University of Southern Queensland

Faculty of Engineering and Surveying

BURDEKIN FALLS DAM

INVESTIGATION OF THE STRUCTURAL INTEGRITY OF THE OUTLET WORKS RADIAL GATE AND FIXED WHEEL GATE UNDER EMERGENCY CLOSURE SITUATIONS

A dissertation submitted by

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ABSTRACT

Burdekin Falls Dam is Sunwater's primary water storage for North Queensland. With a total storage of 1,860,000 ML, it is the largest water reservoir in Queensland, capable of supplying 1,000,000 ML of water per annum.

During the 1991 routine safety inspection of the dam it was observed that the radial gate vibrated considerably when operated in conjunction with the fixed wheel gate.

This project aims to determine the likely source and cause of observed vibrations in the radial gate through scale hydraulic modelling and to develop recommendations and plans to reduce the vibration and remove the possibility of damage to the gates.

Specific project activities include:

- Scale hydraulic modelling of the radial gate and fixed wheel gate.
- Investigating formation of flow through the outlet works and its effect on the radial gate during installation of the fixed-wheel gate under emergency closure.
- Recommending relevant modifications to the gate or structure to alleviate adverse findings from the modelling work.

A 25:1 scale model of Burdekin Falls Dam outlet system was constructed at the SunWater Hydraulics Laboratory, Rocklea and used for flow behaviour experiments.

Discharge from the outlet works went through five distinct flow patterns as the fixed-wheel gate was lowered against flow. Each of these flow patterns formed during a set combination of radial and fixed-wheel gate opening positions.

The resulting impacts of these distinct flow patterns on the structure were recorded visually and by pressure transducers. The transducer data was analysed using the computational program, MatLab.

The results show that the radial gate is required to resist considerable pressure fluctuations. Vibration appears to be related to these pressure fluctuations within the outlet outworks. The data was insufficient to show if there was a dominant or resonant frequency.

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Limitations of Use

CERTIFICATION

I certify that the ideas, design and experimental work, results, analyses and conclusions set out in this dissertation are entirely my own effort, except where otherwise indicated and acknowledged.

I further certify that the work is original and has not been previously submitted for assessment in any other course or institution, except where specifically stated.

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Signature

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Date

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Model technician - Malcolm Lawless

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TABLE OF CONTENTS

LIST OF APPENDICES

INTRODUCTION

The development of various flow patterns and their resulting forces through hydraulic structures can lead to many desirable and many undesirable effects. The consequences of the undesirable effects can range from the slightly annoying to catastrophic. The regulating outlet valve or radial gate at Burdekin Falls Dam in North Queensland, Australia, has been observed during a simulated emergency closure operation to react unfavourably to the hydraulic forces and flow patterns developed within the conduit of the dam. These unfavourable effects manifested themselves as vibrations within the radial gate structure.

A requirement from the owners of the dam, SunWater, is that the dam be well maintained to ensure a high level of performance and integrity. Failure of the radial gate due to vibration could expose SunWater to Political, Corporate, Community, Environmental, and Workplace, Health and Safety risks.

Following these initial observations an inspection of the radial gate structure revealed that some minor damage occurred to the mounting arrangement, but as the gate was exposed to these forces only briefly, the damage was easily repaired. The purpose of this report is to undertake a more detailed investigation of the flow patterns and hydraulic forces generated during an emergency closure. The conditions generating adverse flow patterns and the extent and timing of forces generated by them must be determined before decisions can be made about the capacity of the system to be operated safely and reliably, and before considering modifications to the structures themselves. By modelling the flow through the gates (the likely source and cause of the observed vibrations) and determining when and how particular adverse flow patterns are developed and what forces are produced by them, it may be possible to make recommendations on how to alleviate the potentially damaging vibrations observed.

The investigation of the flow pattern developed within the outlet works required that a background review of the dam design and construction be undertaken, followed by a comprehensive literature review to ascertain if similar events have occurred elsewhere in similar dam structures. A 25:1 scale hydraulic model was constructed in order to study the flow patterns and hydraulic forces reacting with the radial gate.

The method of hydraulic modelling used was based on the Froude relationship, which allows investigation of the dynamic similarity of the inertial forces and the gravitational forces causing flow patterns to develop.

NOTATION

L	Length (m)
ρ	Density (kg/m^3)
Δp	Pressure drop (m of H_2O)
g	Gravity (m/s^2)
μ	Dynamic viscosity (Pa·s)
V, v	Velocity (m/s)
S	Coefficient of surface tension (N/m)
E	Fluid bulk modulus (MPa)
h	Head of water (m)
C	Bernoulli's Constant

1.0 BACKGROUND

1.1 BURDEKIN FALLS DAM

1.1.1 General

Burdekin Falls Dam is the primary water storage for the Burdekin Water Supply Scheme and is located approximately 150 km south-west of Townsville in North Queensland on the Burdekin River, AMTD 159.3 km.

Table 1

Burdekin Falls Main Dam: properties

Catchment Area	114 200 km^2
Type of Dam	Mass Concrete Gravity Dam
Average Annual Rainfall	620 mm
Full Supply Level (FSL)	EL. 154
Storage Capacity at FSL	1 860 000 ML
Inundated Area at FSL	22 000 ha
Dead Storage Level	EL. 130
Total Length of Main Dam	876 m
Total Length of Spillway	504 m
Spillway Crest Level	EL. 154
Height of Spillway Crest above River Bed	37 m
Total Volume of Concrete	620 000 m^3
Outlet Regulator Gates	3 – 3 m x 2 m High Pressure Radial Gates (6.5 T)
Outlet Guard Gate	1 – 3.6 m x 2.47 m Fixed Wheel Gate (10 T)
Emergency Bulkhead Gate	1 – 6 m x 4 m Baulk (10 T)

(*Design Report Burdekin Falls Dam* 1985)

With a total storage of 1,860,000 ML it is the largest water reservoir in Queensland and capable of supplying 1,000,000 ML per annum to the Lower Burdekin Irrigation Area centred on the town of Ayr, approximately 130 km downstream of the dam. It was built to supply water for:

- The irrigation of sugar cane and rice crops in the Lower Burdekin.
- Additional irrigation supplies for existing sugar cane crops along the Haughton River.
- Further agricultural development and the increase in urban and industrial development in the region generally. (Wickham & Russo 1983)

In addition to these original water supply priorities, Burdekin Falls Dam has also been investigated for various hydroelectric power station options and is currently designated as the preferred source of additional water to the Bowen coal fields.

The dam was designed with the provision to increase the storage to full supply level El. 168.4 (+ 14.4 m) by the use of spillway radial gates. This would increase the total storage by an additional 8,900,00 ML.

1.1.2 Outlet Works

The outlet works of Burdekin Falls Dam is comprised of three outlets located on the left bank of the main dam. The design criteria for the outlets were (*Design Report Burdekin Falls Dam* 1985)

- The annual yield at Clare Weir (approximately 130 km downstream) was taken as the required release capacity to be delivered in 100 days. The yield was assessed at 1,000,000 ML for Stage I which required a capacity of 125 m^3s^{-1}.
- The required outflow of 125 m^3s^{-1} must be capable of being released through one outlet when the reservoir is at a level corresponding to 50% of capacity.
- The required outflow of 125 m^3s^{-1} must also be capable of being released through two outlets when the storage is 3 m above dead storage level.
- A third outlet was required to cater for a potential hydroelectric power station.

The final arrangement of the outlet works consisted of three mild steel lined conduits each regulated by a 3 m x 2 m high pressure radial gate controlled by a hydraulic cylinder (Allen 1984). Sealing of the gate is accomplished by pressing the gate onto seals fixed to the outlet conduit by a second hydraulic cylinder turning an excentric trunnion support shaft. Before the gate is moved this cylinder retracts the gate from the seal and after the required opening is obtained the gate is pressed back onto the seal. The hydraulic control system insures that the radial gate cannot be left off the seal after moving the radial gate.

Emergency closure of an outlet is affected by a fixed-wheel gate, designed to close under full flow. There is one gate to service all three outlets. A travelling gantry positions the gate over the required outlet and it is then lowered using a wire cable winch.

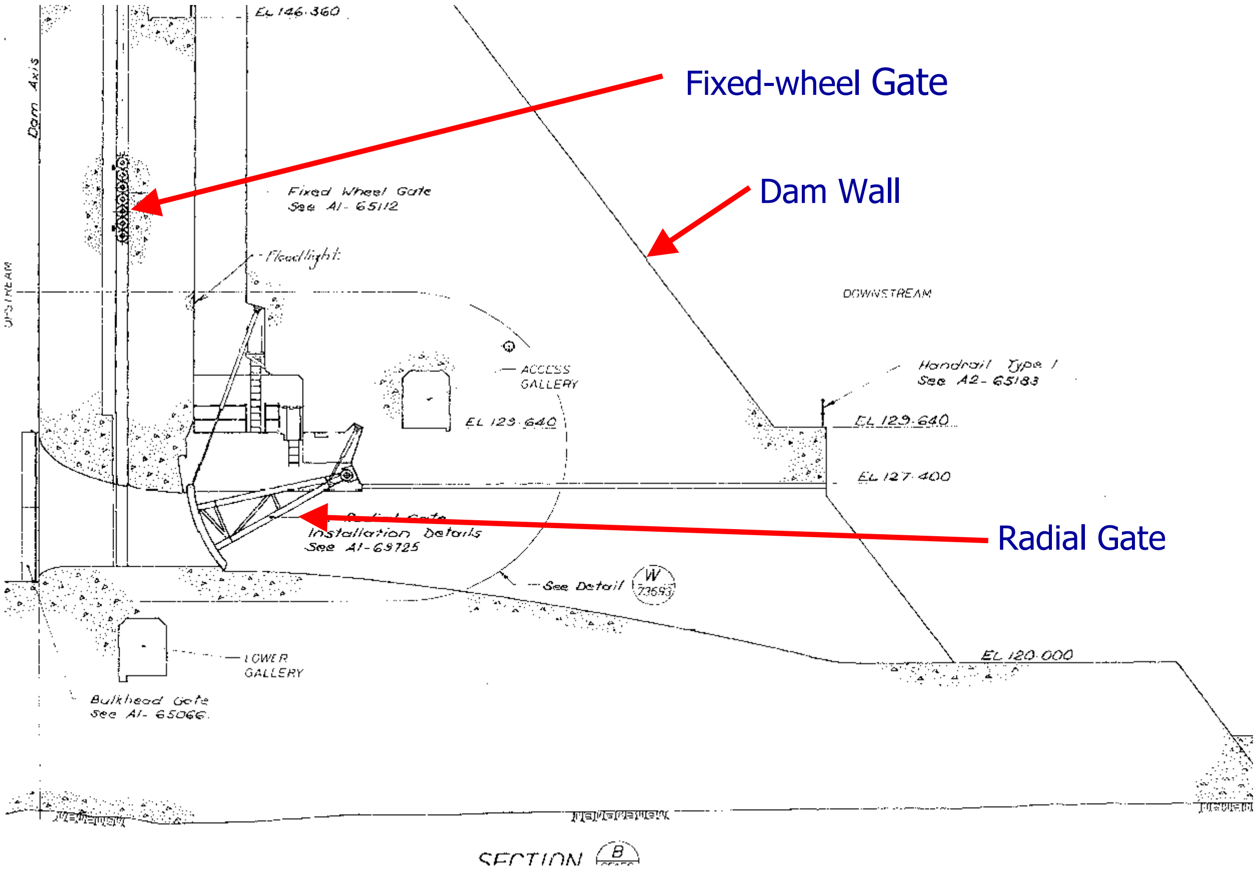

Figure 1. – General Arrangement of Burdekin Falls Dam

(Refer Appendix B - Drawing 65161 & others)

To seal the outlet conduit for maintenance or inspections, a large mild steel bulkhead gate is lowered down the upstream face of the main dam wall, sealing the bellmouth intake. This can only be done under a zero flow situation.

1.1.3 Source of Investigation

During a dam safety inspection of Burdekin Falls Dam it was observed that the radial gate located in the irrigation outlet works vibrated considerably when operated in conjunction with the fixed-wheel gate.

"Radial gate No.2 was left in the 50% open position and the fixed wheel gate closed against flow. During the closure there were violent cavitation explosions and the radial gate vibrated considerably, with the movement visible from the access platform between gates 1 and 2 (measurements not taken)."

Under the conditions of the inspection, i.e. poor lighting in radial gate gallery and water jets obscuring vision, it can be assumed that the amplitude of the vibration was quite appreciable and the frequency fairly low (Read 2004). In order for the radial gate to vibrate when in the locked position the radial gate arms plus the hydraulic cylinder and eccentric locking arrangement would have to deflect, possibly causing damage to the radial gate hub and trunnion bearing arrangement and to the hydraulic cylinder locking arrangement .

As SunWater's largest dam and the primary asset for the Burdekin River Water Supply scheme, with potential for hydroelectric power generation, it is important that the dam be well maintained to ensure a high level of performance and integrity. These factors are paramount to the dam's success.

The failure of the radial gate due to vibration would have the following broad risks associated with it:

- Political – there would be major adverse political and media impacts.
- Corporate – the major failure of a primary asset would pose a serious threat to the operations, viability and reputation of SunWater. Legal impacts such as compensation for damages, personal injury and financial loss could be high.
- Social – would remove community confidence in SunWater activities. The organisation would find it difficult to recover initiative and community support.
- Economic / financial – loss of productivity and income of producers dependent upon the dam's resources; this would reverberate through primary industry value-chains with potential bankruptcies and major social and economic upsets.
- Environmental – potential significant environmental harm, particularly downstream, with long-term recovery prospects.

- Workplace, Health and Safety – potentially very dangerous for staff working in the vicinity of the gates.

1.2 RESEARCH OBJECTIVES

The aim of this project is to determine through scale hydraulic modelling the likely source, cause and extent of the forces inducing the observed vibrations in this system so that recommendations can be made, if necessary, for alleviating the potentially damaging gate-structure vibration, or avoiding the problem in dam outlets of this type built in the future.

1.3 SCOPE

Specific project activities will include:

- Review of literature for reported concerns in similar hydraulic gate structures in Australia or elsewhere.
- Review of original Burdekin Falls Dam literature.
- Review of hydraulic gate structures, vibration in hydraulic gate structures and hydraulic modelling methods.
- Scale hydraulic modelling of the outlet structure incorporating both the radial gate and fixed-wheel gate.
- Investigation of formation of flow through the model outlet works and its effect on the radial gate during operation of the fixed-wheel gate under emergency closure situation.
- Determination of effects of pressure changes in outlet conduit and at the radial gate.
- Analysis of results with the goal of developing plans to remove or reduce the possibility of damage due to vibration.
- Recommendations for relevant modifications to the gate and associated structures to alleviate adverse findings from the modelling if required.
- Proposals for safe operating procedures in the event of an emergency shut-down of the outlet works.

2.0 LITERATURE REVIEW

2.1 INTRODUCTION

The literature review for this research focused on finding relevant information regarding the Burdekin Falls Dam hydraulic gates, existing hydraulic gate design and theories regarding radial and fixed-wheel gates. Searches were conducted for reports or research conducted on vibration problems in other similar structures. Also, a review was conducted of hydraulic modelling methods, including computer-aided modelling and physical scale modelling.

2.2 SIMILAR HYDRAULIC GATE STRUCTURES

An extensive review of hydraulic systems and hydraulics was undertaken as part of this research. During this literature review no report of a similar problem in the same gate arrangement was located. There were many references to vibration of radial spillway gates (termed "Tainter" gates in the USA) usually due to underflow or vortex induced vibrations caused by poor lip geometry (*Gate Vibration* 1987; Sehgal 1996).

Eduard Naudascher (Naudascher 1991) provides considerable information on and references to hydraulic structure and flow induced vibrations of hydraulic gates. But he gives little consideration to the effects of two gates used in tandem, except for a small comment on the effect of the shear layer impingement, referred to as control point shift in this report.

2.3 BURDEKIN FALLS DAM HYDRAULIC GATES

2.3.1 Hydraulic Gates General

"Hydraulic gates" is the common term used for the outlet control structure in dams, weirs, reservoirs and other water storage facilities. Gates that need to operate under water pressures exceeding 25 m are referred to as "high-head gates" (Sagar 1995) and they are designed to cope with the extra forces involved.

Hydraulic gates are designed to perform two operational functions: gates that are required to operate at various positions for extended periods (known as regulating gates) and gates that only operate in the fully open or closed positions (known as non-regulating gates).

The arrangement at Burdekin Falls Dam is a regulating radial gate and a non-regulating "emergency closure" fixed-wheel gate, as depicted in drawing 65161, Appendix B.

The radial gate is constructed of a 16 mm thick mild steel skin plate on radial arc of 6.13 m. The force from water load and discharge is transferred from the skin plate to the stiffening beams and horizontal girders, to the radial gate arms at either side of the gate, back to the radial gate hub and trunnion located at the centre of the arc, and 3.958 m above the maximum flow level to reduce the possibility of debris damaging the trunnion (drawing 69725 appendix B). Usually, the radius is 1.25 times the vertical gate opening (Lewin 2001). Burdekin Falls Dam has a vertical gate opening of 2.0 m giving a radius to gate opening ratio of 3.065. This larger radius provides better control on gate openings.

The trunnion support and anchorage arrangements are critical to the integrity of structure, as all loads acting on the gate are transferred to the trunnion and anchorage.

Width to height ratios are not critical to design considerations, however gates with smaller widths provide better flow regulation because of the greater height of opening for a given flow.

Emergency closure of the outlet is effected via a non-regulating fixed-wheel gate (DWG 65112, Appendix B). The fixed-wheel gate is of a rectangular (2440 mm x 3667 mm) construction with seven wheels up each side designed to reduce the frictional forces common with large slide gates. The large wheel design required wide slots formed in the outlet conduit and this had the possibility of introducing hydraulic flow disturbances, cavitation and vibration if precautions were not taken to streamline the fixed-wheel gate slots and conduit (Richardson 1982).

Hence precautions were taken in the design of the outlet works geometry by undertaking hydraulic modelling to obtain the optimum outlet profile (Allen 1984).

2.3.2 Radial Gate

Methods of determining free-flow from radial gates have been widely studied. Naudascher (Naudascher 1991) summarizes the theoretical and experimental studies in this field. Further studies by Lewin (Lewin 2001) and Montes (Montes 1997) suggest that the theoretical formula of free-flowing discharge from radial gates requires refinement. This refinement is required when the flow downstream of the radial gates is at its minimum depth or "vena contracta" and the ability to define the contraction coefficient in terms of gate opening, depth of vena contracta and angle of gate lip (Lin, Yen & Tsai 2002).

2.3.3 Fixed-wheel Gate

During the design of Burdekin Falls Dam two physical hydraulic models were constructed in order to assist in the design of the outlet chute and fixed-wheel gate, both based on Froude Number scaling.

The first model scale was 1:40 and was constructed to provide preliminary sizing and prove overall design concepts. Results from this model led to small changes in the bellmouth arrangement, improving flow stability (*Design Report Burdekin Falls Dam* 1985)

Once flow stability was proved, a 1:25 model was constructed to assist in improving geometries of the fixed-wheel "emergency" gate and associated conduit slot. It was also used to provide detailed design information on the downpull and possible vibrations of the gate (Allen 1984).

Net hydrodynamic forces acting vertically or parallel to the hoist at various gate openings is termed "Hydraulic Downpull". In some situations the resultant forces may act upward causing uplift on the gate (Sagar, 1977). Accurate evaluation of downpull forces and vibration in the fixed-wheel gate was calculated using a two dimensional boundary integral analysis and scale hydraulic modelling techniques (Allen 1984).

Flow induced vibration in the fixed-wheel gate was shown to be less than 2% of the dead weight deflections of the gate and could be recorded at frequencies well in excess of the model's 17 HZ prototype's natural suspension frequency. No significant vibrations were recorded during testing of the gate (Allen 1984). All records of the experiment show that the test was run under the full flow condition of stage II, and no mention is made of experiments under partial radial gate openings.

Maximum downpull on the fixed-wheel gate was calculated using both numerical and scale hydraulic models for stage II conditions and consequently a 35 tonne hoist was designed in order to retrieve the gate under maximum downpull.

2.4 VIBRATION IN HYDRAULIC GATES

Significant vibration of a radial gate can lead to failure of the gate and associated structures. Some causes of vibration are (Lewin 2001):

- Extraneously induced excitation which is caused by a pulsation in flow or pressure which is not an intrinsic part of the vibrating system (the gate).

- Instability induced excitation which is brought about by unstable flow. Examples are vortex shedding from the lip of a gate and alternating shear-layer reattachment underneath a gate.
- Movement-induced excitation of the vibrating structure. In this situation the flow will induce a force which tends to enhance the movement of the gate.
- Impingement of high velocity jets on the downstream gate components.

Self-excited vibrations in hydraulic gates caused by overflow and underflow is a dangerous phenomenon and has been extensively researched by Naudasher (Naudascher & Rockwell 1994) and supported by a wide range of research (Daneshmand, Sharan & Kadivar 2004; Lewin 2001; Montes 1997, 1999; Naudascher 1991; Speerli & Hager 1999; Watson 2000). Vibrations in the gate caused by hydraulic flow and the excitation forces can form a closed feedback loop resulting in changes in the nature and intensity of vibration.

2.5 HYDRAULIC MODELLING METHODS

2.5.1 Computer Aided Modelling

The dynamic behaviour of hydraulic gates due to fluid flow is an important part of the design procedure. The response of hydraulic gates to fluid pressure affects the gate deformations, which in turn modifies the hydraulic pressures acting on them (Daneshmand, Sharan & Kadivar 2004). The four most common numerical techniques used to solve fluid-structure responses are (Daneshmand, Sharan & Kadivar 2004):

- Uncoupled approach – the fluid response is first calculated assuming the structure to be rigid and the resulting pressure field is then applied to the structure to obtain the structural response.
- Added mass approximation – is a simple formulation and is suitable only when the fluid oscillation frequencies are well removed from the structure's predominant frequencies.
- Lagrangian formulation – is a finite element method described by nodal displacement. It is primarily used for elastic solid elements and displacement based fluid elements and has been used with a wide range of success. However this method can produce deceiving circulation modes within the fluid elements (Chen & Taylor 1992).
- Eulerian formulation – fluid motion is comprised of scalar potential functions, the use of potential functions instead of displacement removes the deceiving circulation modes found within the Lagrangian method. Current methods of applying the Eulerian method use velocity potential functions rather than pressure approach. Recent developments in this area and the

development of the arbitrary Lagrangian-Eulerian (ALE) formulation by (Nitikipaiboon & Bathe 1993) and recent applications have been confined to relatively simple geometry and boundary conditions.

2.5.2 Physical Scale Modelling

Hydraulic modelling in terms of physical scale modelling has been an accepted form of hydraulic engineering for many years.

Various forms of modelling can be found throughout history, but the start of modern hydraulic modelling can be traced back to the late 18th Century and early 19th Century. During this time several theories were raised which remain integral to today's hydraulic engineering. These include Antoine Chézy (the Chézy equation), Robert Manning (flow-resistance in open channels) and the Henri Darcy and Julius Weisbach (flow-resistance equation).

The flow-resistance equation which is universally accepted and widely used was first published in the 1840's.

$$h = f \frac{L}{D} \frac{U^2}{2g}$$

Though many tried to determine the relationship of the non-dimensional flow-resistance coefficient (f) by experiments and modelling it wasn't until 1944 when Moody published his work the "Moody Diagram" that a relationship was proposed.

Early hydraulic models were primary developed to investigate systems such as rivers, channels, harbours and other natural hydraulic systems. This interest in open channel flows led to the development by Robert Manning in the 1890's of the flow-resistance equation for open-channels, another widely accepted flow-resistance equation.

$$U = \frac{1}{n} R^{\frac{2}{3}} S^{\frac{1}{2}}$$

The turning point in hydraulic modelling was the development of dimensionless parameters, the best known being the Reynolds Number and the Froude Number both developed for scale modelling in 1885 by Osborne Reynolds and William Froude respectively.

Both of these modelling techniques require that the model has a geometrical similarity with the prototype and that a dynamic similarity exists in the fluid forces.

The Reynolds Number is a dimensionless ratio that can relate the dynamic similarity of the inertial force and viscous force in liquids and gases.

$$\mathrm{Re} = \frac{\rho v L}{\mu}$$

The Reynolds number is also used for determining whether a flow will be laminar or turbulent. Laminar flow (smooth, constant fluid flow) occurs at low Reynolds numbers, where viscous forces are dominant. Turbulent flow occurs at high Reynolds numbers and is dominated by inertial forces, producing random eddies, vortices and other flow fluctuations.

The dynamic similarity of flows between a model and prototype is such that.

$$\mathrm{Re}_m = \mathrm{Re}_p$$

Alternatively the Froude relationship relates the dynamic similarity of the inertial forces and the gravitational forces in liquids and gases.

$$Fn = \frac{v}{\sqrt{gL}}$$

Once again a dynamic similarity exists between the model and the prototype if:

$$Fn_m = Fn_p$$

Depending on which effects are considered more significant either the Reynolds or the Froude Relationship can be used to accurately model hydraulic structures and are the most important hydraulic modelling techniques used today.

3.0 DEVELOPMENT OF THE SCALE HYDRAULIC MODEL

3.1 SCALE HYDRAULIC MODEL

To develop a scale hydraulic model requires that a geometric similarity must exist between the prototype (actual) and the model. In addition, the dynamic similarity (ratio of forces) and kinematic similarity (particle motion) are the same in the two systems.

In the development of the hydraulic model the predominate forces in fluid mechanic studies are: inertia, pressure, gravity, viscous shear, surface tension and elastic compression. The similarity relationship is derived by Newton's second law of motion

$$F_i = Ma = F_p + F_g + F_v + F_t + F_e$$

Where:

Table 2

Dynamic Relationship

Notation	Force	Dimension
F_i	Inertia	$\rho V^2 L^2$
F_p	Pressure	$\Delta p L^2$
F_g	Gravity	$\rho g L^3$
F_v	Viscous shear	$\mu V L$
F_t	Surface tension	SL
F_e	Elastic compression	EL^2

The ratio of inertia forces must equal the ratio of active forces:

$$\frac{(F_i)_m}{(F_i)_p} = \frac{(F_p + F_g + F_v + F_t + F_e)_m}{(F_p + F_g + F_v + F_t + F_e)_p} = \frac{\text{Model}}{\text{Prototype}}$$

It is impossible to develop a model with a model fluid that has characteristics that satisfies the above equation. By ignoring the effects of surface tension and elastic compression, as they produce only minor errors (*Hydraulic Laboratory Techniques* 1980), a scale hydraulic model can be developed on the predominate forces of either gravity or viscous shear.

In this case predominate forces are inertia and gravity.

$$\frac{(F_i)_m}{(F_i)_p} = \frac{(\cancel{F}_p + F_g + \cancel{F}_v + \cancel{F}_t + \cancel{F}_e)_m}{(\cancel{F}_p + F_g + \cancel{F}_v + \cancel{F}_t + \cancel{F})_p}$$

$$\frac{(F_i)_m}{(F_i)_p} = \frac{(F_g)_m}{(F_g)_p}$$

$$\left(\frac{F_i}{F_g}\right)_m = \left(\frac{F_i}{F_g}\right)_p$$

$$\left(\frac{\rho V^2 L^2}{\rho g L^3}\right)_m = \left(\frac{\rho V^2 L^2}{\rho g L^3}\right)_p$$

$$\left(\frac{V^2}{gL}\right)_m = \left(\frac{V^2}{gL}\right)_p$$

$$\frac{\left(V_m / V_p\right)}{\left(g_m / g_p\right)\left(L_m / L_p\right)} = 1 \quad \text{Froude Number}$$

3.2 DEVELOPMENT OF MODEL

Hydraulic model development for the analysis of causes of vibration in the radial gate at Burdekin Falls Dam is based on two key factors: available laboratory facilities and the requirements of experiment.

A geometric similarity of 25:1 was selected based on the following conditions as it provided a model that could be constructed and operated within the SunWater hydraulic laboratory at Rocklea, Brisbane:

- Physical size.
- Available water supply.
- Ability to record meaningful quantitative values.

3.2.1 Model flow/discharge

$$Q = VA$$

$$Q = \left[Lt^{-1}\right] \cdot \left[L^2\right]$$

$$\frac{Q_m}{Q_p} = \frac{V_m}{V_p} \bullet \frac{A_m}{A_p}$$

From Froude's relationship the velocity ratio can be determined by:

$$\left(\frac{V^2}{gL}\right)_m = \left(\frac{V^2}{gL}\right)_p$$

$$\frac{V_p^2}{V_m^2} = \frac{gL_p}{gL_m}$$

$$\frac{V_p}{V_m} = \left(\frac{\cancel{g}L_p}{\cancel{g}L_m}\right)^{0.5}$$

Substitute back into discharge formula:

$$\frac{Q_p}{Q_m} = \left(\frac{\cancel{g}L_p}{\cancel{g}L_m}\right)^{0.5} \bullet \left(\frac{L_p}{L_m}\right)^2$$

$$\frac{Q_p}{Q_m} = \left(\frac{gL_p}{gL_m}\right)^{0.5} \bullet \left(\frac{L_p^2}{L_m^2}\right)$$

$$Q_m = \frac{Q_p}{\left(L_p/L_m\right)^{2.5}}$$

$$Q_m = \frac{142}{\left(25/1\right)^{2.5}} = 0.04544\ L^3 t^{-1}$$

3.3 CONSTRUCTION OF MODEL

The 25:1 scale model of Burdekin falls dam was constructed at the SunWater hydraulics laboratory at Rocklea, Brisbane in May 2005 by Malcolm Lawless. Mr Lawless, now retired, has over thirty years experience in hydraulic model building.

Preliminary work involved the development of a set of clear and accurate engineering drawings. A requirement of these drawings was that they have been notarised as “As Built” by the supervising construction engineer at the time of the dam construction. A copy of these drawings can be found in appendix B.

The overall laboratory requirements of the model were:

- Floor space of approximately 4 m by 2.5 m.
- Minimum water supply flow of 45 l/s.
- A constant header tank and flow meter on the supply pipe.

The general arrangement of the model consists of a 1.2 m square by 2 m high steel tank simulating the dam reservoir and upstream face of the dam wall. The front face of the tank was constructed of clear Perspex to allow visual monitoring of the model (Fig. 2).

Figure 2. – General Arrangement of Model

On the inside face of the tank is the outlet works inlet tower. This portion of the model was constructed of wood and is considered an important feature of the model as it allows for the placement of blanks to form selective level off-takes (usually the top 3 to 6 metres). By forcing the outlet to draw from only the top 120 mm to 240 mm, the flow was drawn vertically downwards before making a 90^{o} turn into the bellmouth. Due to the arrangement of the inlet tower, flows from the side and bottom effects are negligible.

Figure 3. – Construction of Wooden Inlet Tower

As highlighted by the literature review the rectangular bellmouth was originally designed and improved by the use of hydraulic modelling at the time of design and construction. The geometric details of the rectangular bellmouth can be found on drawing 65135 Appendix B. The model bellmouth was constructed from machined clear Perspex sections.

Figure 4. – Machined Rectangular Bellmouth

The remaining inlet penstock and outlet chute were constructed from shaped clear Perspex sections.

Radial gate construction consisted of a skin section and two solid A-frame arms. The radius of the sealing face and the geometry was considered the most important features of this component. Movement of the radial gate was effected by a steel rod axle passing through the centre point of the arc. Clamping of the radial gate was then completed by two locking screws. A small groove was machined into the sealing face of the outlet chute and rubber o-ring material fitted to simulate the clamping seal of the radial gate.

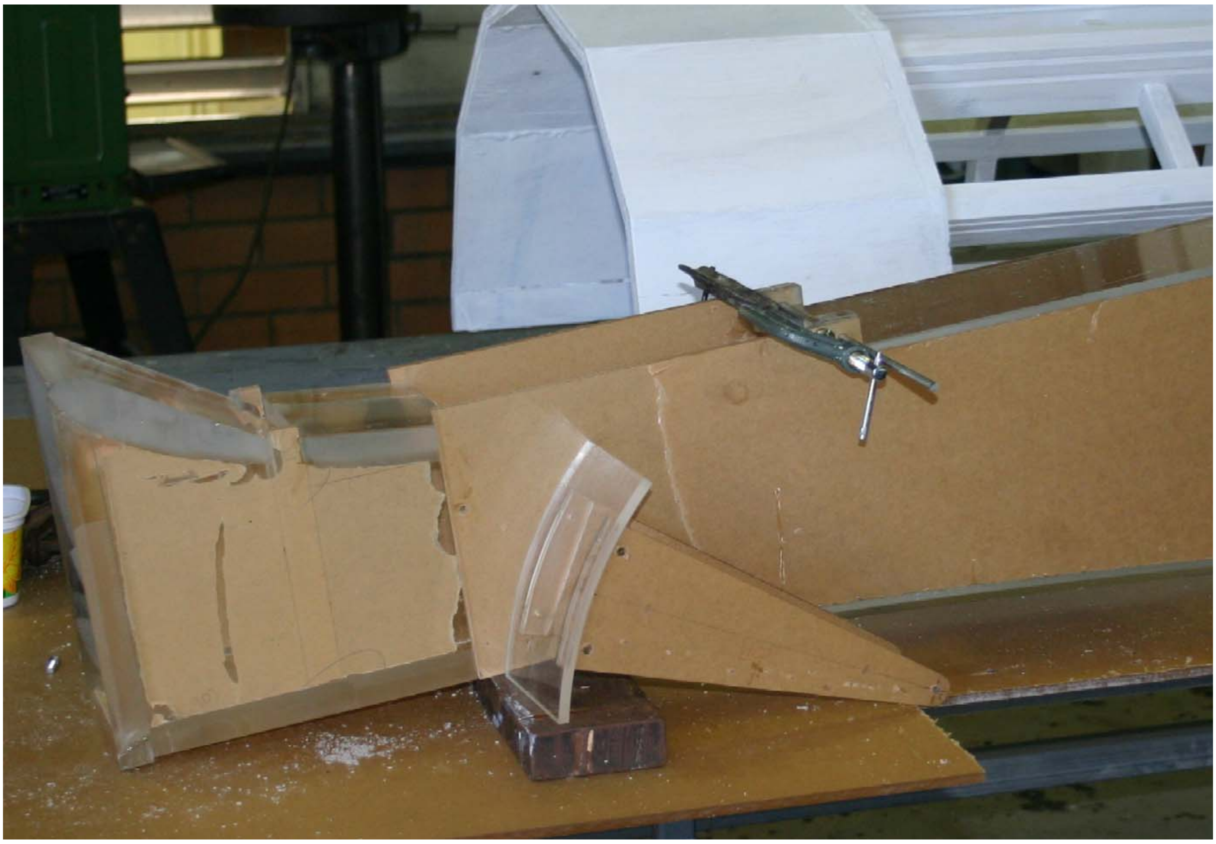

Figure 5. – Construction of Radial Gate and Outlet Chute

The final components of the model include the fixed-wheel gate and fixed-wheel gate guide. Again these were constructed from clear Perspex. The fixed-wheel gate was machined from a solid section so that the gate lip geometry could be accurately replicated. In order to simplify the model, the gate wheels were not constructed and a steel rod with a rising spindle arrangement suspended the gate.

3.4 EVALUATION OF MODEL

During all stages of the construction each model component was evaluated for its suitability, accuracy and design intention to provide an accurate representation of the prototype's performance.

Accurate geometrical modelling of the inlet tower, rectangular bellmouth and inlet penstock was achieved, ensuring an accurate simulation of flow patterns entering and passing through the area of most interest.

