MEASUREMENT OF PRESSURES RELATED TO VESSEL MOVEMENT WITHIN MIRAFLORES UPPER WEST LOCK

by

Raymond A. Povirk and Raymond D. Rush
Pittsburgh District, U.S. Army Corps of Engineers
Water Resources Engineering Branch
Hydraulics and Hydrology Section

for

PANAMA CANAL COMMISSION
CANAL CAPACITY PROJECTS OFFICE

June 30, 1999

MEASUREMENT OF PRESSURES
RELATED TO VESSEL MOVEMENT
WITHIN MIRAFLORES UPPER WEST LOCK

TABLE OF CONTENTS

TABLE OF CONTENTS (continued)

LIST OF FIGURES

LIST OF TABLES

APPENDICES

SECTION 1. INTRODUCTION

The Canal Capacity Projects Office of the Panama Canal Commission (PCC) is considering various alternatives to augment traffic capacity to meet future demand. The studies will include upgrading current Canal infrastructure, incorporating modern lock technology and water saving methods, alternate systems for raising and lowering vessels, and constructing new locks. In connection with these studies, the Office has determined that a measurement of the actual pressures exerted by vessels and water during the operation of the present locks systems is required. Besides helping define the structural requirements for future locks and shiplifts, an understanding of the effects of vessel movements in the locks is needed to improve existing structures and operating modes.

The Pittsburgh District of the U.S. Army Corps of Engineers, Hydraulics and Hydrology Section, Water Resources Engineering Branch, has considerable experience using pressure transducers to measure water surface fluctuations in lock chambers caused by filling and emptying operations. Since similar techniques could be applied to monitor pressures caused by moving vessels, the Capacity Projects Office contracted the District to perform the testing. The Office selected the northwest Miraflores Lock as the testing site.

The overall study plan was developed by Mr. Juan Wong of the Canal Capacity Projects Office under Director John C. Gribar. Mr. Walter P. Leput, Chief of the Hydraulics and Hydrology Section, traveled to Miraflores in early April 1999 for pre-planning, accompanied by Mr. Jeffrey L. Liggett, Hydrologic Technician. The field tests were conducted from 22-27 April 1999 by Messrs. Raymond A. Povirk, Raymond D. Rush, Hydraulic Engineers, Mr. Dennis D. McCune, Hydrologic Technician, and Mr. Liggett of the Hydraulics and Hydrology Section. Control House operations were recorded by Mr. Wong and Mr. Boris Moreno of the Canal Capacity Projects Office. Messrs. Povirk and Rush performed the data reduction and analysis. In early June 1999 Messrs. Gribar, Wong and Moreno visited the Pittsburgh District for a progress and coordination meeting. This report was prepared by Messrs. Povirk and Rush in June 1999.

SECTION 2. EQUIPMENT

2.a. GAGES

Lock chamber pressures (water surface elevations) were measured utilizing nine pressure sensors located within the northwest chamber at Miraflores Locks. Refer to the diagram on Figure 1 for their location within the lock and their datums. Gages are named "Diag1" through "Diag9" in reference to their position in the diagram.

The sensors are Stevens submersible pressure transducers which measure the water depth by sensing pressure above the unit. The 35-, 50- or 75' foot range transducers were connected by cable to Stevens Dataloggers located in the centerwall and northwest wall machinery tunnels. Electricity for the dataloggers was supplied by 12-volt lead storage batteries and backed up with chargers. The dataloggers were set to record the pressures at 1-second intervals and store the readings on data cards. These cards were replaced daily and downloaded onto laptop computers. The times on the dataloggers were synchronized to an official timekeeping watch.

Figure 2 is a photograph of one of the sensors attached to a section of pipe used for mounting and Figure 3 shows a datalogger and battery in the centerwall tunnel. Figures 4 and 5 show the installation and survey of two sensors.

2.b. DAMAGED GAGES

Some of the sensors (gages) were damaged during the study period. Gage Diag3 located on the upstream side of Miter Gate 114 was damaged twice on April 22 when the cable was pinched during operation of the gates. The gage was first repaired at 13:48 and then the cable was pinched again at approximately 14:55. The gage was then replaced with a spare at approximately 17:42 the same day. Damage also occurred to gage Diag8 located on the downstream side of Miter Gate 106. Gage Diag8 was replaced on April 22 at 14:03 but was damaged again beyond repair on April 24 at approximately 04:19.

Gage Diag9 was located on the sill of Miter Gates 102-103. This gage was knocked loose on April 22 at approximately 09:48 and repaired during a work outage at low pool at approximately 11:50 the same day. However the gage was then dislocated again later that day at approximately 16:33 and there was no opportunity to investigate or repair the gage.

Pressure Probe Locations:

#1- On MG-118 upstream miter casting at elevation 5.598 m = 18.366 ft. PDL.
#2- On MG-114 upstream miter casting at elevation 6.518 m = 21.384 ft. PDL.
#3- On MG-114 upstream miter casting at elevation -0.028 m = -0.092 ft. PDL. This was later replaced with sensor no. EX-1 installed at elevation 2.473 m = 8.113 ft. PDL.
#4- On centerwall chainfender north of MG-114 at elevation 6.396 m = 20.984 ft. PDL.
#5- At recess of intermediate MG-110 at elevation 6.012 m = 19.724 ft. PDL.
#6- At chainfender at west sidewall north of MG-111. Elevation 5.704 m = 18.714 ft.
#7- At slot below electric eye on centerwall south of MG-106 at elevation 6.176 m = 20.262 ft. PDL.
#8- On MG-106 downstream miter casting. This was later replaced with sensor # EX-2 installed at elevation 6.192 m = 20.315 ft PDL. Data logger on top of MG.
#9- On sill of MG-102/103 cables run to machinery room of MG-102. At elevation 3.436 m = 11.273 ft. PDL. This was later relocated to elevation 2.866 m = 9.401 ft.
#10- Auxiliary reference point located on top of MG-114 at elev. 16.771 m = 55.023 ft.
Notes: * All elevations are referenced to PCC's PDL (sea level -7.6 ft).
* Probes 50ft deep x 200' cable installed at #1 and 2. Probe 50 ft x 100' at #4, 5,6 and 8. Probe 100 ft x 200' at #3. Probe 75 ft x 200' at #9. Probe 35 ft x 100' at #7.
* All data loggers (except #8), chargers and battery packs were installed inside machinery tunnels.

