle, (the flow of water would normally be evenly distributed through all twelve spans). As a result of the channel and the erosion of the crest of the weir, the potential for the winnowing of smaller stones from the weir was now increased.

3.3.3 Short term events leading up to collapse

On the morning of the 17th August 2009, a canoeist, who regularly canoed in the Broadmeadow Estuary, noticed that some of the stones around the base of Pier 4 had been washed away, and he reported this to Iarnród Éireann on that day (four days before the accident). The reported washing away of stones would indicate that the erosion mechanism had accelerated and the stones close to the foundations of Pier 4 had started to be displaced on the western side of the weir. This can be verified from the photograph taken by Iarnród Éireann during the structural inspection on the 18th August 2009, (three days before the accident), see Photograph 2. It can be seen, from the photograph, that the ebb flow hydraulic control point had moved further west at Piers 4 and 5. This suggests that serious erosion was occurring in the months leading up to the collapse of the viaduct, confirming the flow was accelerating over the crest, resulting in high velocities upstream of the western foundations of Pier 4.



Photograph 2 – Photograph taken three days before the accident

The narrowed flow path (through the channel) and the remaining semi-intact grout rock armour on the western side meant there was an increased potential for piping. Piping occurs when there is a sub-surface formation and progression of a continuous ‘pipe-like’ tunnel. The material is eroded by the flow of water through the tunnel, which then carries way these eroded particles, (see Figure 8).

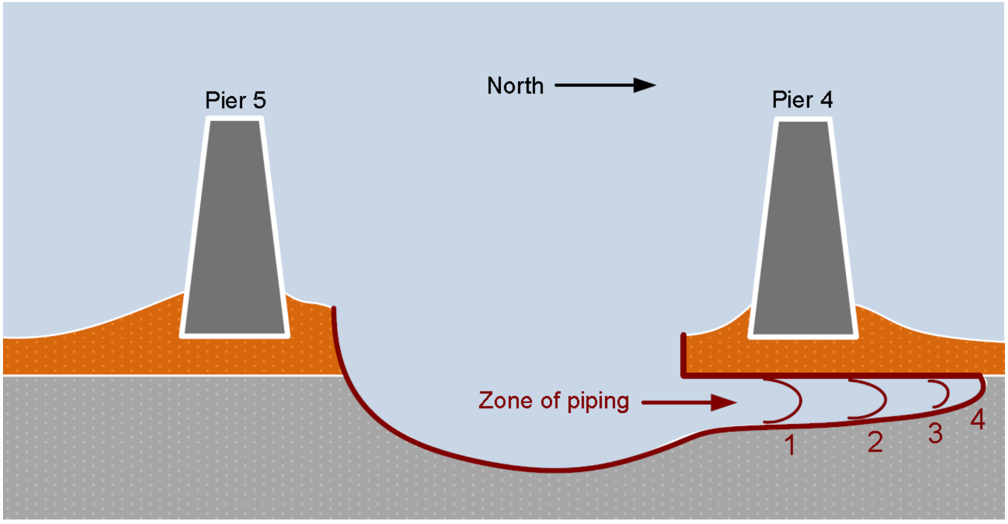


Figure 8 – Piping under Pier 4

The piping flow path was under the remaining grout layer on the west side of the weir with the grout layer acting as an upper boundary to the flow pipe, causing undermining of Pier 4 (see Figure 9).