Issues relevant to the construction of the components are shown in Table 3. This also lists the agreed assumptions and resolutions made by the designers and model builder.

Table 3

Model Construction Issues

Issue	Resolution
Radial Gate Geometry – to what extent should the radial gate be geometrically similar?	Important to model skin plate radius and lip geometry as these feature interact with the fluid. Exact replication of the arms and bracing was not required as they do not interact with the water flow.
Radial gate connection points, i.e. trunnions bearings, hydraulic cylinder clevises and eccentric cam arrangement for locking the gate into place?	As the gate is firmly seated on the seals by the locking eccentric cam it was assumed that the lifting cylinder and trunnions bearings don't support significant weight. Firmly seated on the rubber seals it is assumed the gate will act as a fixed elastic body.
Radial and Fixed-wheel Gate material - Should the gate be made of the same material as the prototype? Is this important to have a similar modulas of elasticity?	The model is not intended to study gate internal structural vibrations therefore a similarity of Modulas of Elasticity and modal shapes of the structure is not required for this stage of the investigation.
Radial and Fixed-wheel gate motion?	The model gates are not being run under an operational cycle situation; gates are to be in fixed positions for each test run.
Fixed-wheel gate geometry?	Gate lip geometry considered most important feature of structure. Gate wheels not included in model.
Location and attachment of monitoring sensors?	The physical size of the transducer heads allowed only one transducer to be located on the radial gate itself; the other two are to be positioned along the outlet conduit wall.
Vibration Sensors?	Use and location of vibration sensors to be determined during course of experiment.

4.0 EXPERIMENT

4.1 SITE INSPECTION

An inspection of the Burdekin Falls Dam radial gate was conducted in April 2005. The purpose of this inspection was to gain an overall appreciation of the radial gate and fixed-wheel gate arrangement, size and scope plus its operation.

Inspections included:

- Structural checks for damage, corrosion and evidence of cavitation on radial gate number two.
- Inspection of hydraulic rams and systems.
- Structural checks for damage, corrosion and evidence of cavitation on the fixed-wheel gate.
- Mechanical inspection of the fixed-wheel gate wire-rope winch.

Operations included:

- Exercise two radial gates to approximately 40% open, the maximum allowable on the particular day due to required flow release. The resident operator advised that all radial gates are exercised through full travel during routine mechanical inspections.
- Dewatering of radial gate number two outlet by lowering of fixed-wheel gate under no flow condition (i.e. radial gate closed).
- Refilling of radial gate number two outlet by raising the fixed-wheel gate under no flow condition, following inspection of radial gate face and seals.

4.2 MATERIALS OR EQUIPMENT

The following materials and equipment were used for the data collection during test runs on the model, (all technical equipment used was either borrowed or supplied free of charge):

- 25:1 Scale Model as constructed.
- Water supplied from constant head tank (max flow 60 l/s).
- Four Druck PDCR 810 General Purpose Pressure Transducer, 1.5 bar 0.06% Full Scale Accuracy.

- Campbell's scientific CR5000 data logger (200 samples per second per transducer)
- Personal Laptop computer (Campbell scientific program and MatLab V13 student edition).
- Video camera.
- Certified measuring equipment (Ruler and Vernier Callipers).

4.3 EXPERIMENTAL PROCEDURE

The procedure for all experiments was as follows.

4.3.1 General

The general arrangement of the pressure transducer and data logger was common to both the calibration and all following test procedures.

The locations and notations for the pressure transducers were:

- Pressure Transducer One (PT1) – at bellmouth upstream of fixed-wheel gate.
- Pressure Transducer Two (PT2) – in penstock down stream of fixed-wheel gate.
- Pressure Transducer Three (PT3) – very bottom centre lip of Radial Gate
- Pressure Transducer Four (PT4) – in middle centre of Radial Gate

All four transducers were connected to the data logger, which collected an unfiltered millivolt output at 200 samples per second.

4.3.2 Calibration Procedure

Before model testing could begin, the pressure transducers had to be calibrated and an algorithm produced to convert millivolt output from the transducers to a known pressure in metres head of water.

The following procedure was followed:

- Installed all pressure transducers into their nominated location.
- Made model watertight and filled.
- Recorded static water height
- Recorded millivolt output from each transducer via data logger

- Incrementally reduced static water height and recorded static water heights and millivolt output
- Tabulated records (Table 4) and determined linear relationship between static water height and millivolt output for each transducer.
- Each pressure transducer recording was graphed and a linear algorithm was produced (Fig. 6).
- Linear algorithm for each transducer was then programmed into MatLab for future calculations.

Table 4

Model Calibration – Static Water Head versus Millivolt Output

m H2O	PT1 (mV)	PT2 (mV)	PT3 (mV)	PT4 (mV)
1.210	0.862	0.641	-1.327	0.733
1.162	0.834	0.610	-1.355	0.703
1.090	0.785	0.561	-1.401	0.654
1.013	0.736	0.511	-1.449	0.605
0.920	0.675	0.449	-1.508	0.546
0.855	0.633	0.407	-1.551	0.504
0.767	0.575	0.350	-1.608	0.447
0.645	0.494	0.269	-1.689	0.366
0.507	0.404	0.179	-1.778	0.277
0.358	0.307	0.083	-1.874	0.182
0.239	0.229	0.005	-1.951	0.102
0.141	0.164	-0.060	-2.015	0.039
0.098	0.136	-0.089	-2.044	0.011

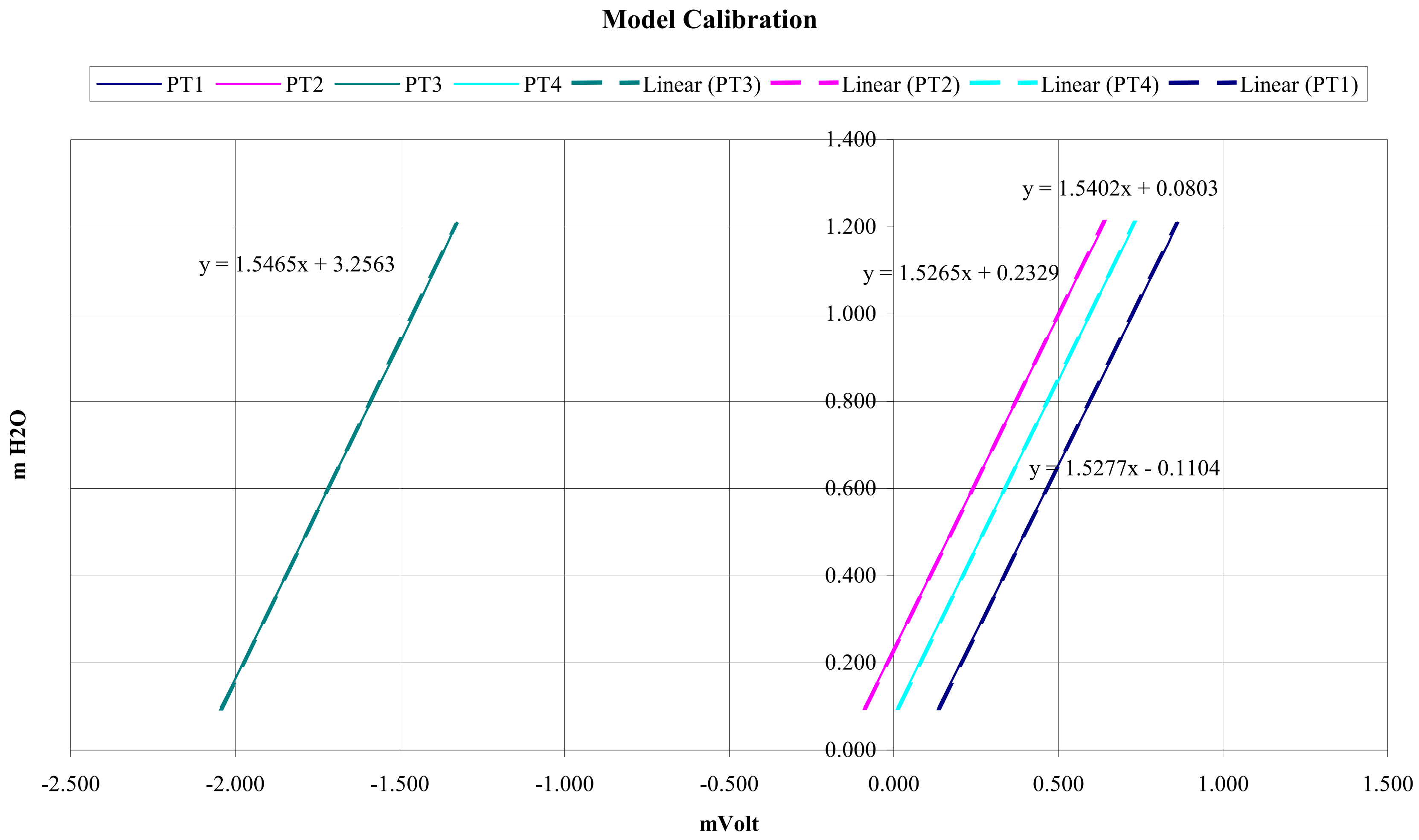

Figure 6. – Pressure Transducer Calibration

4.3.3 Test Procedure

A time domain data series was taken for a range of radial and fixed-wheel gate openings. The following procedure was used to take these recordings.

- The radial gate was opened so that the lip of the gate was positioned at a known distance from the invert (lowest point) of the conduit and firmly clamped into position.
- Moved the fixed-wheel gate so it was within the fixed-wheel gate slot and not within the conduit so it could not interfere with the normal flow in the conduit.
- Begin filling the model reservoir from the constant header tank water supply.
- The water level in the reservoir was maintained at a constant scale full supply level adjusting the inflow via the supply line and the outflow via the drain valve.
- This water level within the reservoir was allowed time to settle to ensure that a constant discharge from the outlet works at full supply was maintained.
- Once a constant flow was maintained a time domain record of the pressures within the conduit and those acting on the front of the radial gate was recorded via the Campbell's Data Logger.
- Data was collected for a minimum period of 30 seconds and downloaded to the laptop as a comma-separated variable (CSV) file.
- After the data was downloaded the fixed-wheel gate was lowered incrementally, its position recorded, before a new recording took place. The in and out flows were adjusted to maintain a constant discharge at full supply level.
- The new data series was recorded.
- The above procedure was repeated for a full range of radial gate openings and fixed wheel gate openings.

A total of 126 combinations of radial gate and fixed-wheel gate positions were recorded as CSV files to the laptop computer.

4.4 RESULTS OF EXPERIMENT

4.4.1 General

The data from the experiment were collated using a MatLab program that summarised the readings from the four pressure transducers. This summary included the amount of radial gate opening, amount of fixed-wheel gate opening and the minimum, median and maximum pressure readings at each transducer (calculated from the 30 second data set) at scale full-supply level of 1.2 m head. Full lists of data recorded for PT1, PT2 and PT3 are in Appendix C.

Pressure transducer number three (PT3) located on the lip of the radial gate produced the most variable readings. Due to the many combinations of gate openings the method used to refer to a gate opening is the ratio of vertical radial gate opening (D) divided by the vertical fixed-wheel gate opening (d) as a percent (D/d %). Figure 15 shows the minimum, median and maximum pressure readings versus the ratio of gate openings for all 126 gate opening combinations recorded.

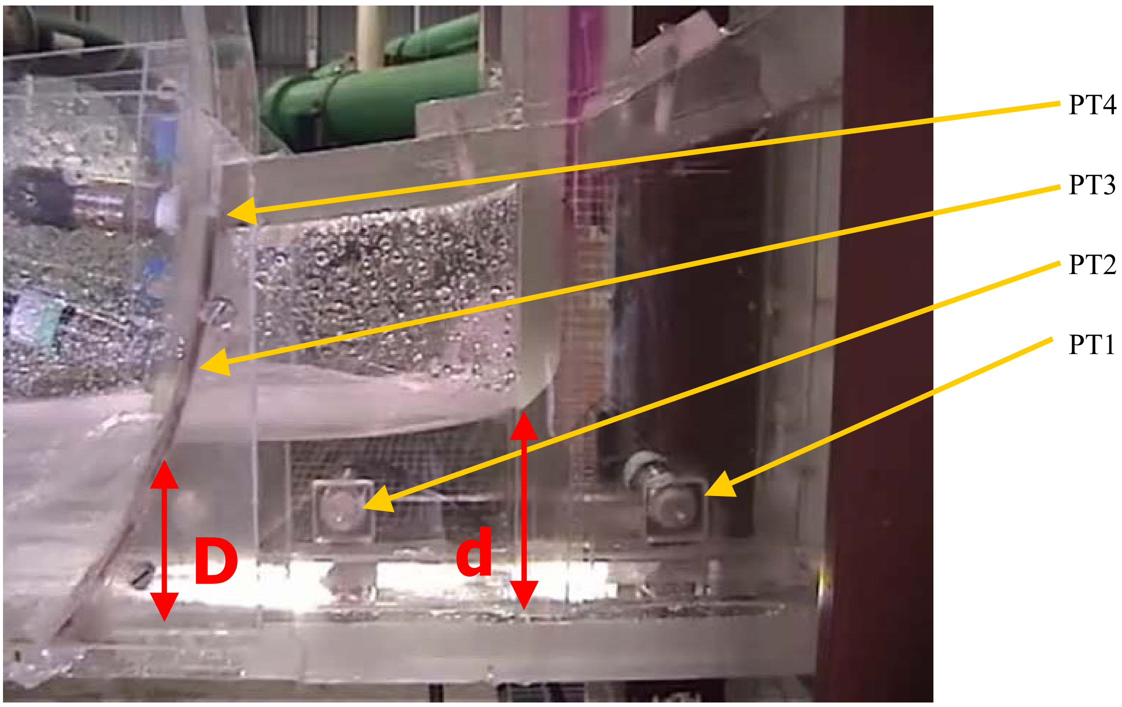

Figure 7. – Gate Opening Ratio

Flow between the fixed-wheel gate and the radial gate, recorded visually by video camera and supported by PT3, went through five distinct flow patterns as the fixed-wheel gate was lowered into the flow. Each of these flow patterns relates to a range of gate opening ratios resulting from various combinations of radial and fixed-wheel gate opening. The five flow patterns are referred to are:

- Flow pattern 1: Initial smooth discharge,
- Flow pattern 2: Visible bubbles,
- Flow pattern 3: Recirculating flow with bubbles coalescing at centre,
- Flow pattern 4: Surging unstable flow,
- and Flow pattern 5: Return to stable flow.

Also included in Appendices D, E and F are graphs showing the pressure recorded at pressure transducers one (PT1), two (PT2) and three (PT3) for each preset radial gate opening as the gate ratio versus metres head of water.

4.4.2 Flow pattern 1: Initial smooth discharge

During the initial lowering of the fixed-wheel gate the radial gate was observed to remain in control of the discharge from the outlet works. The resulting flow pattern was smooth with no visual disturbances affecting the radial gate. A constant and even flow was discharged from beneath the radial gate.

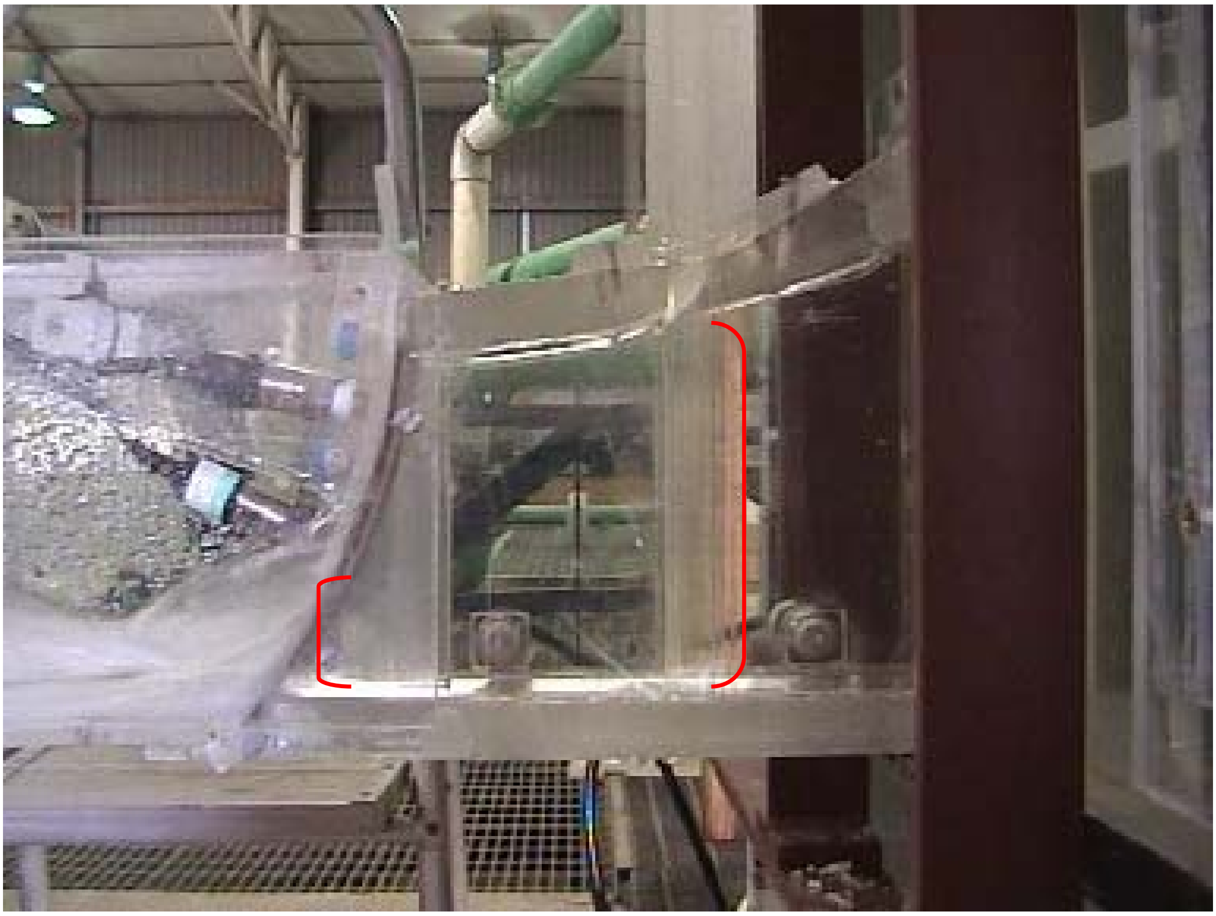

Figure 8. – Flow pattern 1: Initial smooth discharge

Typically this flow pattern occurred when the ratio of D/d was less than 40%, indicating that the radial gate was effecting primary control of the discharge from the outlet. From gate ratio 0% to approximately 40 %, the minimum, median and maximum pressure readings from PT3 were at a uniform level between 0.8 m and 1.0 m head of water.

4.4.3 Flow pattern 2: Visible bubbles

As the fixed-wheel gate was introduced further into the flow, small air bubbles formed within the portion of conduit between the fixed-wheel gate and the radial gate.

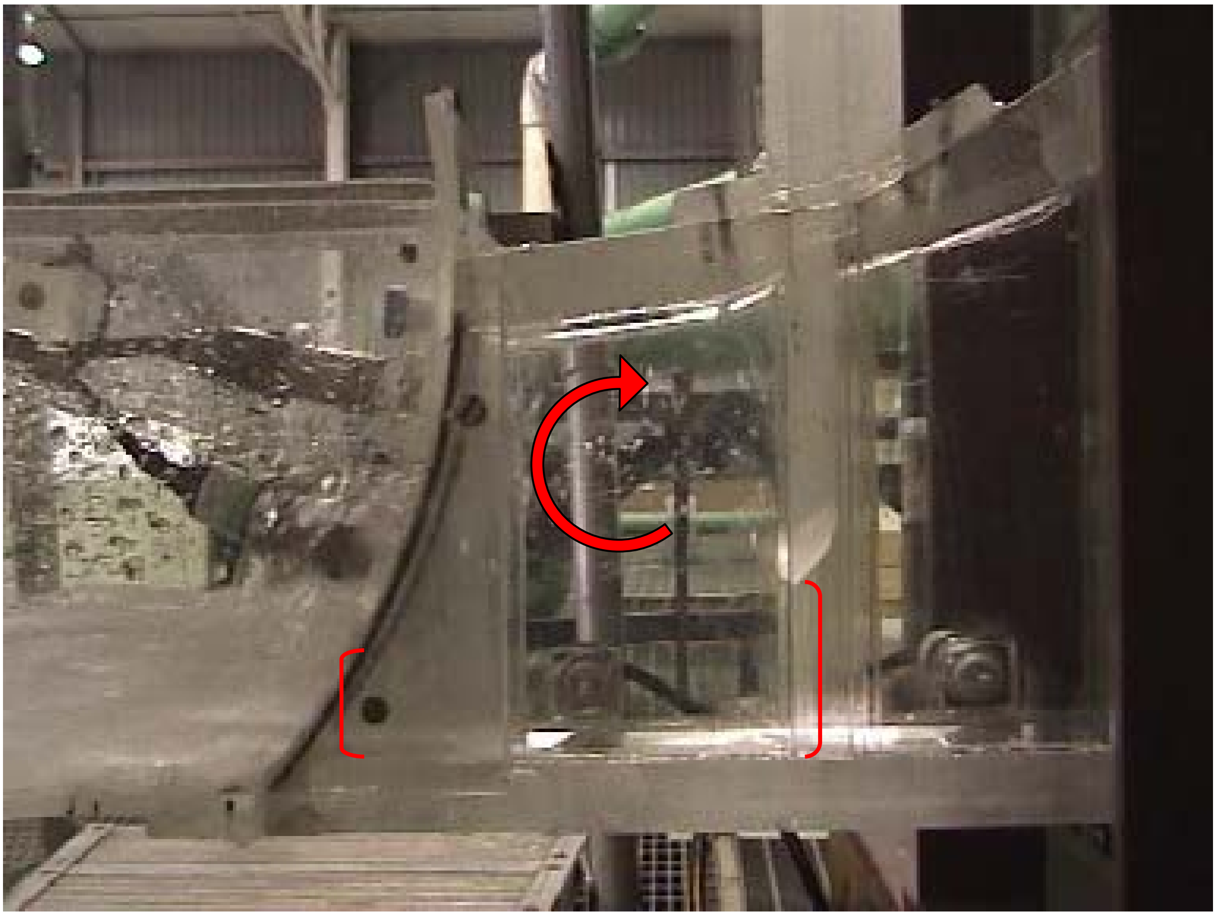

Figure 9. – Flow pattern 2: Point of Visible Bubbles

At gate ratio (D/d) of approximately 40% the appearance of bubbles was accompanied by the first recording of a pressure fluctuation by PT3. The pressure variations appeared to be uniform about the median velocity head pressure reading.

The size of the bubbles grew and they merged as the fixed-wheel gate was lowered, forming a rolling motion in the water. As the ratio of gate openings increased from 40% to nearly 65% there was a linear increase in the size of pressure variations about the median velocity head pressure reading.

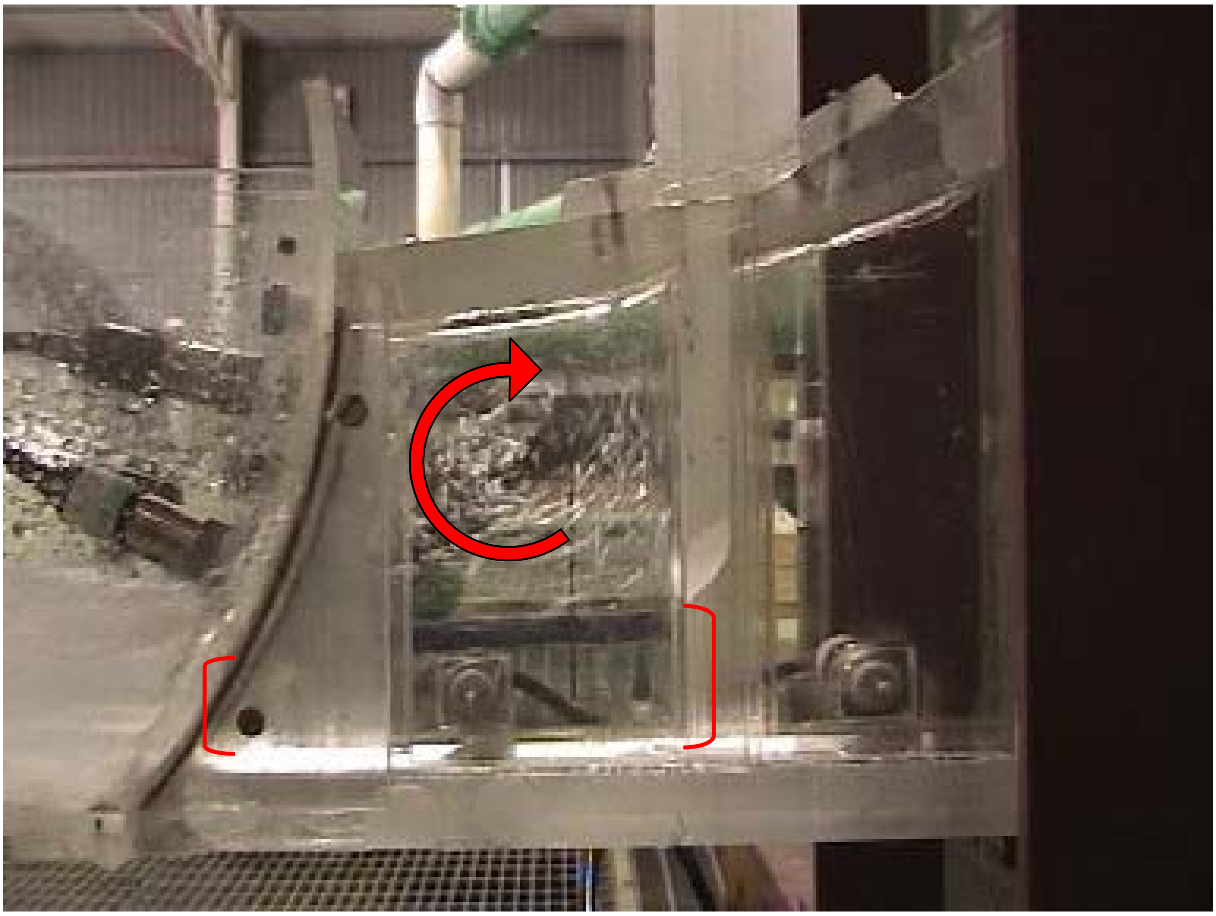

Figure 10. –Flow pattern 2: Larger visible bubbles at higher gate ratios

At a higher gate ratio of 65% the maximum pressure reading in this linear trend was 1.4 m and a minimum of 0.4 m head of water. The maximum pressure readings above the median readings appeared to be increasing at a rate slightly greater than the rate at which the minimum readings were decreasing.

4.4.4 Flow pattern 3: Recirculating flow with bubbles coalescing at centre

At this point the radial gate appeared to be still in control of the discharge, but the bubbles coalesced in the centre of the rotational flow. About this centre, rotational flow is dissipating considerable energy, causing pressure fluctuations within the section between the fixed-wheel gate and radial gate. The major portion of the flow passing underneath the radial gate provides the energy to the rotational flow.

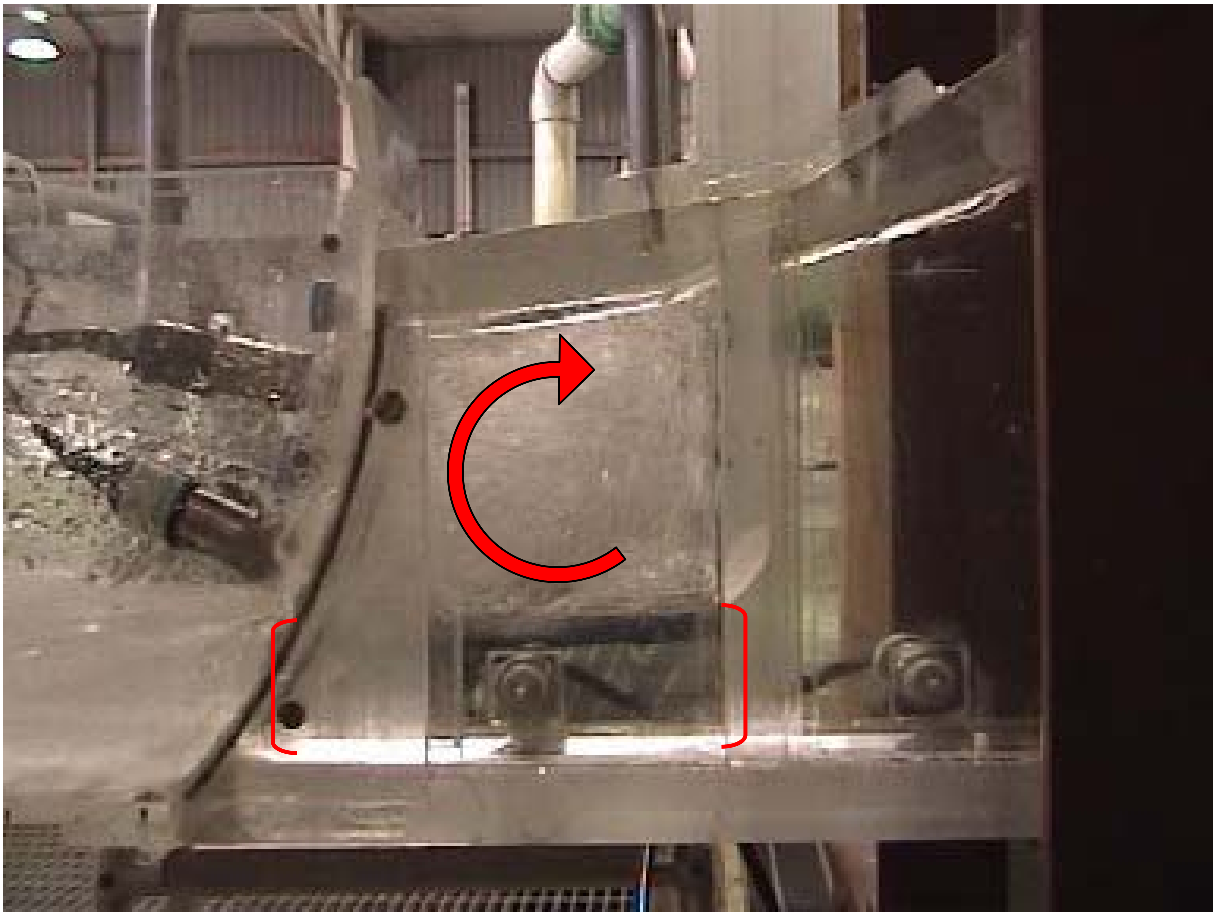

Figure 11. – Flow pattern 3: Early rotational flow

With a gate ratio of approximately 65% the bubbles concentrated to a central void, with this void continuing to grow further up to gate ratio 85%. As this void formed, the median pressure reading on the radial gate started to decrease, while the maximum readings increased to a high of 1.6 m head and the minimum pressure readings decreased to -0.6 m head. At approximately 85% gate ratio the median pressure is 0.0 m head as the flow pattern changed to the surging unstable flow.

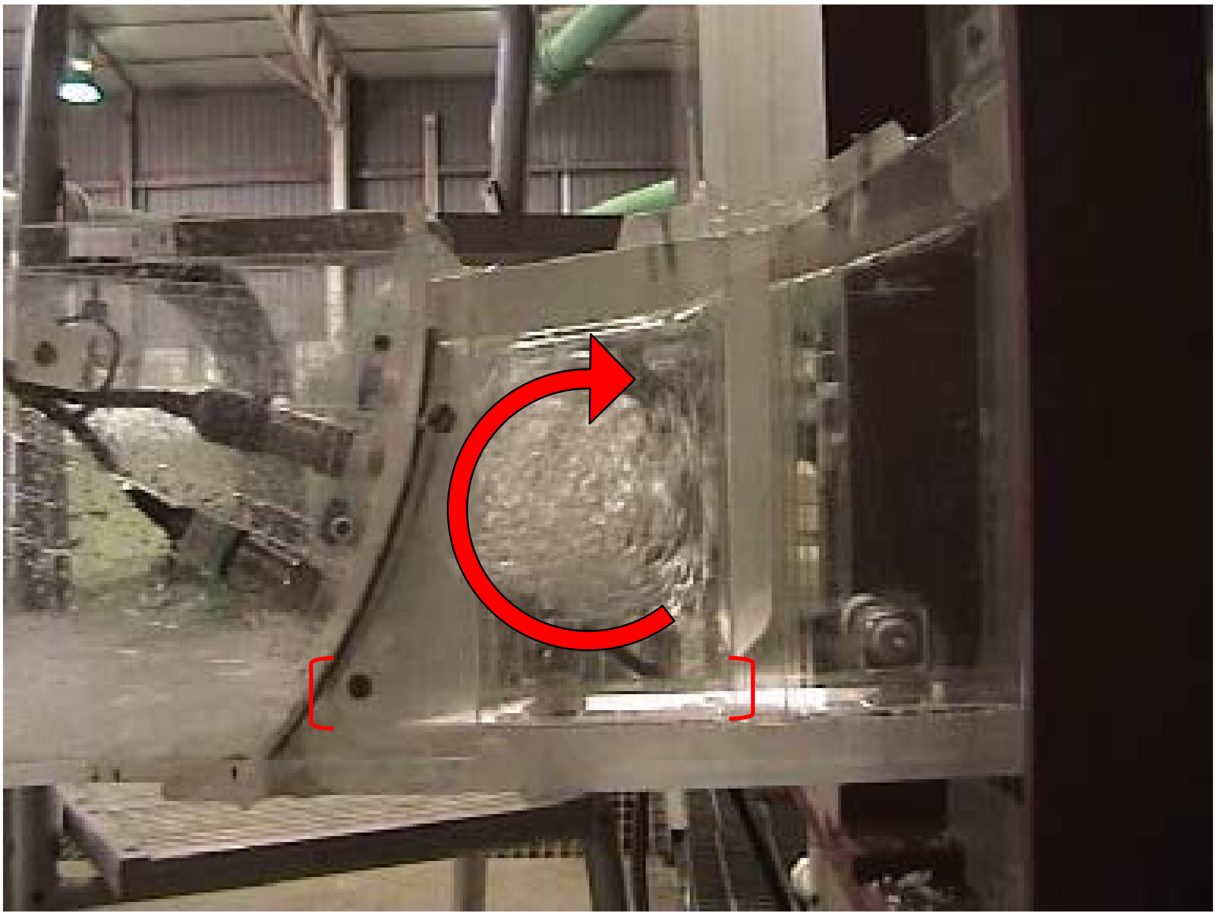

Figure 12. – Flow pattern 3: Later rotational flow with increasing central void

4.4.5 Flow pattern 4: Surging unstable flow

A surging unstable flow developed that appeared to be linked to a control point shift. This occurred at a very unique point within the increasing range of gate ratios. At this point, neither gate appeared to have control of the flow.