Location of Pressure Sensors at Miraflores Locks

Revised April 20,1999

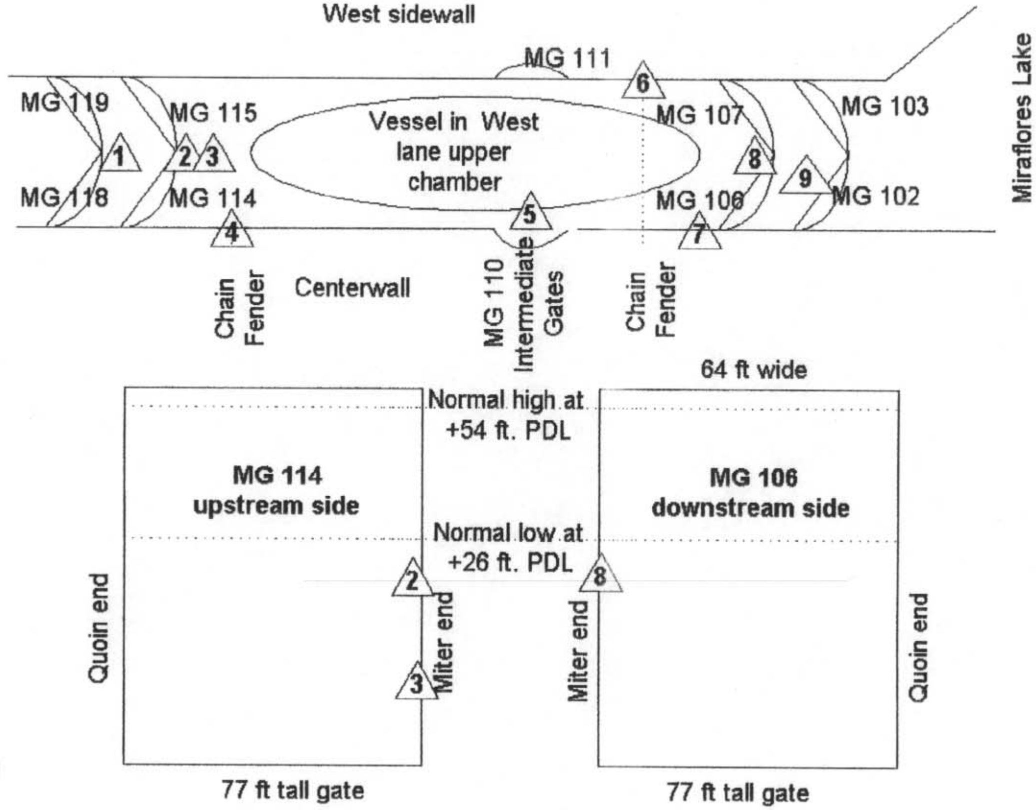


Figure 1 – Location of Pressure Sensors at Miraflores Northwest Lock

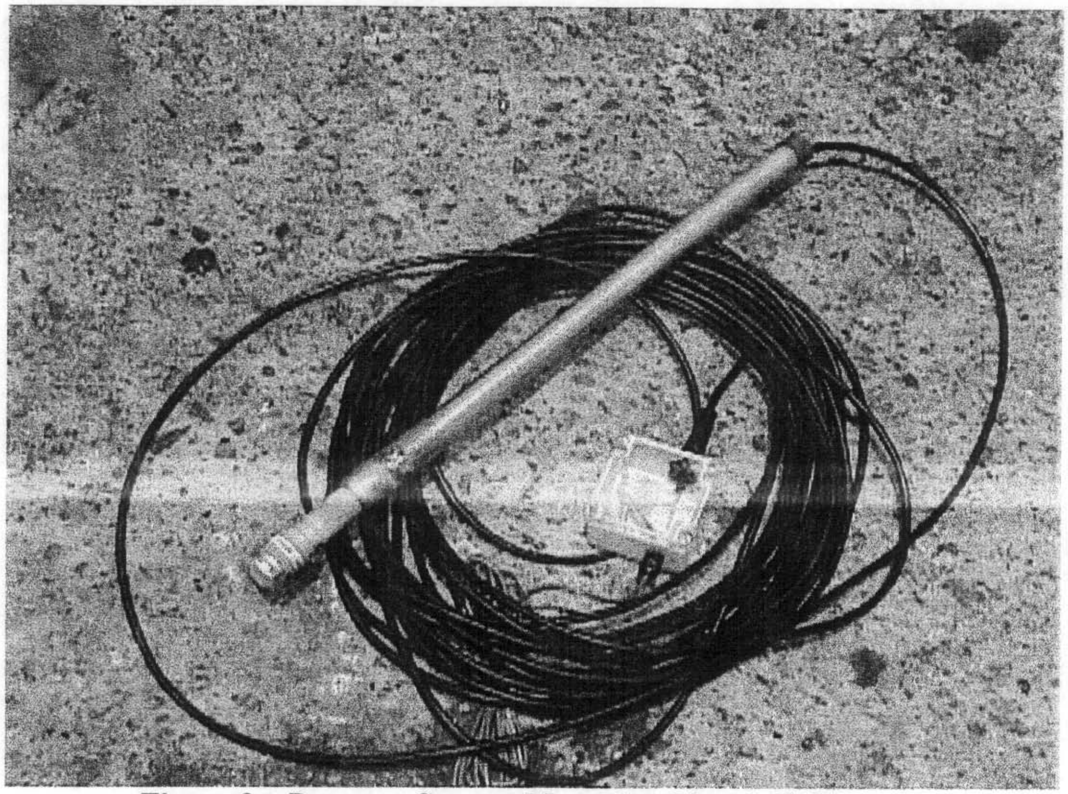


Figure 2 – Pressure Sensor, Mounting Pipe & Cable

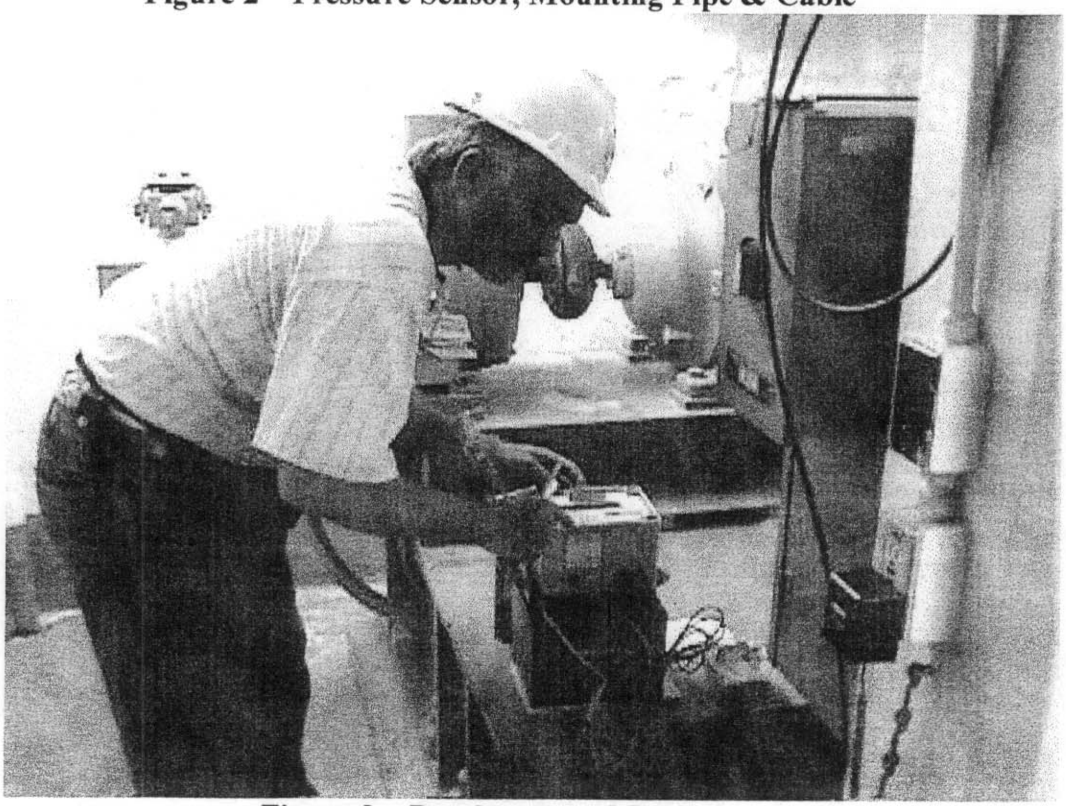


Figure 3 – Datalogger and Battery

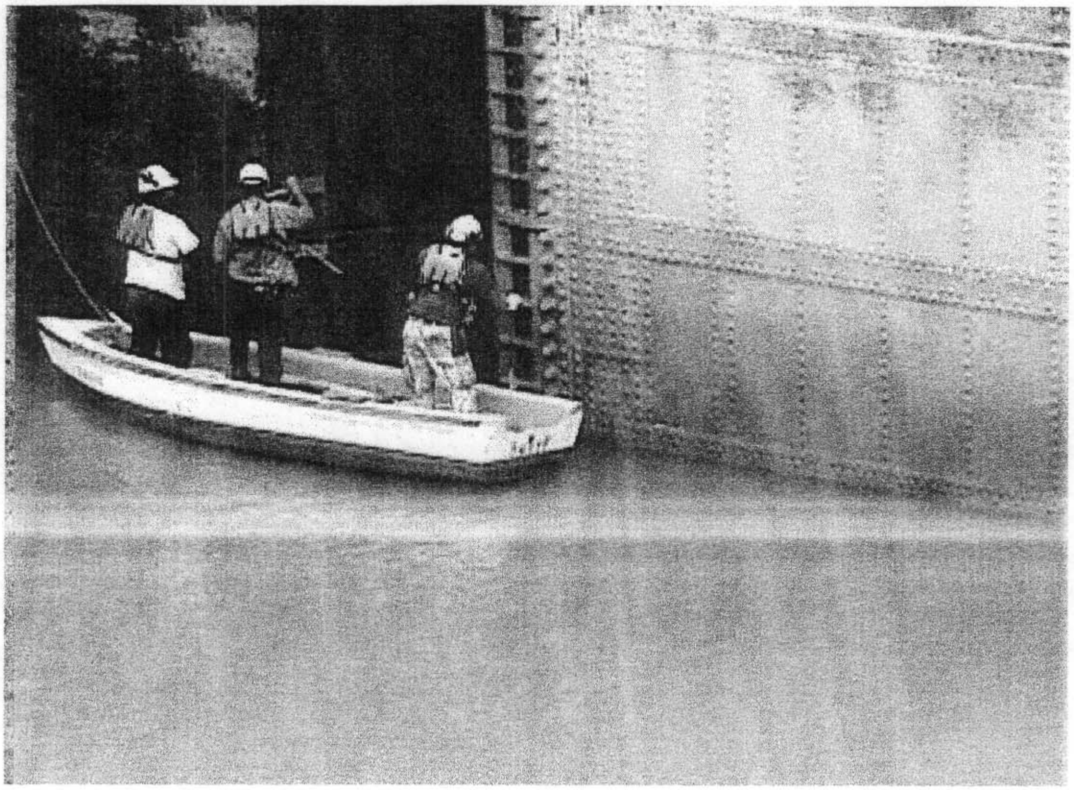


Figure 4 – Installation of Sensor on Miter Gate

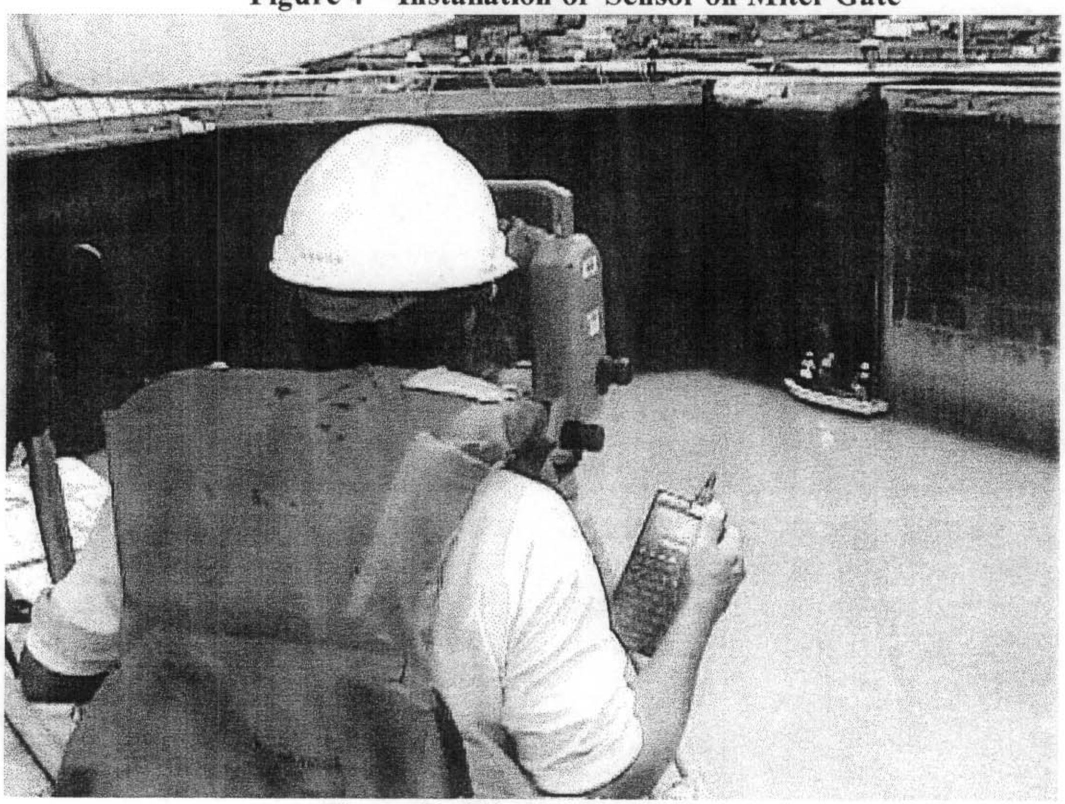


Figure 5 – Diag7 being surveyed

SECTION 3. DATA ACQUISITION

3.a. WORK SHIFTS

Two shifts were established to record vessel data. The first shift started at approximately 04:30 and the last shift ended at approximately 20:00. A shift consisted of two personnel on the lock walls and one in the control house.

The morning shift was responsible for synchronizing watches, removing data cards from the dataloggers, inserting new cards, recording the time deviation on the dataloggers from the official watch and downloading the cards onto the laptop PC at a convenient time.

The second shift was responsible for downloading the data cards to the laptop PC at the end of their shift. These same data cards were then re-inserted into the datalogger minutes later to record the chamber activity overnight. Therefore, the chamber water surface elevations were recorded continuously 24 hours a day except for a few minutes when new cards were inserted at the beginning of the day and when the data cards were downloaded as backup at the end of the second shift. The lock walls crew and the person working in the control house recorded data on the form shown in Figure 6.

3.b. SOUTHBOUND VESSEL

3.b.1. Lock Wall Data Acquisition

For a southbound vessel the lock walls crew recorded when the vessel's bow (at the water surface) crossed the northwest knuckle, which is considered the entry time. The crew then walked along the wall with the vessel to record when the bow and stern crossed the sill for Miter Gates 102-103. The time the vessel stopped was recorded along with the vessel's position in the chamber as the pool was lowered. The vessel's position at bow and stern within the chamber was referenced to lock chamber stationing on the northwest wall and on the centerwall. The stationing is from south to north with station 0+00 at Miter Gates 114-115. The time the vessel started to depart the chamber was noted as was when the bow and stern crossed the sill for Miter Gates 118-119.

3.b.2. Control House Data Acquisition

The person working in the control house was responsible for gathering the name of the vessel, type of vessel, the beam, draft, length, and the number of locomotives and wires used. Also recorded were the vessel's arrival time, when the bow crossed the north approach. The control house also recorded when the bow crossed the northwest knuckle with the aid of an electronic eye. However, the electronic eye times were often considerably different than the lock wall crew's time. Therefore, the time taken on the wall was used. The control house recorded when Miter Gates 102-103 began to close and the water level at normal high pool. The water level for normal high was read from the control house digital display for the gage located near the Miraflores Lake Spillway and from permanent non-recording gages located in the chamber for normal low. The northwest chamber is served by 17' diameter culverts in both the west wall and the centerwall. Each culvert has two 10' x 18' Rising Stem Valves (RSV's) that control flow from Miraflores Lake. Each culvert also has two RSV's on the southern end of the northwest chamber that control flow to the southwest (low) chamber. The center wall culvert is capable of supplying flow to either the northwest and northeast chamber with the use of cylindrical valves (CV's). There are 10 CV's per chamber. There are no CV's in the west wall culvert.

The condition of these CV's was noted in the control house. The CV's could be closed, open or both the northwest and northeast chamber CV's open (open across) while the vessel enters the chamber.

The control house also recorded when the southern RSV's (control house RSV's) were opened to equalize the pools for the northwest and southwest chambers and when Miter Gates 118-119 began to open. Finally the control house recorded when Miter Gates 118-119 began to close, when the lake RSV's were opened and when Miter Gates 102-103 were opened which signified when the chamber was ready for another southbound vessel.

3.c. NORTHBOUND VESSEL

3.c.1. Lock Wall Data Acquisition

For a northbound vessel the lock walls crew recorded when the bow and stern crossed the sill of Miter Gates 118-119. The time the vessel stopped was recorded along with the stationing of the vessel's bow and stern at the water surface. After the ship was raised to high pool, the time the vessel started to depart the chamber was recorded, along with when the bow and stern crossed the sill for Miter Gates 102-103 and the northwest knuckle. Occasionally the water level was determined from the reference point on Miter Gate 114.

3.c.2. Control House Data Acquisition

The person working in the control house recorded when Miter Gates 118-119 began to open and when they closed after the vessel entered the chamber. The condition of the CV's was noted. Also recorded was when the lake RSV's were opened to raise the vessel to high pool. Normal high and low pool were read from non-recording gage displays in the control house. The last events recorded were when Miter Gates 102-103 were opened for the vessel's departure into Miraflores Lake and when the gates were closed to lower the pool for the next northbound vessel.

CHAMBER PRESSURES MEASURMENTS AT MIRAFLORES LOCKS UPPER WEST

Date:		Date taken by:	
Name of Vessel:		Name of Vessel (Tandem):	
Type of Vessel:		Type of Vessel:	
Beam:	meters/feet:	Beam:	meters/feet:
Draft:	meters/feet:	Draft:	meters/feet:
Length:	meters/feet:	Length:	meters/feet:
No. of locomotives & wires:		No. of locomotives & wires:	

	SOUTHBOUND	Times	Tandem Information
1	Bow crosses north approach (arrival time)		
2	**Bow crosses NW knuckle (entry time)(elec**		**(both)**
3	**Bow crosses MG 102-103 sill (triangle)**		**Tandem bow times:**
4	**Stern crosses MG 102-103 sill**		**Tandem stern times:**
5	**Vessel stops**		
6	Close MGs 102-103		
7	**Read water level at normal high (both)**		
8	Condition of CVs in upper level		
9	**Position of bow of vessel**		**Tandem bow position:**
10	**Posiiton of stern of vessel**		**Tandem stern position:**
11	Open control house RSVs		
12	Open MGs 118-119		
13	**Vessel starts moving**		
14	**Read water level at normal low (both)**		
15	**Bow crosses MGs 118-119 sill**		**Tandem bow times:**
16	**Stern crosses MGs 118-119 sill**		**Tandem stern times:**
17	Close MGs 118-119		
18	Open lake RSVs		
19	Open MGs 102-103 chamber ready		

	NORTHBOUND		
1	Open MGs 118-119		
2	**Water level at normal low (both)**		
3	Condition of CVs in upper level		
4	**Bow crosses sill of MGs 118-119**		**Tandem bow time:**
5	**Stern crosses sill of MGs 118-119**		**Tandem stern time:**
6	**Vessel stops**		
7	Close MGs 118-119		
8	**Position of vessel (bow)**		**Tandem bow position:**
9	**Position of vessel (stern)**		**Tandem stern position:**
10	Open lake RSVs		
11	Open MGs 102-103		
12	**Water level at normal high (both)**		
13	**Vessel starts moving**		
14	**Bow crosses sill MGs 102-103**		**Tandem bow time:**
15	**Stern crosses sill MGs 102-103**		**Tandem stern time:**
16	**Bow crosses NW knuckle (both)**		**Tandem bow time:**
17	**Stern crosses NW knuckle**		**Tandem stern time:**
18	Close MGs 102-103		

Notes: Items in **bold**, data to be taken by person on locks walls. All other data to be filled by person in control house. Items that indicate "both" are to be taken by both person on locks wall and person in control house for cross reference.

Figure 6 – Data form used on lock walls and in control house

SECTION 4. DATA REDUCTION

4.a. RAW GAGE DATA

Raw data from each gage was recorded continuously 24 hours a day except for a few minutes when new cards were inserted at the beginning of the day and when the data cards were downloaded as backup at the end of the second shift. After a complete day, the data was downloaded to the PC to be analyzed later in Pittsburgh. The raw data file names consist of the gage number followed by two numerals designating the calendar date in April 1999 when the data card was inserted. Another letter may follow the date. Each gage has one or two associated files per day, i.e., the raw data for gage Diag3 on April 24 is labeled Diag324n.dat. Some data may overlap and early morning data may appear on the previous day's file. The format is six readings per line with time stamps at even 10-minute intervals. All raw data is included on the CD accompanying this report.

4.b. CALIBRATION

4.b.1. Elevations. The pressure sensors and data loggers that were used in the experiment do not necessarily produce highly accurate readings in raw form. Experience has shown that the raw readings may be in error by as much as several tenths of a foot in a 20-foot range. In past studies, adjustments were applied after the fact based on averages over periods of time, and satisfactory results were always obtained without any separate calibration tests. However, in this study, all of the equipment was pre-tested in order to better understand the variations in readings and determine the best adjustment method.

The pre-tests were performed in a building using a 20-foot standpipe. Sensors and loggers were paired and readings taken at heads of 20-, 15-, 10-, 5-, 2- and zero-feet of water. Analysis of the results indicated that subtracting the "zero" reading as an offset and applying a constant range correction factor to the result produced adjusted readings within 0.02-0.03 feet of the true value at all levels. In other words, it was determined that any error is nearly linear over the test range. The pre-test data and analysis are included in the "Calibrat.xls" file on the data CD.

Temperature and salinity are two obvious factors (and there may be others) which varied between the lab and field installation at the Miraflores Lock and which could affect the readings. It was not surprising, then, to find that readings of most instruments under zero head (though wet) did not match those taken in the lab. Therefore, the lab-determined offsets and range factors could not be used and new adjustments had to be derived from the field data.

Diag2 was used as the reference gage in determining the adjustments. The datum of Diag2 and all other gages were surveyed, in addition to a reference point located above Diag2 on top of Miter Gate 114, about a foot above the normal high pool level. It was known at the low end that the instrument reading with the pool drained below the sensor, 0.07 feet, corresponded to the elevation of the sensor, 21.38 feet PDL. At the high end, a reading of 33.06 feet was recorded on Diag2 at the exact time when the pool was measured to be 0.42 feet below the RP, which is elevation 55.02-0.42=54.60 feet PDL. With an offset of -0.07 feet the range adjustment factor was calculated as follows:

Diag2 Factor = (54.60-21.38) / (33.06-0.07) = 1.0069718

Next, the data was searched for periods of time over the 5-day record when the most stable high and low pool conditions existed. Two such high pool periods lasting 30 minutes were selected, one near the start of testing and the other toward the end. Although oscillations with a range of about 0.7 feet existed in both cases, the average water surface elevations on all gages should still be approximately the same over these periods because they cover several oscillation cycles.

It was more difficult finding stable periods with low pool because of a persistent overempty wave and the usual practice of keeping the chamber at high pool. However, three shorter periods ranging from about 5 to 11 minutes were able to be used because the oscillation cycles are much shorter at low pool than at high pool.

For each of the remaining gages, the best offset and range factor were determined by trial and error. The optimum values were those that closely matched the elevations of Diag2 after adjustment, and which minimized differences between the average readings of all gages for periods analyzed. The adopted set of offsets and range factors resulted in a maximum overall variation of only 0.08 feet between the average readings for all gages during all five calibration periods. All of the calculations can be found in the spreadsheet "Calibrat.xls". The adjusted data for one high and one low period are plotted on Figures 7 and 8, respectively. Knowing the gage datums, offsets and range factors, any reading can be converted to an elevation as follows:

PDL elevation = Datum + Factor * (Offset + Reading)

The final adjustment parameters for all gages are listed below:

	DIAG1	DIAG2	DIAG3	DIAG4	DIAG5	DIAG6	DIAG7	DIAG8	DIAG9
DATUM	18.37	21.38	8.11	20.98	19.72	18.71	20.26	20.32	9.40
OFFSET	-0.10	-0.07	-0.37	0.10	-0.09	-0.20	-0.26	-0.28	-0.20
FACTOR	1.0073193	1.0069718	1.0205363	1.0015915	1.0109707	1.0067992	1.0171212	1.0167961	1.0073883

The same adjustments can be applied to readings at any time during the test period. Although there are some indications of a slight drift in calibration over time, the small improvement in accuracy would not be worth the complications associated with varying the adjustment parameters. All of the adjusted readings should be accurate to within 0.1 foot of the true elevation.