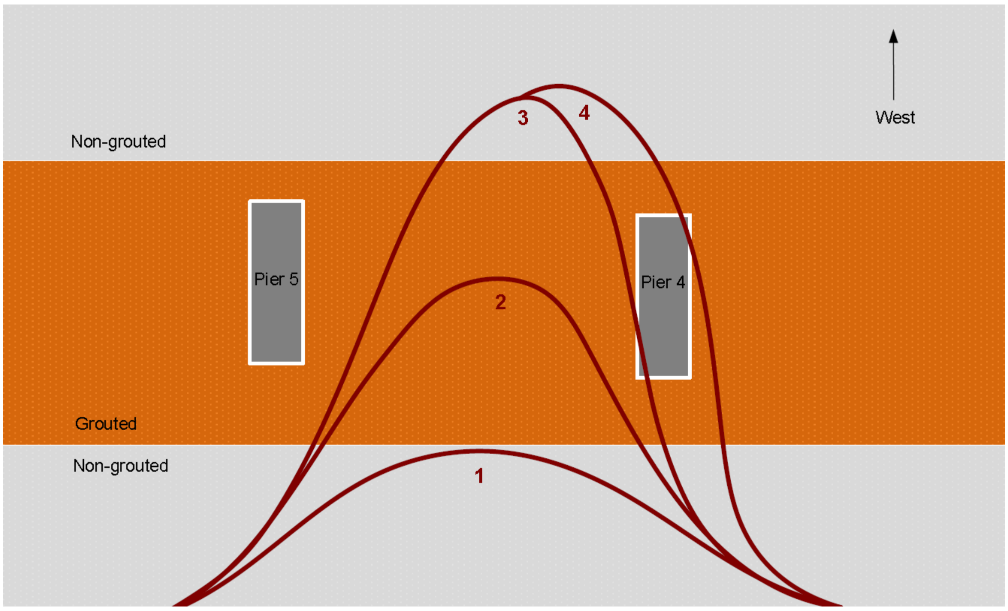


Figure 9 - Undermining of Pier 4 as a result of piping

The red lines 1 – 3 in Figure 9, illustrate the general westward propagation of the hydraulic jump where the grouted and non-grouted weir material has been removed by the scour action (as occurred in the medium term events), the addition of red line 4 indicates the post collapse zone of the 'piped' scour that undermined the grout apron.

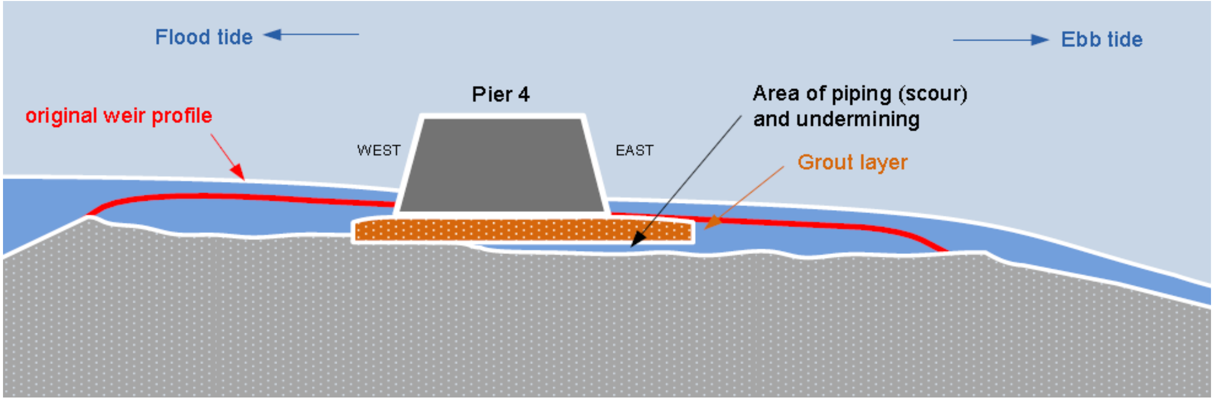


Figure 10 – Piping and undermining

4 Causes of the accident

4.1 Immediate cause

Section 3 of this paper, describes the immediate cause of the collapse of Pier 4, which was as a result of the undermining of the weir that surrounds and supports Pier 4 through the action of scouring. This was as a result of a combination of factors:

- An inspection carried out on the Malahide Viaduct three days before the accident, after a report of a defect from the canoeist, did not identify the scouring defects visible at the time, see Photograph 2;
- A scour inspection undertaken in 2006 by diving engineer consultants, did not identify the Malahide Viaduct as a high-risk structure to the effects of scouring;
- Iarnród Éireanns likely failure to take any action after an independent inspection carried out on the Malahide Viaduct in 1997 identified that scouring had started at the base of Pier 4 and that the rock armour weir was "too light for the job";
- The historic maintenance regime for the discharge of stones along the Malahide Viaduct appears to have ceased in 1996, resulting in the deterioration of the weir which was protecting the structure against scouring.

4.2 Contributory factors

The above factors were necessary for the accident to happen. Contributory to the accident happening were the following factors:

- Iarnród Éireann had not developed a flood/scour management plan at the time of the accident, despite independent safety reviews carried out in 2001 and 2006 by two separate independent consultants, recommending that this plan be developed. Contributory to Iarnród Éireann not developing this flood/scour management plan was the fact that the Railway Safety Commission closed this recommendation in 2008;

- Engineers were not appropriately trained for inspection duties, in that the inspections training course they completed was an abridged version of the intended format, and there no formal mentoring programme, for Engineers on completion of this course;
- There was a shortfall in Iarnród Éireann's suite of structural inspection standards in that a standard which provided guidance for inspectors in carrying out inspections was not formalised;
- There existed an unrealistic requirement for patrol gangers to carry out annual checks for scour, as they do not have access under the structure and in addition, they did not have the required specialist training/ skills to identify defects caused by scouring;
- A formal programme for Special Inspections for structures vulnerable to scour was not adopted, as per Iarnród Éireanns's Structural Inspections Standard, I-STR-6510, at the time of the accident.