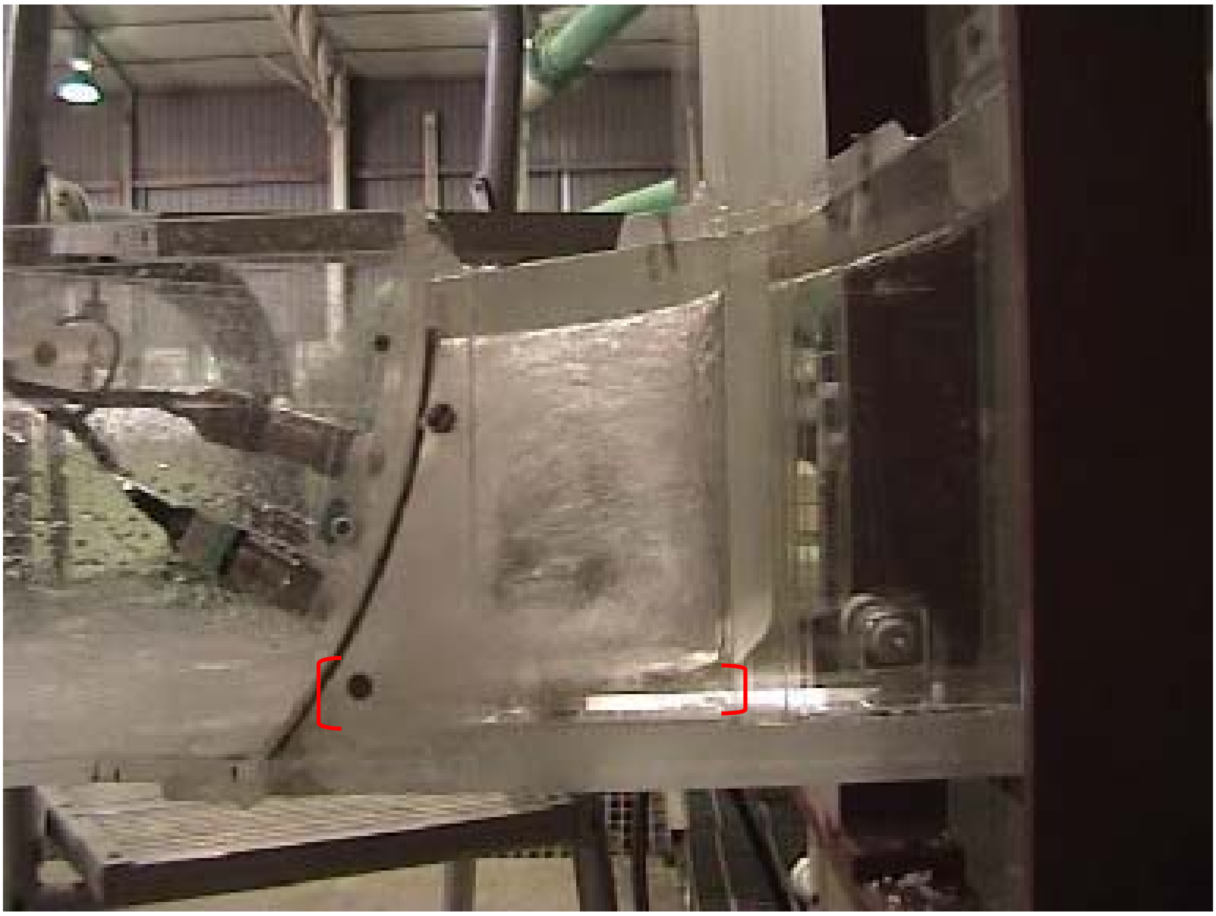

Figure 13. – Flow pattern 4: Unstable flow at control point shift

The flow from the fixed-wheel gate was still impinging on the radial gate causing a rotating flow that collapsed and reformed as the water level in the section between the radial gate and fixed-wheel gate rose and fell. PT3 recorded pressure variations of +1.4 m to -0.6 m.

The control point shift is unique to each radial gate opening, but was found between gate ratios of 85% and 90%.

4.4.6 Flow pattern 5: Return to stable flow

The final flow pattern occurred when the reduced water level down stream of the fixed-wheel gate, called the *venna contracta*, was such that the flow passed under radial gate without impinging on the face of the radial gate. Once again the flow returned to a stable and smooth flow pattern without any visible signs of turbulence or recorded pressure fluctuations. The fixed- wheel gate had regained control.

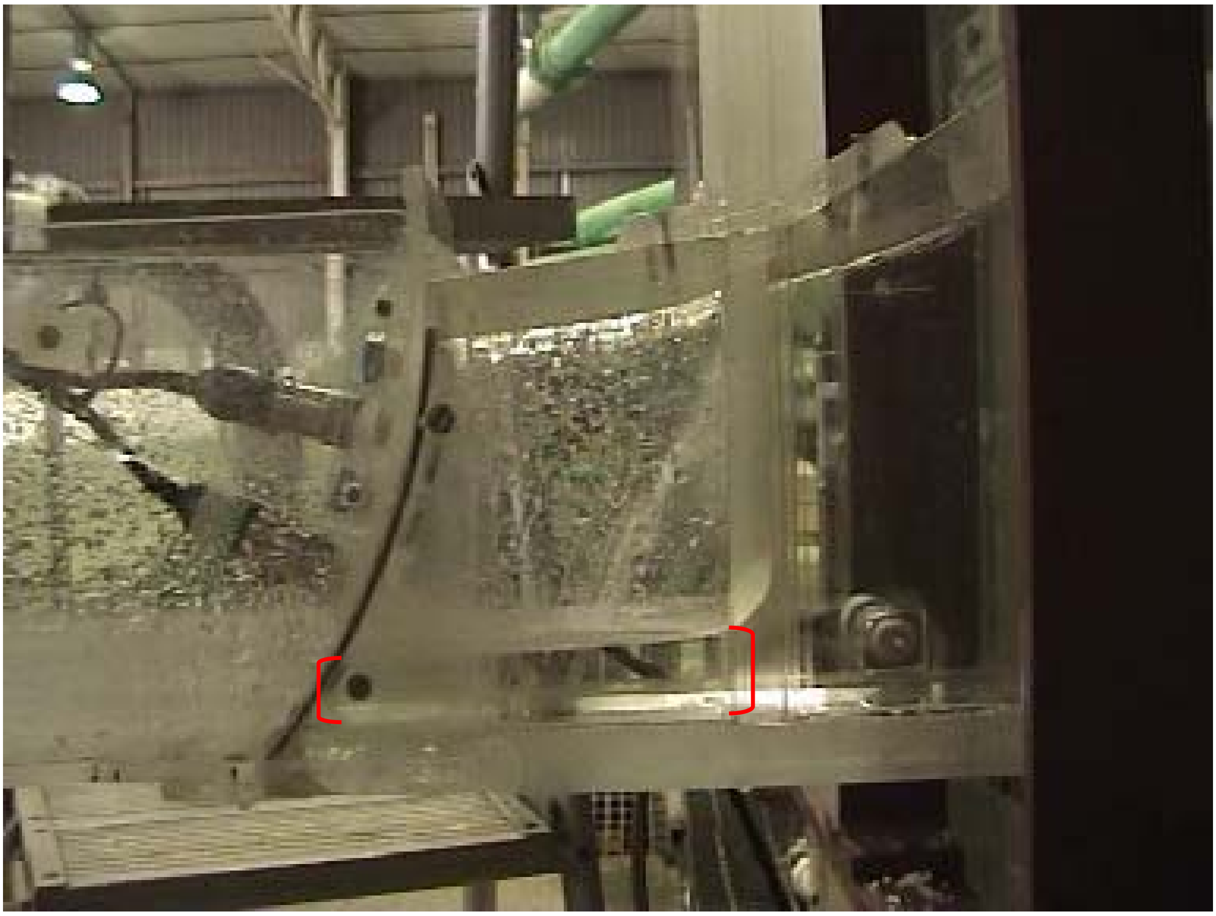

Figure 14. – Flow pattern 5: Return to stable flow

Pressure readings on PT3 returned to zero once the fixed-wheel gate gained primary control of the discharge.

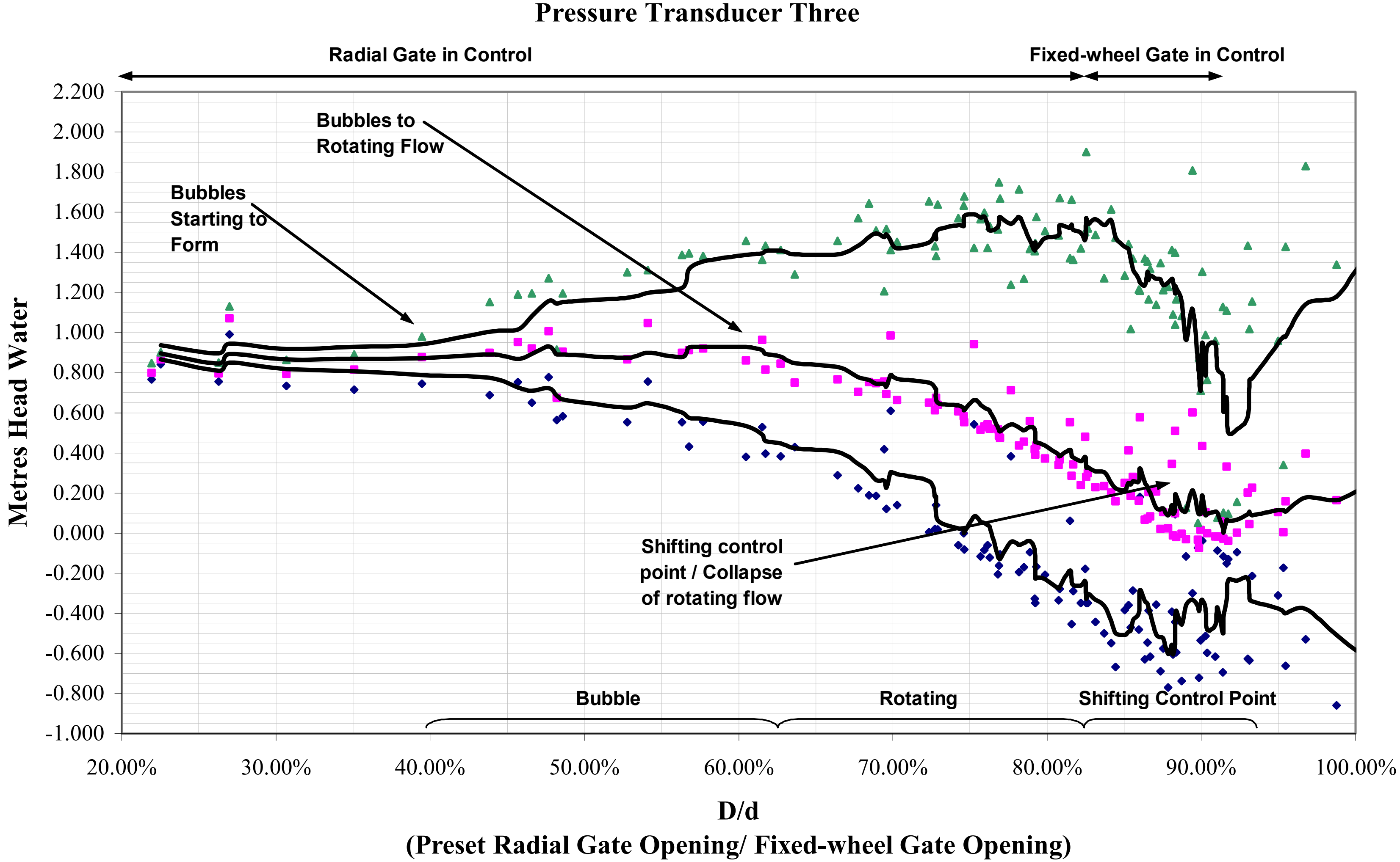

Figure 15 – Minimum, median and maximum pressure readings at all preset Radial Gate openings.

4.5 DISCUSSION

4.5.1 General

The results indicate strongly fluctuating pressures between the gates during Flow Patterns 2, 3 and 4, which are surging and unstable. These occurred at gate ratios between 40% and 85% when neither gate appeared to have primary control of the flow. Fluctuating pressures built up from around a gate ratio of 40% but were particularly noticeable at ratio from 65 – 85%, and are the likely cause of observed vibrations in the system. They are being caused by fluctuating pressures extraneous to the radial gate itself, as described by Lewin (Lewin 2001).

- Extraneously induced excitation which is caused by a pulsation in flow or pressure which is not an intrinsic part of the vibrating system (the gate).

The close proximity of the two gates in the conduit combined with angle of impact of the water flow on the radial gate surface is inducing a turbulent recirculation flow between the two gates. This can be confirmed visually in the area between the two gates.

This impingement of the flow and the alternating pressure will be inducing a fluctuating force and therefore a vibration of the radial gate.

4.5.2 Flow Patterns

The data recorded by pressure transducer one (PT1) is very useful in determining the amount of water passing through the conduit. Bernoulli's equation of continuity for fluid flow provides a method of determining the velocity of the fluid and therefore the volume or mass flow rate being discharged through the model.

Bernoulli's equation:

$$h + \frac{v^2}{2g} + \frac{p}{\rho g} = C$$

Rearranging for velocity and dropping zero terms the velocity of the flow is determined as:

$$v = \sqrt{2gh}$$

From the above equation the velocity of the flow in the model under scale full supply level is between 3.5 and 4.9 ms^{-1}. Using Froude's relationship as determined in section 3.2.1 Model Flow/Discharge the prototype velocity will be,

$$\frac{V_p}{V_m} = \left(\frac{\not{g} L_p}{\not{g} L_m} \right)^{0.5}$$

$$V_p = V_m \left(\frac{\not{g} L_p}{\not{g} L_m} \right)^{0.5}$$

between 17.5 and 24.5 ms^{-1}. This result correlates well with the rating curves for the outlet on drawing 69709 Appendix B.

During the initial lowering of the fixed-wheel gate, the radial gate has control of the flow and there is no visual indication of the recirculating flow.

Generally, in the range of gate ratio openings from (D/d) of 0% to 40% the hydraulic forces acting on the gate are those from the velocity head from steady flow. There is no indication at this point of fluctuating pressures within the system.

As the fixed-wheel gate is lowered further into the flow, D/d gate ratio of 40%, small bubbles of air appear in the area between the two gates. On first inspection, cavitation was considered as the cause of their appearance but, as the pressure within the conduit had not reached the vapour point for water, cavitation was excluded.

The source of these bubbles could be either from aerated water being drawn into the conduit or from dissolved air in the water coming out of solution due to the reduction of pressure (head loss across the fixed-wheel gate).

As air is soluble in water, the source of the bubbles could come from dissolved air in the water being forced out as the water pressure drops. The amount of air that water can absorb is related to pressure, a reduction in pressure causes a reduction in soluble air. As the area between the two gates is totally enclosed the air that has come out of solution is unable to escape and is consequently trapped.

The movement of the bubbles are a good indication of early formation of the recirculating flow. With the continued lowering of the fixed-wheel gate up to a gate ratio (D/d) of 60% the presence of the bubbles becomes more noticeable.

From gate ratio (D/d) of 40% all pressure transducers are now indicating a growing unsteady pressure fluctuation along the entire length of the conduit. The pressure fluctuations indicate that the flow from the outlet works has changed from a steady flow with a constant mass flow rate to an unsteady flow with a fluctuating mass flow rate.

By looking at the two control points in the system, the fixed-wheel gate and the radial gate, the pressure fluctuations recorded on transducers one, two and three are a result of difference in mass flow rate entering and exiting the system at these two control points.

If the mass flow rate through the conduit was steady the pressures recorded by the transducers would remain constant for each combination of gate openings (D/d).

As more mass enters a system than exits the overall pressure increases; conversely as more mass exits the system than enters, the pressure decreases.

4.5.3 Model Modifications

In order to reduce the severity of the pressure fluctuations and turbulence in the model, the model was modified following the collection of the first set of data. A common method of reducing cavitation damage or unstable flows in hydraulic systems is to allow the introduction of air into the system when it drops below zero gauge pressure. This method was trialled but, due to time constraints, a complete data set was not collected. The model was modified by drilling a small hole through the face of the radial gate, allowing air to be drawn into the normally totally enclosed conduit between the fixed-wheel gate and the radial gate (Modification 1).

During the early formation of the bubbles, this method appeared to have little effect as the bubbles remained in solution and were unable to escape. This is due to their rapid velocity. They moved past the opening, not out through the hole. In addition, the mean pressure within the conduit was still above zero gauge pressure, ensuring that no air could be drawn into the system to potentially stabilize the vacuum (negative gauge pressure).

As the gate ratio approached (D/d) 65% it was noticeable that by allowing air to be drawn into the closed system, the point at which the large visible bubbles converged to form a rotating flow was at a point slightly before the nominated gate ratio of 65%. The proportion of gate openings that had a rotating flow was also slightly reduced due to the introduction of air. The flow changed from a fully recirculating flow to a constant impinging flow, although this impinging flow did record a pulsating pressure on both pressure transducers two and three.

Collapse of the rotating flow to normal flow being controlled by the fixed-wheel gate was comparatively quick and there was little indication of an oscillating control point shift between the two gates. While the conduit was enclosed it is possible that the pulsating positive and negative pressure raised and dropped the water level, exaggerating the oscillating control point shift under normal conditions.

5.0 CONCLUSIONS

5.1 REVIEW OF EXISTING LITERATURE

An extensive review of hydraulic systems and hydraulics was undertaken as part of this research. No reports of similar problems with the same gate arrangement was located, though there were many references to vibration of radial spillway gates (termed "Tainter" gates in the USA) due to underflow or vortex induced vibrations caused by poor lip geometry.

Eduard Naudascher (Naudascher 1991) provided considerable information on and references to hydraulic structures and flow-induced vibrations of hydraulic gates. Most of this did not take into consideration the effects of two gates used in tandem, except for a small reference to the effect of the shear layer impingement, referred to as control point shift in this report.

5.2 SCALE HYDRAULIC MODELLING

Major vibrations in the radial gate structure observed during a dam inspection result from pressure fluctuations within the flow between the fixed-wheel and radial gates. Modelling has shown that there is a stage in gate closure that causes a surging turbulent flow of water between the two gates and that this flow pattern coincides with widely fluctuating water pressures. This surging turbulent flow starts at approximately gate ratio 40% and continues to about gate ratio 95%, with the peak in pressure fluctuations occurring at around gate ratio 85%. Although there is insufficient data to show if there was a dominant or resonant frequency, stages in gate closure where major vibrating inducing fluctuations in pressure begin, reach a maximum and then decline, were identified.

5.3 FLOW PATTERNS THROUGH OUTLET WORKS.

During the early stages of closure of the fixed-wheel gate there is no evidence of major pressure fluctuations or turbulent flow within the conduit and the discharge is stable and steady (pattern 1). Once the fixed-wheel gate has entered the flow and the ratio of radial gate opening to fixed-wheel gate opening reaches approximately 40% a dramatic and significant change in the discharge flow occurs. First, air bubbles develop, most probably from dissolved air in water coming out of solution as the pressure drops due to the restriction in flow from the fixed-wheel gate. In addition there was evidence of the formation of a recirculating flow (pattern 2) between the fixed-wheel gate and radial gate. This flow pattern became more distinct as the gates closed, with air bubbles becoming larger and coalescing in the centre of the rotating flow to form a void (pattern 3). As the fixed-wheel gate was introduced further into the flow both the volume of air and magnitude of the recirculating flow increased dramatically. Pressure recordings within the conduit also increased in magnitude, reaching a maximum at about gate ratio 85%. Pressure transducers before and after the fixed-wheel gate and on the front face of the radial gate recorded the pressure fluctuations.

At this point the recirculating flow with bubbles coalescing at centre flow (pattern 3) quite rapidly turned into a surging unstable flow (pattern 4). The surging unstable flow was impinging on the radial gate causing a rotating flow that collapsed and reformed as the water level in the section between the radial gate and fixed-wheel gate rose and fell. It was associated with the maximum-recorded variations in pressure in the conduit between the gates. These ranged from 1.4 m to –0.6 m oscillating at an underdetermined frequency. This would exert forces on the radial gate that could cause the observed vibrations. There was an oscillating control point shift between to the two control points - the radial gate and fixed-wheel gate. This flow pattern appeared quite abruptly at gate ratio 85% and lasted only until around gate ratio 95%, when the discharge returned to a stable steady flow (pattern 5) controlled by the fixed-wheel gate.

The estimated time to effect full fixed-wheel gate closure from the point of entry to the outlet conduit is 200 seconds. The critical period from the formation of flow pattern one (D/d = 40%) until the fixed-wheel gate takes control of the flow (D/d = 95%) is approximately 120 seconds. During this time travel of the fixed-wheel gate should not stop. It should be allowed to continue until the conduit is effectively sealed.

5.4 EFFECTS OF PRESSURE CHANGES IN OUTLET CONDUIT

The effects of these flows and the considerable forces generated by the fluctuating pressures found within the conduit and at the radial gate have yet to be determined as the results collected during the model study were insufficient to identify a dominant frequency.

5.5 PLANS TO REMOVE OR REDUCE THE POSSIBILITY OF DAMAGE

Preliminary visual results from the modified model suggest a reduction in the intensity of the pressure fluctuations and an earlier collapse of the turbulent rotating flow than is the case under normal conditions. They suggest that further experiments should be conducted with this kind of modification to the model.

5.6 MODIFICATIONS TO THE GATE OR GATE STRUCTURE

Interim recommendations to alleviate adverse findings in the model are detailed in the following section.

6.0 RECOMMENDATIONS AND FURTHER WORK

The results and conclusions drawn from experiments on a 1:25 hydraulic model have confirmed that the radial gate structure at Burdekin Falls Dam is subject to fluctuating hydraulic forces developed between the radial and fixed-wheel gate during emergency closure of the fixed-wheel gate.

Previous model studies reviewed as apart of this project show that the fixed-wheel gate was designed and modelled to shut under full flow with the radial gate at its maximum opening. Damage to the radial gate due to an emergency fixed-wheel gate closure under partial radial gate opening is possible and requires further investigation. It would be premature to recommend any permanent changes to the structure at this stage, but the following interim recommendations can be actioned immediately.

6.1 EMERGENCY CLOSURE PROCEDURE

6.1.1 Avoid use of the procedure

In the interim, the fixed-wheel gate should only be utilized as an emergency closure device and not be operated if another alternative is available. If the emergency gate is to be operated then damage to the radial gate could result, though this damage is not expected to hinder the effectiveness of closure.

6.1.2 Interim procedures

Sections of the Dam Operating Manual covering emergency closure procedures should be revised immediately and the revisions brought to the attention of staff. The revisions should alert staff to the dangers. In particular, no personnel should be in the vicinity of the radial gate or lower outlet works at the time of emergency closure. Responses to gate failure scenarios should be incorporated. Observations that should be recorded during emergency closure should be listed, as should the required safety inspections after the operation.

6.2 FURTHER TESTING OF THE 25:1 MODEL

6.2.1 Current Model

Work should be continued on the current model to see if a dominant or resonant frequency can be found. A different approach to the data collection should be undertaken including:

- Instrumentation may be improved by matching operating range of transducers to expected pressure maximum and minimum values.
- A data logger or a real time recorder with a much higher sampling rate is also required if there is to be any attempt to determine a dominant frequency.
- Modify arrangement of model fixed-wheel gate so it more accurately represents the prototype including actuating the closing mechanism and closing speed.

6.2.2 Modified model

Preliminary observation of venting or allowing air to be drawn into the enclosed space between the two gates should be conducted to confirm or reject this as a possible solution.

Other investigations, which may be relevant to both this dam and to future dam designs, on modifications to this model are:

- Various methods of venting the enclosed space (adding air) for reducing the pulsating pressure in the conduit – by tubes or air valve.
- Internal baffles to modify rotating or surging flows.
- Changing conduit proportions ─ flow patterns may be different if gates are further apart

6.2.3 Computer modelling

Computer modelling of complex computational fluid mechanics may also provide a method to verify results obtained from physical modelling. If scale modelling produces a potential feasible option then it is recommended that this technique be investigated to validate results.

6.3 ASSESS STRUCTURAL INTEGRITY

Depending to the outcome from the modelling, it may be necessary to asses the structural integrity of the radial gate. If this is required, results from either the final hydraulic model or computer model should then be applied to the radial gate and supporting structure. Damage from induced vibration and possible resonant frequency can only be determined once the natural frequency or modal shapes of the structure are known. Methods for determining these frequencies are by physical bump test of the prototype or by finite element analysis. The final phase of the project can be undertaken once the magnitude and possible frequencies of hydraulic forces are known and the preferred structural modifications (if any) are identified.

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APPENDIX A

PROJECT SPECIFICATION

University of Southern Queensland

FACULTY OF ENGINEERING AND SURVEYING

ENG 4111/4112 Research Project
PROJECT SPECIFICATION

FOR: **MANU GRAVATT, Q98214400**

TOPIC: BURDEKIN FALLS DAM – INVESTIGATION OF THE STRUCTRUAL INTEGRITY OF THE OUTLET WORKS RADIAL GATE AND FIXED WHEEL GATE UNDER EMERGENCY CLOSURE SITUATIONS.

SUPERVISORS: Dr. Ahmad Sharifian
Brian Watson, Senior Mechanical Engineer – SunWater

ENROLMENT: ENG 4111 – S1, X, 2005
ENG 4112 – S2, X, 2005

PROJECT AIM: The aim of this project is to determine the likely source and cause of vibration in the radial gate through scale hydraulic modelling to develop recommendations and plans to reduce the vibration and remove the possibility of damage to the gates.

SPONSORSHIP: SunWater

Programmed: Issue A. 7th March 2005

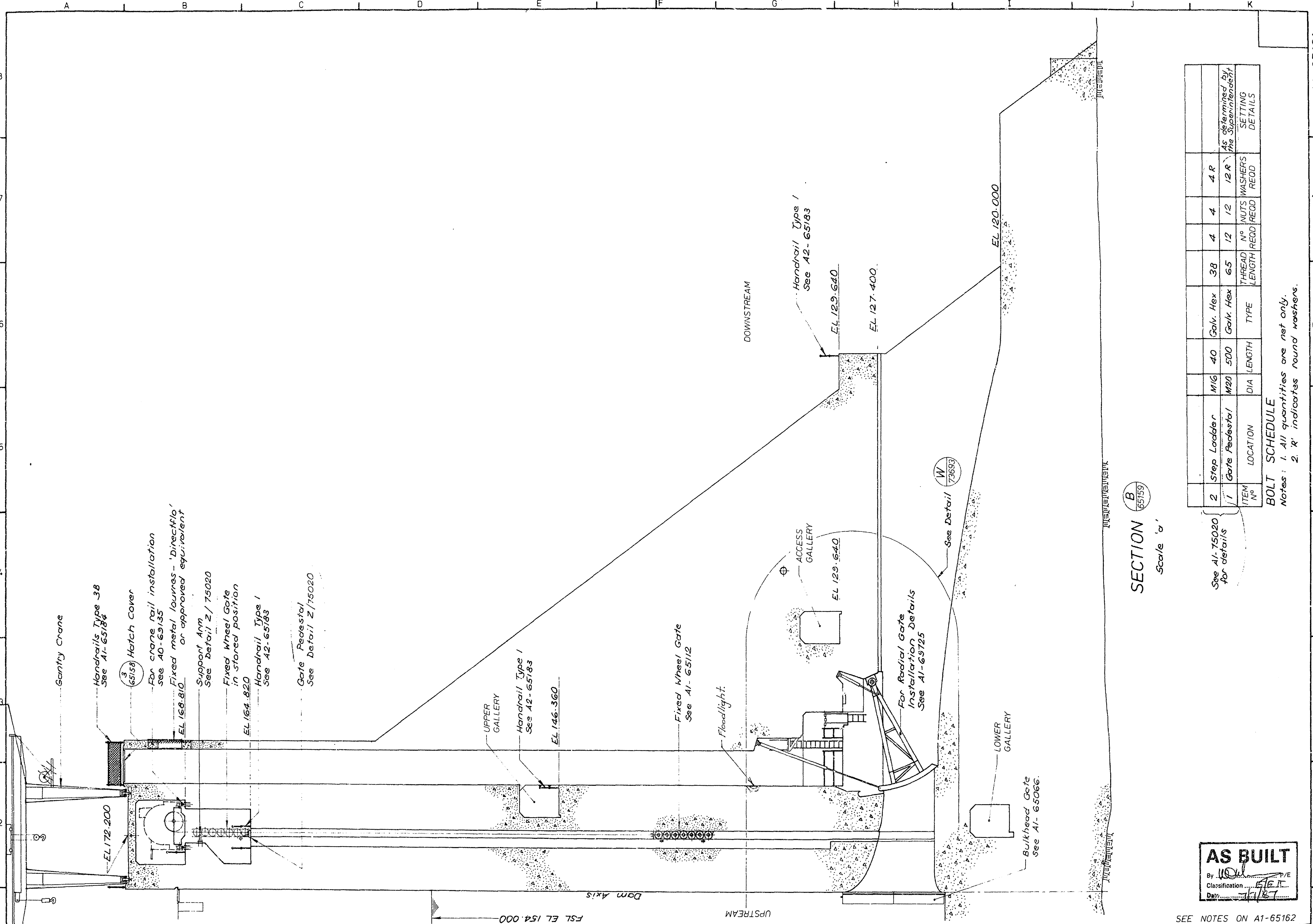
1. Review of existing literature.
2. Scale hydraulic modelling of the radial gate and fixed wheel gate.
3. Investigate formation of flow through outlet works and its effect on the radial during installation of fixed-wheel gate under emergency closure situation.
4. Determine effects of pressure changes in outlet conduit and at the radial Gate.
5. Analyse results with the goal of developing plans to remove or reduce the possibility of damage from vibration caused by pressure fluctuations.
6. Recommend relevant modifications to the gate/structure to alleviate adverse findings in the model work.
7. Propose safe operating procedures in the event of an emergency shut down of the outlet works.

AGREED: ____________________ (student): ________________________ (Supervisor)

(dated) ______ / ______ / ______

APPENDIX B

AS CONSTRUCTED DRAWINGS



REVISION DATE		REMARKS	ZONE	CKD	PSD
7.7.87	C	AS BUILT			DM
21.8.85	B	Detail Z transferred to 7th sheet and modified		CRC	J.K.R.
11.7.84	A	Tender to working drawing		CRC	

DRAWING SCHEDULE	
A0-69135	F.W.G. Crane Rail - Installation & Details
A1-65188	Std. Safety Chains
A1-65184	Handrails Types 3 & 4
A1-65183	Handrails Types 1 & 2
A1-69702	F.W.G. Support - Metal Items
A1-69725	Radial Gate - Installation Details
A1-65159	Arrangement (Sh 1 of 7)

SCALE
'a' 0 5 10 m (1:100)
'b' 0 500 1000 mm (1:10)
(Scales before reduction)

DESIGN	DRAFTING
PREP	DR KFP
CKD J.K.R.	CKD CRC
SUPV	SUPV
SUBMITTED	SUBMITTED
EXEC ENGINEER	SUPV D'MAN

RECOMMENDED — SENIOR ENGINEER DESIGNS
APPROVED — CHIEF DESIGNING ENGINEER

Queensland Water Resources Commission

BURDEKIN FALLS DAM

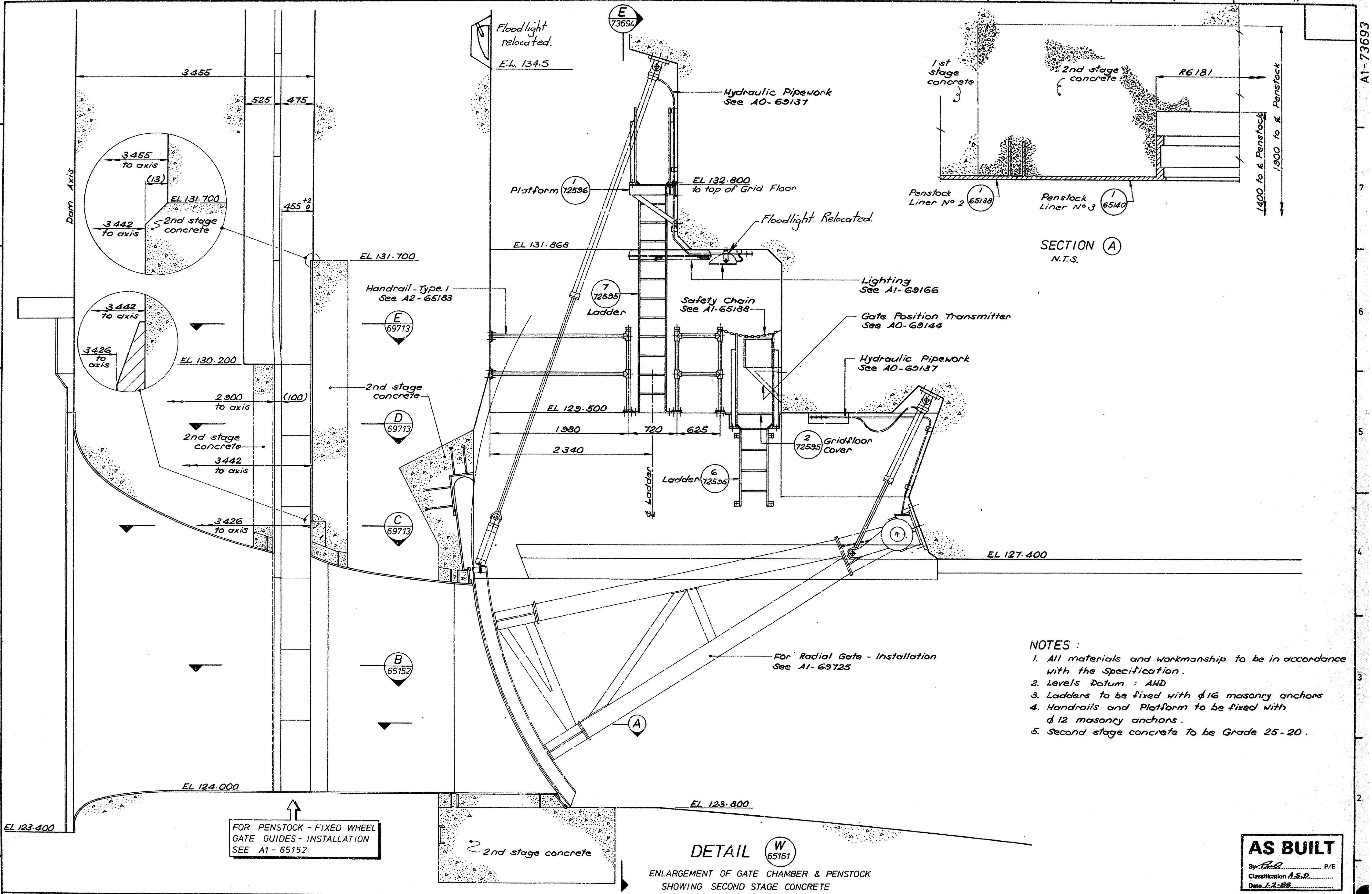
MONOLITHS LH2 & LH3

ARRANGEMENT

Sh 3 of 7

CONTRACT NUMBER 2360
DRAWING NUMBER A1-65161
DATE 18.2.83
A B C

DWG 65161C.tif



NOTES :
1. All materials and workmanship to be in accordance with the Specification.
2. Levels Datum : AHD
3. Ladders to be fixed with ϕ16 masonry anchors
4. Handrails and Platform to be fixed with ϕ12 masonry anchors.
5. Second stage concrete to be Grade 25-20.