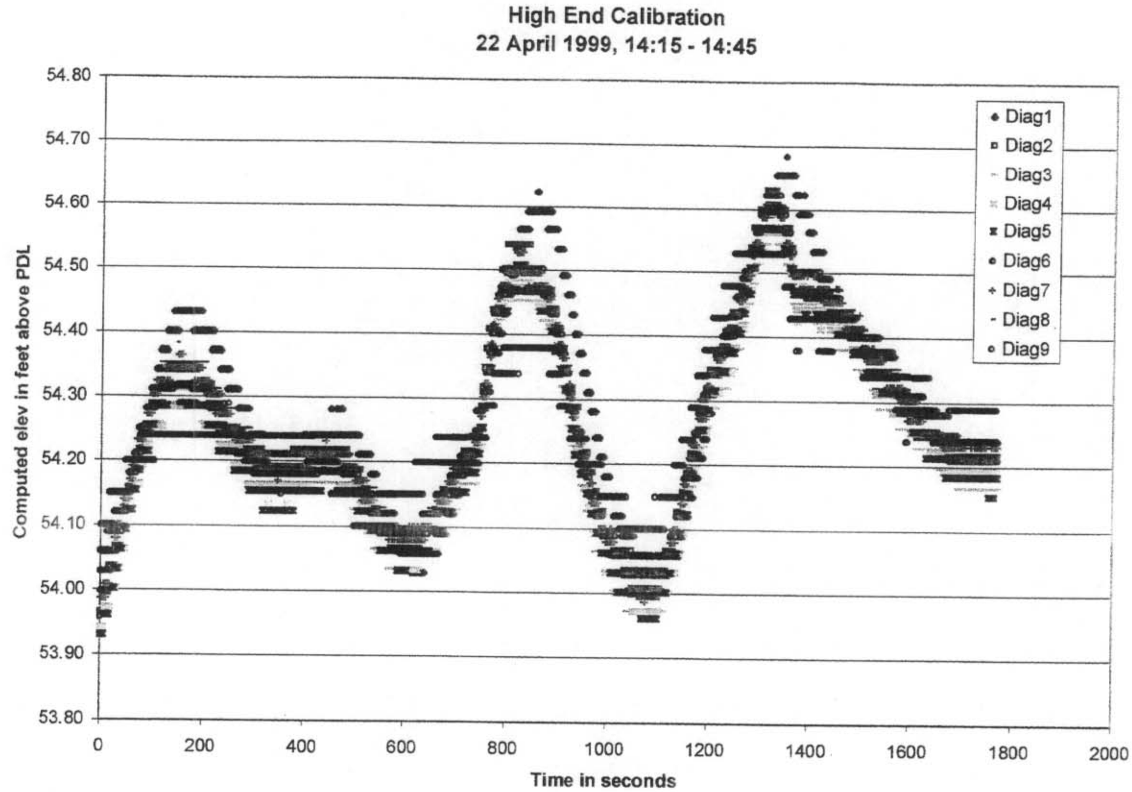


Figure 7

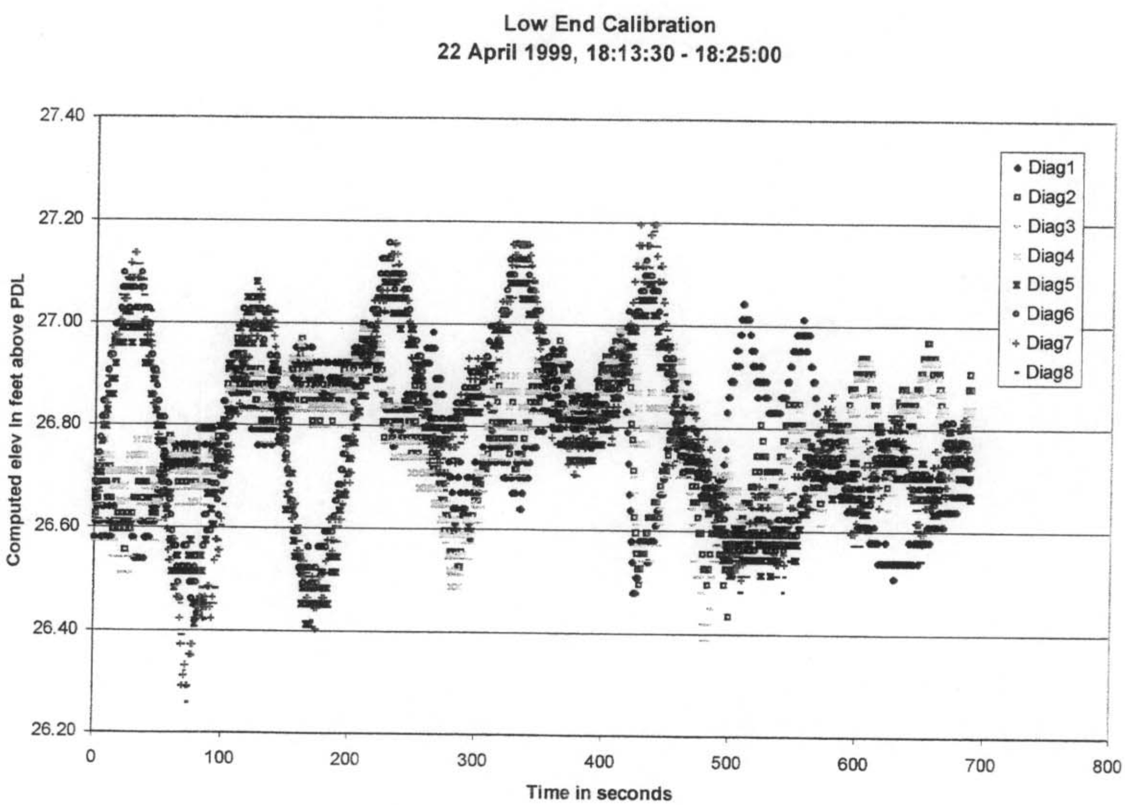


Figure 8

4.b.2. Time Adjustment. The instrument clocks are only guaranteed accurate to within 1.4 seconds per day. Over a 5-day period, the cumulative error might be unacceptable unless corrected for timing. Therefore, each day the deviation of each instrument from the official clock was recorded to approximately ¼ second. Over five days the fastest clock had gained 6¼ seconds while the slowest had lost 2½ seconds. More importantly, the daily comparisons all indicated linear deviation patterns. A rate of deviation was calculated based on the cumulative deviation at the end of testing. Time adjustments could easily be applied to the raw data by multiplying the elapsed time from initialization of the clock by the deviation rate. In analyzing the individual measurements, the amount of deviation was determined for the beginning time and held constant for the measurement. This made interpolation of readings corresponding to the official time much easier with negligible loss of accuracy. The final time-adjusted elevations should be accurate to within ½ second.

It is noted that the files containing raw data have not been time-adjusted. In fact, it would be difficult to apply an adjustment to the bulk data because of the file format and because each file covers at least several hours over which the deviation would vary significantly. Therefore, any blocks of data extracted later for analysis will need to be adjusted for time if a high degree of accuracy is desired.

4.c. SPREADSHEET ANALYSIS

The effects of vessels entering and exiting the lock were analyzed utilizing Microsoft Excel. Each lockage or "measurement" has its own file on the accompanying CD. The file for measurement #1 on April 24 is designated "Msmt241n.xls", where the "n" is for northbound, "s" for southbound. The first sheet of the Excel file is labeled "Loginfo" and contains information on the vessel, such as name, type, length, draft, beam, etc and specific times as the ship entered and exited the lock. Using the data, the vessel's blockage ratio at high and low pool was computed along with the average speeds of the vessel.

A time block of data was extracted for each gage from the raw data files. A utility program "Reforml.exe" was used to reformat the data into a single column of numbers. The reformatted text files were then imported into the Excel file and placed in sheet "RawData". The raw data was then adjusted for the gages' datum elevations and for the gages' calibration under the sheet "Elevs". The final step was to adjust for time under sheet "TimeAdj". Statistical averages and differences were then computed on the "TimeAdj" and/or "Loginfo" sheets to obtain estimates of the base pools, surcharges, and drawdowns.

Twenty-five southbound and 21 northbound measurements were obtained from April 22-27 and later processed. Appendix A is an index of all measurements. Additionally, nine overnight southbound lockages were processed, e.g. "Nite224s.xls". Since nobody was present to log information overnight, only limited data from the official record was available and many items had to be omitted in the spreadsheet analyses of overnight lockages.

4.d. GRAPHICAL REPRESENTATION OF DATA

4.d.1. Water Surface Elevations Plots

The "TimeAdj" sheet contains the final elevations for the gages and was used to develop four plots. The first plot in Figure 9 is typical for Northbound, Low Pool and shows the water surface elevations for each gage versus time as the vessel enters the northwest lock from the southwest lock at equalized low pool. Time is in seconds after Miter Gates 118-119 begin to open. The plot in Figure 10 is typical for Northbound, High Pool and shows the water surface elevations as the vessel is exiting into Miraflores Lake. Time is in seconds after Miter Gates 102-103 begin to open.

4.d.2. Profile Plots

The plot in Figure 11 is a typical profile plot for Northbound Low Pool and Figure 12 applies to Northbound High Pool. The plots were developed from the sheet labeled "Plot Data" and show water surface profiles in the lock at specific times versus lock stationing. Also plotted are the chamber floor and the various sills for miter gates and the emergency dam. The plot at Low Pool displays profiles for when the chamber is overemptied, at the time of the greatest surcharge and drawdown and when the vessel stops. The plot at High Pool has profiles of when the chamber is initially overfilled, for when the bow of the vessel reaches the sill for Miter Gates 106-107, and at the time of the greatest surcharge and drawdown. Each plot displays the vessel's position in the chamber at these times and also the vessels' average velocities during entry and exiting of the lock. A southbound vessel has four similar plots. Refer to Appendix B for southbound and Appendix C for northbound plots.