4.3 Underlying factors

Underlying factors to the accident were:

- There was a loss of corporate memory when former Iarnród Éireann staff left the Division, which resulted in valuable information in the relation to the historic scouring and maintenance not being available to the staff in place at the time of the accident;
- There was a dearth of information in relation to the Malahide Viaduct due to Iarnród Éireanns failure to properly introduce their information asset management system;
- Iarnród Éireanns inadequate resourcing of Engineers for structural inspections to be carried out at the Malahide Viaduct;
- Iarnród Éireanns failure to meet all the requirements of their Structural Inspections Standard, I-STR-6510, in that:
    - Visual inspections were not carried out for all visible elements of structures;
    - Bridge Inspection Cards, for recording findings of inspections, were not completed to standard or approved by the relevant personnel;

- A formal programme for systematic visual inspections of all elements of a structure, including hidden or submerged elements, despite an independent review recommending that Iarnród Éireann implement this programme in 2006.

5 RAIU Recommendations

As a result of the findings of this RAIU investigation, the RAIU have made fifteen safety recommendations. Thirteen safety recommendations have been made to Iarnród Éireann, one safety recommendation has been made to the Railway Safety Commission, and one joint recommendation has been made to Iarnród Éireann and the Railway Safety Commission. The recommendations are as follows:

Recommendation 1

Iarnród Éireann should put appropriate interface processes in place to ensure that when designated track patrolling staff (who report to two or more divisional areas) are absent from their patrolling duties, that appropriate relief track patrolling staff are assigned to perform these patrolling duties.

Recommendation 2

Iarnród Éireann should amend the Track Patrolling Standard, I-PWY-1307, to remove the requirement for track patrollers to carry out annual checks for scour.

Recommendation 3

Iarnród Éireann should formalise their ‘Civil Engineering and Earthworks Structures: Guidance Notes on Inspections Standard’, I-STR-6515, which should include guidance for inspectors on conducting inspections and identifying structural defects. On formalising this document Iarnród Éireann should re-issue, in the appropriate format, to all relevant personnel.

Recommendation 4

Iarnród Éireann should introduce a verification process to ensure that all requirements of their Structural Inspections Standard, I-STR-6510, are carried out in full.

Recommendation 5

Iarnród Éireann should ensure that a system is put in place for effective implementation of existing standards and to manage the timely introduction of new and revised standards.

Recommendation 6

Iarnród Éireann should ensure that a programme of structural inspections is started immediately in accordance with their Standard for Structural Inspection, I-STR-6510, and ensure that adequate resources are available to undertake these inspections.

Recommendation 7

Iarnród Éireann should carry out inspections for all bridges subject to the passage of water for their vulnerability to scour, and where possible identify the bridge foundations. A risk-based management system should then be adopted for the routine examination of these vulnerable structures.

Recommendation 8

Iarnród Éireann should develop a documented risk-based approach for flood and scour risk to railway structures through:

- Monitoring of scour risk at sites through scour depth estimation, debris and hydraulic loading checks, and visual and underwater examination;
- Provision of physical scour / flood protection for structures at high risk;
- Imposing of line closures during periods of high water levels where effective physical protection is not in place.

Recommendation 9

Iarnród Éireann should adopt a formal process for conducting structural inspections in the case of a report of a structural defect from a member of the public.

Recommendation 10

Iarnród Éireann should introduce a training, assessment and competency management system in relation to the training of structural inspectors, which includes a mentoring scheme for engineers to gain the appropriate training and experience required to carry out inspections.

Recommendation 11

Iarnród Éireann should review their network for historic maintenance regimes and record this information in their information asset management system. For any future maintenance regimes introduced on the network, Iarnród Éireann should also record this information in their information asset management system.

Recommendation 12

Iarnród Éireann should incorporate into their existing standards the requirement for the input of asset information into the technical database system upon completion of structural inspections.

Recommendation 13

Iarnród Éireann should carry out an audit of their filed and archived documents, in relation to structural assets, and input this information into their information asset management system.

Recommendation 14

The Railway Safety Commission should review their process for the closing of recommendations made to Iarnród Éireann by independent bodies, ensuring that they have the required evidence to close these recommendations. Based on this process the Railway Safety Commission should also confirm that all previously closed recommendations satisfy this new process.

Recommendation 15

The Railway Safety Commission, in conjunction with Iarnród Éireann, should develop an action plan in order to close all outstanding recommendations in the AD Little Review (2006) and the IRMS Reviews (1998, 2000, 2001). This action plan should include defined timescales for the implementation and closure of all these recommendations.

6 Further information

The full investigation report carried out by the RAIU is available at www.raiu.ie