AS BUILT
By P.A.D. P/E
Classification A.S.D.
Date 1-2-88

REVISION	DATE		REMARKS	ZONE	CKD	PSD
	1.2.88	B	AS BUILT		PMD.	
	21.8.85	A	7th sheet added to set	K1	CRC	JKR

DRAWING SCHEDULE	
A0-69137	Hydraulic Equip. & Pipework-Arrg't
A1-69166	Lighting & Power Layout
A1-69713	Fixed Wheel Gate Guides - Install'n
A1-65152	Fixed Wheel Gate Guides - Install'n
A1-65146	Penstock Liners - Install'n Details
A1-72599	Concrete (Sh 7 of 11)
A1-65153	LH2 & LH3 - Arrangement (1 of 7)

SCALE
0 0.5 1.0 1.5 2.0 2.5m
(1:25 before reduction)

DESIGN	DRAFTING
PREP JKR	DR KFP
CKD J.K.R.	CKD CRC
SUPV	SUPV
SUBMITTED EXEC ENGINEER	SUBMITTED SUPV D'MAN

Queensland Water Resources Commission
RECOMMENDED — SENIOR ENGINEER DESIGNS
APPROVED — CHIEF DESIGNING ENGINEER

BURDEKIN FALLS DAM
MONOLITHS LH2 & LH3
ARRANGEMENT
Sh 5 of 7

CONTRACT NUMBER 2360
DRAWING NUMBER A1-73693
DATE 12.7.84
A B

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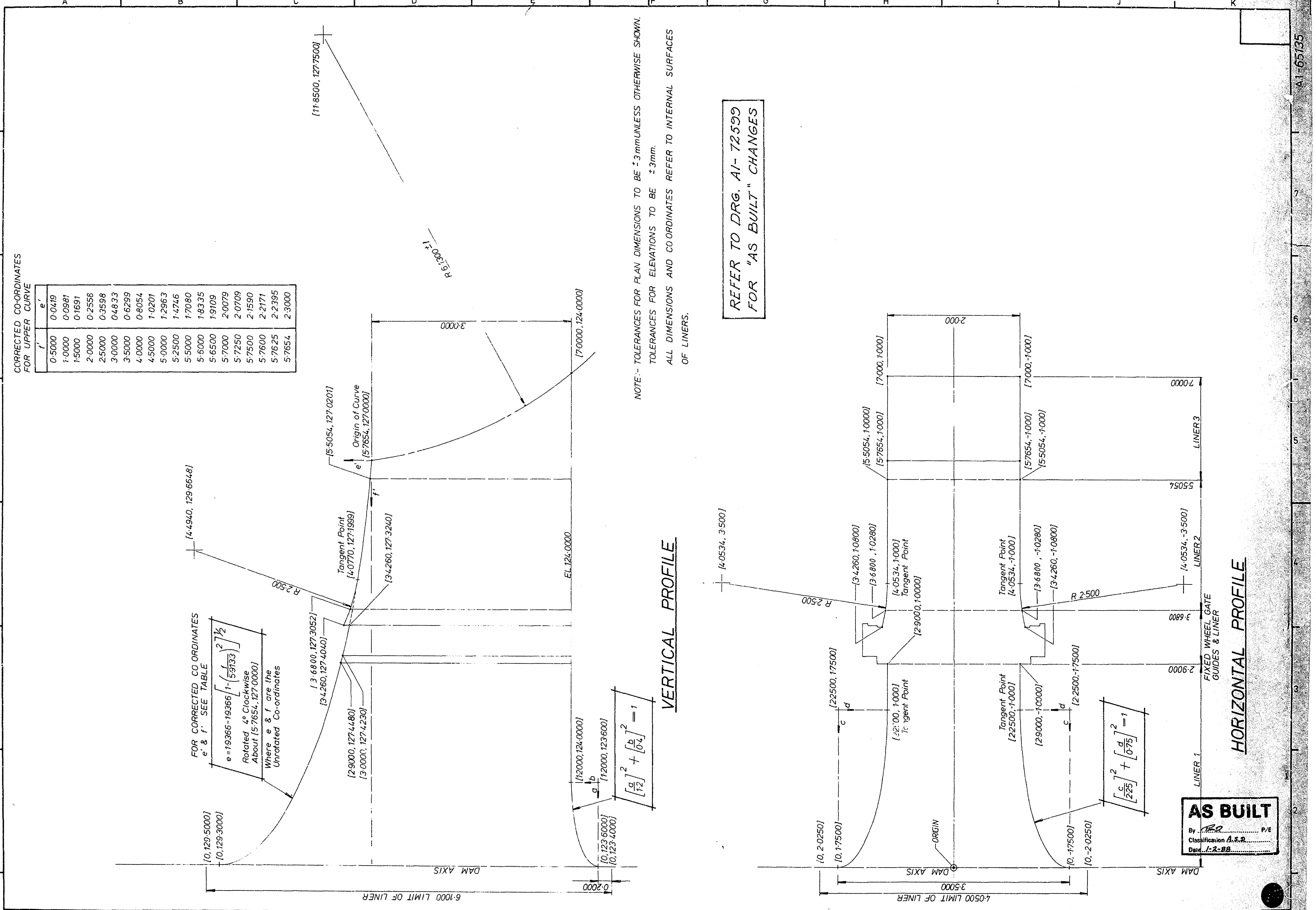


CORRECTED CO-ORDINATES FOR UPPER CURVE

f'	e'
0·5000	0·0419
1·0000	0·0981
1·5000	0·1691
2·0000	0·2556
2·5000	0·3598
3·0000	0·4833
3·5000	0·6299
4·0000	0·8054
4·5000	1·0201
5·0000	1·2963
5·2500	1·4746
5·5000	1·7080
5·6000	1·8335
5·6500	1·9109
5·7000	2·0079
5·7250	2·0709
5·7500	2·1590
5·7600	2·2171
5·7625	2·2395
5·7654	2·3000

REVISION	DATE		REMARKS	ZONE	CKD	PSO
	1.2.88	B	AS BUILT		PMD.	
	27.4.84	A	Tender to Working Drg.		CRC	

DRAWING SCHEDULE

SURVEY BOOKS

SCALES

0 500 1000 1500 2000 2500 mm

Scale 1:25 (Before Reduction)

DESIGN PREP. L. L. / DRAFTING DR G.J.G.
CKD J.K.R. / CKD
SUPV / SUPV
SUBMITTED EXEC. ENGINEER / SUBMITTED SUPV. D'MAN
RECOMMENDED — SENIOR ENGINEER DESIGNS
APPROVED/DATE 24·2·83 CHIEF DESIGNING ENGINEER

Queensland Water Resources Commission

BURDEKIN FALLS DAM

MONOLITHS LH2 & LH3 - OUTLET WORKS

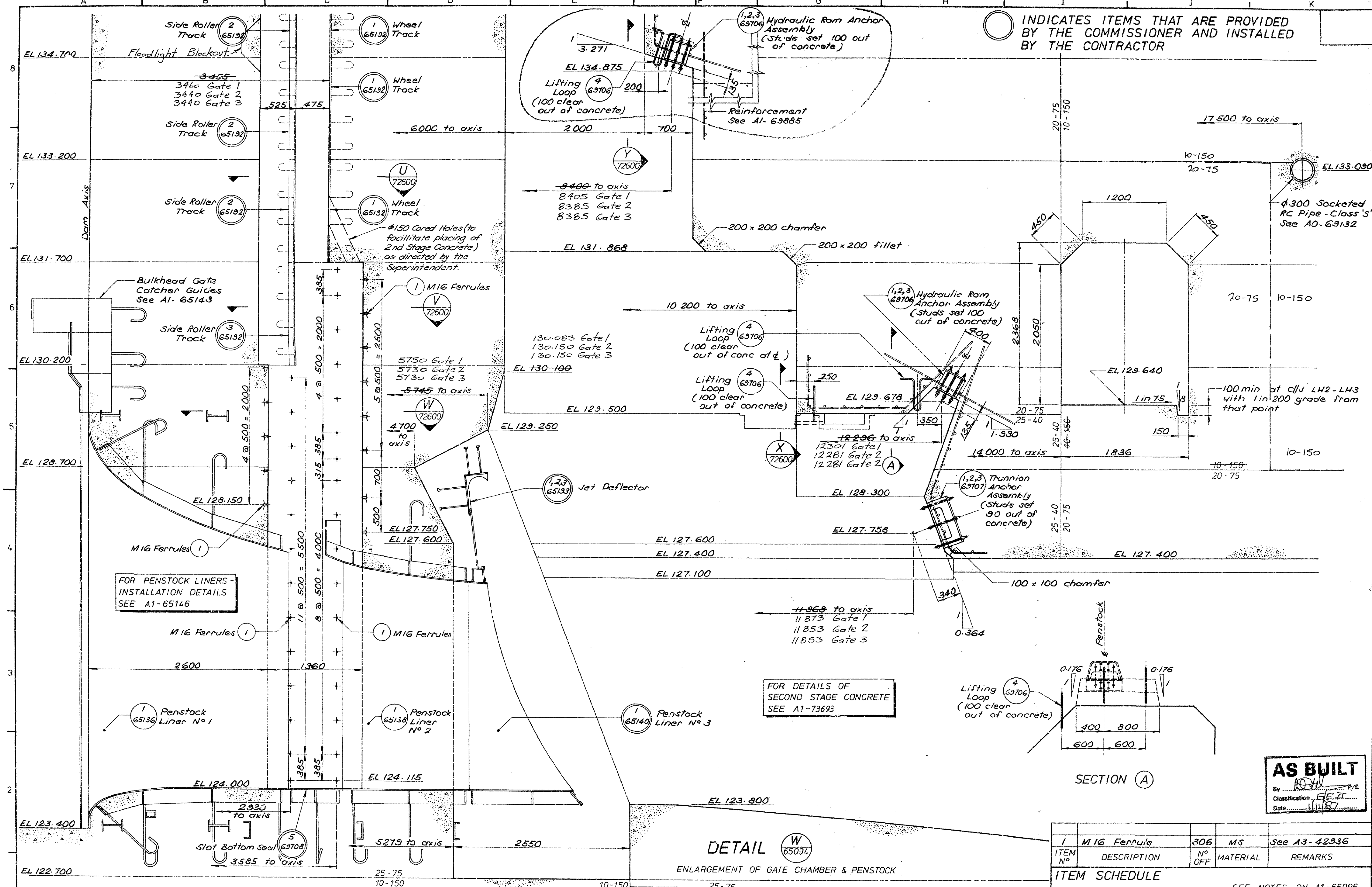
GEOMETRY

CONTRACT NUMBER 2360

DRAWING NUMBER A1-65135

A B

DWG 65135B.tif



REVISION					
1.11.87	B	AS BUILT		PHD	KDH
13.3.85	A	Ram Anchor pt. raised	F 8	CRC	
DATE		REMARKS	ZONE	CKD	PSD

DRAWING SCHEDULE	
A1-65143	Bulkhead Gate Catcher Guide - Arrg't
A0-63132	Ventilation System (Sh. 3)
A3-42936	Metric Anchorage Ferrules
A1-65152	Fixed Wheel Gate Guides - Install'n
A1-65146	Penstock Liners - Install'n Details
A1-65092	Concrete (Sh 1 of 11)

SCALE 0 0.5 1.0 1.5 2.0 2.5m (1:25 before reduction)

DESIGN: PREP [illegible]; CKD J.K.R.; SUPV [illegible]
DRAFTING: DR KFP; CKD CRC; SUPV [illegible]
SUBMITTED — EXEC. ENGINEER | SUBMITTED — SUPV D'MAN | RECOMMENDED — SENIOR ENGINEER DESIGNS | APPROVED — CHIEF DESIGNING ENGINEER

Queensland Water Resources Commission

BURDEKIN FALLS DAM

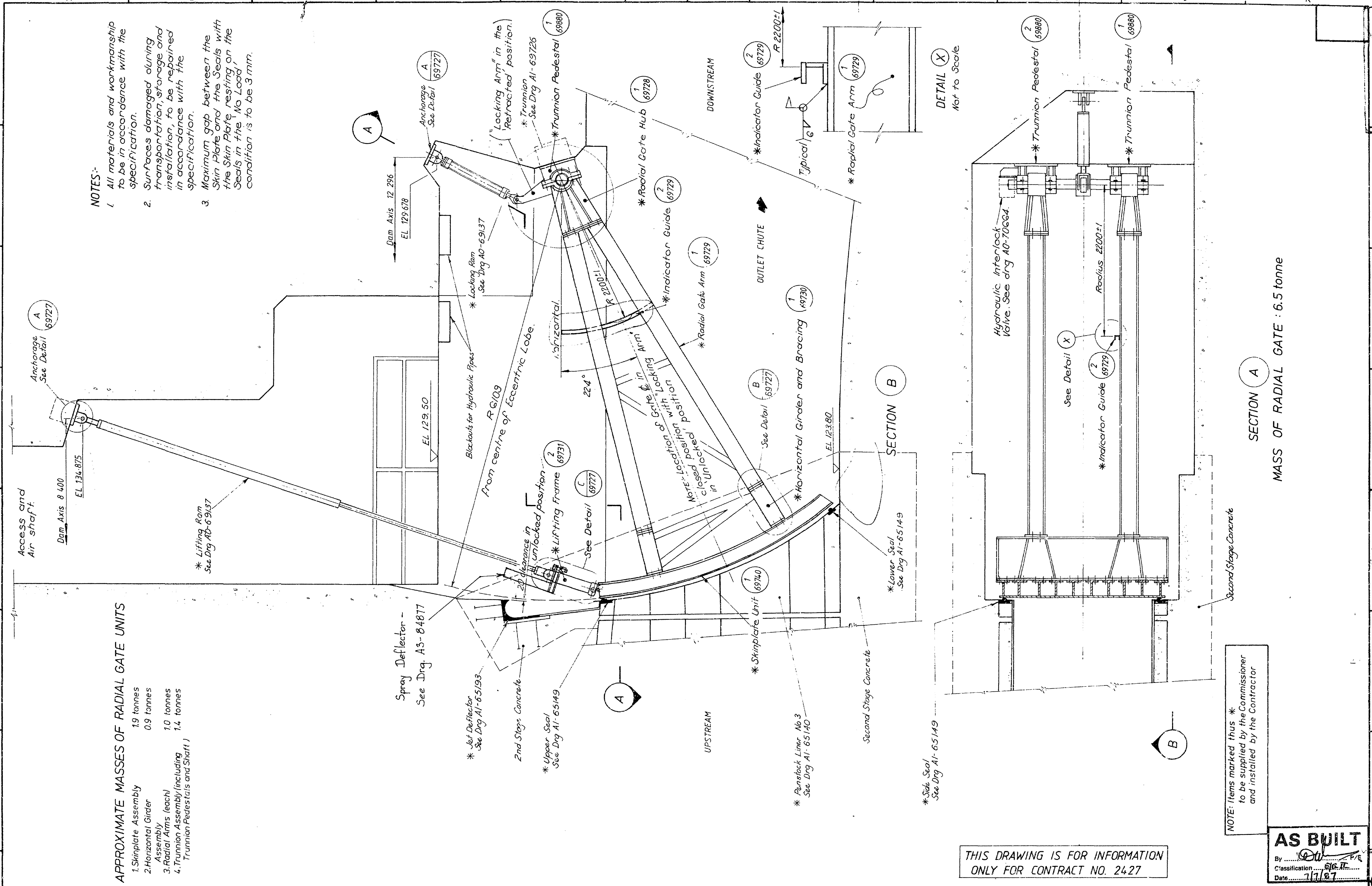
MONOLITHS LH2 & LH3

CONCRETE

Sh 7 of 11

CONTRACT NUMBER 2360
DRAWING NUMBER A1-72599
DATE 12.7.84
A B

DWG 72599B.tif



Date	Rev	Remarks	Zone	CKD	PSD
7.7.87	D	AS BUILT			DM
1.7.86	C	Indicator Guide Lengthened		CRC	
3.1.85	B	Note removed, EL altered & note added	G4		
26.4.84	A	Section A amended. Item Nos. and Detail X added.		CRC	

Drawing	Title
A1-65140	Penstock Liner No 3 - Fabrication
A1-65149	Penstock Liners - Installation Details
A1-65193	Jet Deflector - Fabrication
A0-69137	Hydraulic Equipment & Pipework - Arrgt
A1-69727	Radial Gate Installation Sh 3 of 3
A1-69726	Radial Gate Installation Sh 2 of 3
A1-65161	Monoliths LH 2 & LH 3 Arrangement

SCALE (Before reduction) 0 500 1000 1500 2000 2500 mm (1:25)

Queensland Water Resources Commission

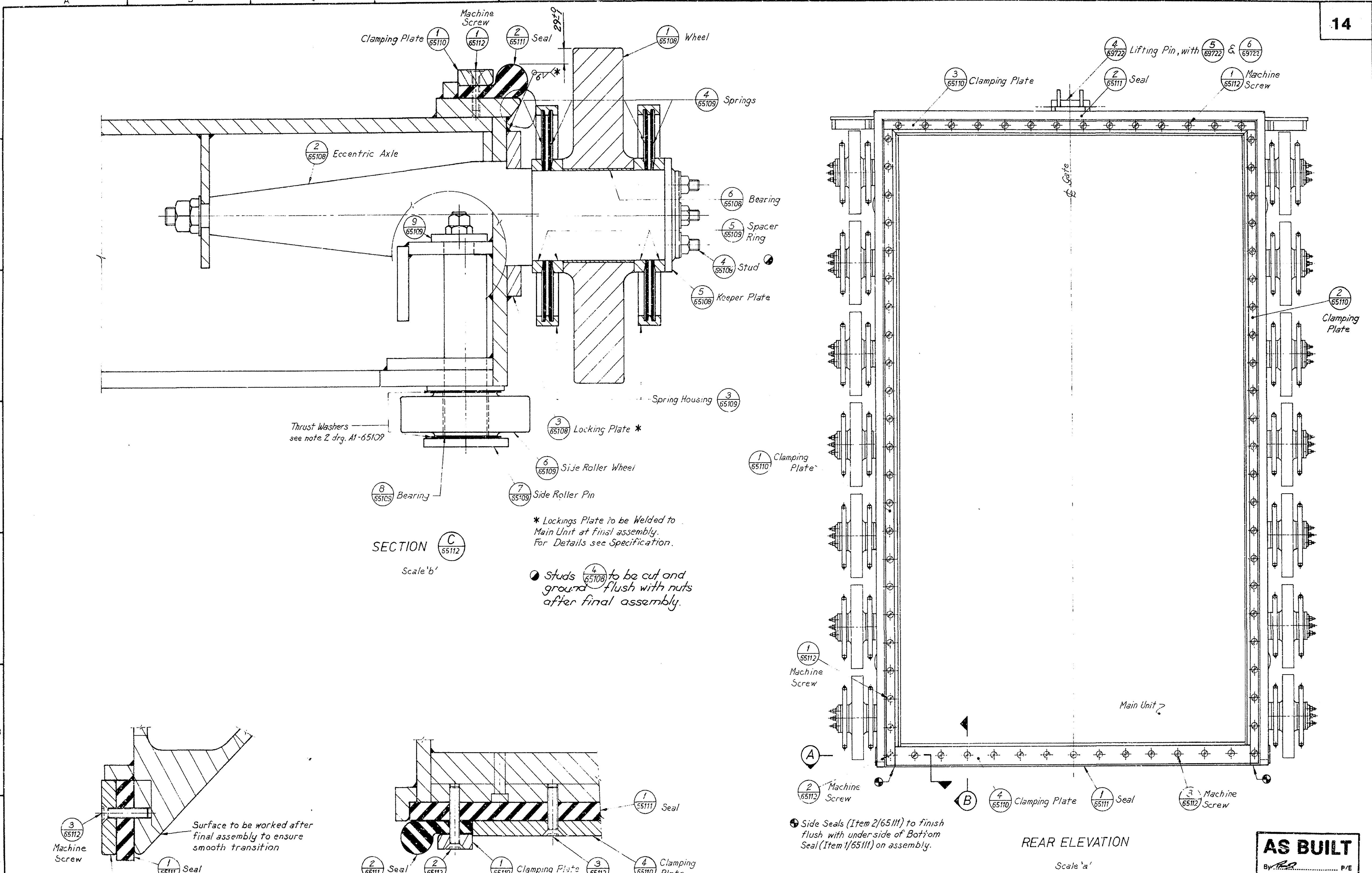
BURDEKIN FALLS DAM
MONOLITHS LH2 & LH3 - OUTLET WORKS

RADIAL GATE - INSTALLATION

Recommended: R. Russo, Senior Engineer Designs
Approved / Date: P.K. 7.3.83, Chief Designing Engineer

CONTRACT NUMBER 2360
DRAWING NUMBER A1-69725
Sh 1 of 3
A B C D

DWG 69725D.tif



NOTES:
1. All materials and workmanship shall be in accordance with the specification.

FOR INFORMATION ONLY
TO BE SUPPLIED BY THE COMMISSIONER AND INSTALLED BY THE CONTRACTOR

AS BUILT
Classification A.S.D.
Date 1.2.88

DATE	REV	REMARKS	ZONE	CKD	PSD	DRAWING	SCHEDULE
1.2.88	E	AS BUILT		PMD.			
4-2-85	D	Chamfer added Sect C	E8			A1-65111	Fixed Wheel Gate - Rubber Seals
29-6-84	C	Lifting Pin altered	I8		J.K.K.	A1-65110	" " " Clamp Plates - Fabrication
5-7-84	B	Note added	E4	CRC		A1-65108-9	" " " Wheel Comp. - Fabr'n Sh. 1&2 of 2
28-4-83	A	Items amended		CRC		A1-65105-7	" " " Main Unit - Fabr'n Sh. 1,2&3 of 3
						A1-65112	" " " Assembly Sh. 1 of 2

SCALE
Scale 'a' 0 500 1000mm 1:10
Scale 'b' 0 50 100 150 200 250mm 1:2.5
BEFORE REDUCTION

DESIGN / DRAFTING
PREP S.P.J. DR C.W.
CKD J.K.R. CKD M.P.G.
SUBMITTED / RECOMMENDED / APPROVED
EXEC ENGINEER / SUPV D'MAN / SENIOR ENGINEER DESIGNS / CHIEF DESIGNING ENGINEER

Queensland Water Resources Commission

BURDEKIN FALLS DAM
FIXED WHEEL GATE
ASSEMBLY
sh 2 of 2

CONTRACT NUMBER 2427
DRAWING NUMBER A1-65113
DATE 21-2-83
A B C D E

DWG 65113E.tif

APPENDIX C

SUMMARY OF DATA

TABLE

Radial gate Opening	Fixed-wheel Gate Opening	D/d	PT1 min	PT1 med	PT1 max	PT2 min	PT2 med	PT2 max	PT3 min	PT3 med	PT3 max	PT4 min	PT4 med	PT4 max
10.2	37.8	26.98%	1.1943	1.2004	1.208	1.1058	1.1241	1.1409	0.99056	1.0709	1.1297	1.0858	1.1089	1.132
10.2	18.85	54.11%	1.1897	1.1973	1.205	0.8143	0.92265	1.0127	0.7556	1.0478	1.3105	0.81773	0.89477	0.97335
10.2	14.6	69.86%	1.1882	1.1989	1.2111	0.5793	0.7792	0.97605	0.61029	0.98592	1.4126	0.61897	0.74377	0.87474
10.2	13.55	75.28%	1.1851	1.1989	1.2126	0.46333	0.71053	0.95774	0.54073	0.94187	1.4234	0.52653	0.67136	0.84701
10.2	7.4	137.84%	1.1698	1.1821	1.1958	-0.07992	0.19933	0.49385	0.064615	0.57783	1.4543	-0.0528	0.14596	0.34626
10.2	6.4	159.38%	1.1882	1.2034	1.2187	-0.25541	0.057416	0.43738	0.059978	0.45107	1.2255	-0.26697	0.008829	0.25073
10.2	4.95	206.06%	1.1958	1.2034	1.2096	-0.3195	-0.06314	0.20391	-0.07296	0.32431	0.95964	-0.24386	-0.09594	0.067379
10.2	3.7	275.68%	1.1973	1.2034	1.2111	-0.41259	-0.1669	0.11845	-0.16107	0.19601	0.80042	-0.32706	-0.19147	-0.04356
10.2	2	510.00%	1.2004	1.205	1.2096	-0.16538	-0.0784	0.016214	-0.15953	0.049157	0.46498	-0.14217	-0.06051	-0.0035
10.2	1.8	566.67%	1.1958	1.2004	1.2065	-0.16233	-0.07534	0.01011	-0.17189	0.049157	0.53763	-0.13138	-0.05896	-0.0035
20	106.55	18.77%	1.1897	1.1912	1.1943	1.1164	1.1302	1.1485	0.89008	0.938	0.98901	1.1166	1.1336	1.1721
20	41.95	47.68%	1.1759	1.1821	1.1897	0.90128	0.94248	0.99437	0.77724	1.006	1.2704	0.84701	0.91788	0.98413
20	32.5	61.54%	1.1591	1.1759	1.1958	0.68001	0.77615	0.90281	0.52836	0.96428	1.3616	0.61743	0.73761	0.86395
20	18.2	109.89%	1.1148	1.1759	1.2325	-0.81544	-0.06619	1.0508	-0.43623	0.50054	1.7094	-0.75539	-0.14679	0.54502
20	16.8	119.05%	1.1286	1.1698	1.2126	-0.64911	-0.20353	0.31683	-0.41768	0.3104	1.3538	-0.55663	-0.26697	0.082786
20	15.45	129.45%	1.1576	1.1698	1.1821	-0.60181	-0.36681	-0.06161	-0.59545	0.098623	1.1544	-0.58591	-0.41488	-0.14217
30	133.1	22.54%	1.179	1.1805	1.1821	1.0569	1.0707	1.0875	0.84216	0.86689	0.9009	1.0889	1.1028	1.1197
30	65.65	45.70%	1.1423	1.15	1.1576	0.86924	0.90586	0.94706	0.7525	0.95346	1.19	0.8393	0.88553	0.93791
30	52	57.69%	1.1347	1.1484	1.1637	0.70596	0.7792	0.85398	0.55618	0.91945	1.3817	0.65441	0.74069	0.84238
30	33.55	89.42%	1.0629	1.1271	1.1943	-0.11197	0.19628	0.5381	-0.3002	0.60256	1.8083	-0.22691	0.10436	0.45257
30	31	96.77%	1.0644	1.1209	1.1821	-0.36375	0.004007	0.47706	-0.52898	0.39542	1.8299	-0.60131	-0.0944	0.42484
30	29.9	100.33%	1.0736	1.1225	1.1714	-0.36375	-0.0845	0.28021	-0.75467	0.35214	1.7465	-0.70455	-0.18377	0.41559
30	28.7	104.53%	0.94372	1.1286	1.3165	-1.0199	-0.15012	1.0005	-0.71293	0.42943	1.7094	-1.042	-0.2531	0.7484
30	27.7	108.30%	0.91775	1.1332	1.3486	-1.0916	-0.22184	0.97605	-0.77631	0.39078	1.5409	-1.0974	-0.32552	0.58353
40	85.85	46.59%	1.1255	1.1316	1.1393	0.84329	0.89213	0.92875	0.65048	0.921	1.1962	0.80695	0.86858	0.93637
40	70.45	56.78%	1.1041	1.1164	1.1286	0.71206	0.77463	0.8494	0.43097	0.91172	1.394	0.60973	0.71296	0.7977
40	58.05	68.91%	1.0736	1.095	1.1179	0.45417	0.57167	0.71053	0.18519	0.74632	1.5084	0.31544	0.47414	0.65441
40	50.7	78.90%	1.04	1.0797	1.1209	0.21612	0.35956	0.55031	-0.09615	0.55928	1.4172	0.027319	0.24611	0.48339
40	48.5	82.47%	1.0232	1.0705	1.1194	0.098617	0.26953	0.49995	-0.17962	0.48044	1.5007	-0.11443	0.15058	0.42175
40	46.9	85.29%	1.0201	1.0659	1.1133	-0.03262	0.18712	0.4267	-0.36048	0.41242	1.4419	-0.21766	0.062756	0.36166
40	45.4	88.11%	1.0171	1.0614	1.1072	-0.09823	0.12151	0.40686	-0.3914	0.34595	1.4126	-0.30241	-0.0035	0.29849
40	43	93.02%	1.0171	1.0568	1.0965	-0.2722	-0.01736	0.32751	-0.62637	0.20065	1.4327	-0.47035	-0.14987	0.18448
40	41.9	95.47%	1.0155	1.0522	1.0934	-0.34392	-0.09518	0.21001	-0.66346	0.15814	1.4265	-0.78312	-0.20996	0.35088
40	40.5	98.77%	0.91775	1.0598	1.2019	-0.84902	-0.13638	0.76547	-0.85824	0.16355	1.3384	-1.0651	-0.25464	0.80386
40	39.2	102.04%	1.0675	1.0736	1.0782	-0.01431	0.02537	0.061994	-0.12552	0.004328	0.36914	-0.09902	-0.05126	-0.01582
50	102.9	48.59%	1.098	1.1072	1.1164	0.79141	0.83872	0.90739	0.58246	0.90245	1.1946	0.81311	0.87628	0.93021
50	75.3	66.40%	1.0461	1.0659	1.0889	0.46485	0.58998	0.71511	0.28876	0.76642	1.4574	0.35242	0.55426	0.7068
50	68.75	72.73%	1.0155	1.0446	1.0736	0.32294	0.45264	0.62355	0.019786	0.61338	1.4311	0.16599	0.40327	0.66211
50	65.85	75.93%	1.0002	1.0308	1.0614	0.21917	0.37787	0.56099	-0.08378	0.52991	1.5981	0.039645	0.31852	0.58045
50	63.7	78.49%	0.99414	1.0277	1.0644	0.15813	0.32141	0.53352	-0.17189	0.45571	1.2673	0.004207	0.25689	0.50496
50	61.2	81.70%	0.98191	1.014	1.0491	0.033	0.22833	0.4618	-0.29092	0.34286	1.3631	-0.15141	0.15058	0.44333
50	58.8	85.03%	0.97122	1.0018	1.0339	-0.11197	0.14287	0.37635	-0.38522	0.25011	1.2843	-0.23461	0.059675	0.431
50	57.75	86.58%	0.97122	1.0002	1.0293	-0.08755	0.10625	0.32904	-0.38676	0.20374	1.1652	-0.29316	0.022696	0.36166