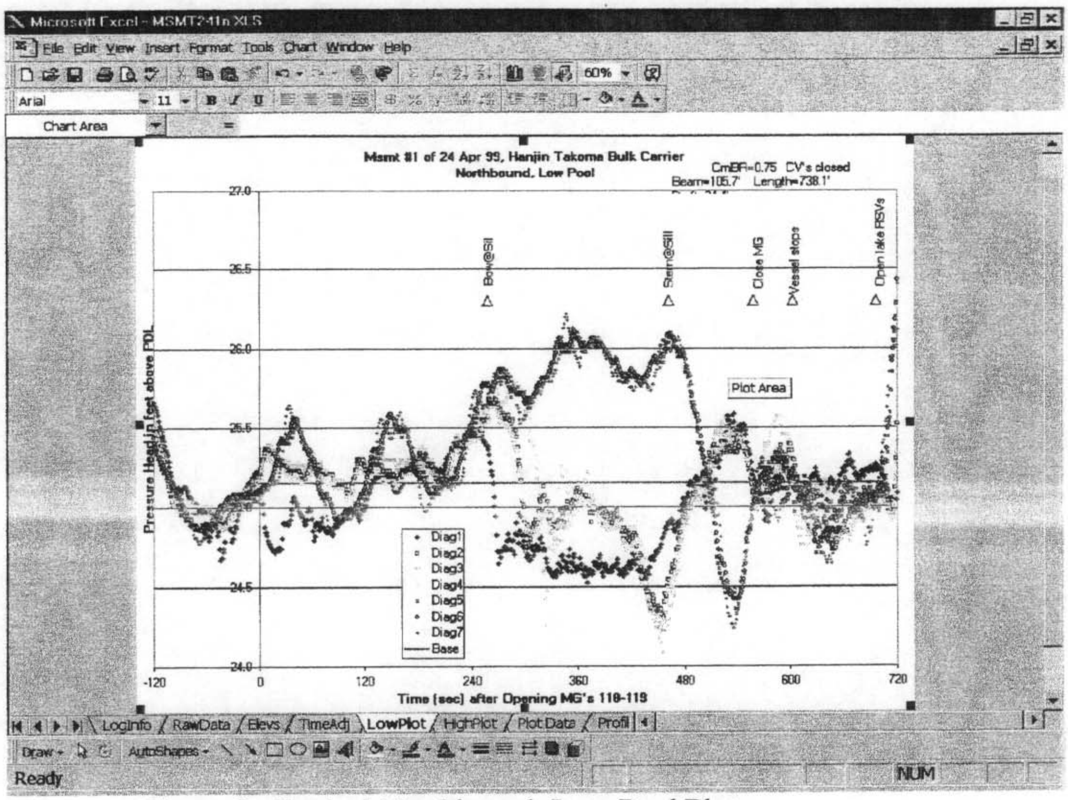


Figure 9 - Typical Northbound, Low Pool Plot

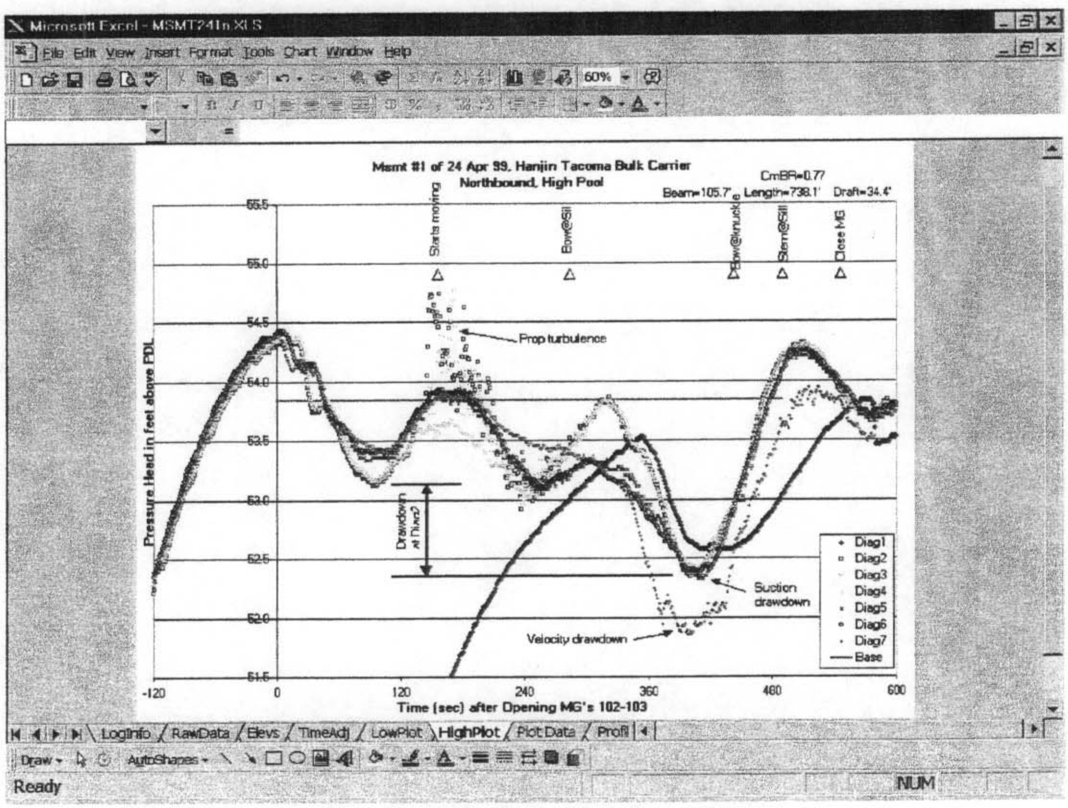


Figure 10 – Typical Northbound, High Pool Plot

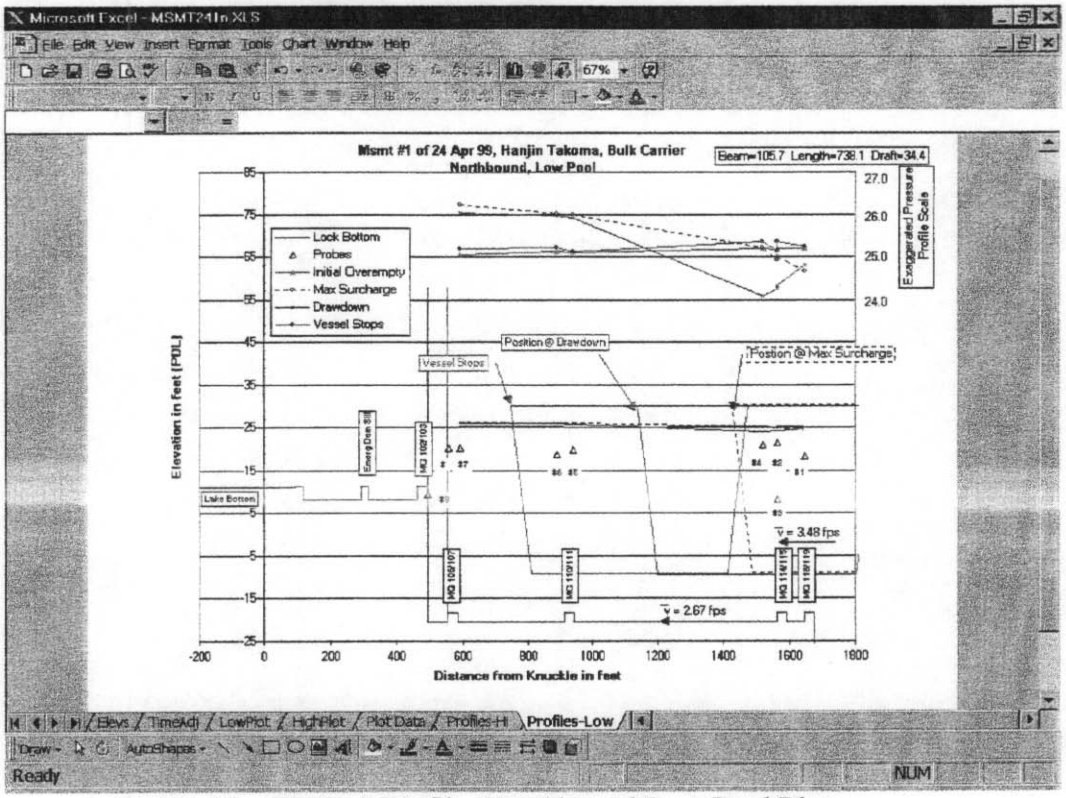


Figure 11 – Typical Profile, Northbound Low Pool Plot

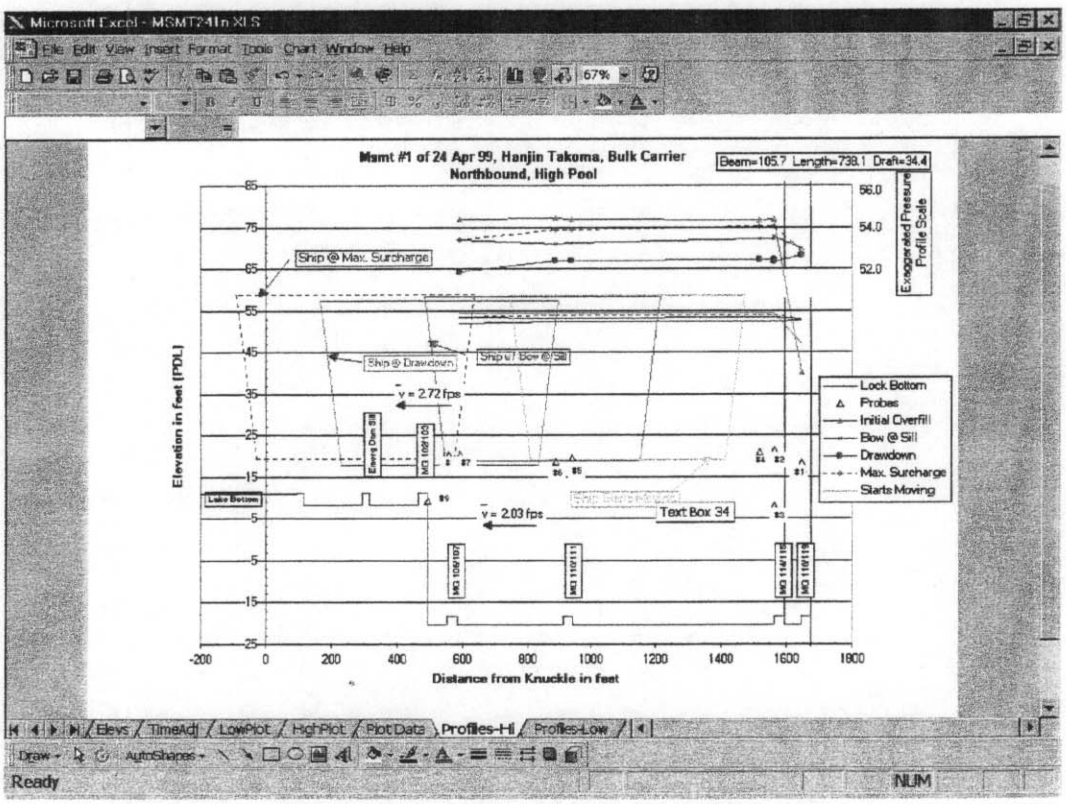
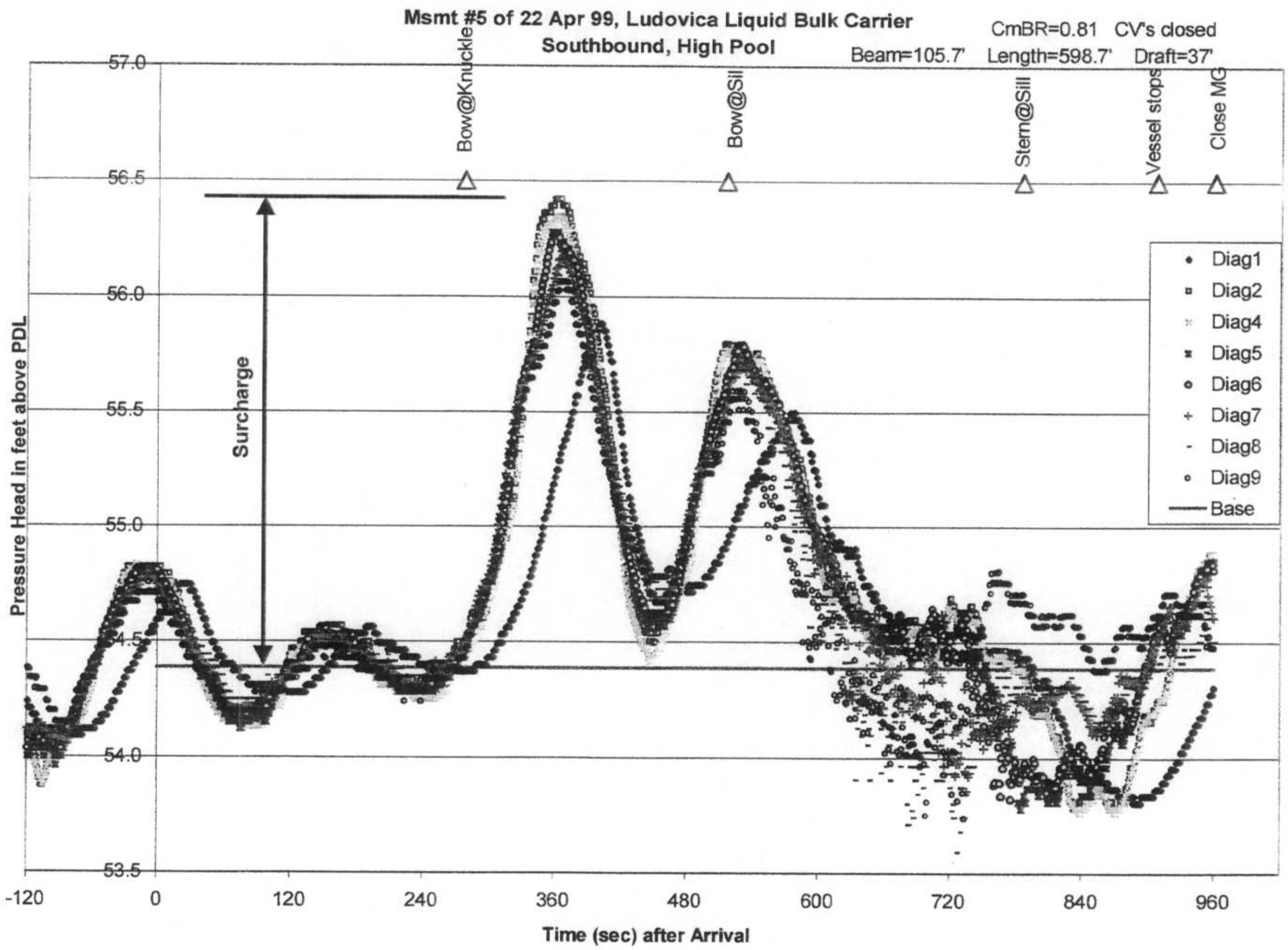


Figure 12 – Typical Profile, Northbound High Pool Plot

SECTION 5. DISCUSSION OF RESULTS

5.a. SOUTHBOUND ENTERING CONDITION

5.a.1. Observations. Typical reaction of gages within the lock chamber to the entry of a large ship is shown in Figure 13.



Typical Southbound Entering Condition, Large Ship
Figure 13

A series of small waves precedes the bow of the ship reaching the knuckle of the north wall. The waves are probably caused by the ship moving in open water because the period generally decreases as it gets closer to the knuckle. Approximately 1.5 to 3 minutes after the bow reaches the knuckle, a large surcharge in the lock is evident. This is usually the highest surcharge generated, especially for boats with the highest blockage ratios. The highest water level occurs at the downstream miter gate (Diag2 & 3). The peak surcharge is slightly lower farther upstream as the water surface assumes a wedge profile sloping toward the ship. The surcharge wave recedes, and 2 to 3 minutes later a second surcharge occurs. The second peak is generally lower than the initial rise with the larger boats, though with the moderate-sized boats the second peak may equal or exceed the first. Following the second surcharge wave, the water surface returns toward base level. A drawdown at the upstream gages (Diag7, 8 & 9) may occur due to high velocity of the exiting water flowing past these sensors.

Base level is the estimated average water level that would obtain absent boat effects. In this case it is calculated from the average reading on gage Diag5 from the time of ship arrival until one minute prior to its bow reaching the knuckle. Maximum surcharge is defined as the difference between the peak reading on Diag2 at lower Miter Gates 114-115 and base level. (There would likely be a "surcharge" averaging a few tenths of a foot even without the effects of a boat as there are constantly small oscillations in the chamber from other sources.) The highest observed surcharge was 2.35 feet.

5.a.2. Data Summary. Table 1 below lists surcharges and other key information for all measurements of the southbound entering condition.

Table 1
Summary Data
Southbound entering (High pool)

Msmt No.	Blockage Ratio Cm BR	Speed Knuckle to Sill, fps	Speed Across Sill, fps	Obs Max Surcharge Feet	Cylindrical Valves Position	Ship Type	Length feet
Measurements with larger ships and surcharges:							
224	0.53	5	4.31	0.55	C	Car	591
225	0.81	2.21	2.07	2.03	C	Tanker	599
226	0.82	1.61	1.56	0.91	C & O	Tanker	810
228	0.87	1.11	1.14	0.84	O	Bulk	738
235	0.83	3.03	1.95	1.15	OA	Cont	965
236	0.87	3.5	1.82	2.35	OA	Cont	965
238	0.77	4.13	1.37	1.53	C	Tanker	601
245	0.57	0.62	3.77	1.13	O	Cont	579
246	0.64	2.65	3.72	0.79	C	Tanker	573
247	0.78	1.84	2.12	0.76	C	Cont	905
248	0.50	1.43	2.42	0.51	O	Pass	719
249	0.79	1.88	1.87	0.86	O	Bulk	607
255	0.74	5.36	1.7	1.09	OA	Bulk	645
257	0.77	1.52	1.73	0.63	C	Bulk	735
266	0.62	0.67	3.38	0.75	O	Bulk	556
267	0.67	2.55	2.77	0.64	O	Tanker	560
269	0.87	1.55	1.67	1.37	OA	Bulk	738
Measurements with smaller ships and surcharges:							
227	0.36	3.14	2.87	0.29	C	Bulk	425
237	0.53	2.57	2.97	0.37	OA	Bulk	548
244	0.04	12.21	10.3	0.19	O	Pass	119
254	0.27	4.2	3.8	0.19	O	Mil	579
256	0.29	2.35	2.43	0.33	OA	Pass	537
258	0.4	3.85	2.46	0.37	OA	Bulk	550
268	0.06	3.26	4.4	0.44	O	Barge	230

2610	0.52	2.31	2.78	0.34	C	Tanker	509
Overnight data:							
Nite222	0.87			0.76			614
Nite223	0.51			0.53			487
Nite224	0.25			0.32			461
Nite225	0.75			0.76			588
Nite226	0.42			0.57			466
Nite227	0.58			0.63			557
Nite231	0.85			1.44			738
Nite241	0.87			1.71			738

The blockage ratio, "BR" is the ratio of maximum cross-sectional area at mid-ship to chamber area at the miter gate sill with base pool. Ship cross-sectional area was calculated as the product of beam times draft. When the type of ship was known, the area was refined by multiplying by Cm, the "Midship Coefficient", which is characteristic of the type of vessel, and varies from 0.956 for passenger ships to 0.990 for bulk carriers. Average speeds from knuckle to sill and across the sill were calculated from the recorded times. The position of the CV's connecting the centerwall culvert to the west lock was noted because an additional avenue is available for water trapped by the ship to escape when they are open. When the valves to the northeast lock are also open ("OA" in table) flow may escape into the adjacent lock without passing through the Lake RSV's. Vessel length as tabulated refers to the gross reported length rather than actual length at the water line.

5.a.3. Correlations. It was beyond the scope of the study to fully characterize and analyze the hydraulic phenomena producing water surface (pressure) fluctuations and surcharges. However, attempts were made to identify trends and correlations. The two major factors are expected to be blockage ratio and ship speed. Figure 14 shows the plot of surcharge versus blockage ratio. The plot indicates a general increase in surcharge for blockage ratios exceeding 0.5. The exponential best-fit line indicates the following average relationship between blockage ratio and maximum surcharge:

$$\text{Surcharge} = 0.1932e^{2.1781*BR}$$

However, this equation underpredicts the maximum observed surcharge by more than a foot. For lower blockage ratios, a "surcharge" averaging about 0.3 feet may have other causes.

The plot of surcharge versus approach velocity in Figure 15 appears to show a trend of decreasing surcharge with speed, which is unreasonable. The actual trend is the exact opposite of this but is masked by the fact that ships with high blockage ratios tend to move much slower. Approach speed was taken as the average of speed from knuckle to sill and speed over the sill, or, if greater, the speed over the sill.

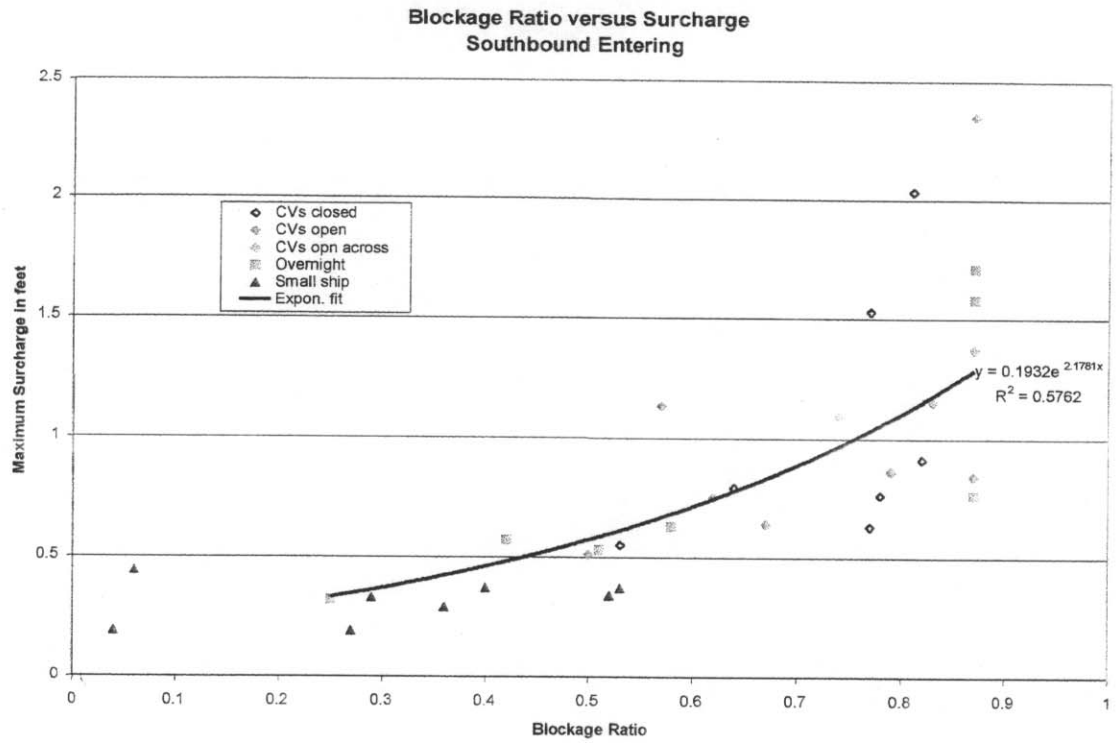


Figure 14

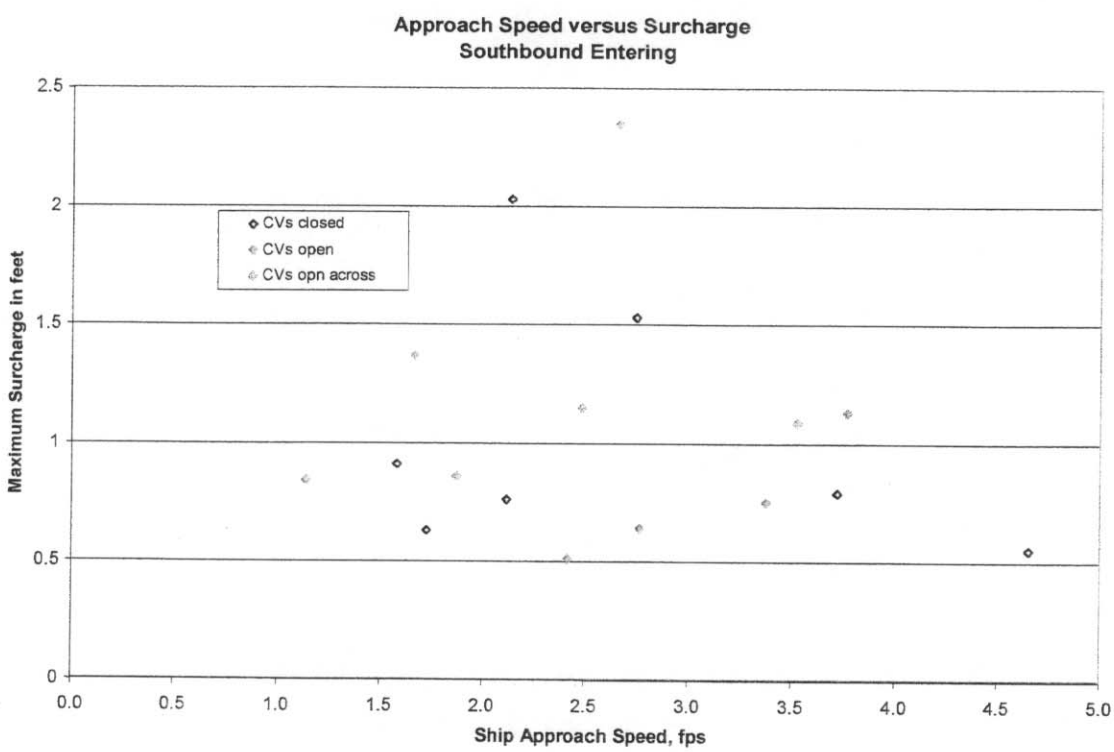
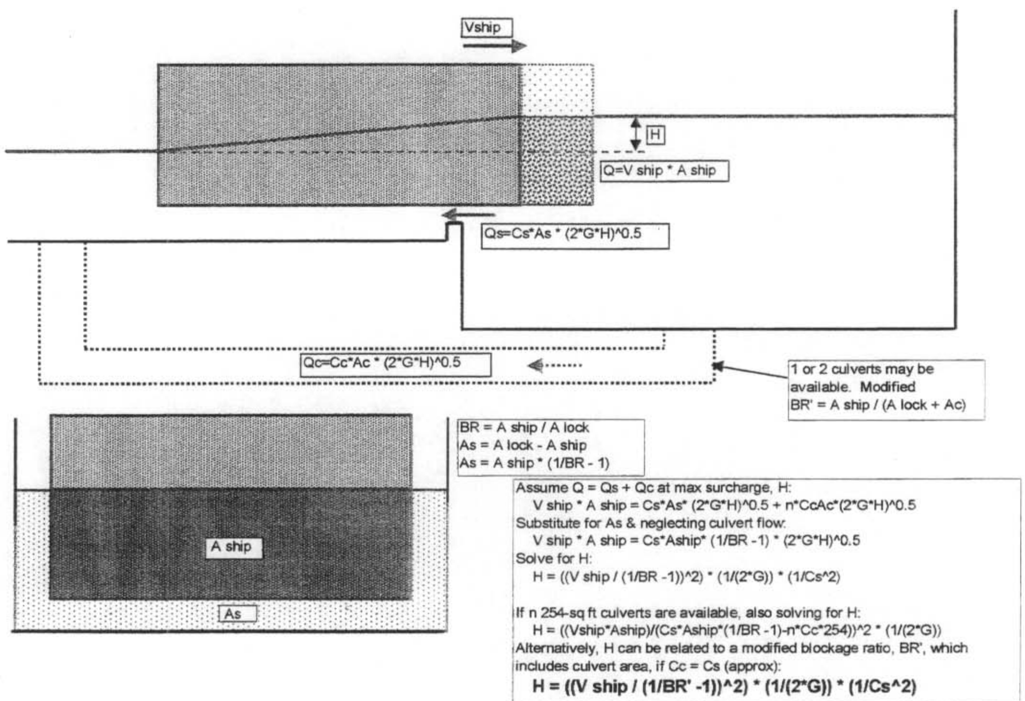


Figure 15

Various methods were tried to better define the correlation between blockage ratio, speed and surcharge. Association between surcharge and other parameters including ship length and Cb, the "Block Coefficient", which is a measure of streamlining, were also investigated. Initially the data were placed in three separate categories for analysis according to the CV's position. This approach was presented during the progress meeting on 1-2 June 1999, and, although the results seemed promising, some of the sample sizes were too small to assure reliability of results. Also, it relied on a weak inverse association between ship length and surcharge, which could not be explained.

The approach that was ultimately used allows all southbound entering measurements to be analyzed together regardless of the CV's position. The basic procedure is also adaptable to computing the surcharge for the northbound entering condition as well as the drawdown for southbound exiting. A key concept is including available culvert area in the computation of blockage ratio, which will be referred to here as "Modified Blockage Ratio" or BR'. The probable relationship of BR' and ship speed (Vship) to surcharge (H) was inferred by relating the rate of displacement of water by the ship to the flow exiting the lock via the open area around the ship plus available culvert area, as shown in Figure 16, below.



Derivation of H as a function of BR' and Vship
Figure 16

Flow under the ship and through culverts can be estimated using the orifice equation, which can also apply to a submerged weir representing flow alongside the ship. Of course, the discharge coefficient and head for all escaping flow must be assumed to be the same in this simplified representation.

Table 2 lists BR', the function $(Vship/(1/BR' - 1))^2$, which will be called the "V&BR' Function" and other correlation analysis parameters.

Table 2
Correlation Analysis Parameters
Southbound Entering (High pool)

Msmt No.	Block-age Ratio Cm BR	Use Vship fps	CV's Pos-ition	Ship Type	Cb	Length feet	Width feet	Draft Feet	Aship sq ft	As sq ft	No. of Culverts at 254 sq ft	Atotal sq ft	Modi-fied BR'	V&BR' Func-tion	Obs Max Surcharge feet
224	0.53	4.66	C	Car	0.61	590	105.7	24.3	2495	2212	1	4961	0.50	22.2	0.55
225	0.81	2.14	C	Tanker	0.757	599	105.7	37	3825	897	1	4976	0.77	50.6	2.03
238	0.77	2.75	C	Tanker	0.757	601	105.8	35.2	3638	1087	1	4979	0.73	55.7	1.53
246	0.64	3.72	C	Tanker	0.757	573	96.8	32.3	3053	1717	1	5025	0.61	33.2	0.79
247	0.78	2.12	C	Cont	0.71	905	105.8	35.57	3688	1040	1	4982	0.74	36.5	0.76
257	0.77	1.73	C	Bulk	0.874	735	105.2	35.5	3697	1104	1	5056	0.73	22.2	0.63
226	0.82	1.59	C&O	Tanker	0.757	810	105.2	38.08	3918	860	1.5	5159	0.76	25.0	0.91
228	0.87	1.14	O	Bulk	0.874	738	105.7	39.41	4124	616	2	5248	0.79	17.5	0.84
245	0.57	3.77	O	Cont	0.71	579	90.9	30	2672	2016	2	5197	0.51	15.9	1.13
248	0.5	2.42	O	Pass	0.597	719	101.1	24.89	2406	2406	2	5319	0.45	4.0	0.51
249	0.79	1.88	O	Bulk	0.874	607	100.1	38.08	3774	1003	2	5285	0.71	21.9	0.86
266	0.62	3.38	O	Bulk	0.874	556	89.4	33.25	2943	1804	2	5254	0.56	18.5	0.75
267	0.67	2.77	O	Tanker	0.757	560	96.9	33.89	3212	1582	2	5302	0.61	18.1	0.64
235	0.83	2.49	OA	Cont	0.71	965	105.8	37.89	3929	805	2.3	5317	0.74	49.6	1.15
236	0.87	2.66	OA	Cont	0.71	965	106	39.33	4086	610	2.3	5280	0.77	82.7	2.35
255	0.74	3.53	OA	Bulk	0.874	645	105.7	33.75	3532	1241	2.3	5357	0.66	46.7	1.09
269	0.87	1.67	OA	Bulk	0.874	738	105.7	39.5	4133	618	2.3	5335	0.77	33.0	1.37

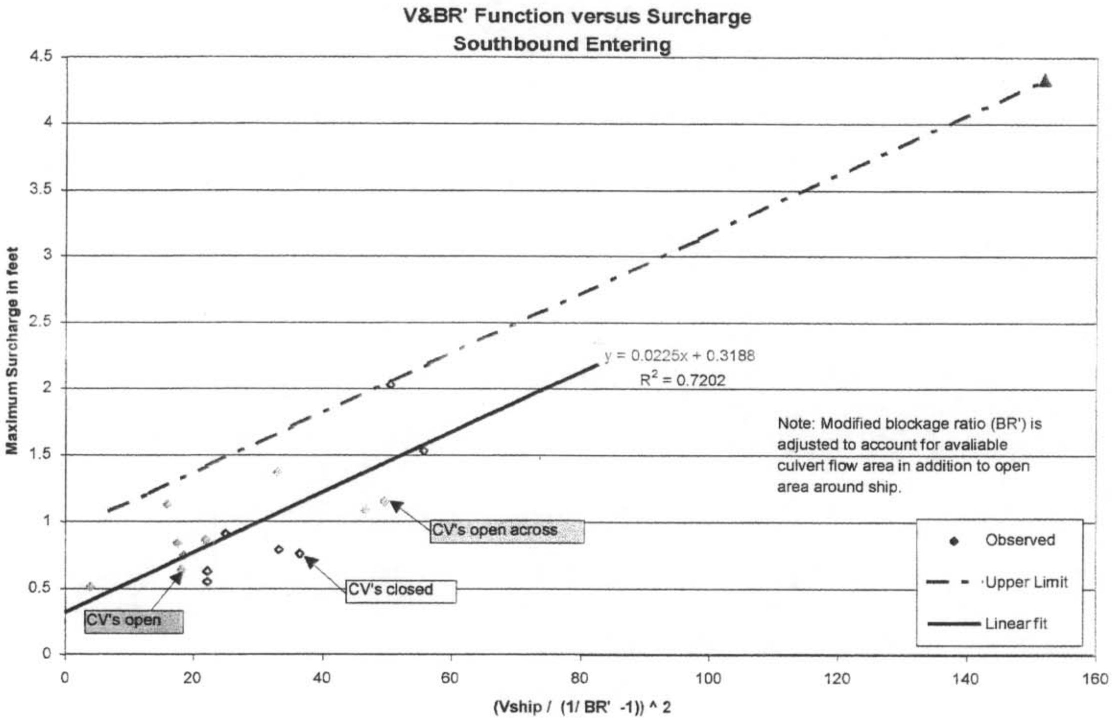


Figure 17

Figure 17 shows surcharge plotted against the V&BR' Function. The slope of the best fit line represents constants $(1/2G)*(1/Cs^2)$ in the equation derived in Figure 16. The discharge coefficient Cs would be 0.83, which is a reasonable value. The Determination Coefficient for the line, R^2, is 0.72 and standard error of estimate, 0.28 feet. The y-axis intercept, 0.32 feet, is assumed to represent that part of the surcharge not directly caused by the ship trapping water in the lock although it could be related to waves generated earlier by the ship moving through open water.

The equation for surcharge is:

$$\text{Surcharge (ft)} = 0.32 + 0.0225*(\text{Vship}/(1/\text{BR}' - 1))^2$$

Also shown on the graph is an "Upper Limit" line drawn parallel to the best fit but extending through the highest upper deviate. Extending this line to the point on the x-axis representing the maximum probable value of the function for vessels operating in the present environment gives an estimate of maximum probable surcharge. The maximum function value was calculated using minimum operating pool of 53 feet, maximum ship beam of 106 feet, draft 39.5 feet, Cm of 0.99, and CV's closed. The associated Vship was estimated by extending a line through the highest points of a BR' vs. Vship plot shown in Figure 18. Accuracy of this projection of maximum surcharge, which gives 4.34 feet, cannot be guaranteed. Although Figure 17 has a theoretical basis, both Figures

17 and 18 are based on a relatively small sample. However, combining the upper limits of both relationships is expected to produce a conservative high estimate.

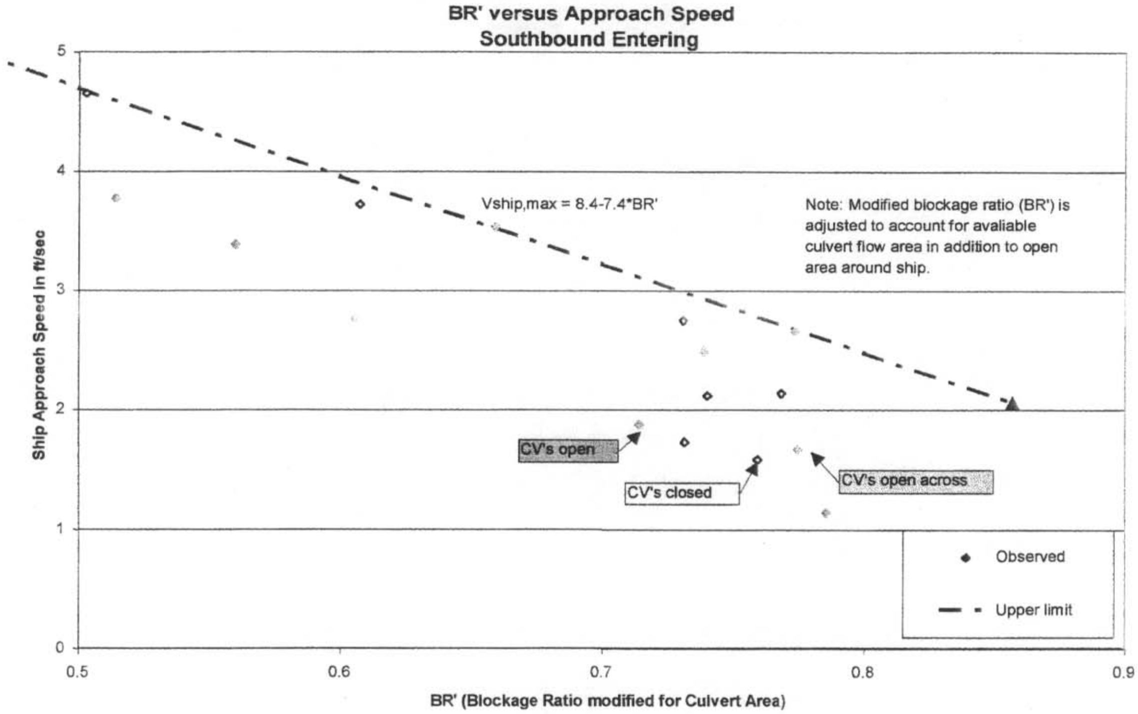
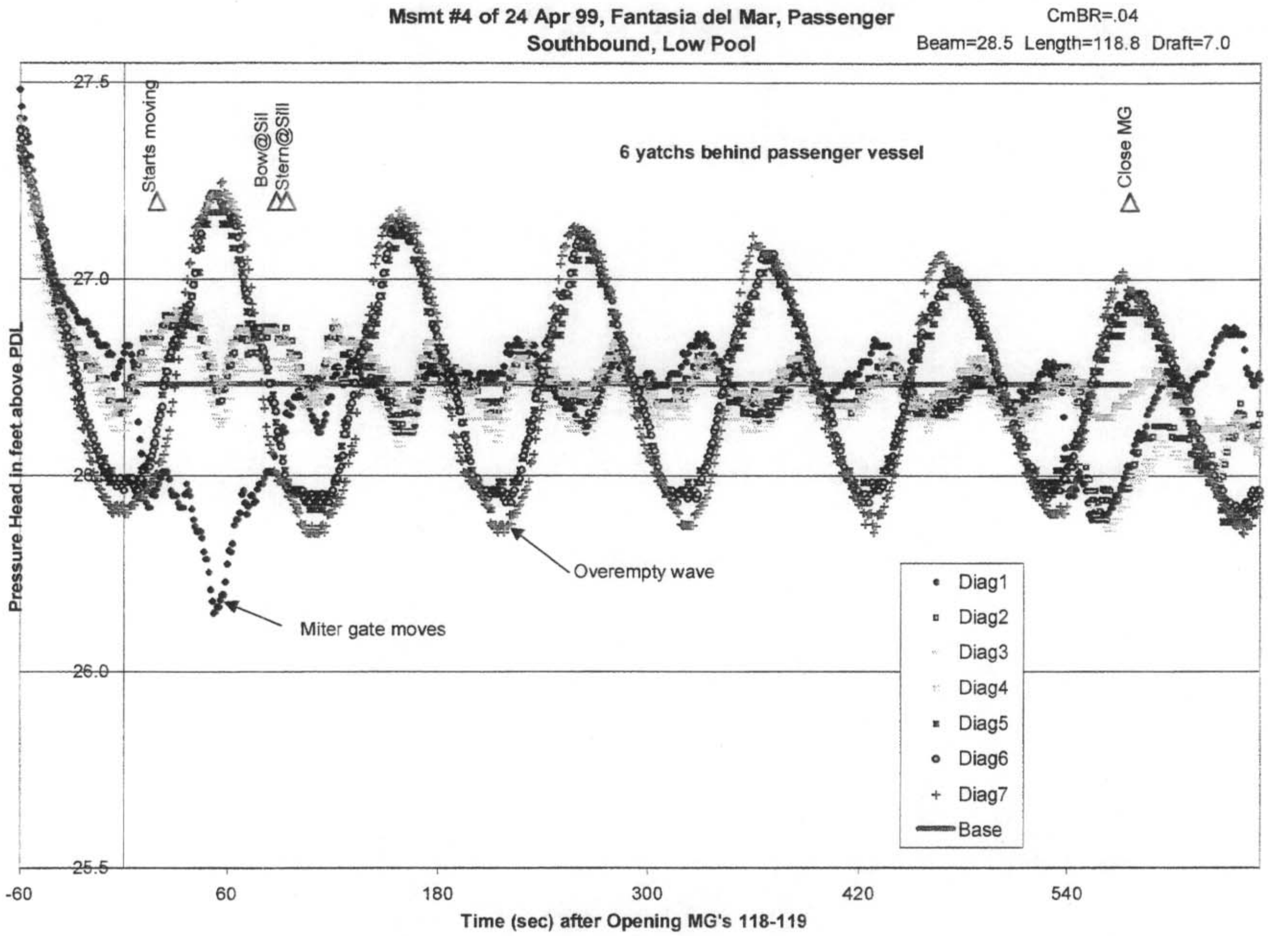


Figure 18

The final correlations were performed using curve fitting in Microsoft EXCEL. The Corps of Engineers Hydrologic Engineering Center's Multiple Linear Regression Program (MLRP) was also tried. Correlations between surcharge and individual variables, including blockage ratio, speed length, and Cb were analyzed along with the adopted V&BR' function. The results tended to corroborate those obtained with EXCEL. No significant correlations were found between Cb (Block Coefficient) and surcharge using either program. This indicates that, although hull shape may affect the magnitude of waves that form in front of a ship, the net flow area is far more important in determining surcharges when the vessel enters a confined space. Results of correlation trials are also included on the accompanying data CD.