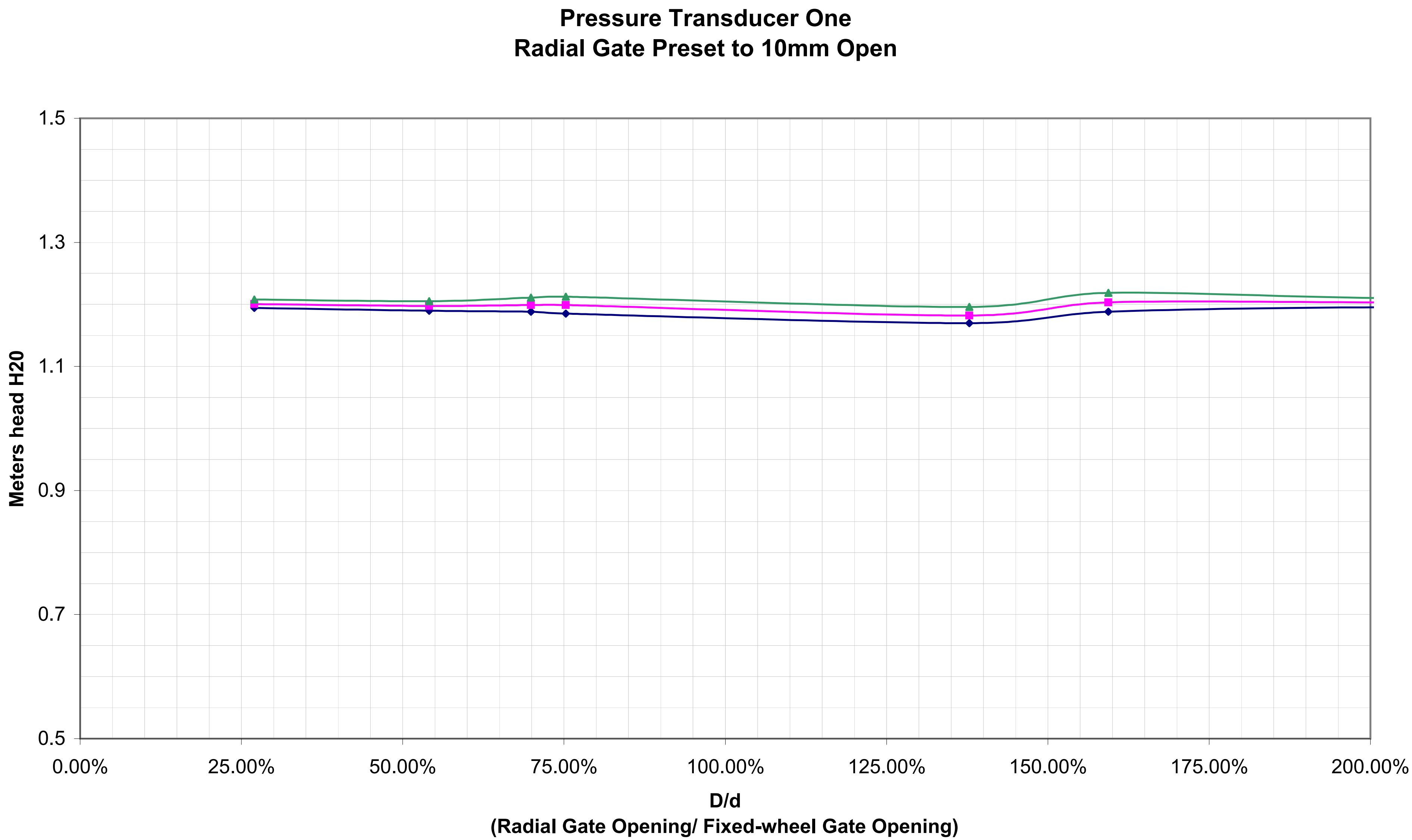
50	55.4	90.25%	0.96511	0.99108	1.0171	-0.20505	0.014688	0.25274	-0.51352	0.10326	0.98747	-0.39485	-0.07283	0.32623
50	54.7	91.41%	0.95136	0.98955	1.0293	-0.34697	-0.05246	0.31225	-0.69438	0.063069	1.1266	-0.71995	-0.12059	0.52961
50	53.7	93.11%	0.9483	0.98802	1.0293	-0.36223	-0.07229	0.25579	-0.63564	0.046065	1.0168	-0.66757	-0.136	0.51266
50	52.45	95.33%	1.0109	1.0171	1.0216	0.008585	0.054364	0.10625	-0.17344	0.004328	0.33822	-0.06051	-0.02661	-0.00966
60	113.65	52.79%	1.0644	1.0751	1.0858	0.79752	0.84329	0.90891	0.55309	0.86689	1.2997	0.79616	0.94099	1.2522
60	106.55	56.31%	1.0552	1.0659	1.0782	0.738	0.80057	0.87381	0.55155	0.89781	1.3878	0.73145	0.86858	1.1721
60	99.2	60.48%	1.0339	1.0491	1.0629	0.6617	0.73495	0.82651	0.37996	0.86071	1.4574	0.62976	0.76843	0.93483
60	95.65	62.73%	1.0247	1.04	1.0568	0.61135	0.6968	0.78683	0.38305	0.84525	1.4126	0.55426	0.71142	0.95486
60	87.65	68.45%	0.98955	1.0155	1.0415	0.42975	0.58083	0.71511	0.18828	0.7525	1.6429	0.3216	0.54964	0.83468
60	82.3	72.90%	0.96358	0.99566	1.0293	0.32141	0.48469	0.6617	0.018241	0.63966	1.6383	0.1136	0.42792	0.66365
60	80.8	74.26%	0.95441	0.99108	1.0293	0.2741	0.44654	0.64339	-0.05905	0.6072	1.5702	0.12593	0.37399	0.64979
60	78.1	76.82%	0.94219	0.98191	1.0232	0.22222	0.39008	0.59761	-0.2059	0.51754	1.513	0.039645	0.30003	0.62976
60	75.75	79.21%	0.93455	0.97275	1.014	0.12151	0.32141	0.53352	-0.32802	0.41861	1.4048	-0.07745	0.20451	0.55888
60	72.6	82.64%	0.9208	0.95594	0.99261	0.019266	0.24053	0.46638	-0.34812	0.29958	1.5208	-0.2454	0.092031	0.45873
60	71.7	83.68%	0.91775	0.95136	0.9865	-0.06009	0.1917	0.43281	-0.49961	0.23311	1.2704	-0.36095	0.036563	0.50342
60	70.25	85.41%	0.91469	0.94525	0.97886	-0.08145	0.1566	0.40839	-0.47024	0.18519	1.0168	-0.31781	-0.01428	0.3555
60	69.8	85.96%	0.90858	0.94066	0.97275	-0.08603	0.13219	0.39466	-0.4826	0.16046	1.2132	-0.40718	-0.04664	0.38786
60	68.55	87.53%	0.90705	0.93608	0.96664	-0.14554	0.092513	0.33972	-0.5769	0.10481	1.2116	-0.43337	-0.09748	0.39864
60	66.7	89.96%	0.90552	0.92997	0.95441	-0.14707	0.02537	0.21764	-0.53516	0.015149	0.70922	-0.47035	-0.17452	0.18756
60	66	90.91%	0.90094	0.92539	0.95289	-0.21726	-0.0021	0.23138	-0.61709	-0.01577	0.9581	-0.53044	-0.21458	0.25073
60	65	92.31%	0.95289	0.959	0.96511	0.020792	0.10625	0.17949	-0.09615	0.002782	0.15582	-0.06821	-0.02353	0.053512
70	113.35	61.76%	0.99414	1.0094	1.0247	0.64034	0.70443	0.81735	0.39542	0.81434	1.4327	0.62359	0.80232	1.0396
70	100.6	69.58%	0.95289	0.97122	0.99108	0.42365	0.54725	0.67086	0.12026	0.69376	1.5161	0.34163	0.56042	0.81311
70	93.8	74.63%	0.91927	0.94372	0.96969	0.29242	0.43281	0.58998	-0.08224	0.55155	1.68	0.10744	0.3894	0.65903
70	92.5	75.68%	0.90858	0.93455	0.96052	0.27868	0.40534	0.55488	-0.11779	0.51599	1.5641	0.048889	0.35396	0.67906
70	90.95	76.97%	0.89941	0.92691	0.95441	0.22985	0.37787	0.53657	-0.10542	0.47426	1.6692	0.036563	0.3139	0.60511
70	89.55	78.17%	0.89636	0.92691	0.959	0.17797	0.34735	0.5732	-0.19508	0.43561	1.714	-0.03893	0.27076	0.60819
70	88.35	79.23%	0.87955	0.91316	0.94677	0.1505	0.31378	0.50911	-0.34812	0.39078	1.4466	-0.11135	0.223	0.57737
70	86.7	80.74%	0.87497	0.90552	0.93761	0.11998	0.28021	0.49079	-0.33575	0.33977	1.4852	-0.12676	0.17523	0.62976
70	85.8	81.59%	0.86427	0.89789	0.93455	-0.02346	0.24969	0.49537	-0.45323	0.28567	1.6614	-0.20842	0.13055	0.50496
70	84.2	83.14%	0.86122	0.8933	0.92844	0.028422	0.21764	0.43891	-0.44396	0.23002	1.4883	-0.24848	0.085868	0.50342
70	82.9	84.44%	0.85052	0.88261	0.91622	-0.04635	0.17339	0.43128	-0.6681	0.15736	1.4744	-0.34709	0.022696	0.38632
70	80.75	86.69%	0.83983	0.87191	0.904	-0.0784	0.12151	0.33057	-0.61554	0.083165	1.3183	-0.45956	-0.04664	0.39094
70	79.7	87.83%	0.8383	0.86886	0.90094	-0.13944	0.084883	0.30462	-0.77013	0.022878	1.2286	-0.5366	-0.09902	0.42484
70	78.9	88.72%	0.83066	0.86122	0.89483	-0.13333	0.061994	0.27716	-0.73921	-0.0034	1.0818	-0.48267	-0.12676	0.34626
70	77.9	89.86%	0.82761	0.85816	0.8933	-0.14707	0.02537	0.22222	-0.72066	-0.07296	0.87462	-0.58437	-0.17144	0.38015
70	76.9	91.03%	0.89483	0.90247	0.91011	0.028422	0.13677	0.21764	-0.08688	-0.01731	0.078527	-0.04664	-0.03277	-0.01736
80	125.7	63.64%	0.96205	0.9758	0.98955	0.62661	0.68612	0.74563	0.42788	0.75096	1.2904	0.71604	0.9148	1.1243
80	118.1	67.74%	0.92844	0.95136	0.9758	0.51063	0.59914	0.69985	0.22383	0.70458	1.5718	0.5219	0.75764	1.0242
80	113.85	70.27%	0.90094	0.92997	0.959	0.43433	0.53505	0.68154	0.14036	0.66439	1.4512	0.36475	0.65133	0.96719
80	110.55	72.37%	0.88414	0.91316	0.94219	0.38092	0.48622	0.64339	0.004328	0.65048	1.6553	0.29695	0.58508	0.9641
80	107.25	74.59%	0.87191	0.89941	0.92844	0.30005	0.43433	0.5793	-0.00186	0.58246	1.6321	0.20297	0.50804	0.91634
80	104.85	76.30%	0.86122	0.88719	0.91469	0.27868	0.39161	0.53962	-0.12243	0.51909	1.5316	0.16907	0.44487	0.83314
80	104.05	76.89%	0.84747	0.87344	0.90094	0.23138	0.35956	0.48316	-0.16262	0.48508	1.748	0.09049	0.40018	0.7638
80	100.15	79.88%	0.83372	0.85969	0.88566	0.14745	0.29852	0.45112	-0.20899	0.37223	1.5053	0.004207	0.3062	0.69139

80	97.35	82.18%	0.8108	0.83677	0.86427	0.092513	0.23138	0.39923	-0.34812	0.23929	1.4203	-0.20071	0.20605	0.54656
80	92.65	86.35%	0.78177	0.81233	0.84747	-0.03872	0.13371	0.31683	-0.62946	0.066161	1.3693	-0.35171	0.061215	0.54039
80	91.6	87.34%	0.77261	0.80622	0.84289	-0.06924	0.10777	0.32904	-0.68974	0.021332	1.3476	-0.47343	0.019615	0.57891
80	90.75	88.15%	0.76497	0.80011	0.83983	-0.10281	0.086409	0.34888	-0.60627	-0.01268	1.0895	-0.50887	-0.00966	0.61127
80	89.9	88.99%	0.82608	0.8383	0.85052	0.054364	0.15508	0.24664	-0.11779	-0.02968	0.12645	-0.05742	-0.02045	0.045808
80	87.5	91.43%	0.849	0.85969	0.86886	0.069624	0.15355	0.24359	-0.11779	-0.02659	0.10171	-0.03123	-0.02199	-0.0112
90	129.65	69.42%	0.89941	0.91316	0.92539	0.57625	0.62355	0.68459	0.41706	0.7556	1.2054	0.019615	0.022696	0.022696
90	123.6	72.82%	0.8658	0.88872	0.91164	0.48164	0.55183	0.64797	0.14036	0.67521	1.3817	0.019615	0.021156	0.021156
90	118.2	76.14%	0.8215	0.85511	0.88872	0.3504	0.46027	0.59456	-0.0606	0.54227	1.4218	0.018074	0.019615	0.021156
90	113.5	79.30%	0.794	0.82914	0.8658	0.25732	0.3855	0.55031	-0.16726	0.43793	1.5764	0.013452	0.018074	0.021156
90	111.35	80.83%	0.77872	0.81233	0.849	0.18255	0.3382	0.52894	-0.2801	0.3676	1.6707	0.014992	0.016533	0.018074
90	109.05	82.53%	0.76497	0.79705	0.83372	0.14897	0.28936	0.48774	-0.34812	0.28103	1.901	0.014992	0.016533	0.018074
90	106.95	84.15%	0.74969	0.78025	0.81386	0.04826	0.24359	0.41755	-0.54907	0.20142	1.6151	0.013452	0.014992	0.016533
90	104.05	86.50%	0.72983	0.75733	0.78788	0.043682	0.17949	0.33972	-0.54598	0.072344	1.3554	0.013452	0.014992	0.024237
90	101.85	88.37%	0.7115	0.74358	0.77872	-0.03262	0.13524	0.33209	-0.59545	-0.02041	1.1668	0.011911	0.013452	0.022696
90	100.25	89.78%	0.77566	0.78788	0.80011	0.1032	0.1917	0.25427	-0.07296	-0.03277	0.049157	0.019615	0.021156	0.022696
100	128.8	77.64%	0.80927	0.8215	0.83525	0.43738	0.48927	0.53962	0.38151	0.71231	1.2394	0.007289	0.007289	0.011911
100	122.7	81.50%	0.75733	0.7833	0.80927	0.31225	0.3855	0.48622	0.059978	0.55309	1.3708	0.004207	0.005748	0.007289
100	116.9	85.54%	0.70997	0.74052	0.77413	0.16881	0.2741	0.44044	-0.28783	0.28103	1.3677	0.005748	0.007289	0.008829
100	114.85	87.07%	0.69622	0.72983	0.7665	0.13219	0.24206	0.38245	-0.35739	0.20683	1.139	0.005748	0.007289	0.01037
100	113.25	88.30%	0.6733	0.70997	0.74816	0.065046	0.1917	0.3504	-0.44241	0.098623	1.0385	0.002666	0.004207	0.013452
100	110.65	90.38%	0.66108	0.69775	0.73747	0.029948	0.1505	0.31073	-0.59699	-0.00031	0.76332	0.001126	0.002666	0.014992
100	109	91.74%	0.71608	0.73288	0.74663	0.097091	0.18255	0.24511	-0.1317	-0.03741	0.097077	0.001126	0.002666	0.004207
110	127.9	86.00%	0.65955	0.67788	0.69622	0.25732	0.31378	0.36414	0.18055	0.57628	1.2101	0.001126	0.001126	0.002666
110	124.55	88.32%	0.64733	0.66566	0.68552	0.21459	0.27563	0.33972	0.093986	0.50981	1.3987	0.001126	0.002666	0.004207
110	122.15	90.05%	0.629	0.65344	0.67788	0.13219	0.23138	0.33514	-0.03741	0.43407	1.3044	0.001126	0.002666	0.004207
110	120.05	91.63%	0.61372	0.63969	0.66719	0.10167	0.1856	0.28936	-0.15335	0.3305	1.1096	0.002666	0.004207	0.008829
110	117.9	93.30%	0.59844	0.62441	0.65191	0.039104	0.14745	0.24664	-0.21518	0.22693	1.156	0.001126	0.002666	0.011911
110	115.8	94.99%	0.5908	0.61677	0.6458	0.013162	0.11388	0.22985	-0.31256	0.10326	0.9581	0.001126	0.004207	0.011911

APPENDIX D

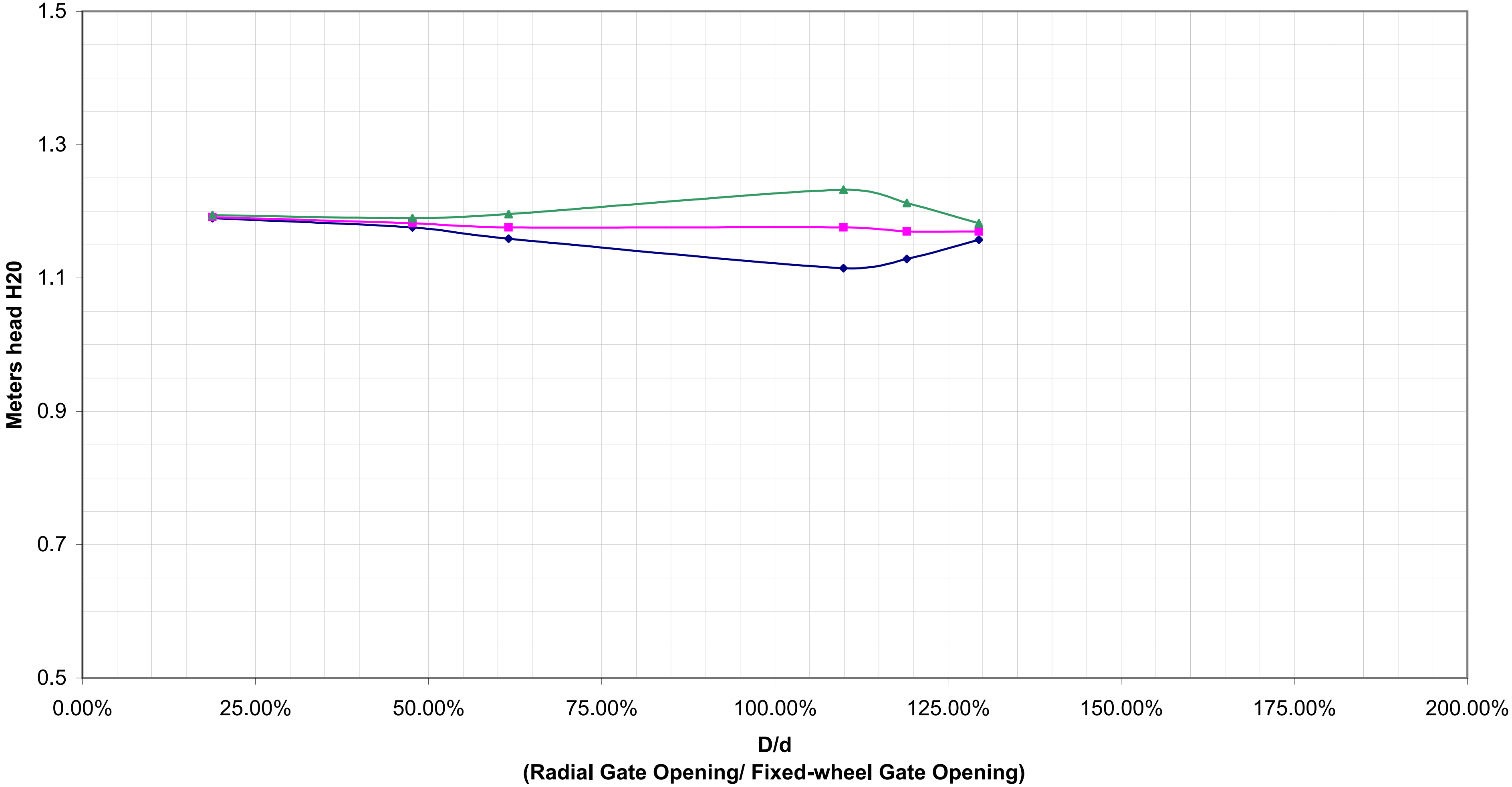
SUMMARY OF DATA

PRESSURE TRANSDUCER ONE

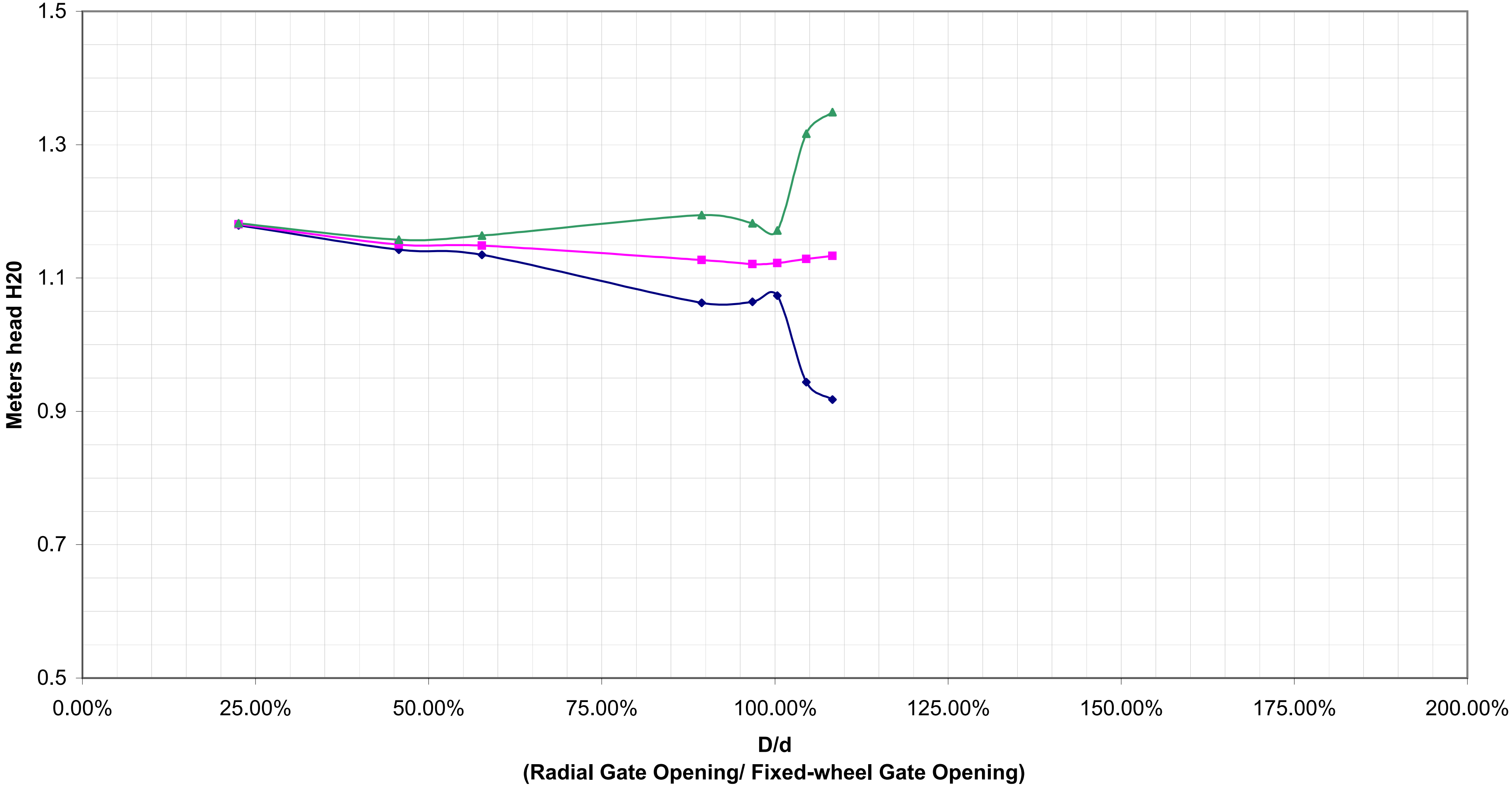


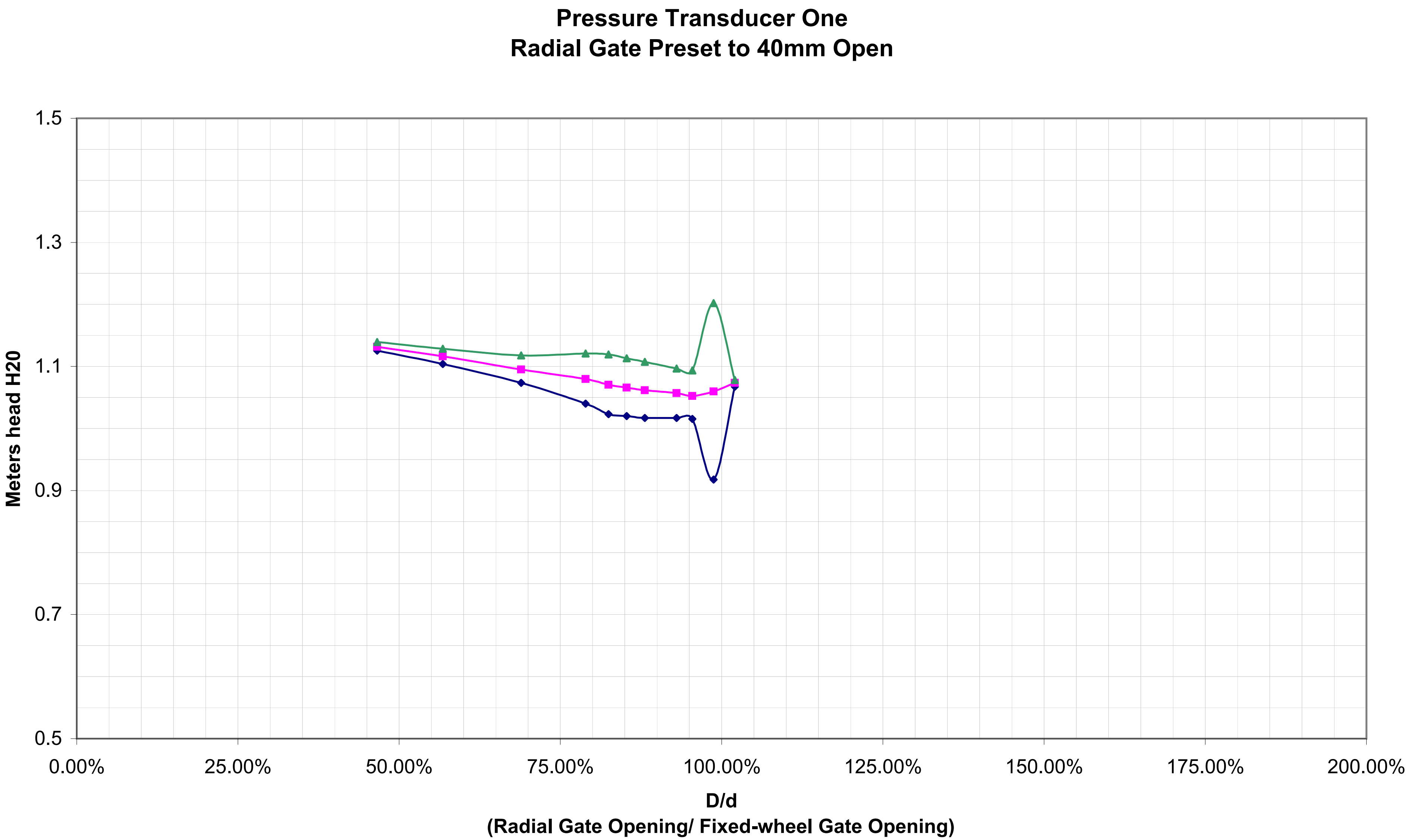
Pressure Transducer One
Radial Gate Preset to 10mm Open
Meters head H20
1.5
1.3
1.1
0.9
0.7
0.5
0.00%
25.00%
50.00%
75.00%
100.00%
125.00%
150.00%
175.00%
200.00%
D/d
(Radial Gate Opening/ Fixed-wheel Gate Opening)

Pressure Transducer One
Radial Gate Preset to 20mm Open

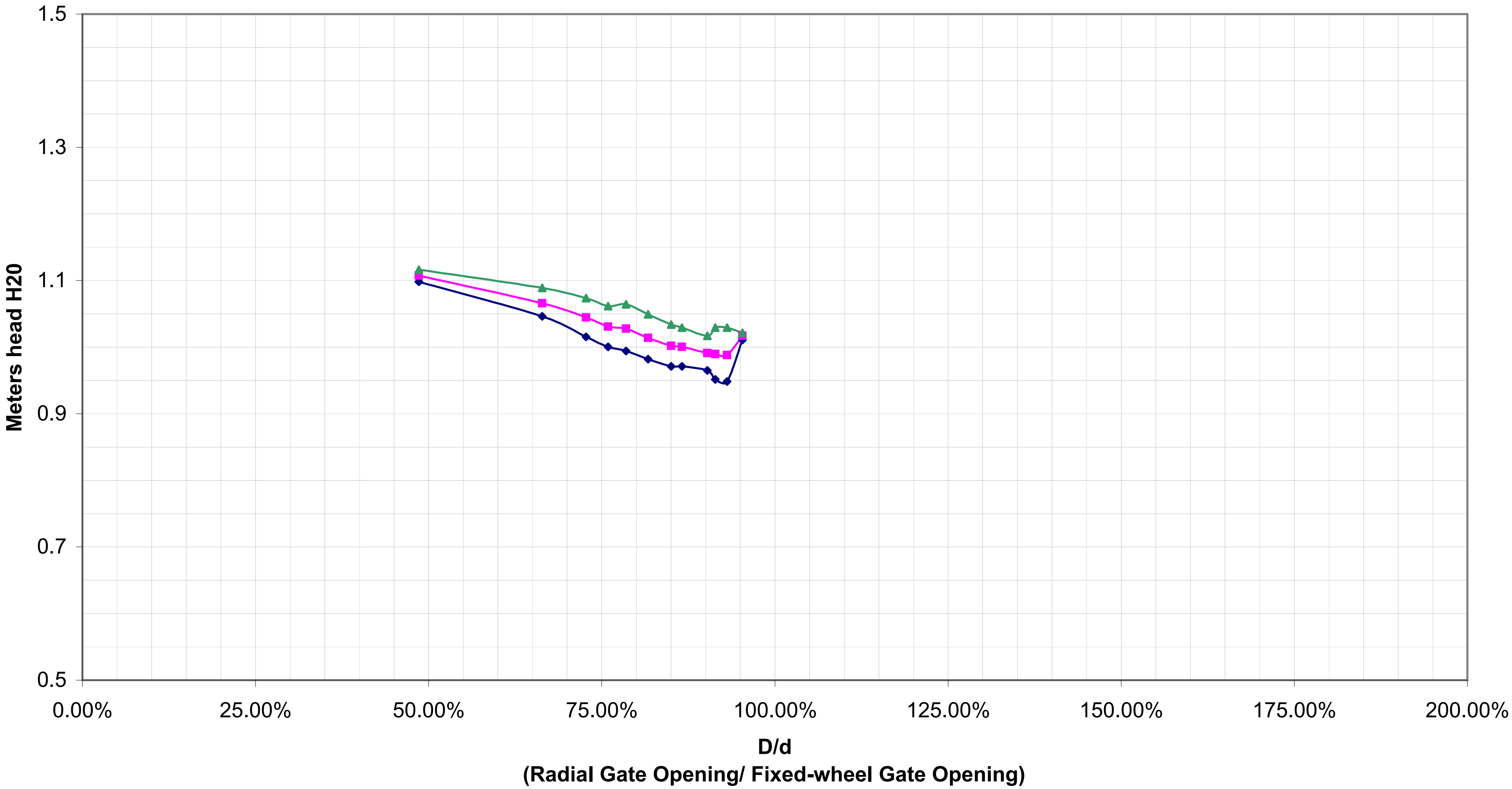


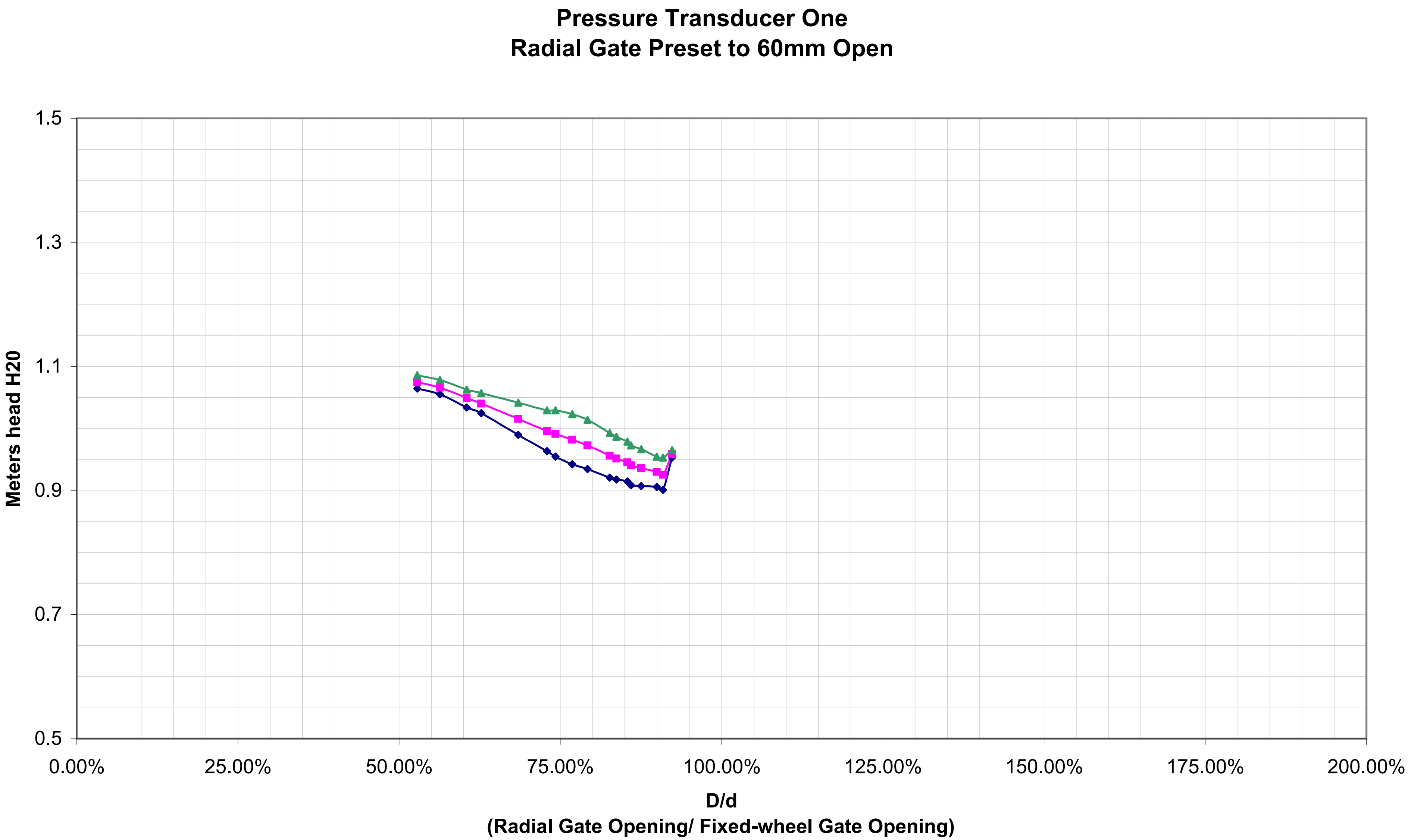
Pressure Transducer One
Radial Gate Preset to 30mm Open



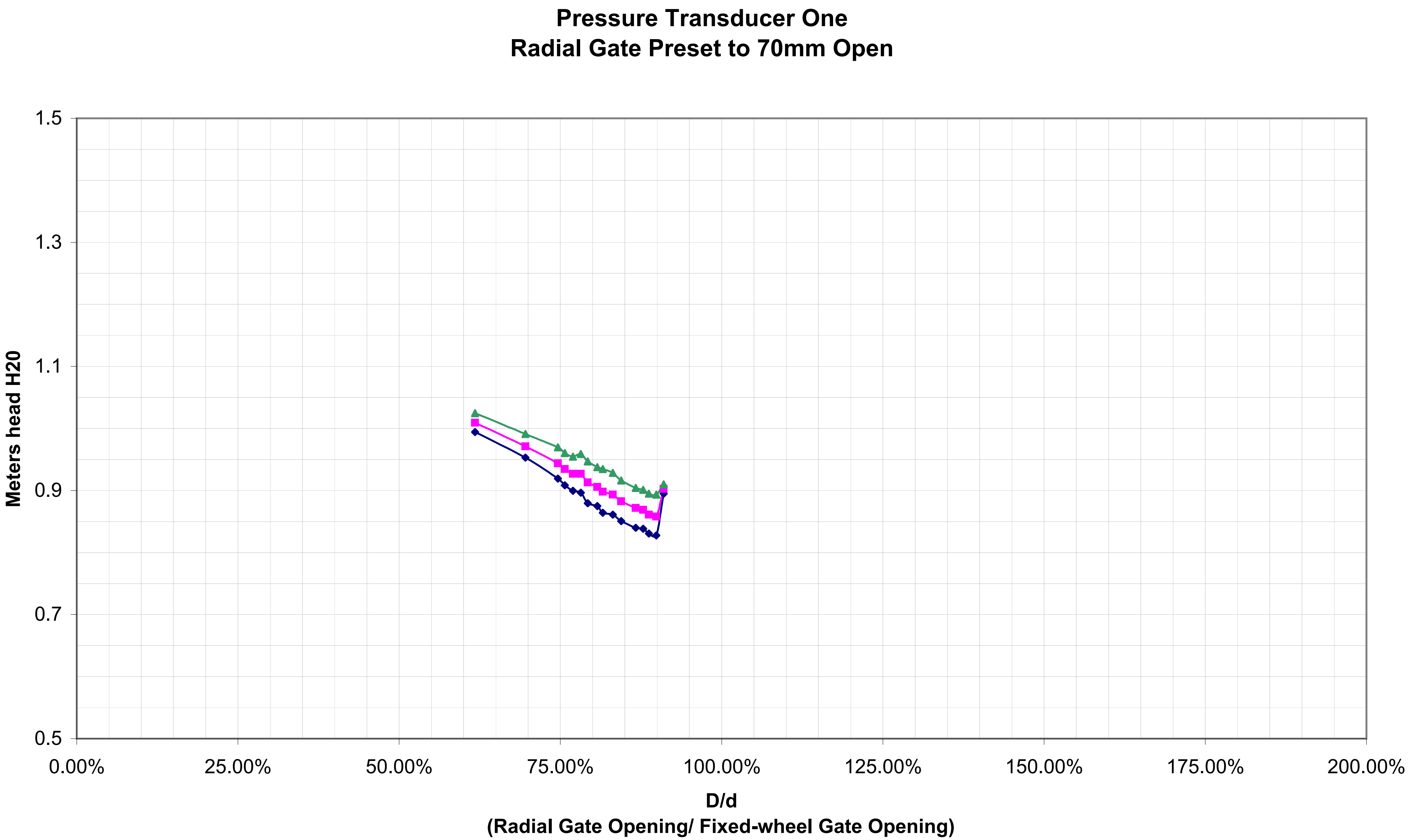

Pressure Transducer One
Radial Gate Preset to 40mm Open
Meters head H20
1.5
1.3
1.1
0.9
0.7
0.5
0.00%
25.00%
50.00%
75.00%
100.00%
125.00%
150.00%
175.00%
200.00%
D/d
(Radial Gate Opening/ Fixed-wheel Gate Opening)