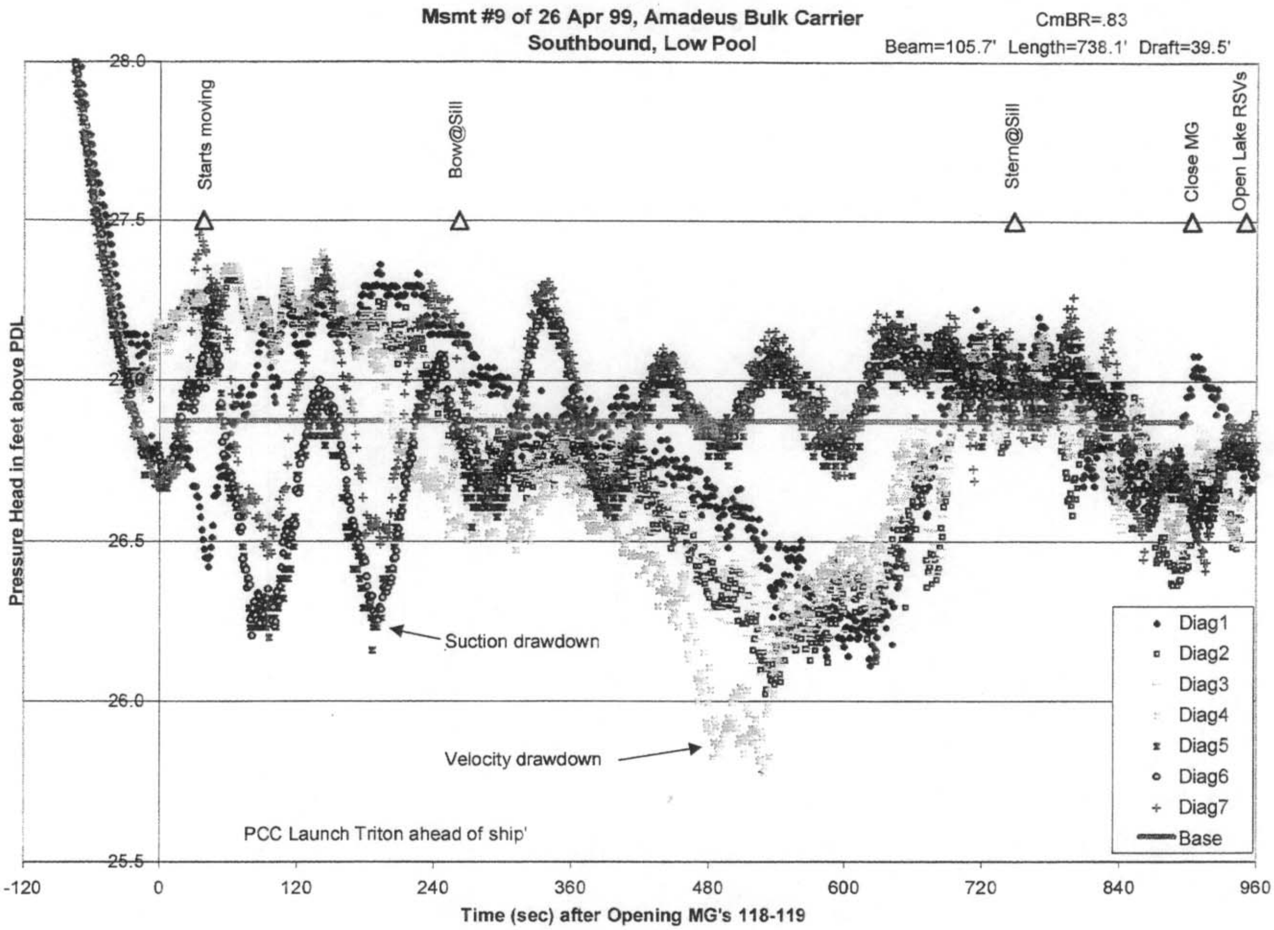
5.b. SOUTHBOUND EXITING CONDITION

5.b.1 Observations. In order to understand the reaction of gages within the northwest lock to ships exiting southbound, it is necessary to first examine the case where there are little or no ship effects. An example is shown in Figure 19, which is a measurement made with only small recreational boats in the lock.



Typical Southbound Exiting Condition, Small Craft
Figure 19

Gage Diag1 mounted on Miter Gate 114 is seen to react to flow moving past the swinging gate. A rocking of the pool set up by overemptying of the chamber is also very evident. The magnitude of the wave toward the north end of the chamber begins at approximately one-half foot and gradually diminishes as seen on gage Diag7. The phenomenon does not have all the characteristics of a typical water wave in that it is much less pronounced toward the south end of the northwest lock, as shown by Diag1-4. However, the average period between crests, about 105 seconds, nearly matches the expected time, about 100 seconds, for a gravity wave to move from one end of the double lock to the other, and return. Any effects of boat movements would be superimposed on this pattern. A good example with a large vessel exiting is shown in Figure 20.



Typical Southbound Exiting Condition, Large Ship
Figure 20

Once the vessel starts moving, a void is created behind it in the north end of the lock as shown by gages Diag5-8. This is labeled "Suction drawdown" in Figure 20 and causes the overempty oscillation to be depressed about one-half foot. Later, the ship moves to a position opposite Diag1-4 and water rushes past the ship to fill the void. The high velocity head in this area results in a depression at these gages labeled "Velocity drawdown". This depression appears first and is greatest at Diag4 because the ship reaches this gage before the others. Also, the head loss is greater because this gage is downstream of the others in the direction of flow, which is toward the north.

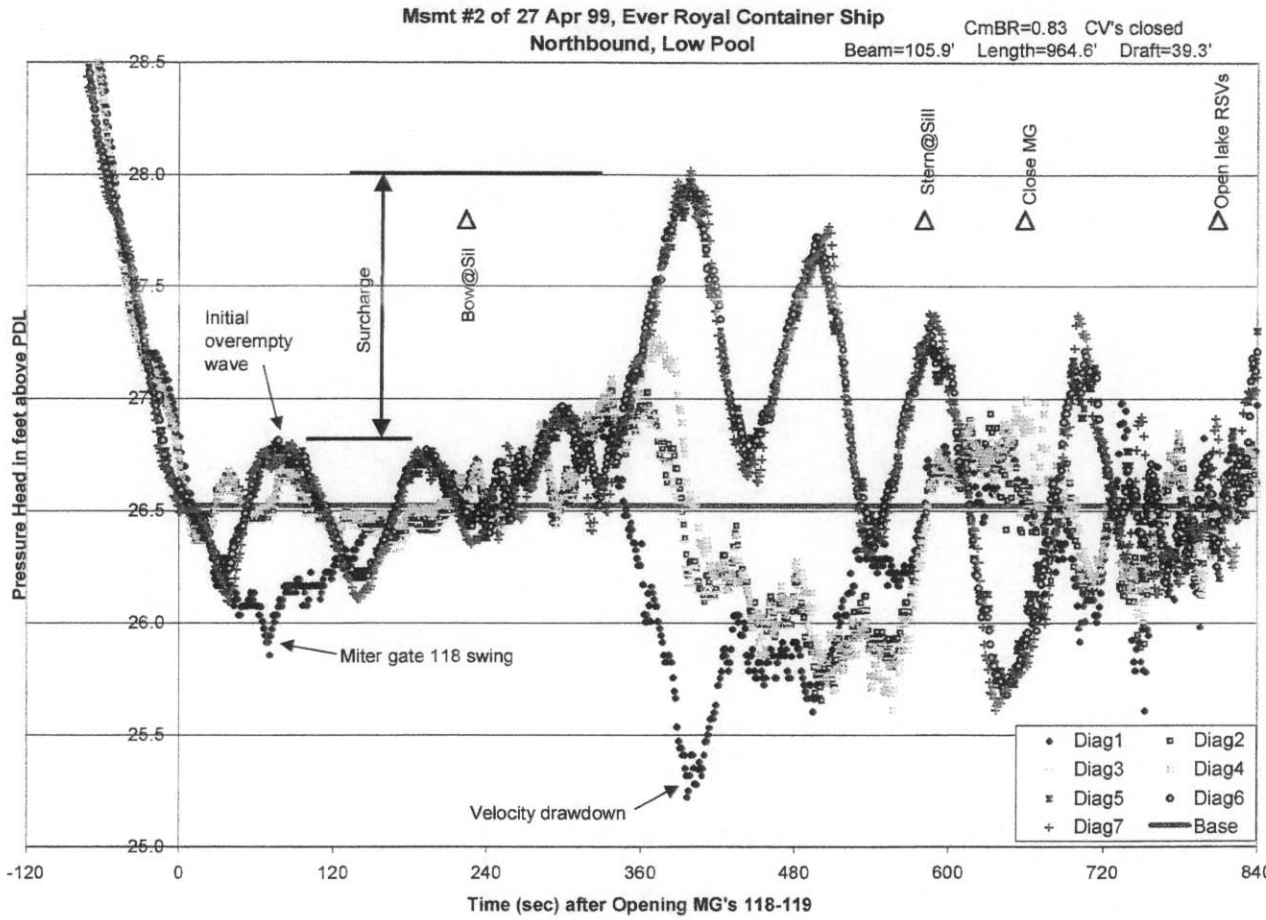
A satisfactory means of estimating the base pool was to average several gages at 26 seconds prior to and after opening and closing miter gates 118-119 (i.e., one-half of the overempty wave cycle apart). Maximum drawdowns below base pool were calculated at all gages but no attempt was made to separate the ship effects from the background oscillations and no correlation studies were performed for this condition. The gage showing the maximum drawdown varied from one measurement to the next but the overall maximum value calculated was 3.23 feet on Diag8.

5.b.2. Data Summary. Table 3 below lists drawdowns and other key information for all measurements of the southbound exiting condition.

Table 3 Summary Data Southbound Exiting (Low pool)						
Msmt No.	Blockage Ratio Cm BR	Speed Across Sill fps	Obs Max Drawdown (feet)	Gage Where Max occurs	Ship Type	Length feet
Logged measurements:						
224	0.51	4.50	0.64	Diag3	Car	591
225	0.76	2.20	2.04	Diag4	Tanker	599
226	0.79	1.55	0.64	Diag5	Tanker	810
227	0.34	3.25	0.29	Diag3	Bulk	425
228	0.84	0.94	0.79	Diag5	Bulk	738
235	0.79	2.09	3.23	Diag8	Cont	965
236	0.82	1.78	2.13	Diag8	Cont	965
237	0.42	3.55	0.79	Diag7	Bulk	547+135
238	0.73	2.38	1.13	Diag2	Tanker	601
244	0.04	17.2	0.38	Diag3&7	Pass	119
245	0.54	4.67	1.26	Diag4	Cont	579
246	0.63	3.51	1.67	Diag4	Tanker	573
247	0.74	2.83	1.27	Diag4	Cont	905
248	0.49	2.08	0.49	Diag5	Pass	719
249	0.76	2.05	1.04	Diag2	Bulk	607
254	0.22	4.33	0.41	Diag5	Mil	362
255	0.71	2.47	1.16	Diag4	Bulk	645
256	0.27	3.24	0.68	Diag7	Pass	557
257	0.76	1.48	0.68	Diag5	Bulk	735
258	0.38	4.38	0.51	Diag6	Bulk	550
266	0.60	2.91	0.76	Diag4	Bulk	556
267	0.64	2.58	1.08	Diag4	Tanker	560
268	0.05	3.96	0.50	Diag7	Barge	230+69
269	0.83	1.42	1.09	Diag4	Bulk	738
2610	0.50	3.92	0.72	Diag4	Tanker	509
Overnight measurements:						
Nite222	0.82		0.85	Diag5		614
Nite223	0.48		0.67	Diag3		487
Nite224	0.24		0.64	Diag7		461
Nite225	N/A		0.81	Diag4		588
Nite226	0.39		0.79	Diag3		466
Nite227	0.56		0.83	Diag3		557
Nite231	N/A		1.49	Diag5		738
Nite241	0.83		1.38	Diag6		738
Nite261	0.85		1.15	Diag5		607

5.c. NORTHBOUND ENTERING CONDITION

5.c.1 Observations. Typical reaction of gages within the lock chamber to the entry of a large ship from the southwest lock is shown in Figure 21.



Typical Northbound Entry Condition, Large Ship
Figure 21

The initial overempty wave discussed in Section 5.b.1 is again apparent. Base pool level was obtained by averaging several gages zero and 52 seconds after opening and closing Miter Gates 118-119. A surcharge builds in front of the vessel after its bow crosses the sill that is usually evident at the northern gages, Diag5-8 (Diag8 not operative in example). The surcharge usually retains a spiked appearance suggesting that the initial wave pattern has simply been elevated. The method of calculating surcharge discounts the initial wave so that the surcharge value used represents only ship movement effects. The maximum surcharge is usually highest at Diag8 (where available). The profile ahead of the ship is normally wedge-shaped at the time of maximum surcharge, with Diag7 through Diag5, in order, each slightly lower than the previous gage. Surcharges ranged up to the 1.22 feet shown in Figure 21.

5.c.2. <u>Data Summary.</u> Table 4 below lists surcharges and other parameters including correlation parameters for all measurements of the northbound entering condition.

Table 4
Summary Data
Northbound Entering (Low pool)

Surcharge is amount in excess of overempty wave

Msmt No.	Blockage Ratio Cm BR	Sill Vship fps	CV's Pos-Ition	Ship Type	Cb	Length Feet	Width feet	Draft feet	Aship sq ft	As sq ft	No. of Cul-verts	A total sq ft	Midi-fied BR'	V&BR' Func-tion	Obs Max surcharge feet
Measurements with surcharge:															
222	0.62	3.27	C	N/A	N/A	555	98	31.8	3057	1874	1	5185	0.59	22.07	0.17
231	0.71	2.47	C	Cont	0.71	607	106	33.7	3491	1426	1	5171	0.68	26.35	0.69
232	0.69	2.6	C	Bulk	0.874	738	106	32.5	3407	1531	1	5192	0.66	24.64	0.70
233	0.57	2.3	C	Car	0.61	655	106	28.0	2871	2166	1	5291	0.54	7.45	0.12
234	0.55	3.57	C	Cont	0.71	536	82.2	33.3	2685	2197	1	5136	0.52	15.30	0.56
241	0.75	2.69	C	Bulk	0.874	738	106	34.4	3601	1200	1	5055	0.71	44.36	0.58
242	0.48	2.76	C	Tanker	0.757	577	105	22.6	2318	2511	1	5083	0.46	5.35	0.15
243	0.34	3.59	C	Bulk	0.874	558	86.4	19.4	1660	3223	1	5137	0.32	2.94	0.11
252	0.82	1.75	C	Cont	0.71	965	106	39.1	4056	890	1	5200	0.78	38.47	0.60
261	0.59	3.56	C	Tanker	0.757	607	100	29.5	2888	2007	1	5149	0.56	20.68	0.47
262	0.66	1.86	C	Car	0.61	623	106	31.1	3187	1642	1	5082	0.63	9.78	0.20
263	0.7	2.61	C	Bulk	0.874	607	100	35.0	3468	1486	1	5209	0.67	27.05	0.49
264	0.52	1.65	C	Pass	0.597	867	106	25.6	2592	2393	1	5239	0.49	2.61	0.05
271	0.84	1.32	C	Coke	0.61	738	106	39.4	4049	771	1	5075	0.80	27.18	0.61
272	0.83	2.56	C	Cont	0.71	965	106	39.3	4082	836	1	5172	0.79	91.90	1.22
273	0.7	2.91	C	Cont	0.71	618	99.4	35.0	3409	1461	1	5125	0.67	33.46	0.34
253	0.55	1.43	O	Grain	0.71	656	106	26.1	2702	2210	2	5420	0.50	2.02	0.14
265	0.46	3.14	O	Bulk	0.874	597	95.4	24.3	2290	2689	2	5487	0.42	5.06	0.24
274	0.34	4.66	O	Cont	0.71	484	75.2	23.0	1695	3290	2	5493	0.31	4.32	0.12
Measurements not used in correlation analysis (zero surcharge):															
223	0.07	3.4	O	Mil	0.71	183	42	9.8	403	5359	2	6270	0.06	0.05	0
251	0.46	5.36	O	Car	0.61	541	90.6	25.5	2241	2631	2	5380	0.42	14.65	0

5.c.3. <u>Correlations.</u> Correlation analyses were performed in the same manner as described for the southbound entering condition. A reasonable correlation was obtained between the surcharge and the V&BR' Function, $(Vship/(1/BR' - 1))^2$. In this case the y-intercept for the best fit equation was forced to pass through the graph origin because effects other than those due to ship movement had been removed previously, and noting that the function will approach zero as Vship and/or BR' get very small. The slope of the line, .0155, represents a discharge coefficient of 0.71 in the orifice equation for flow around the ship and through all available culverts. This is considerably lower than the 0.83 found for southbound entering. The difference may stem from the fact that suction drawdown behind the northbound ship causes the effective head to actually be greater than the surcharge, whereas with southbound entering ships, the availability of lake water to fill the void prevents suction drawdown from developing. Figure 22 shows the plot of the V&BR' Function vs. surcharge while Figure 23 presents Vship vs. BR'.

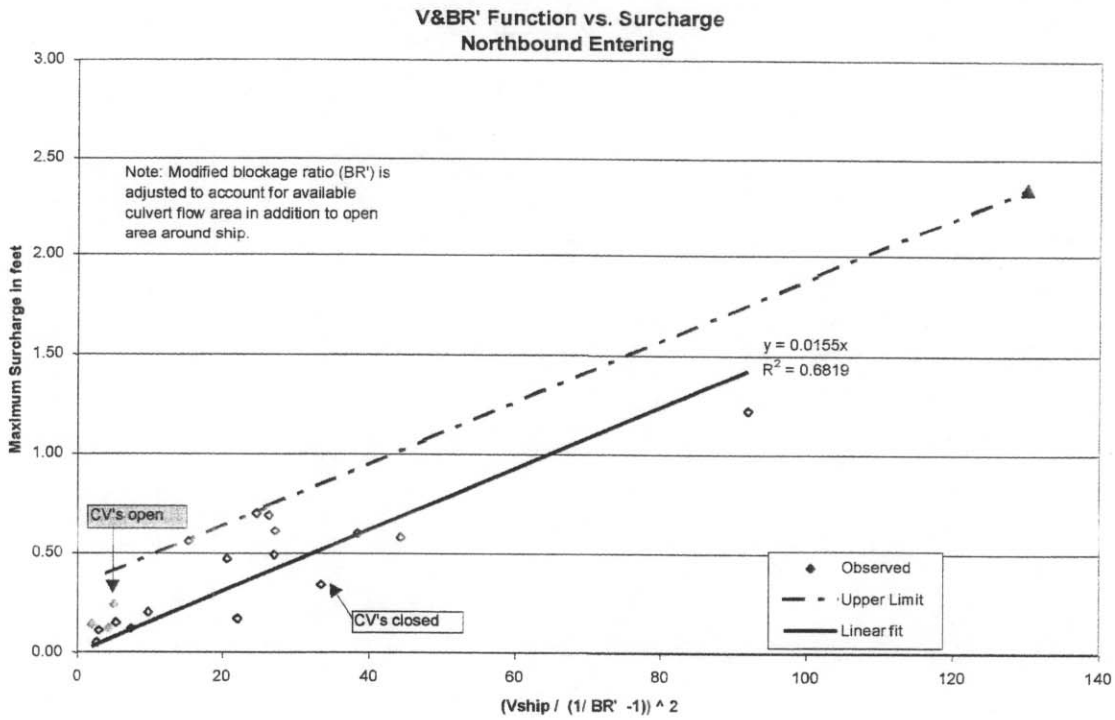


Figure 22

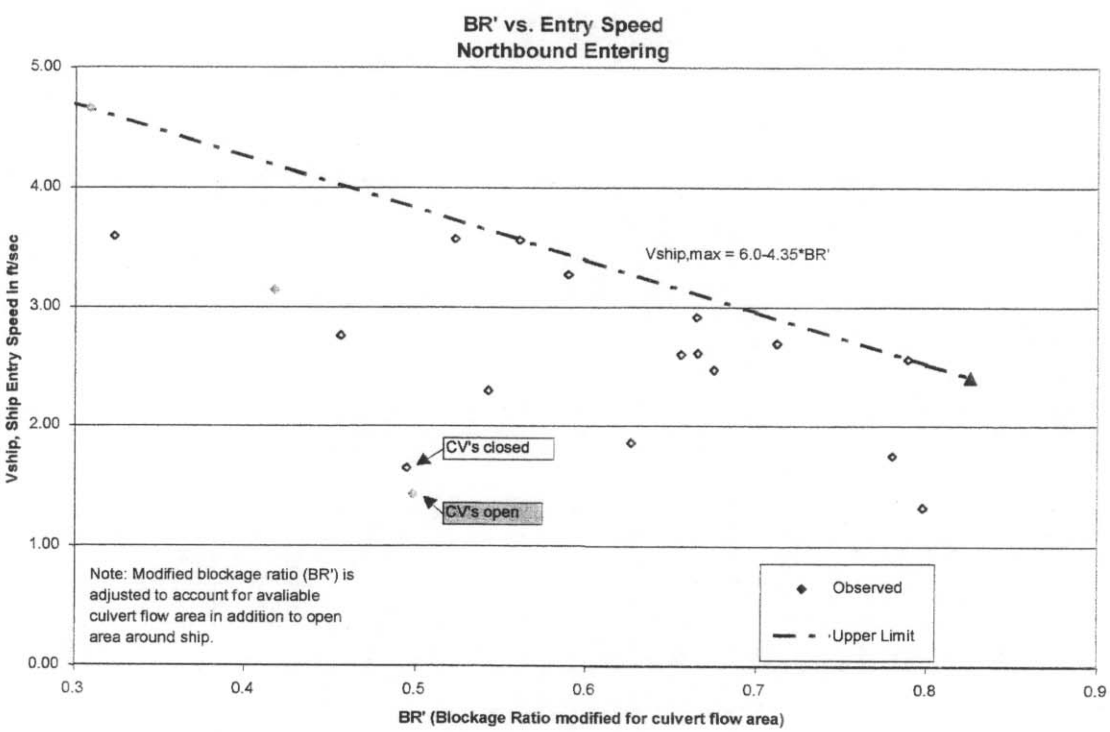


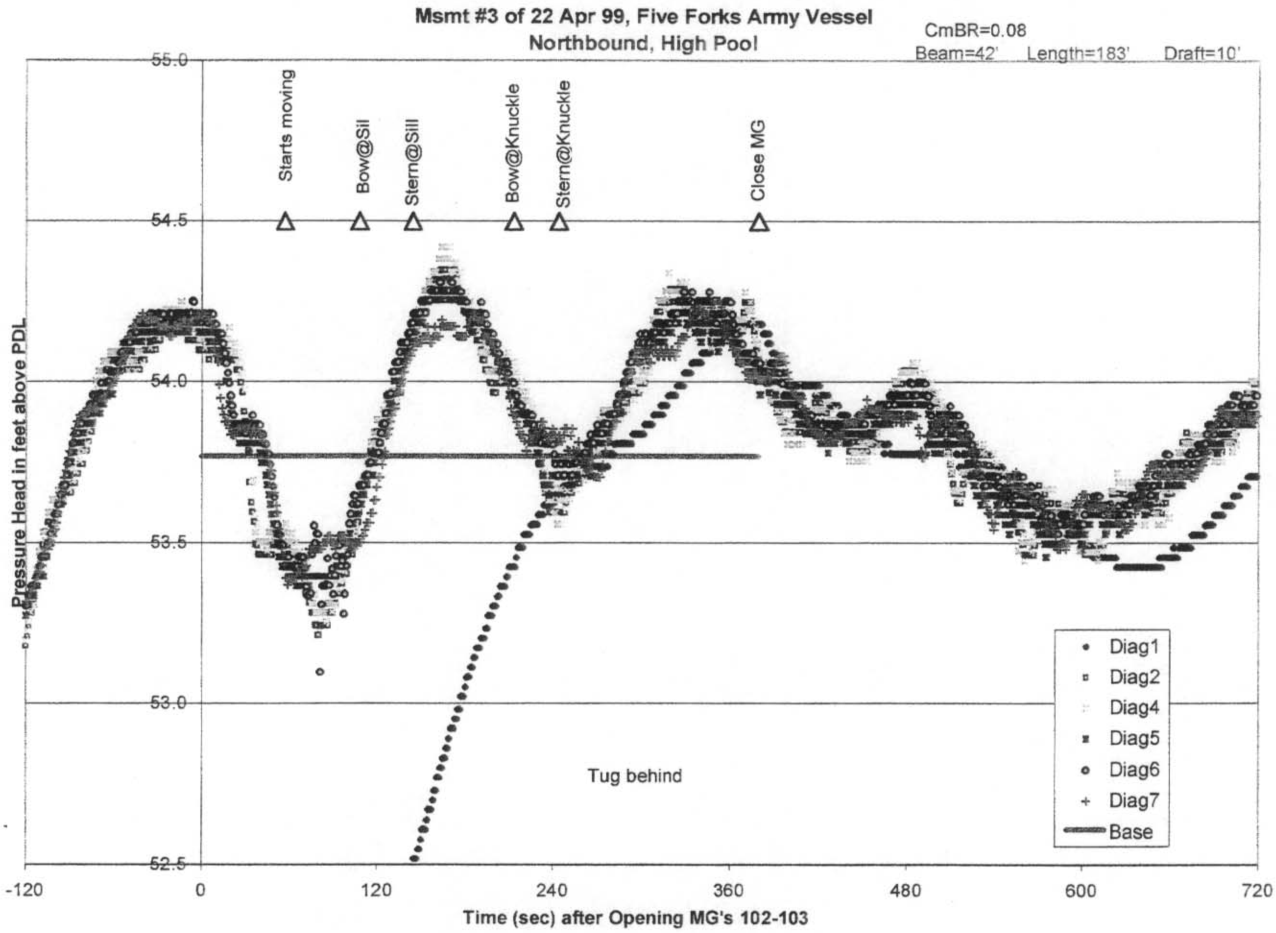
Figure 23

For the maximum BR' (0.83) the highest entry speed likely to occur under the present system at low pool is projected to be approximately 2.4 feet per second from Figure 23. The associated maximum surcharge prediction is 2.35 feet.

No significant correlations were found between surcharge and Cb or length for northbound entering.

5.d. NORTHBOUND EXITING CONDITION

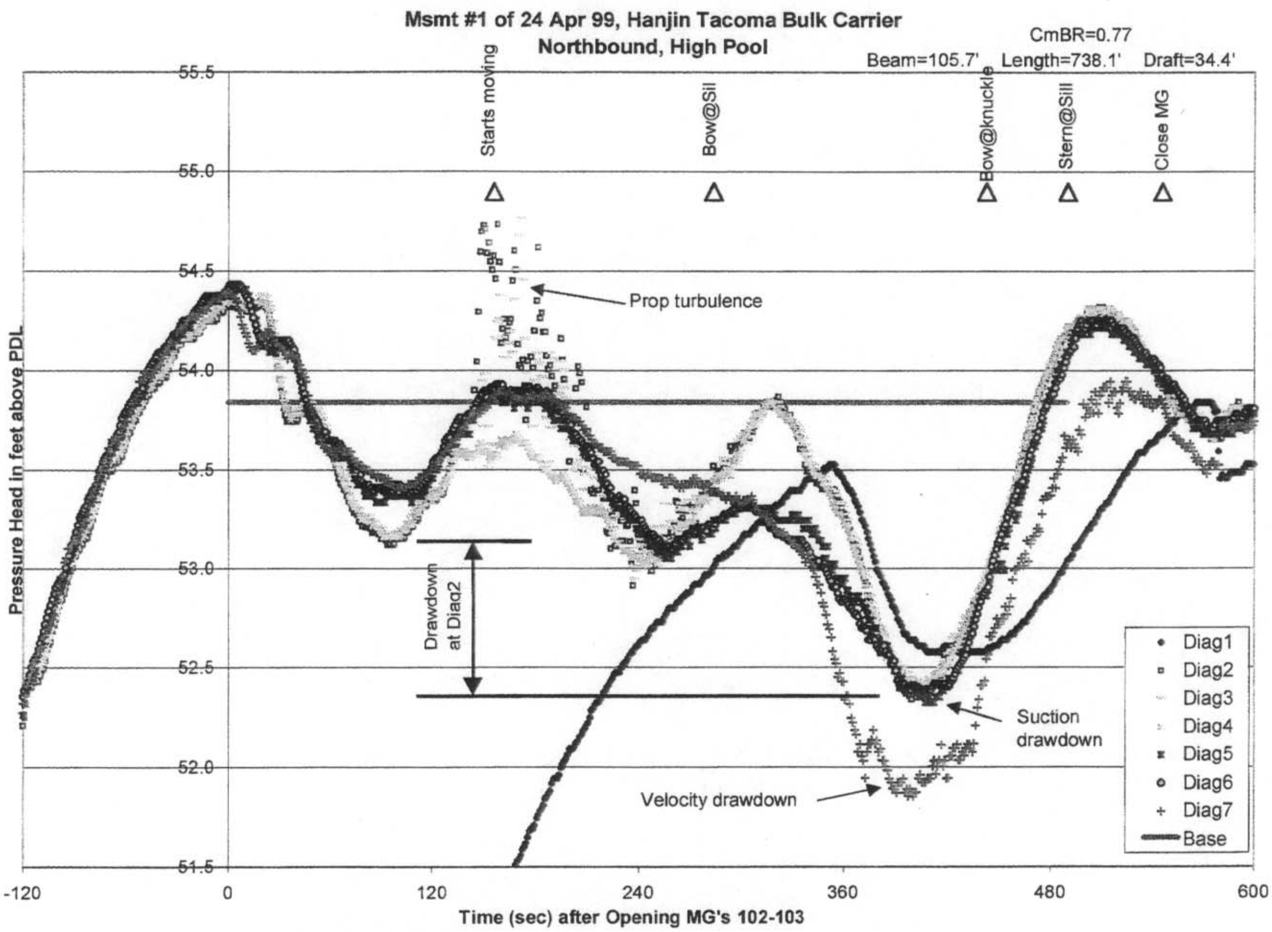
5.d.1 Observations. Overfill of the chamber produces a wave as shown in Figure 24, a measurement which includes minimal ship effects because of the small vessel size.



Typical Northbound Exiting Condition, Small Ship
Figure 24

Magnitude of the wave averages about one-half foot if filling with two culverts and about 0.3 feet when using only the west wall culvert. Wave period averages 180 seconds. The base pool elevation was estimated by averaging the readings of several gages at the time miter gates 102-103 were opened and 90 seconds later. Maximum drawdowns were determined by taking the difference between the trough of the background wave and minimum elevation on gage Diag2.

A typical measurement with a large ship is shown in Figure 25. Suction drawdown is apparent at Diag2-6. Note that Diag1 lags because miter gates 114-115 are closed. Turbulence from the ship's propellers is reflected at Diag2-3 (on miter gates) as the ship starts moving. Velocity drawdown occurs at Diag7 as the ship moves past it.



Typical Northbound Exiting condition, Large Ship
Figure 25

Although not apparent in the above measurement where the miter gates were closed relatively early, many measurements with larger ships where the gates remained open longer (e.g., nos. 271 & 272) indicate that a surcharge occurs late in the cycle. This surcharge in the lock chamber tends to reach a maximum at about the time when the stern of the departing ship reaches the knuckle. It ranged up to about 1.5 feet above base pool level.

5.d.2 <u>Data Summary.</u> Table 5 below lists surcharges and other key information for all measurements of the southbound exiting condition.

Table 5 Summary Data Northbound Exiting (High pool)							
Msmt No.	Blockage Ratio Cm BR	Speed to sill fps	Speed Across Sill, fps	Obs Max Drawdown Feet	Cylindrical Valves Position	Ship Type	Length feet
Measurements with larger ships and surcharges:							
231	0.75	1.93	2.53	1.22	Closed	Cont	607
232	0.74	1.73	2.02	0.16	Open	Bulk	738
234	0.57	2.07	3.22	0.27	Open	Cont	536
241	0.77	2.03	2.72	0.78	Open	Bulk	738
252	0.86	1.69	2.20	1.24	Closed	Cont	965
253	0.58	1.64	1.85	0.06	Open	Bulk	656
261	0.61	2.25	3.67	0.28	Open	Tanker	607
263	0.74	1.85	2.44	1.10	Closed	Bulk	607
271	0.88	1.37	1.03	0.85	Open	Bulk	738
272	0.87	1.39	2.70	1.44	Open	Cont	965
273	0.72	1.93	2.94	0.56	Closed	Cont	618
Measurements with smaller ships, no drawdown, or missing data							
222	0.65	N/A	N/A	0.06	Closed	Bulk	555
223	0.08	3.82	4.44	0.00	Open	Mil	183
233	0.62	1.73	3.20	0.00	Open	Car	656
243	0.36	2.31	4.42	0.00	Open	Bulk	558
251	0.47	1.79	3.22	0.00	Open	Car	541
262	0.67	2.23	3.52	0.00	Open	Car	623
264	0.55	2.05	3.38	0.00	Closed	Pass	867
265	0.49	2.12	4.13	0.00	Open	Bulk	597
274	0.36	2.9	4.80	0.00	Open	Cont	485

5.d.3 <u>Correlations</u>. Correlation analyses were performed on the maximum drawdown for the northbound exiting condition. Parameters are listed in Table 6.