Pressure Transducer One
Radial Gate Preset to 50mm Open

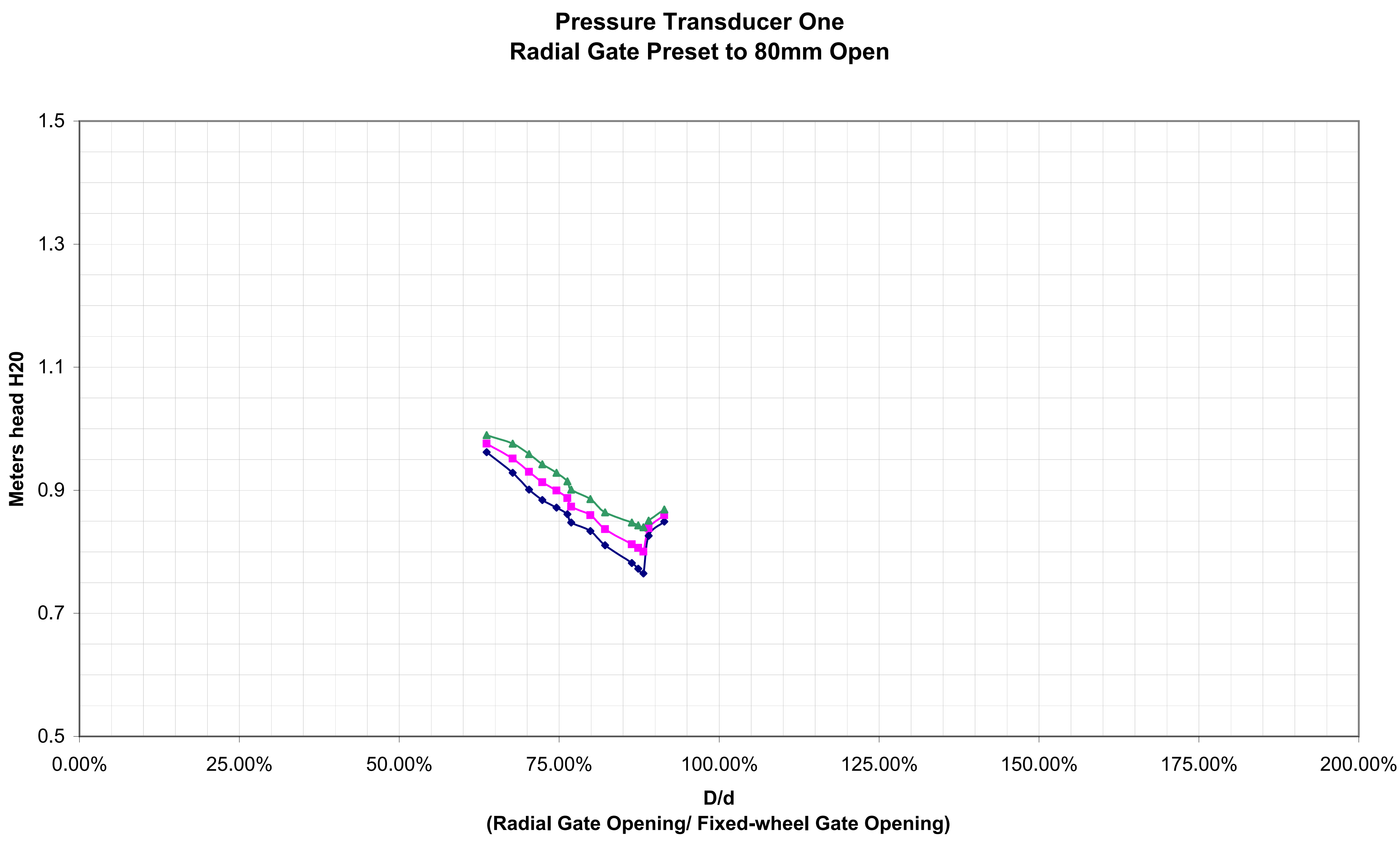


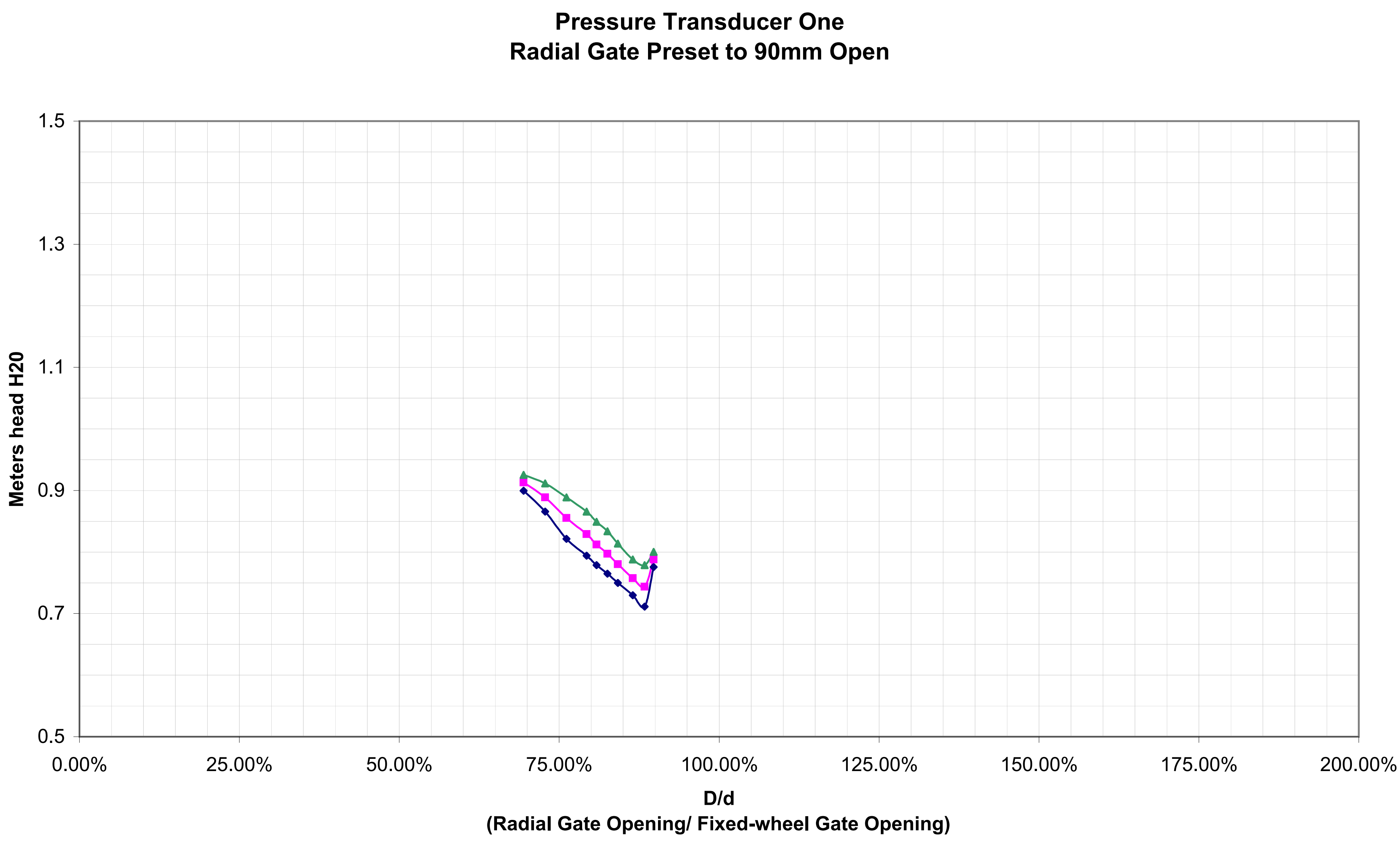


Pressure Transducer One
Radial Gate Preset to 60mm Open
1.5
1.3
1.1
0.9
0.7
0.5
Meters head H20
0.00%
25.00%
50.00%
75.00%
100.00%
125.00%
150.00%
175.00%
200.00%
D/d
(Radial Gate Opening/ Fixed-wheel Gate Opening)

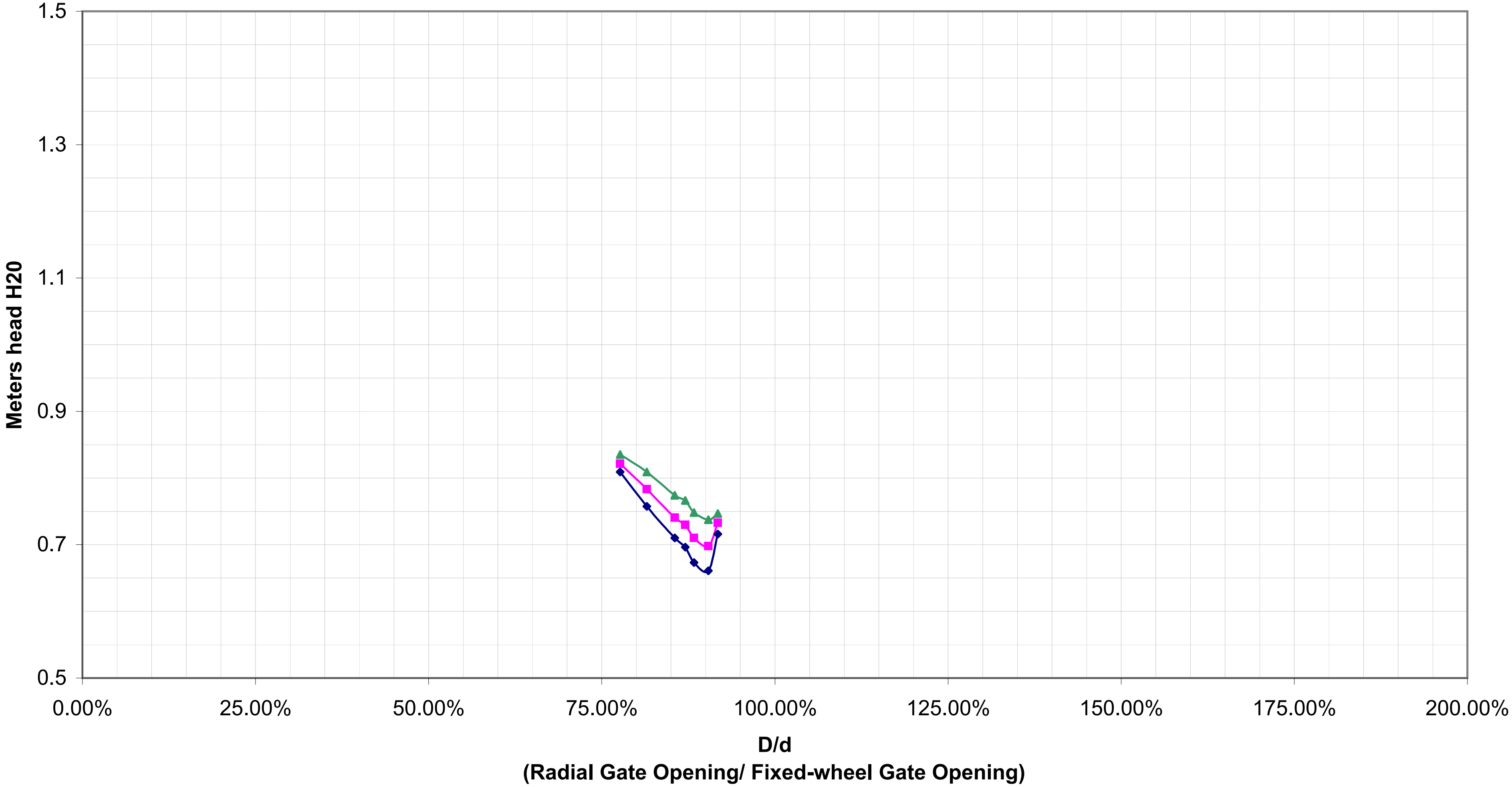


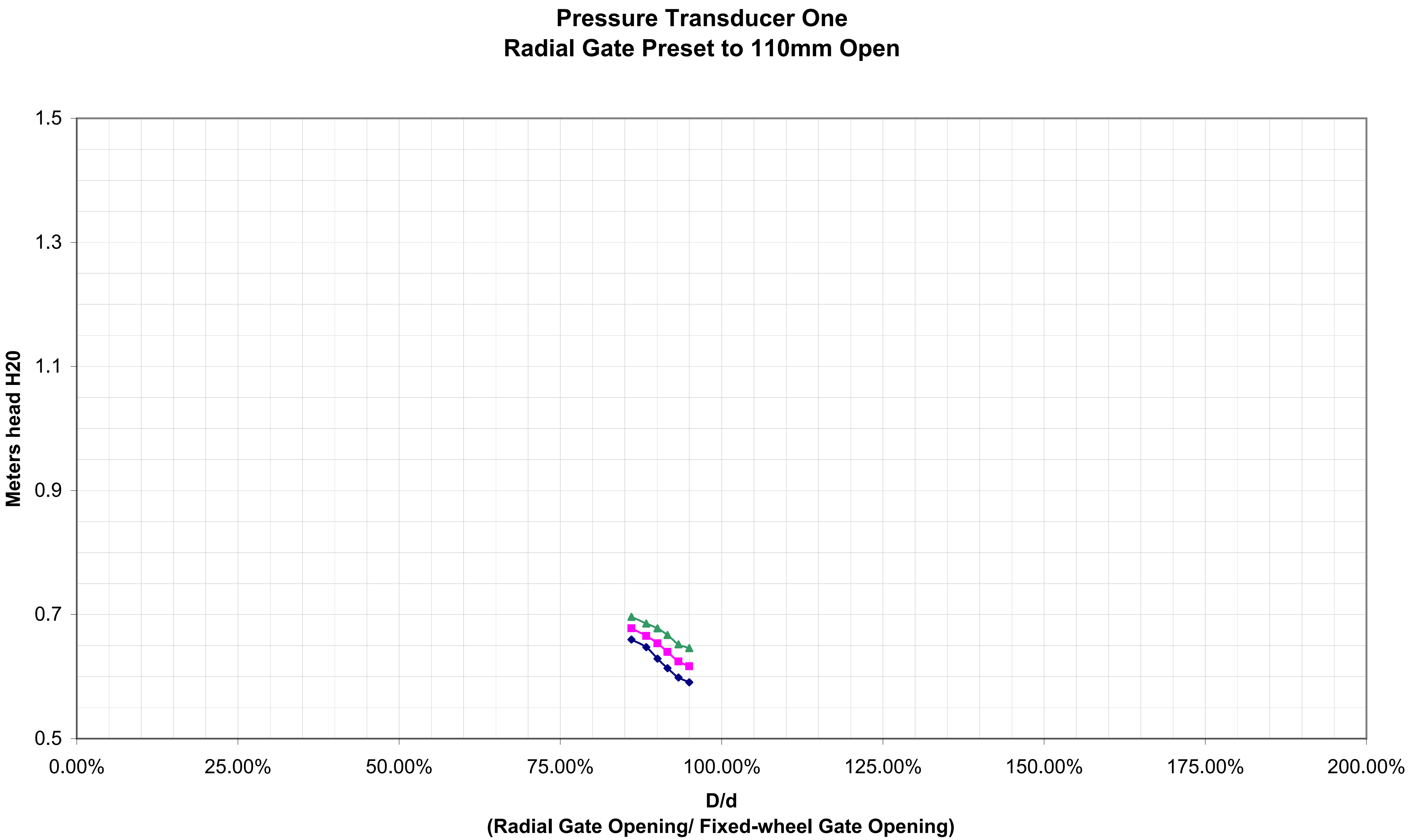
Pressure Transducer One
Radial Gate Preset to 70mm Open
Meters head H20
1.5
1.3
1.1
0.9
0.7
0.5
0.00%
25.00%
50.00%
75.00%
100.00%
125.00%
150.00%
175.00%
200.00%
D/d
(Radial Gate Opening/ Fixed-wheel Gate Opening)


Pressure Transducer One
Radial Gate Preset to 80mm Open
Meters head H20
1.5
1.3
1.1
0.9
0.7
0.5
0.00%
25.00%
50.00%
75.00%
100.00%
125.00%
150.00%
175.00%
200.00%
D/d
(Radial Gate Opening/ Fixed-wheel Gate Opening)


Pressure Transducer One
Radial Gate Preset to 90mm Open
Meters head H20
1.5
1.3
1.1
0.9
0.7
0.5
0.00%
25.00%
50.00%
75.00%
100.00%
125.00%
150.00%
175.00%
200.00%
D/d
(Radial Gate Opening/ Fixed-wheel Gate Opening)

Pressure Transducer One
Radial Gate Preset to 100mm Open

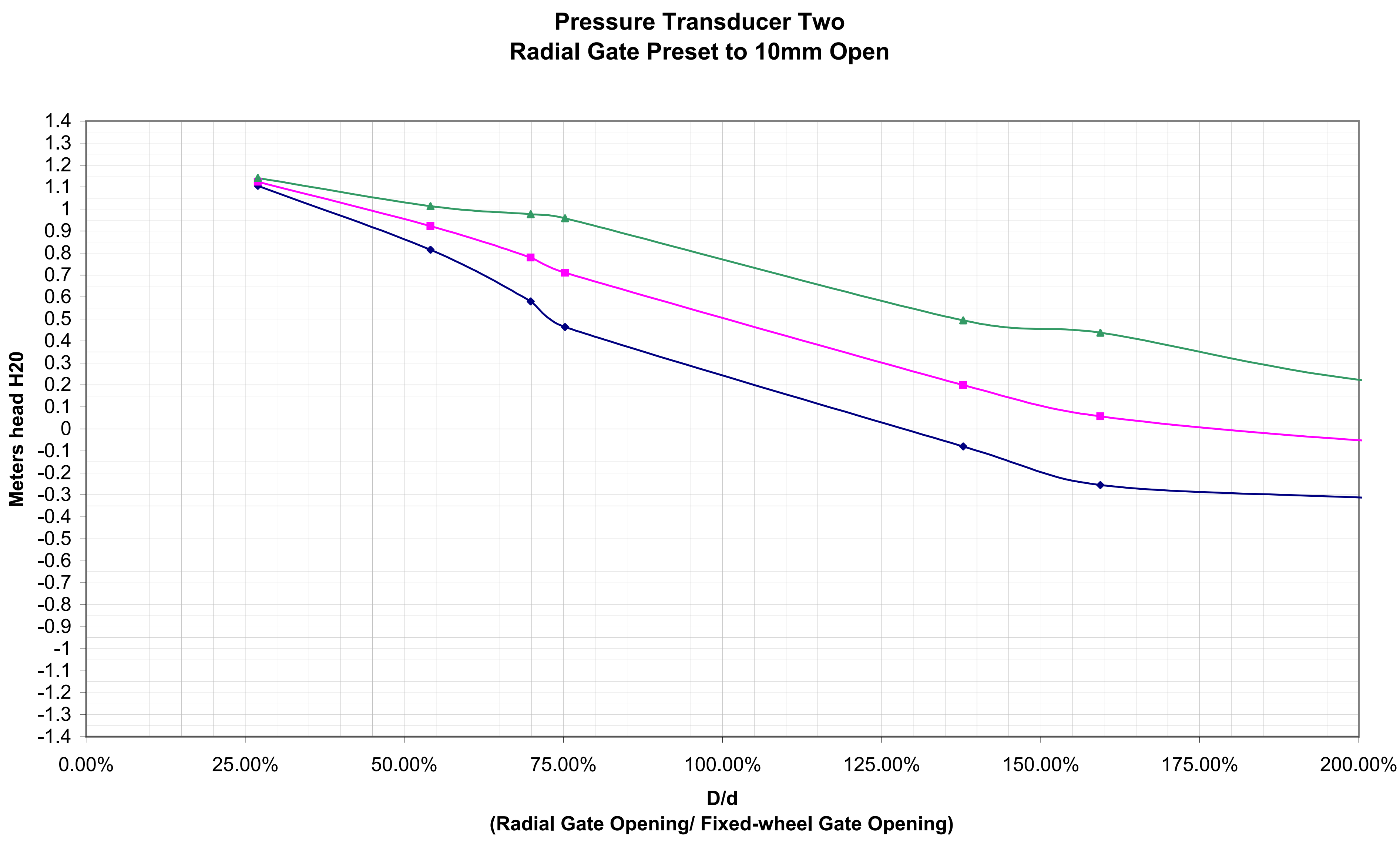



Pressure Transducer One
Radial Gate Preset to 110mm Open
Meters head H20
1.5
1.3
1.1
0.9
0.7
0.5
0.00%
25.00%
50.00%
75.00%
100.00%
125.00%
150.00%
175.00%
200.00%
D/d
(Radial Gate Opening/ Fixed-wheel Gate Opening)

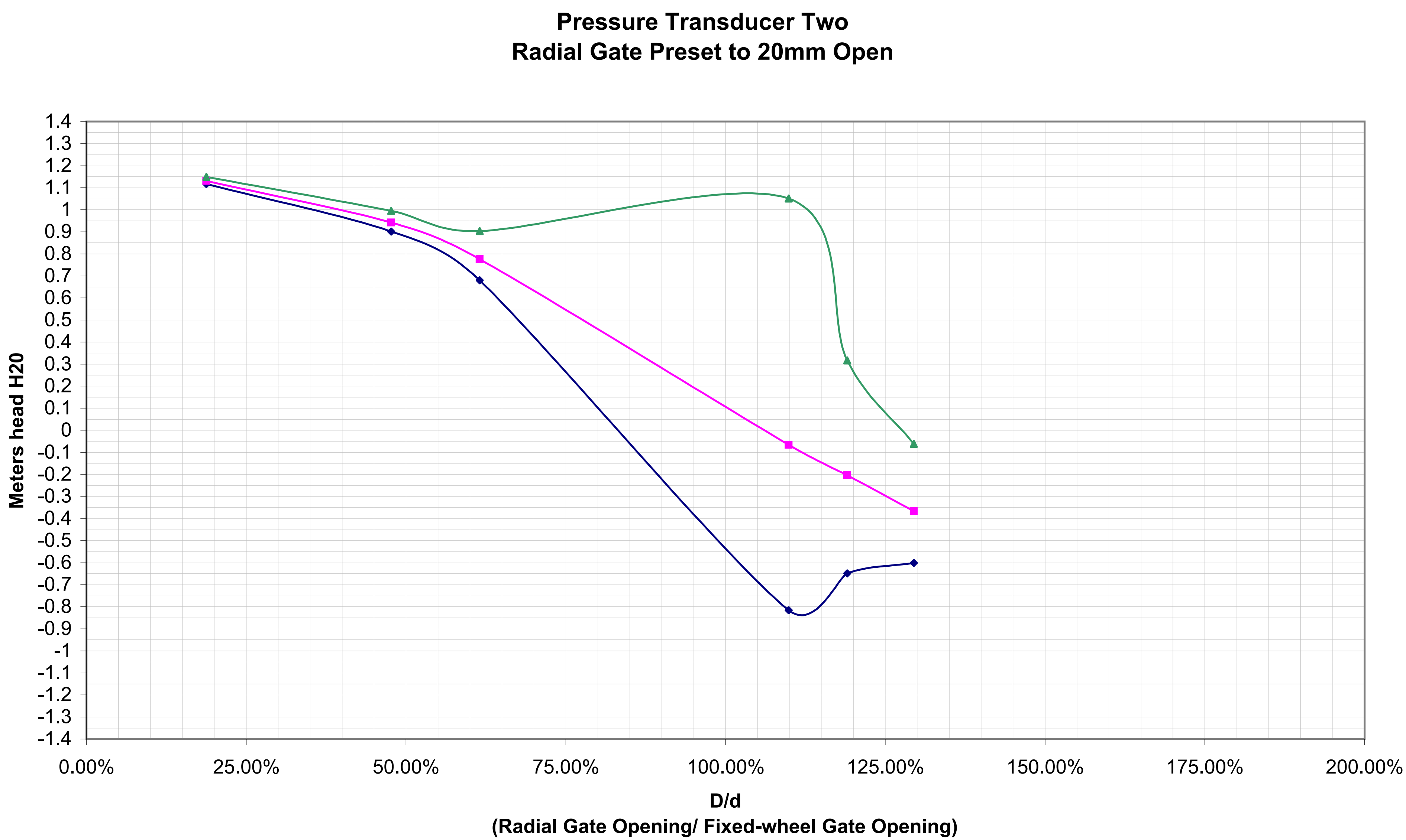
APPENDIX E

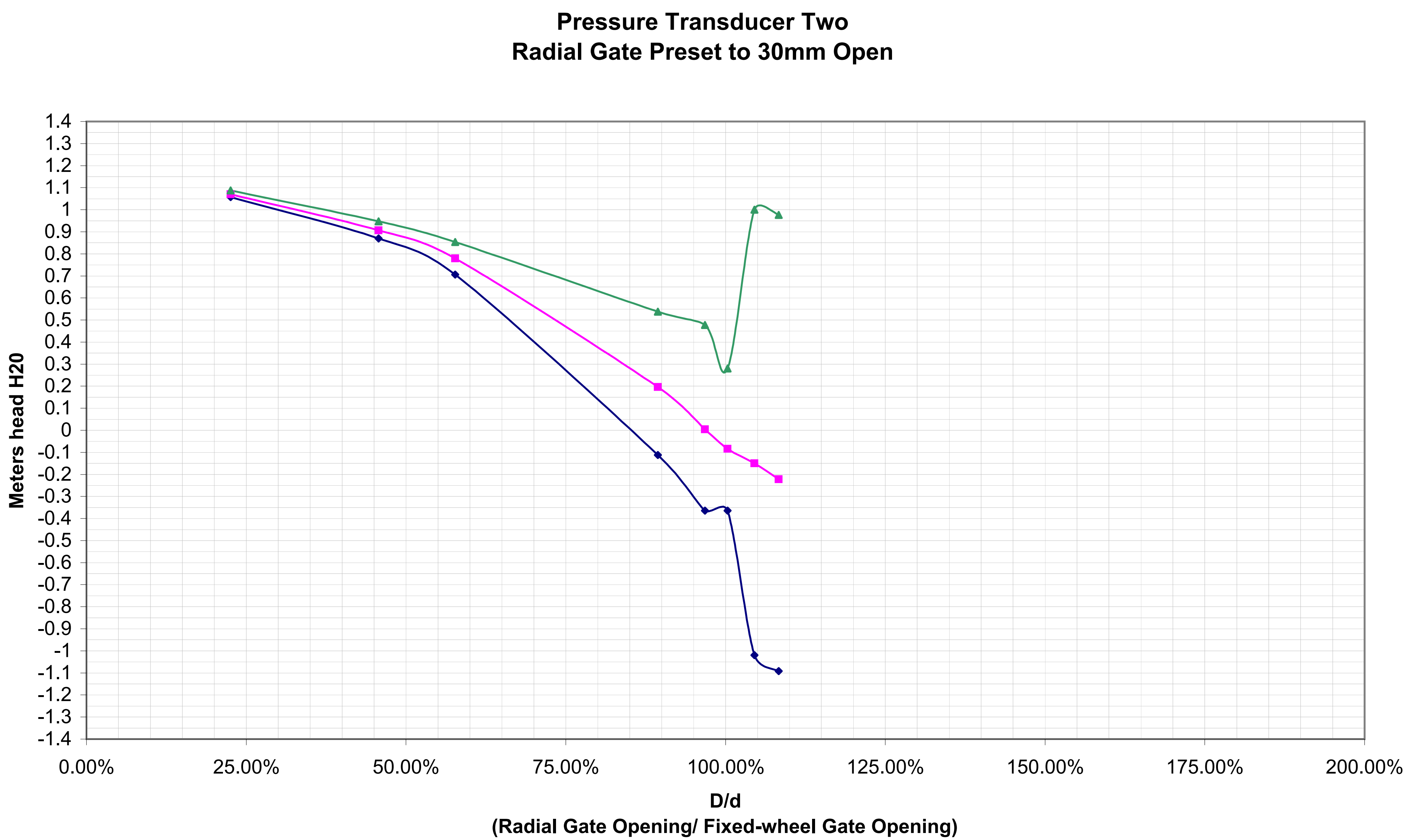
SUMMARY OF DATA

PRESSURE TRANSDUCER TWO

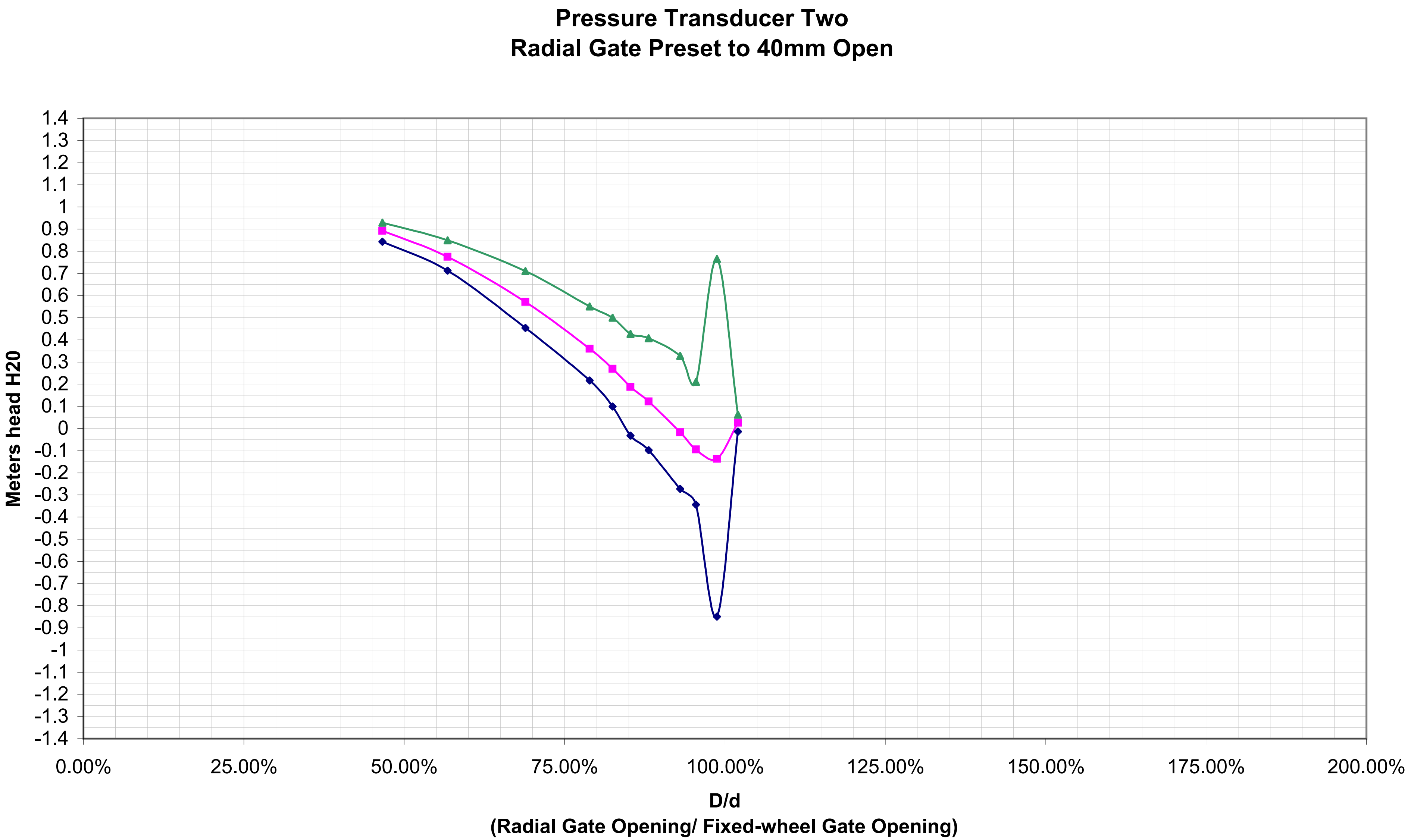


Pressure Transducer Two
Radial Gate Preset to 10mm Open
Meters head H20
D/d
(Radial Gate Opening/ Fixed-wheel Gate Opening)
0.00%
25.00%
50.00%
75.00%
100.00%
125.00%
150.00%
175.00%
200.00%
1.4
1.3
1.2
1.1
1
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0
-0.1
-0.2
-0.3
-0.4
-0.5
-0.6
-0.7
-0.8
-0.9
-1
-1.1
-1.2
-1.3
-1.4


Pressure Transducer Two
Radial Gate Preset to 20mm Open
Meters head H20
1.4
1.3
1.2
1.1
1
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0
-0.1
-0.2
-0.3
-0.4
-0.5
-0.6
-0.7
-0.8
-0.9
-1
-1.1
-1.2
-1.3
-1.4
0.00%
25.00%
50.00%
75.00%
100.00%
125.00%
150.00%
175.00%
200.00%
D/d
(Radial Gate Opening/ Fixed-wheel Gate Opening)

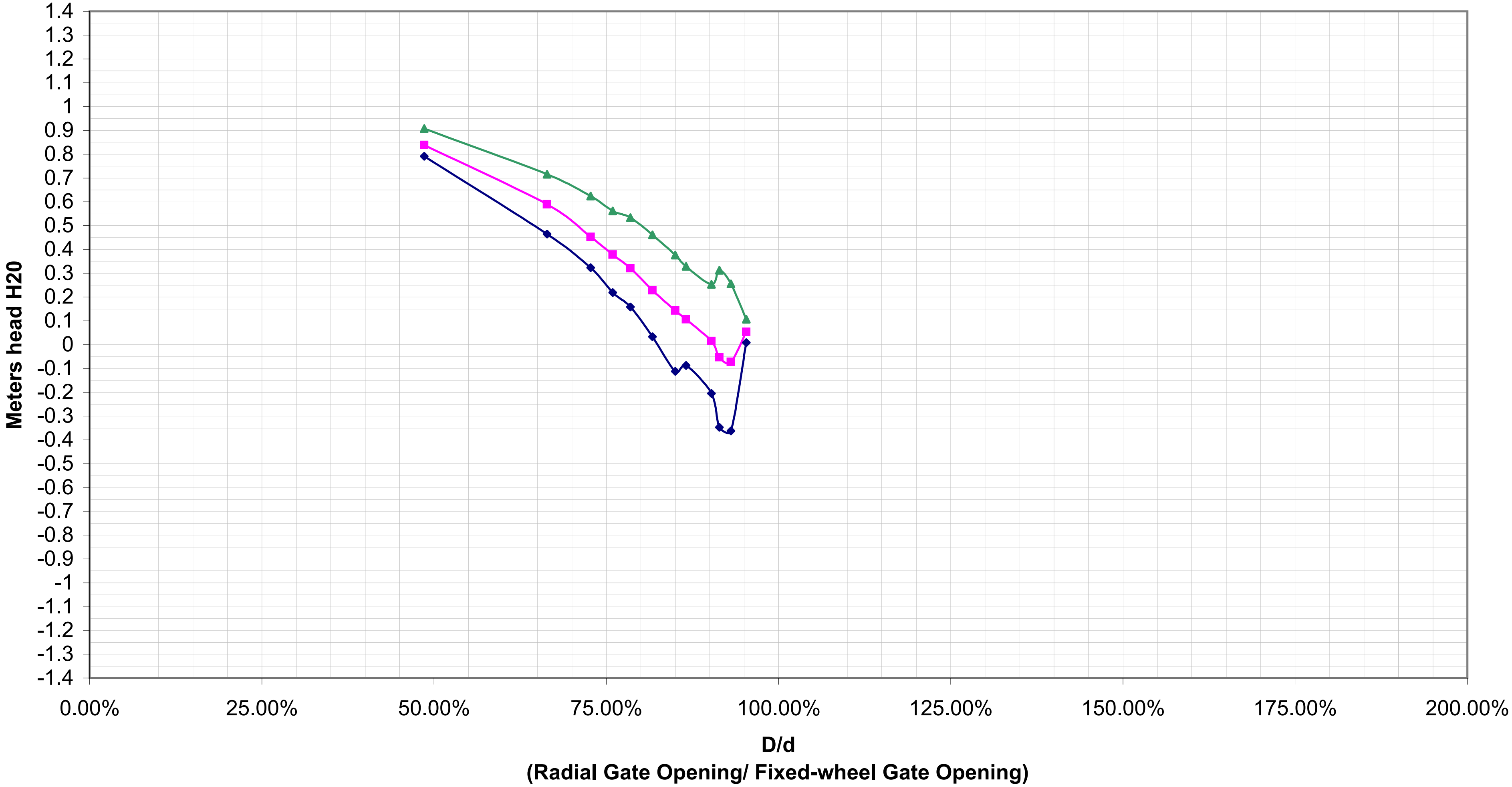


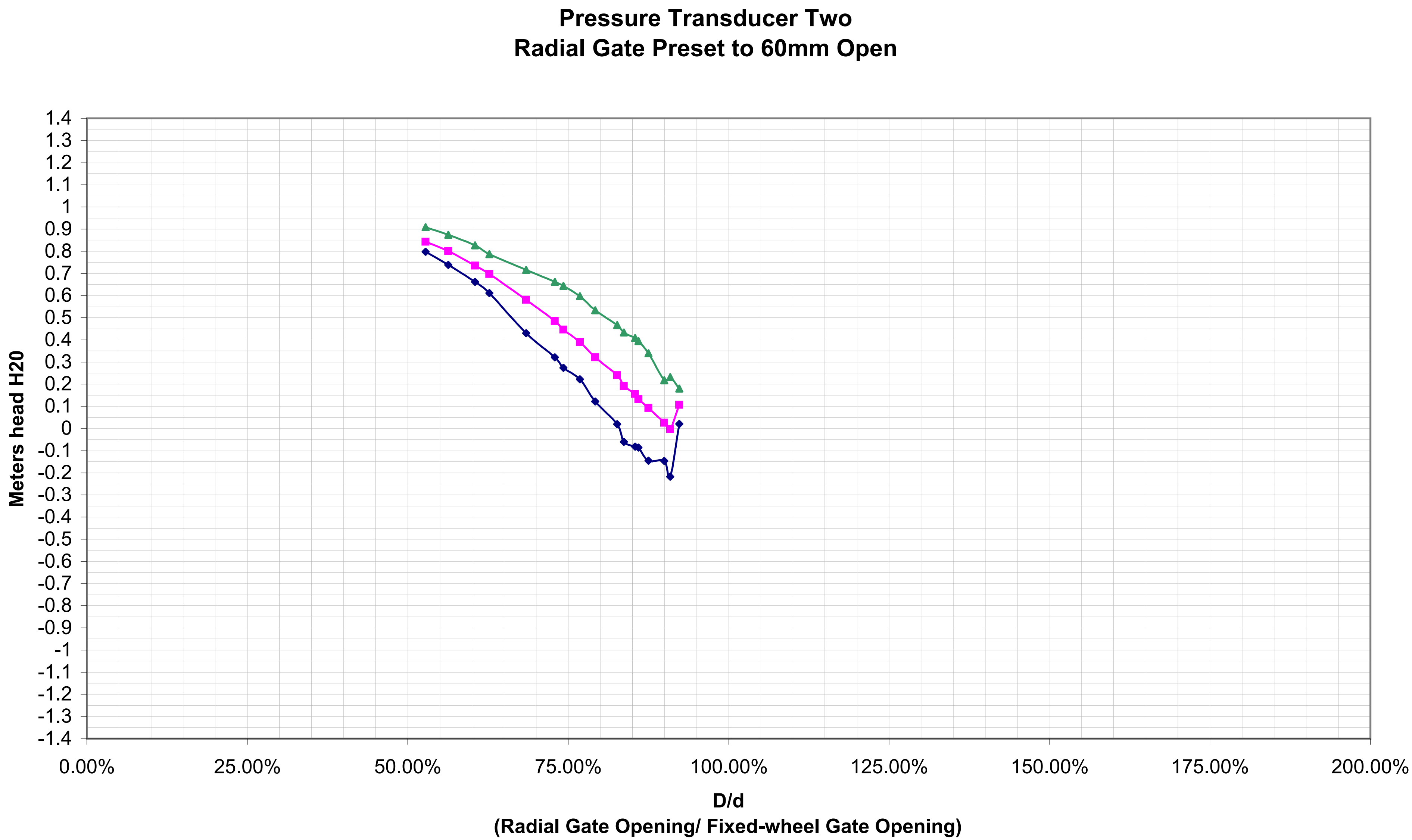
Pressure Transducer Two
Radial Gate Preset to 30mm Open
Meters head H20
1.4
1.3
1.2
1.1
1
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0
-0.1
-0.2
-0.3
-0.4
-0.5
-0.6
-0.7
-0.8
-0.9
-1
-1.1
-1.2
-1.3
-1.4
0.00%
25.00%
50.00%
75.00%
100.00%
125.00%
150.00%
175.00%
200.00%
D/d
(Radial Gate Opening/ Fixed-wheel Gate Opening)

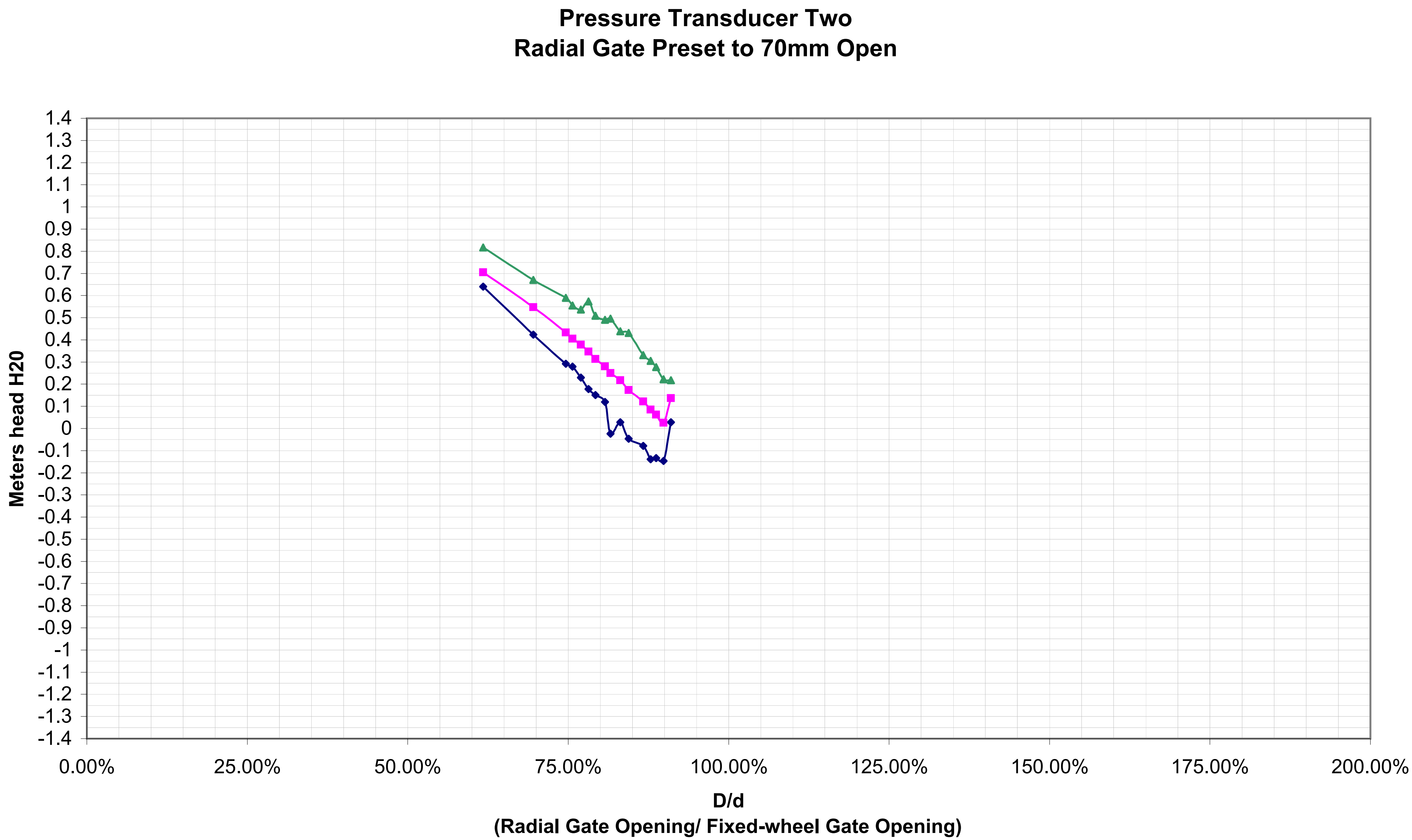


Pressure Transducer Two
Radial Gate Preset to 40mm Open
Meters head H20
1.4
1.3
1.2
1.1
1
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0
-0.1
-0.2
-0.3
-0.4
-0.5
-0.6
-0.7
-0.8
-0.9
-1
-1.1
-1.2
-1.3
-1.4
0.00%
25.00%
50.00%
75.00%
100.00%
125.00%
150.00%
175.00%
200.00%
D/d
(Radial Gate Opening/ Fixed-wheel Gate Opening)

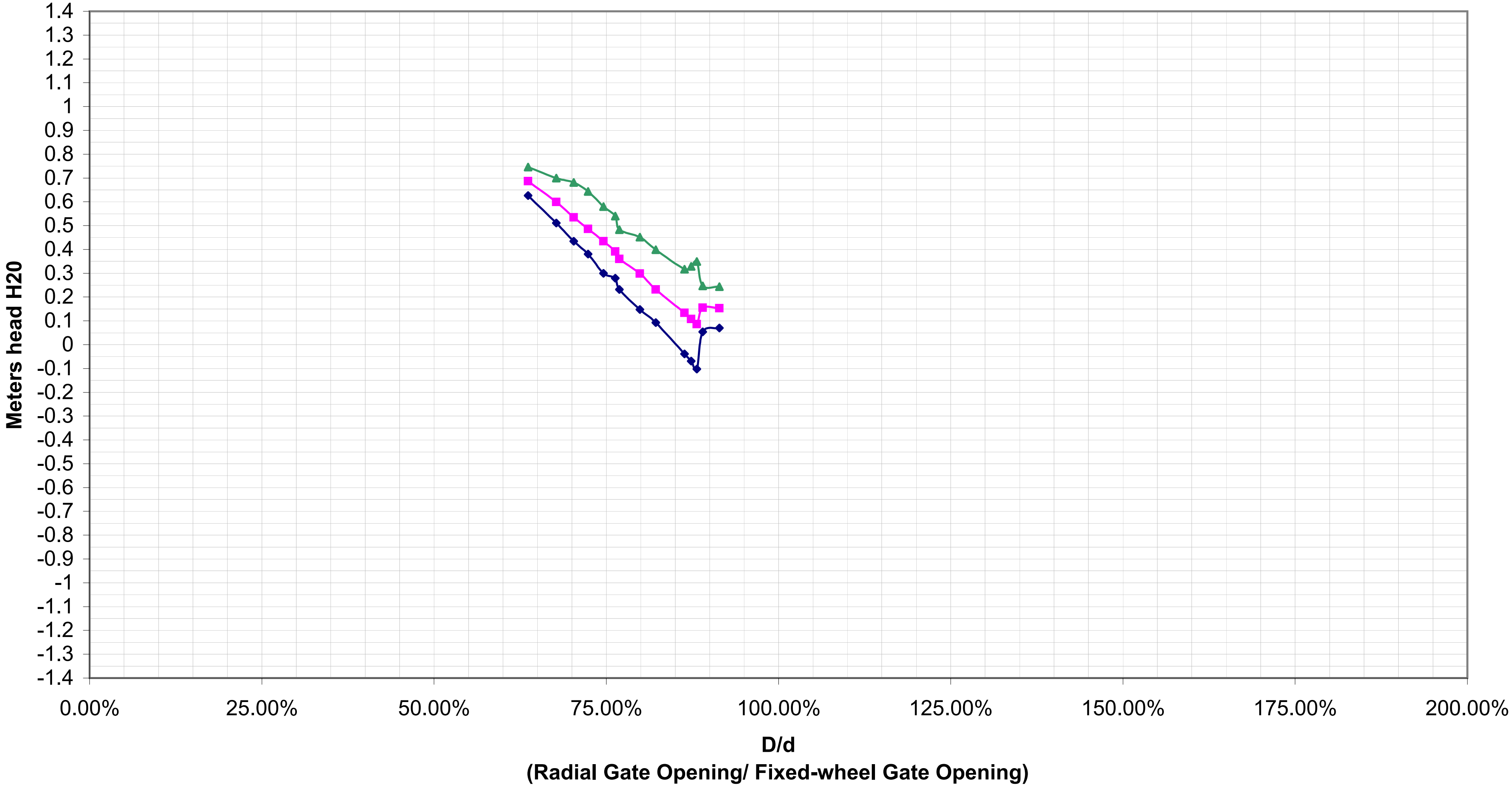
Pressure Transducer Two
Radial Gate Preset to 50mm Open

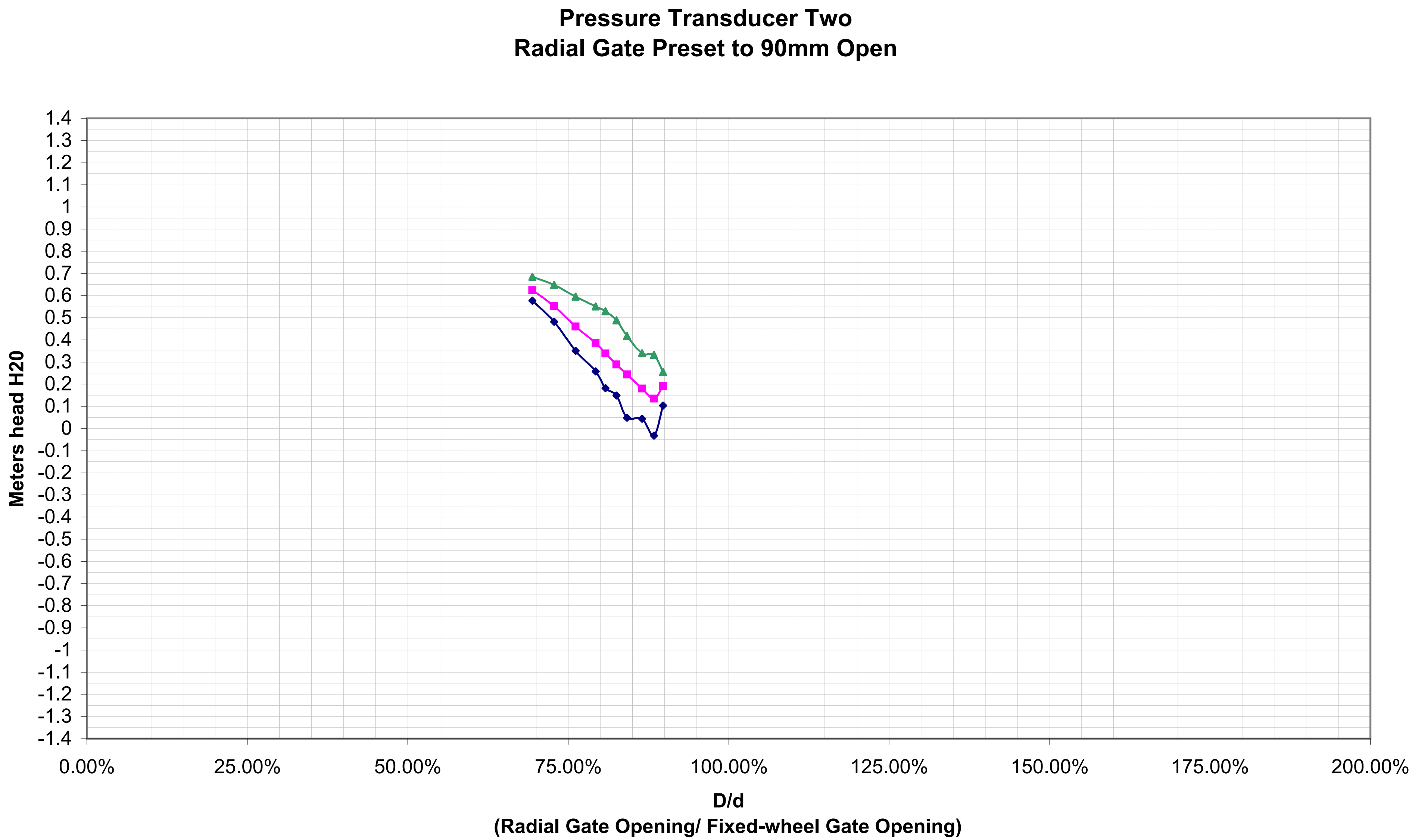



Pressure Transducer Two
Radial Gate Preset to 60mm Open
Meters head H20
1.4
1.3
1.2
1.1
1
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0
-0.1
-0.2
-0.3
-0.4
-0.5
-0.6
-0.7
-0.8
-0.9
-1
-1.1
-1.2
-1.3
-1.4
0.00%
25.00%
50.00%
75.00%
100.00%
125.00%
150.00%
175.00%
200.00%
D/d
(Radial Gate Opening/ Fixed-wheel Gate Opening)

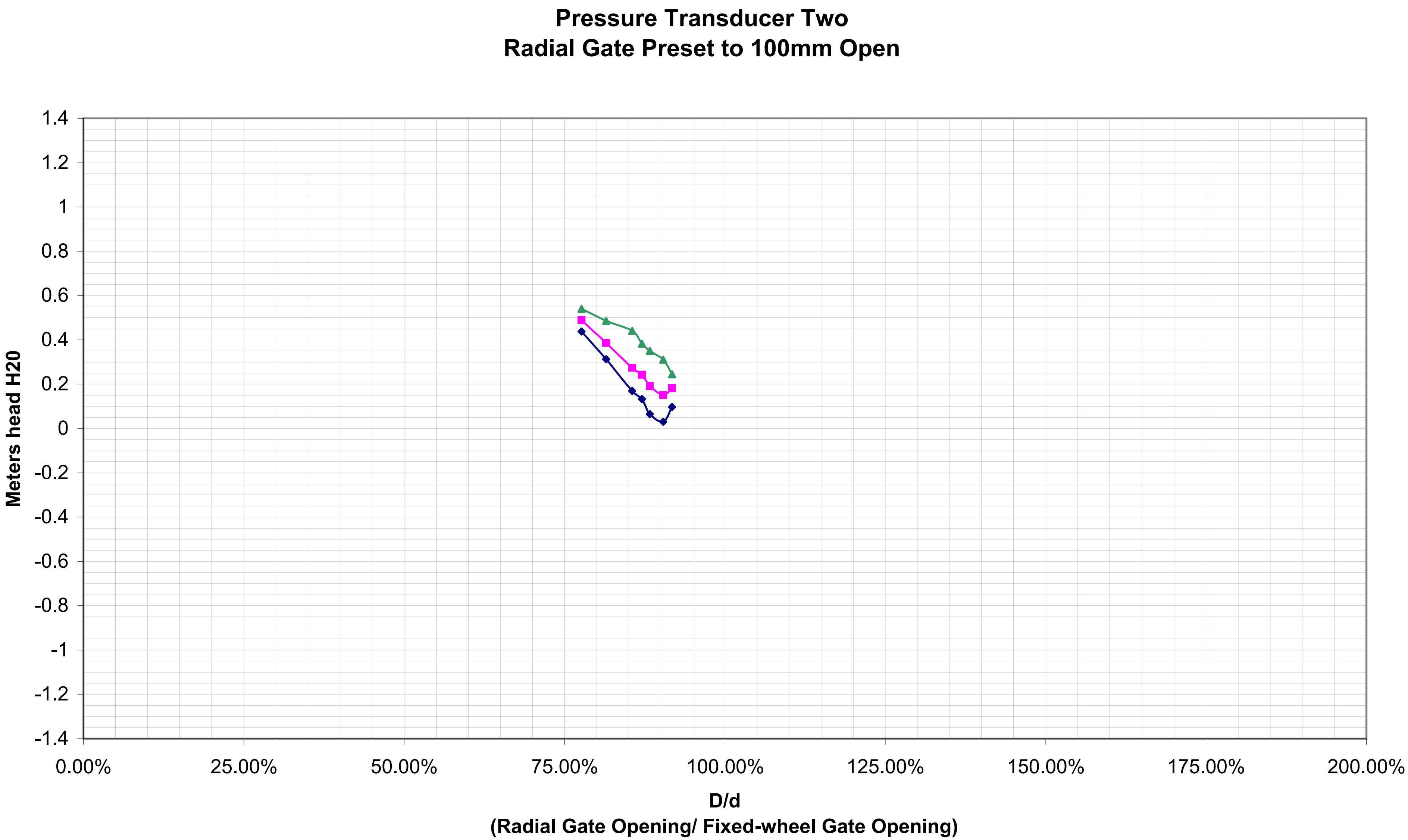

Pressure Transducer Two
Radial Gate Preset to 70mm Open
Meters head H20
1.4
1.3
1.2
1.1
1
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0
-0.1
-0.2
-0.3
-0.4
-0.5
-0.6
-0.7
-0.8
-0.9
-1
-1.1
-1.2
-1.3
-1.4
0.00%
25.00%
50.00%
75.00%
100.00%
125.00%
150.00%
175.00%
200.00%
D/d
(Radial Gate Opening/ Fixed-wheel Gate Opening)

Pressure Transducer Two
Radial Gate Preset to 80mm Open

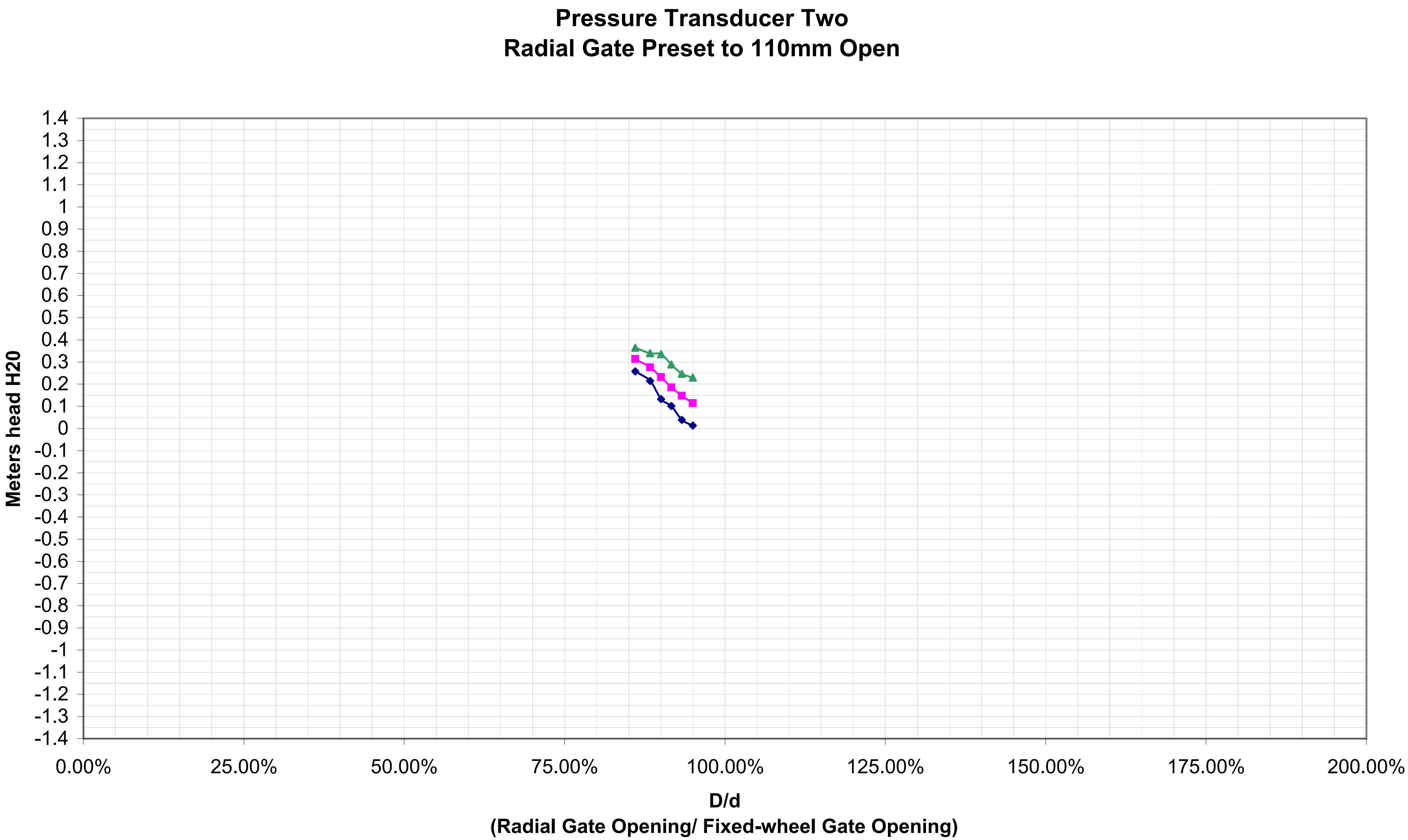




Pressure Transducer Two
Radial Gate Preset to 90mm Open
Meters head H20
1.4
1.3
1.2
1.1
1
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0
-0.1
-0.2
-0.3
-0.4
-0.5
-0.6
-0.7
-0.8
-0.9
-1
-1.1
-1.2
-1.3
-1.4
0.00%
25.00%
50.00%
75.00%
100.00%
125.00%
150.00%
175.00%
200.00%
D/d
(Radial Gate Opening/ Fixed-wheel Gate Opening)



Pressure Transducer Two
Radial Gate Preset to 100mm Open
Meters head H20
1.4
1.2
1
0.8
0.6
0.4
0.2
0
-0.2
-0.4
-0.6
-0.8
-1
-1.2
-1.4
0.00%
25.00%
50.00%
75.00%
100.00%
125.00%
150.00%
175.00%
200.00%
D/d
(Radial Gate Opening/ Fixed-wheel Gate Opening)

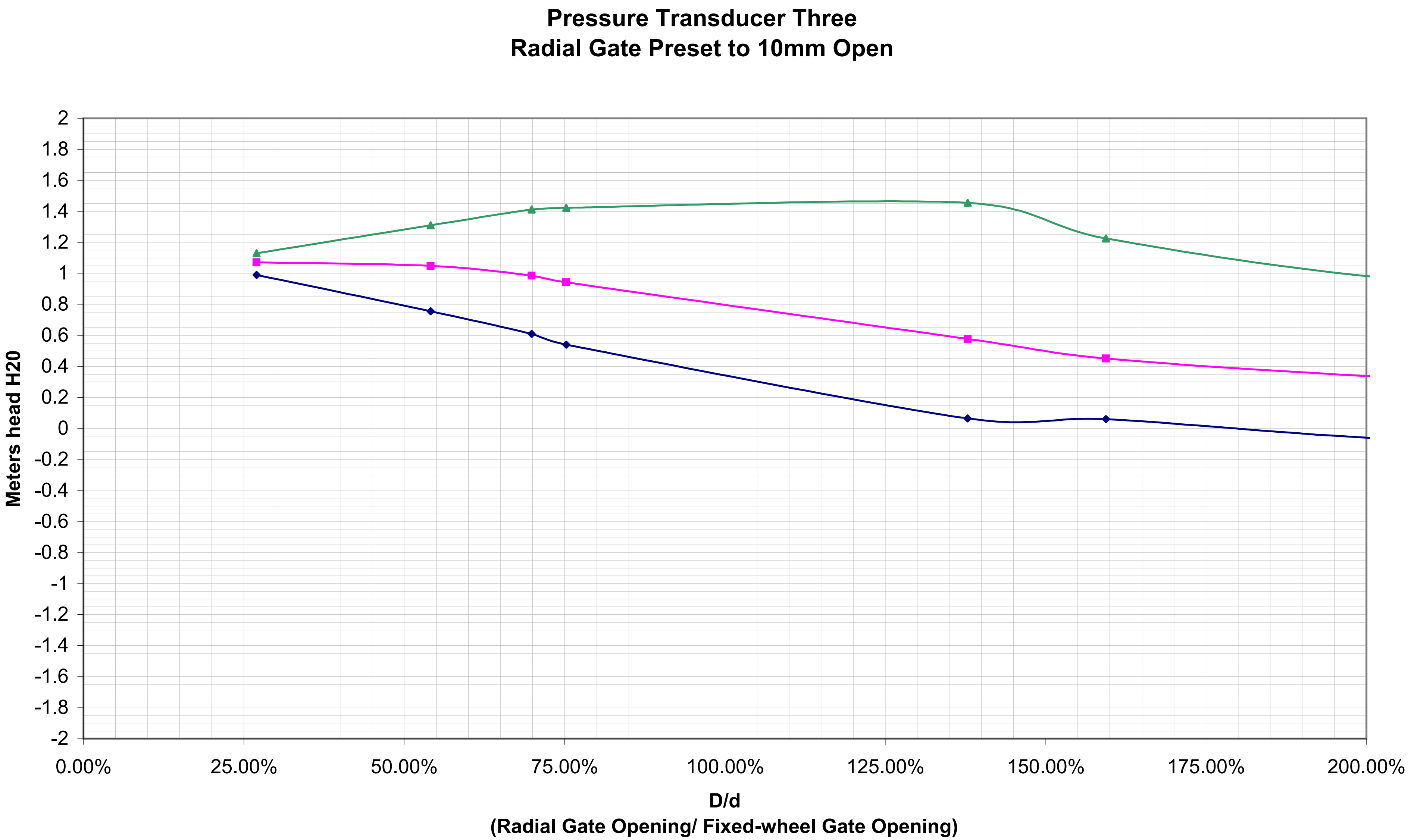


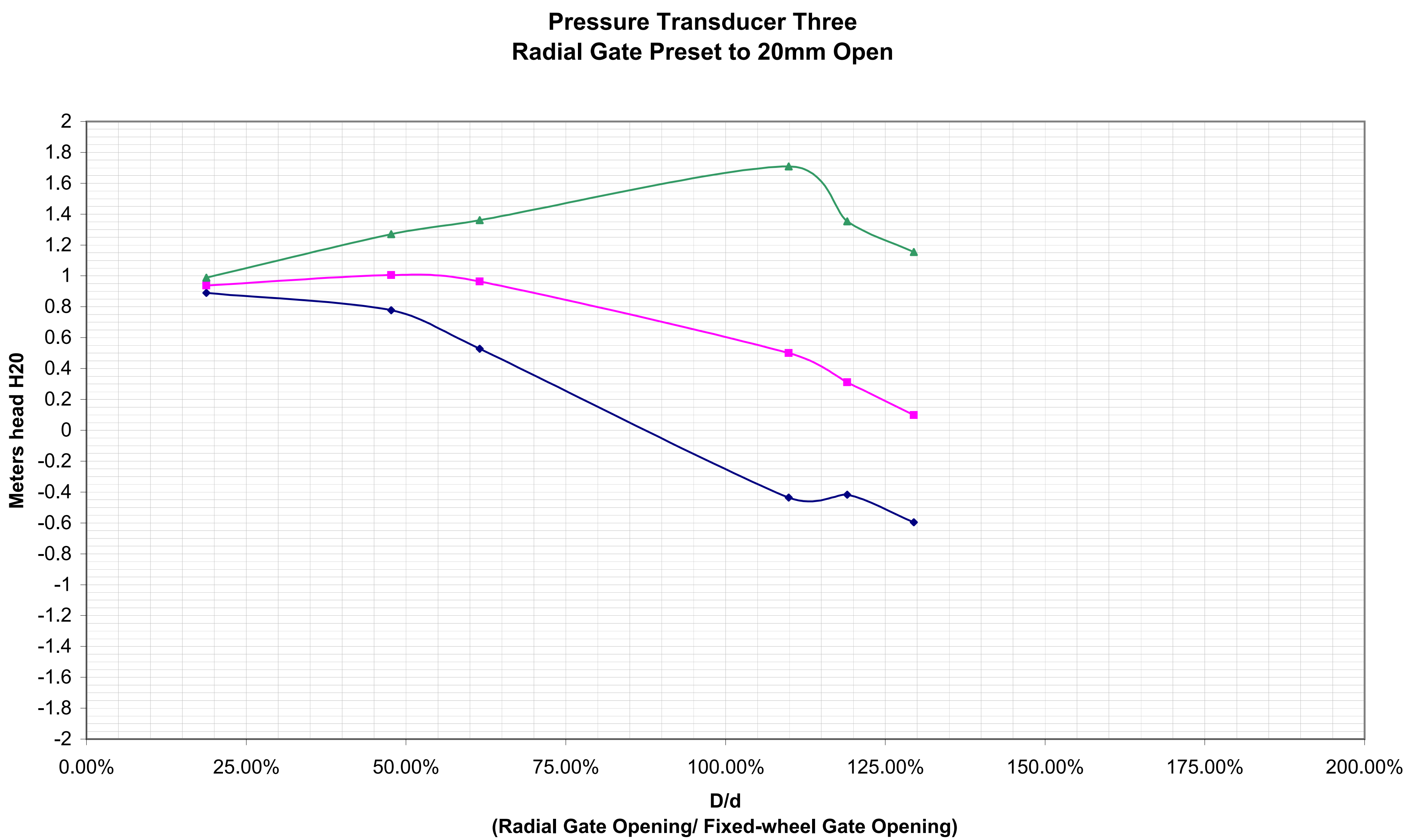
Pressure Transducer Two
Radial Gate Preset to 110mm Open
Meters head H20
1.4
1.3
1.2
1.1
1
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0
-0.1
-0.2
-0.3
-0.4
-0.5
-0.6
-0.7
-0.8
-0.9
-1
-1.1
-1.2
-1.3
-1.4
0.00%
25.00%
50.00%
75.00%
100.00%
125.00%
150.00%
175.00%
200.00%
D/d
(Radial Gate Opening/ Fixed-wheel Gate Opening)

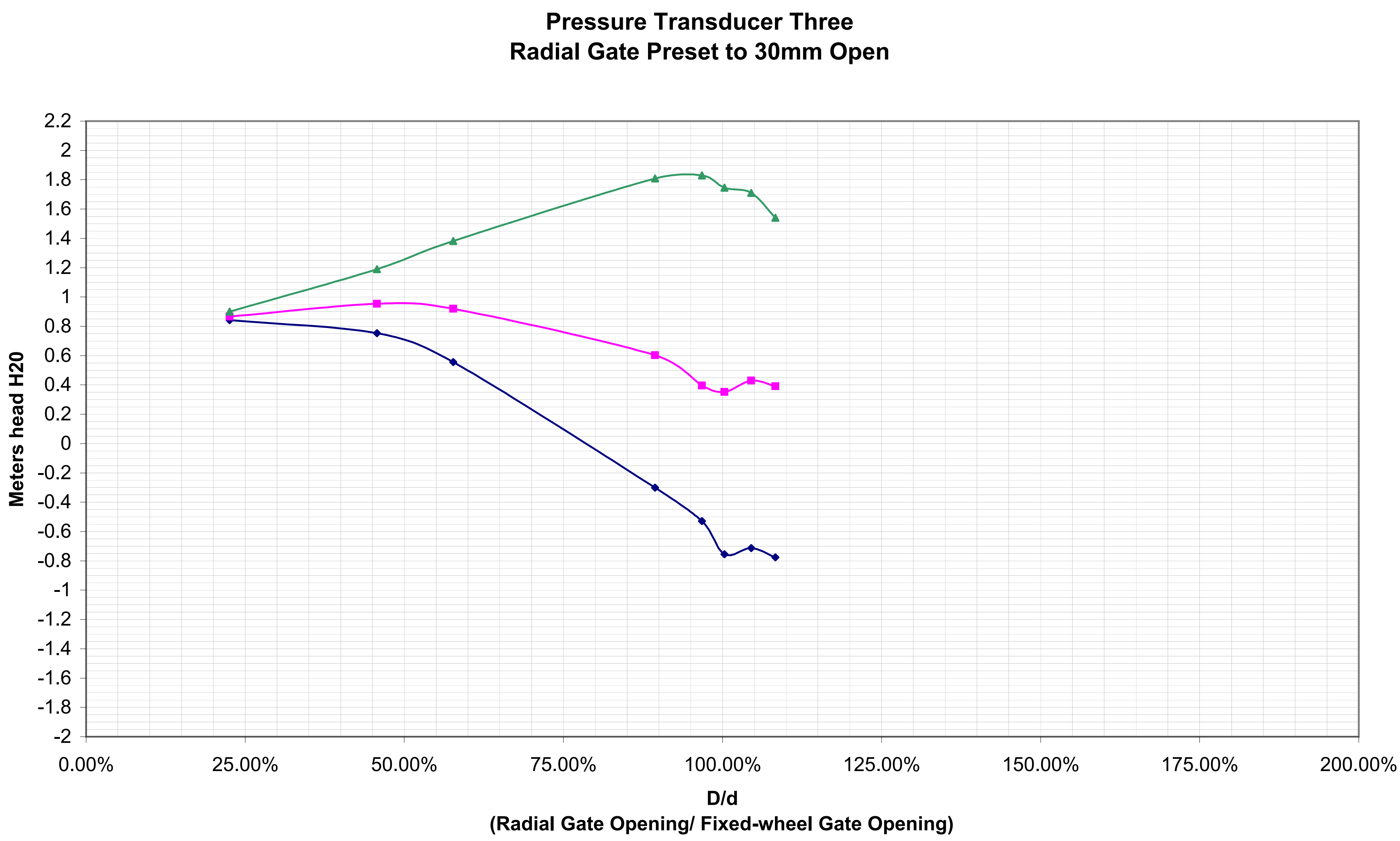
APPENDIX F

SUMMARY OF DATA

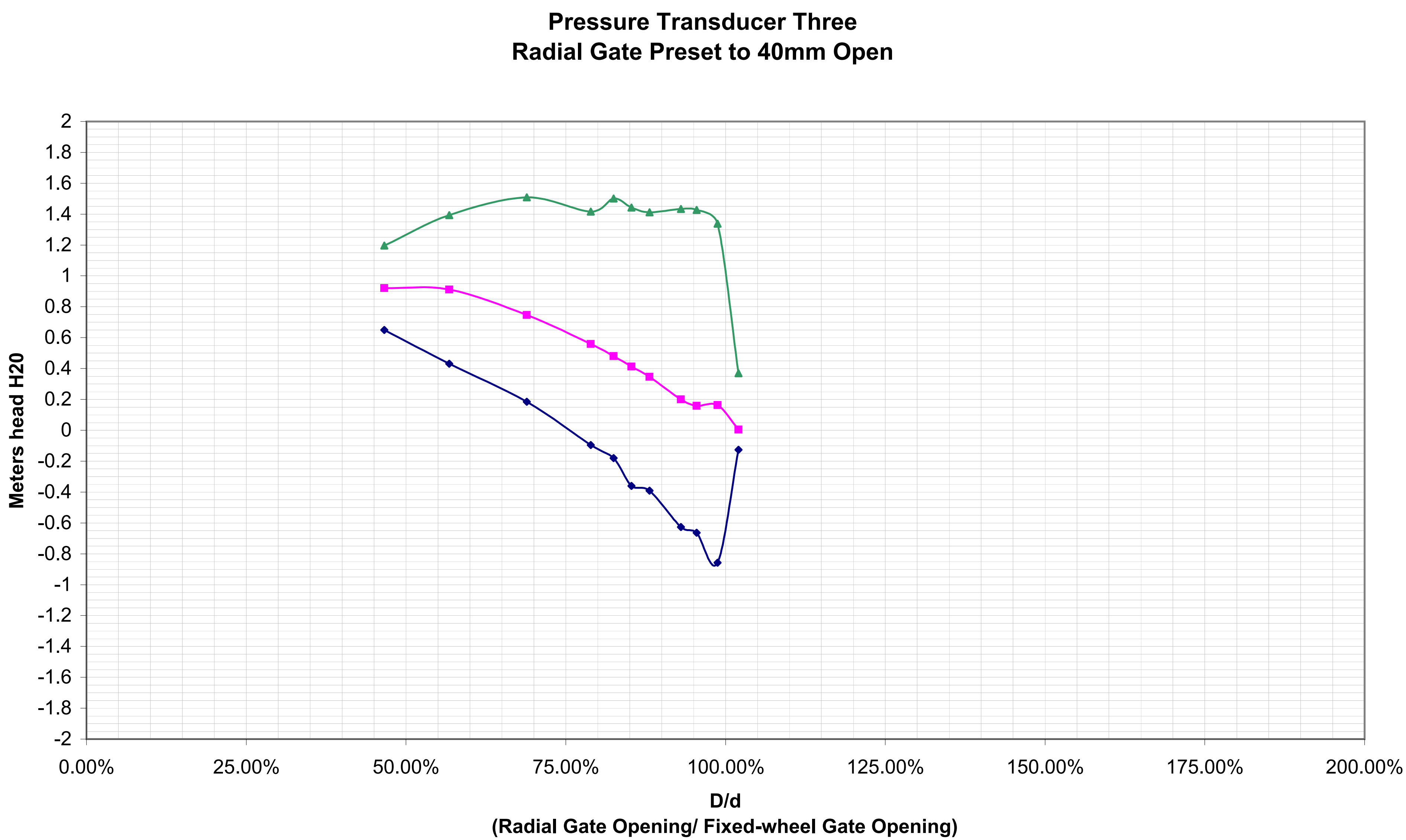
PRESSURE TRANSDUCER THREE

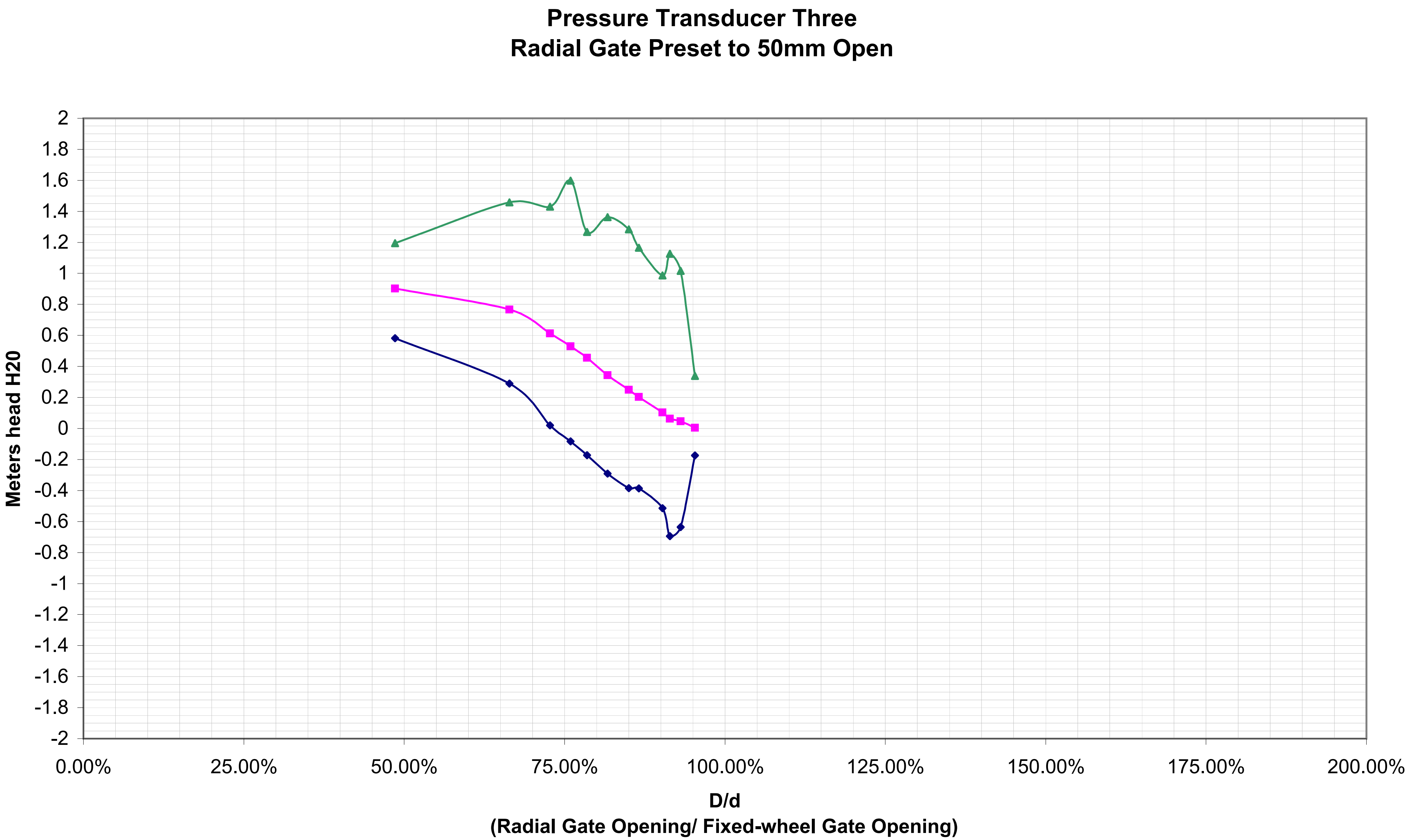

Pressure Transducer Three
Radial Gate Preset to 10mm Open
Meters head H20
2
1.8
1.6
1.4
1.2
1
0.8
0.6
0.4
0.2
0
-0.2
-0.4
-0.6
-0.8
-1
-1.2
-1.4
-1.6
-1.8
-2
0.00%
25.00%
50.00%
75.00%
100.00%
125.00%
150.00%
175.00%
200.00%
D/d
(Radial Gate Opening/ Fixed-wheel Gate Opening)

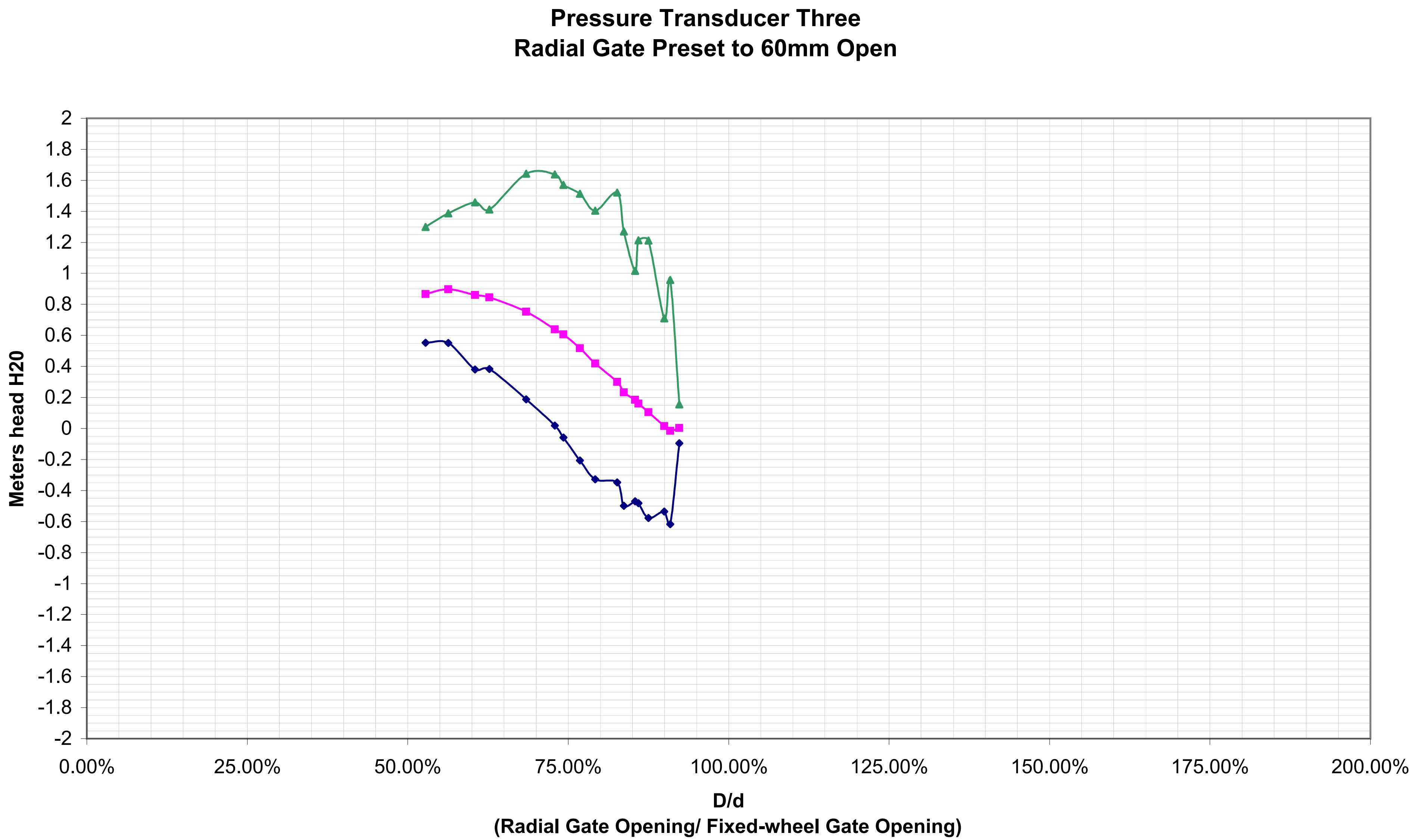

Pressure Transducer Three
Radial Gate Preset to 20mm Open
Meters head H20
2
1.8
1.6
1.4
1.2
1
0.8
0.6
0.4
0.2
0
-0.2
-0.4
-0.6
-0.8
-1
-1.2
-1.4
-1.6
-1.8
-2
0.00%
25.00%
50.00%
75.00%
100.00%
125.00%
150.00%
175.00%
200.00%
D/d
(Radial Gate Opening/ Fixed-wheel Gate Opening)



Pressure Transducer Three
Radial Gate Preset to 30mm Open
Meters head H20
2.2
2
1.8
1.6
1.4
1.2
1
0.8
0.6
0.4
0.2
0
-0.2
-0.4
-0.6
-0.8
-1
-1.2
-1.4
-1.6
-1.8
-2
0.00%
25.00%
50.00%
75.00%
100.00%
125.00%
150.00%
175.00%
200.00%
D/d
(Radial Gate Opening/ Fixed-wheel Gate Opening)

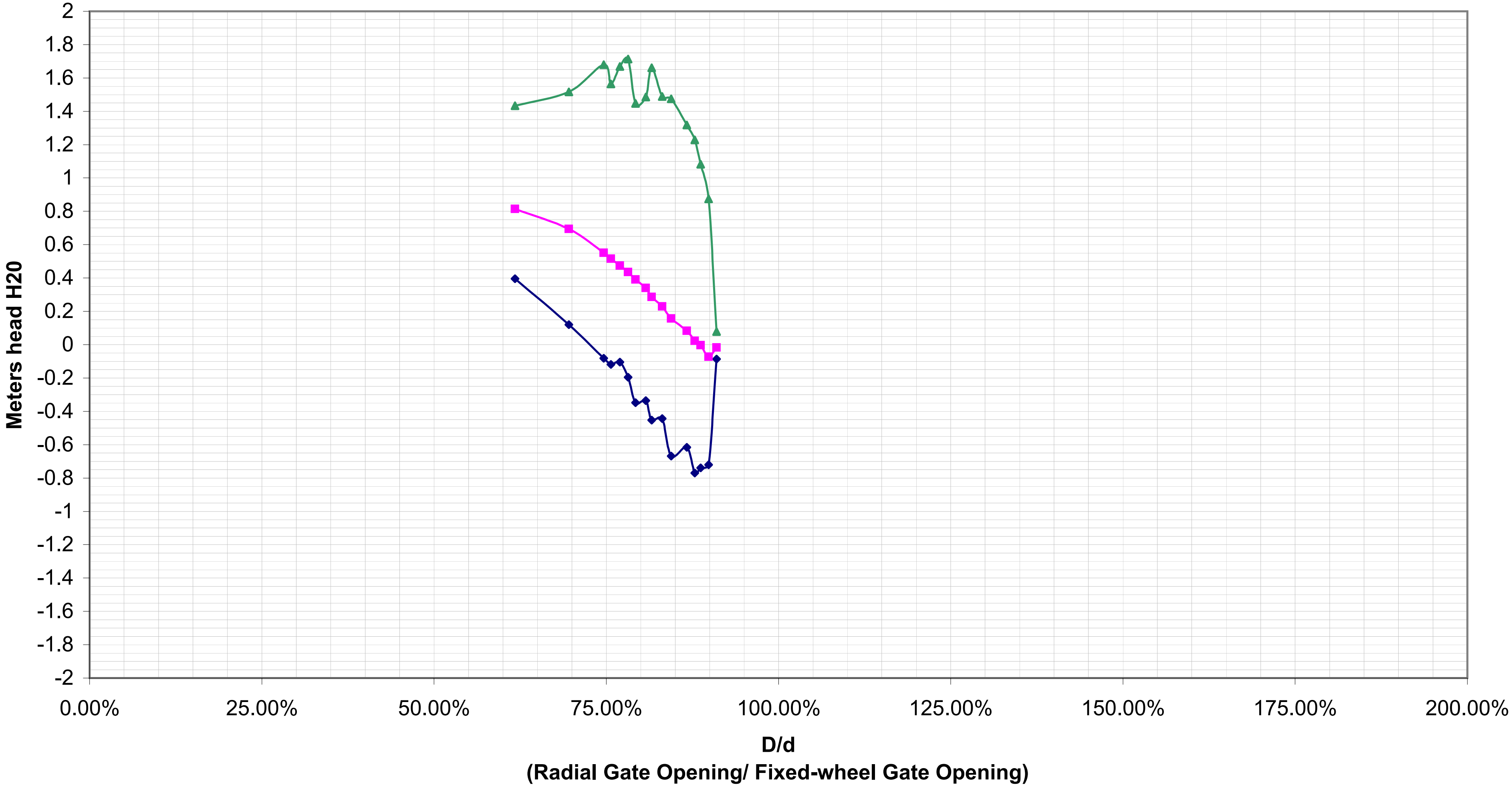

Pressure Transducer Three
Radial Gate Preset to 40mm Open
Meters head H20
2
1.8
1.6
1.4
1.2
1
0.8
0.6
0.4
0.2
0
-0.2
-0.4
-0.6
-0.8
-1
-1.2
-1.4
-1.6
-1.8
-2
0.00%
25.00%
50.00%
75.00%
100.00%
125.00%
150.00%
175.00%
200.00%
D/d
(Radial Gate Opening/ Fixed-wheel Gate Opening)

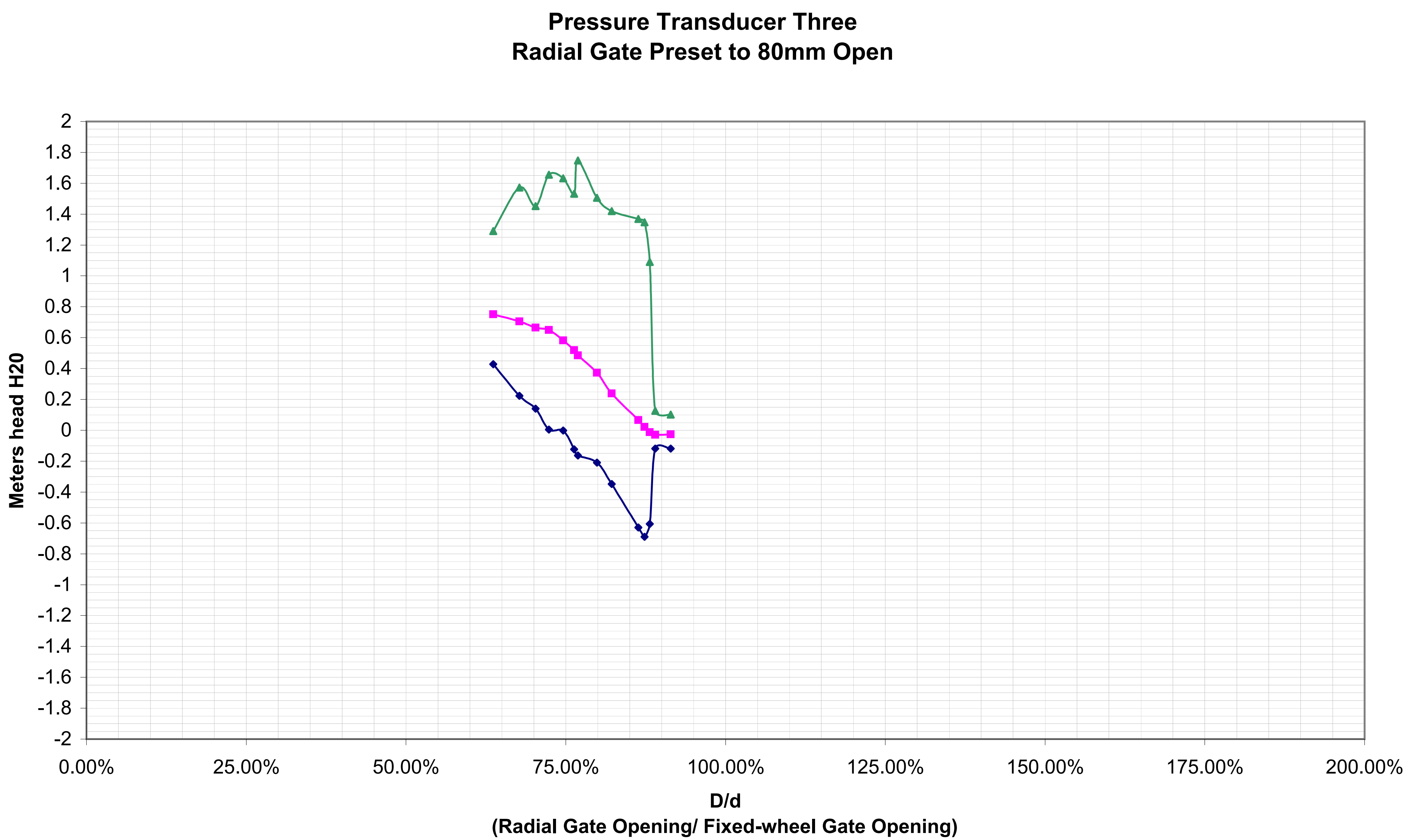

Pressure Transducer Three
Radial Gate Preset to 50mm Open
Meters head H20
2
1.8
1.6
1.4
1.2
1
0.8
0.6
0.4
0.2
0
-0.2
-0.4
-0.6
-0.8
-1
-1.2
-1.4
-1.6
-1.8
-2
0.00%
25.00%
50.00%
75.00%
100.00%
125.00%
150.00%
175.00%
200.00%
D/d
(Radial Gate Opening/ Fixed-wheel Gate Opening)



Pressure Transducer Three
Radial Gate Preset to 60mm Open
Meters head H20
2
1.8
1.6
1.4
1.2
1
0.8
0.6
0.4
0.2
0
-0.2
-0.4
-0.6
-0.8
-1
-1.2
-1.4
-1.6
-1.8
-2
0.00%
25.00%
50.00%
75.00%
100.00%
125.00%
150.00%
175.00%
200.00%
D/d
(Radial Gate Opening/ Fixed-wheel Gate Opening)

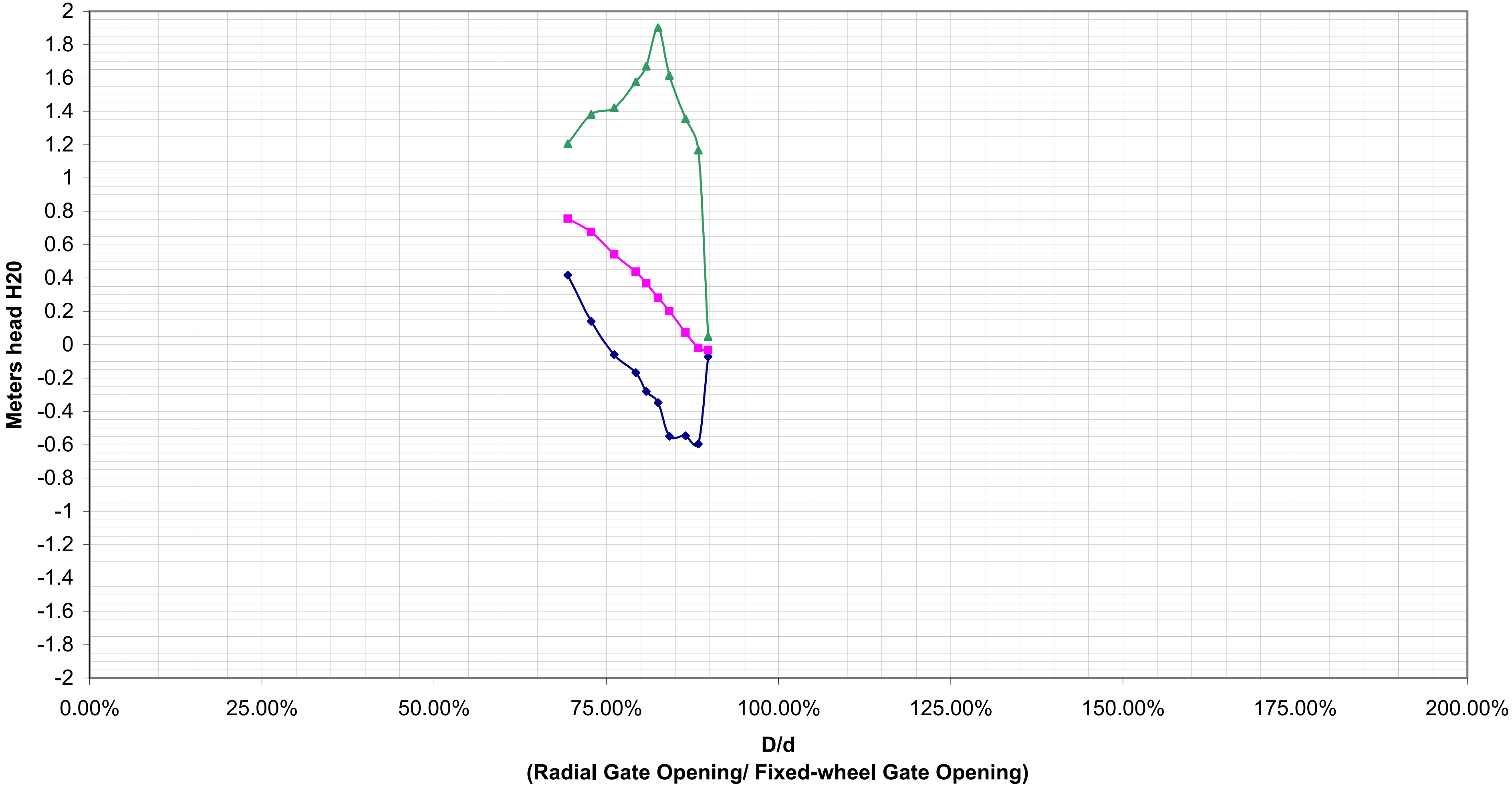
Pressure Transducer Three
Radial Gate Preset to 70mm Open

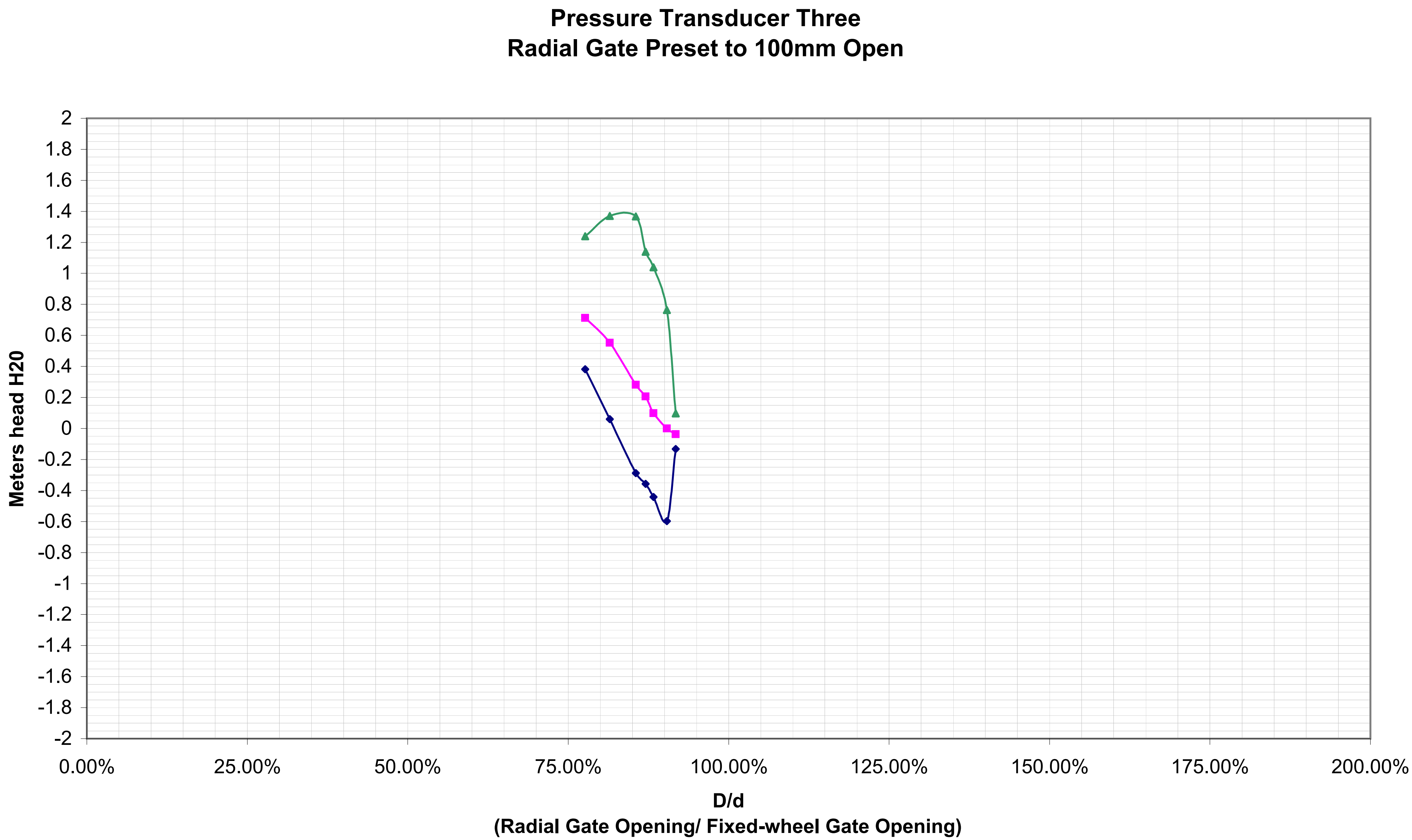




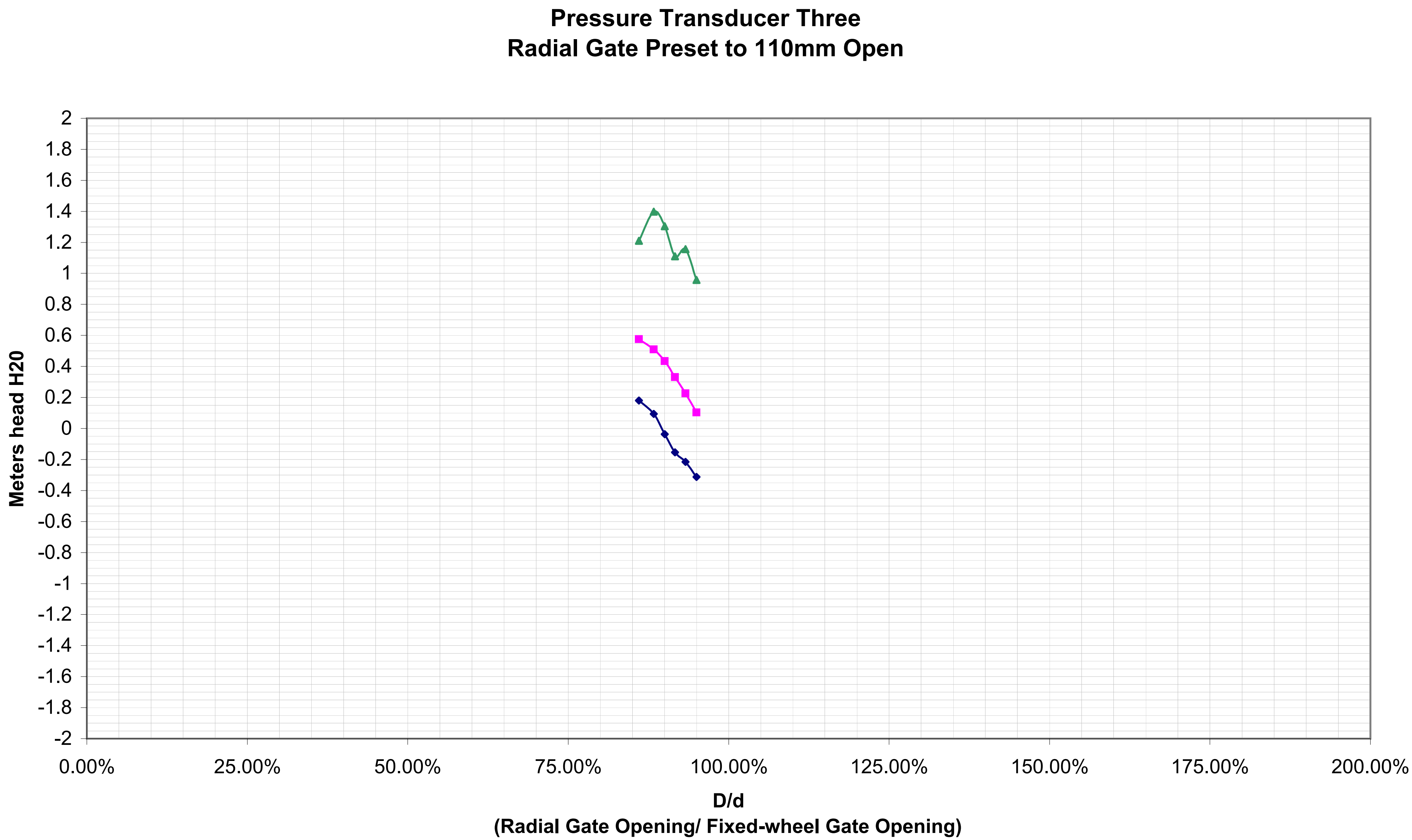
Pressure Transducer Three
Radial Gate Preset to 80mm Open
Meters head H20
2
1.8
1.6
1.4
1.2
1
0.8
0.6
0.4
0.2
0
-0.2
-0.4
-0.6
-0.8
-1
-1.2
-1.4
-1.6
-1.8
-2
0.00%
25.00%
50.00%
75.00%
100.00%
125.00%
150.00%
175.00%
200.00%
D/d
(Radial Gate Opening/ Fixed-wheel Gate Opening)

Pressure Transducer Three
Radial Gate Preset to 90mm Open





Pressure Transducer Three
Radial Gate Preset to 100mm Open
Meters head H20
2
1.8
1.6
1.4
1.2
1
0.8
0.6
0.4
0.2
0
-0.2
-0.4
-0.6
-0.8
-1
-1.2
-1.4
-1.6
-1.8
-2
0.00%
25.00%
50.00%
75.00%
100.00%
125.00%
150.00%
175.00%
200.00%
D/d
(Radial Gate Opening/ Fixed-wheel Gate Opening)



Pressure Transducer Three
Radial Gate Preset to 110mm Open
Meters head H20
2
1.8
1.6
1.4
1.2
1
0.8
0.6
0.4
0.2
0
-0.2
-0.4
-0.6
-0.8
-1
-1.2
-1.4
-1.6
-1.8
-2
0.00%
25.00%
50.00%
75.00%
100.00%
125.00%
150.00%
175.00%
200.00%
D/d
(Radial Gate Opening/ Fixed-wheel Gate Opening)