Table 6 Correlation Analysis Parameters Northbound Exiting (High pool)														
Msmt No.	Blockage Ratio Cm BR	Use Vship fps	CV's position	Ship Type	Cb	Width feet	Draft feet	Aship Sq ft	As sq ft	No.of Cul- verts	Atotal sq ft	Modified BR'	V&BR' Func- tion	Obs Max Drawdown feet
263	0.74	2.15	Closed	Bulk	0.874	100.1	35.0	3468	1219	1	4941	0.70	25.52	1.10
231	0.75	2.23	Closed	Cont	0.71	105.8	33.7	3494	1165	1	4913	0.71	30.16	1.22
252	0.86	1.95	Closed	Cont	0.71	105.9	39.1	4058	661	1	4972	0.82	74.47	1.24
273	0.72	2.44	Closed	Cont	0.71	99.4	35.0	3409	1326	1	4989	0.68	27.61	0.56
232	0.74	1.88	Open	Bulk	0.874	105.9	32.5	3407	1197	2	5113	0.67	14.04	0.16
241	0.77	2.38	Open	Bulk	0.874	105.7	34.4	3600	1075	2	5183	0.69	29.16	0.78
253	0.58	1.75	Open	Bulk	0.874	105.7	26.1	2731	1978	2	5217	0.52	3.68	0.06
271	0.88	1.37	Open	Bulk	0.874	105.9	39.4	4131	563	2	5202	0.79	27.91	0.85
234	0.57	2.65	Open	Cont	0.71	82.2	33.3	2683	2024	2	5214	0.51	7.85	0.27
272	0.87	2.05	Open	Cont	0.71	105.9	39.3	4079	609	2	5196	0.78	55.71	1.44
261	0.61	2.96	Open	Tanker	0.757	100.1	29.5	2888	1846	2	5242	0.55	13.18	0.28

Two average speeds were calculated from the logged information. These are speed from the time the vessel started moving until its bow reached the sill, and speed across the sill. For the correlation analyses, the average of the two speeds was used, or, if larger, the former value. Correlation analyses were performed in a manner similar to those discussed previously for the southbound and northbound entering conditions. A fair correlation was obtained between the $(Vship/(1/BR' - 1))^2$ function and drawdown. The adopted equation is:

$$\text{Drawdown} = 0.0236*(Vship/(1/BR' - 1))^2$$

The constant in the equation represents a discharge coefficient of 0.81 in the governing equation. This is not much different than the value (0.83) derived for the similar case of southbound entering. The observed data and best-fit curve are shown on Figure 26.

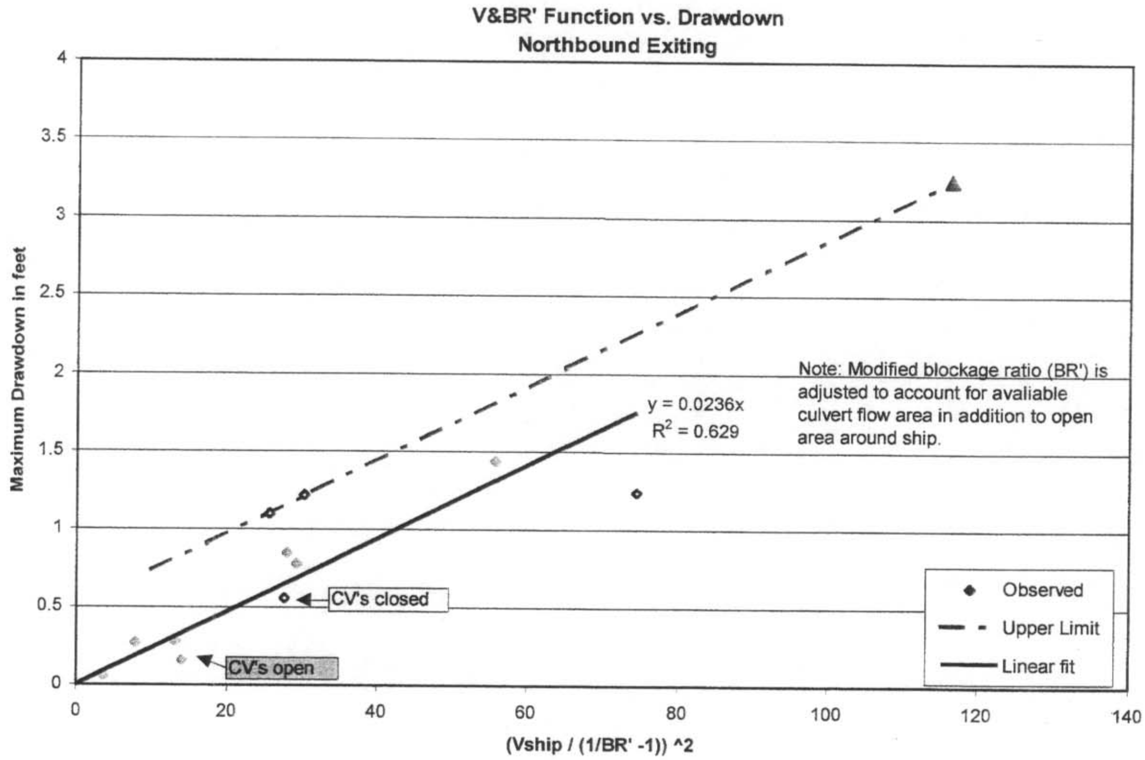


Figure 26

In order to estimate the maximum drawdown that is likely to occur under present conditions, Vship was plotted against BR' as shown on Figure 27. Extending a line through the highest points to the maximum BR' of 0.86 indicates an exit speed of 1.80 fps. Calculating the V&BR' Function for these conditions and extending a line parallel to the best fit on Figure 26 to this limit produces an estimated maximum drawdown of 3.25 feet.

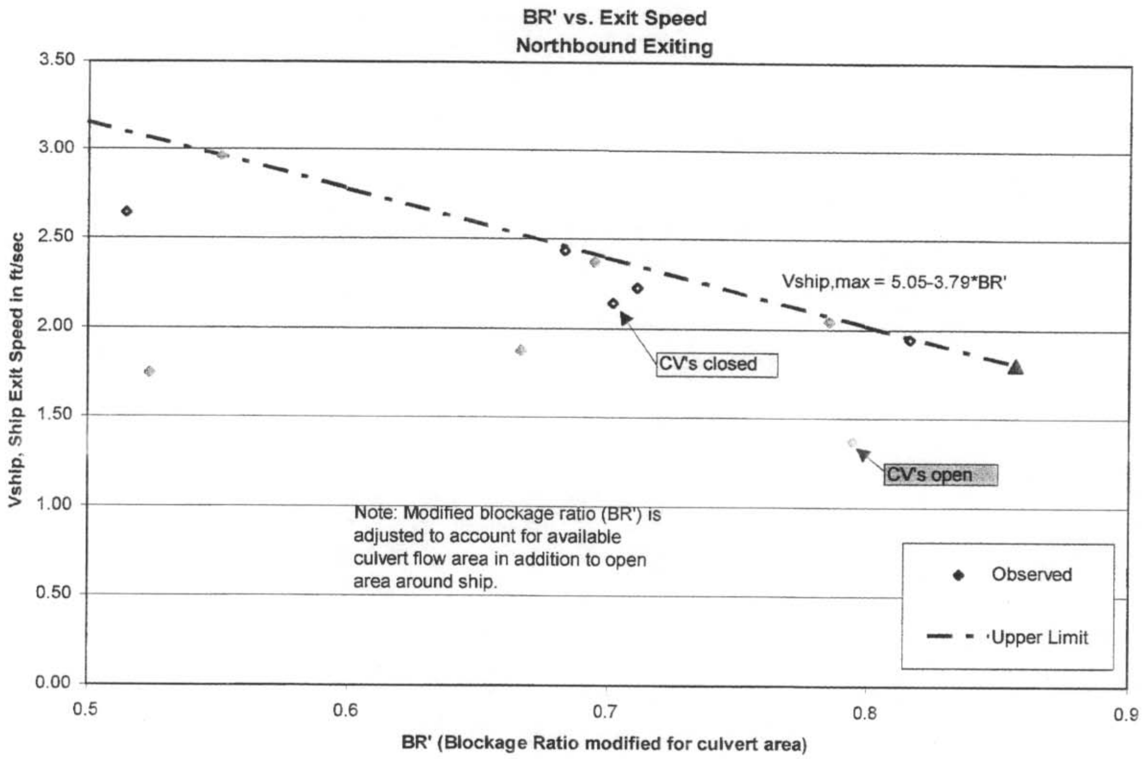


Figure 27

Again, no significant correlation was found between drawdown and Cb.

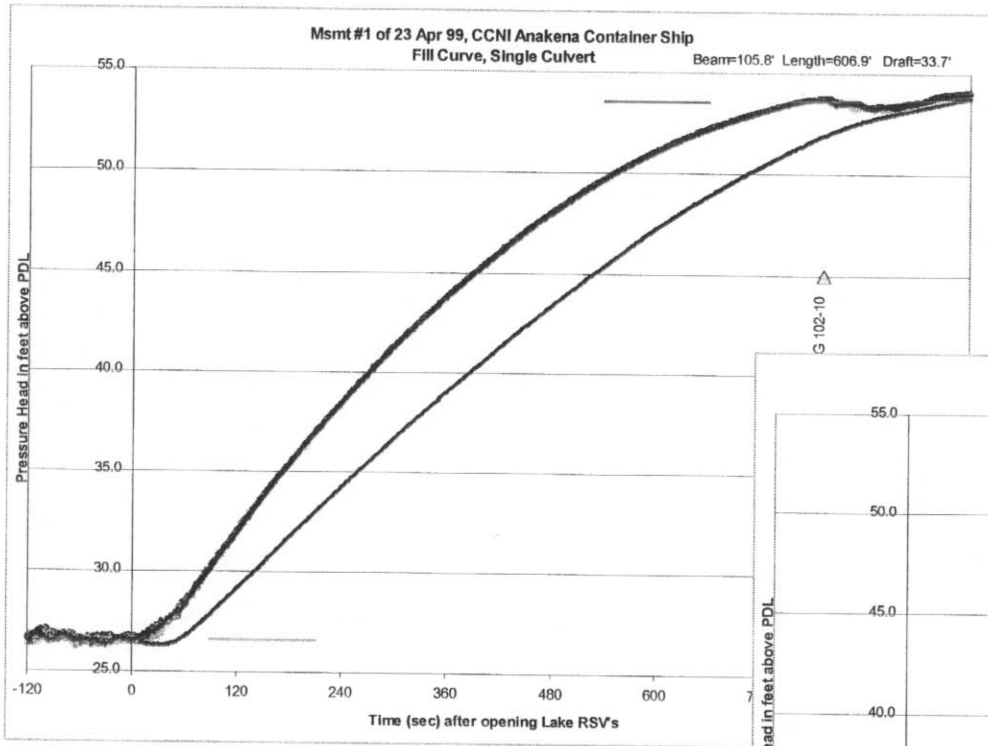
5.e. Filling and Emptying Curves

Although not a focus of the study, a by-product of the continuous data collection is detailed information on water surfaces in the lock during filling and emptying. The Canal Capacity Projects Office, therefore, requested that typical curves for these operations be produced. Four curves were developed so as to include both single and double culvert conditions. Plots can be found in Appendices B and C with the associated measurements as listed below and in the Excel files under sheet "FillCurve" or "EmptyCurve".

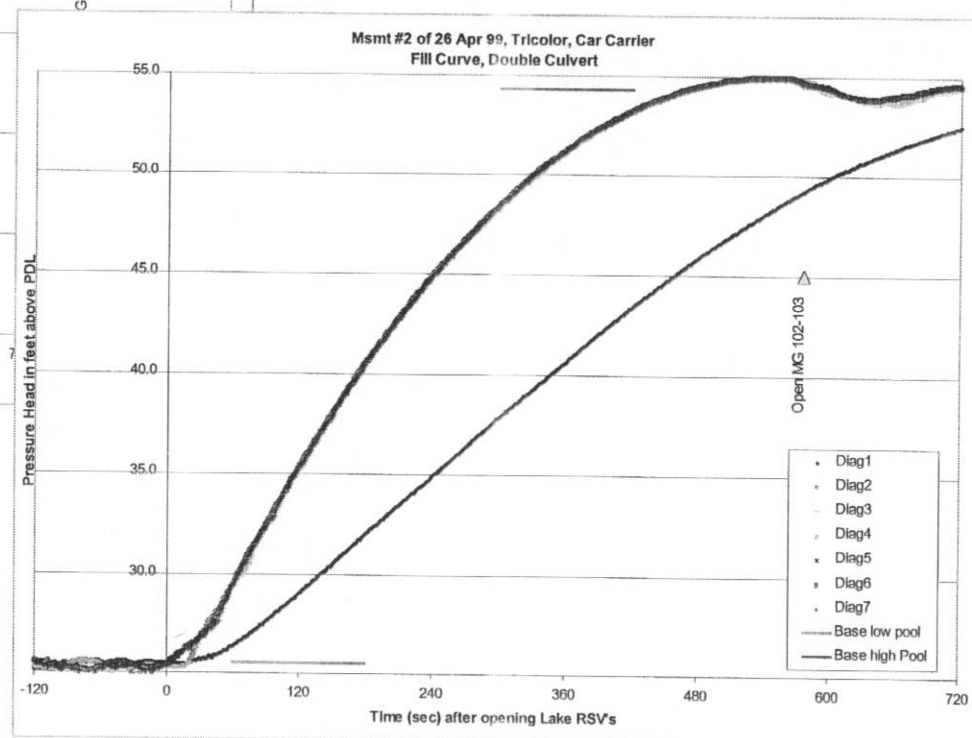
	Approx. Cycle Time (min)	Measurement No.
Filling, single culvert	12.5	231
Filling, double culvert	8	262
Emptying, single culvert	13	247
Emptying, double culvert	8	236

Data are available in these and all of the other measurements that would enable further analysis of filling and emptying effects such as the determination of chamber water surface slopes.

Locks Chamber Filling Curves

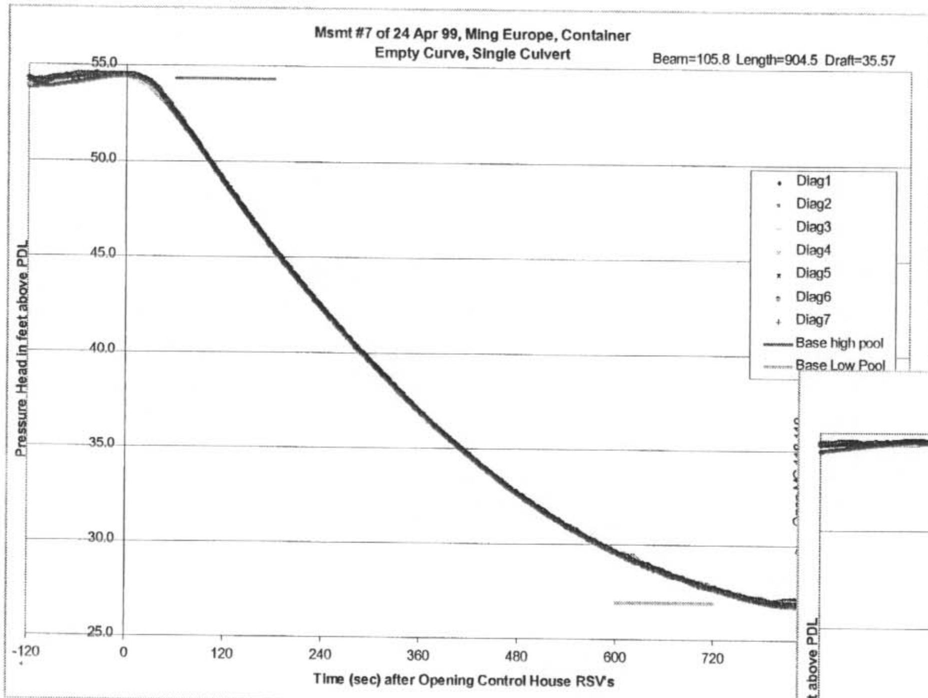


- **Single culvert filling 12.5 minutes**

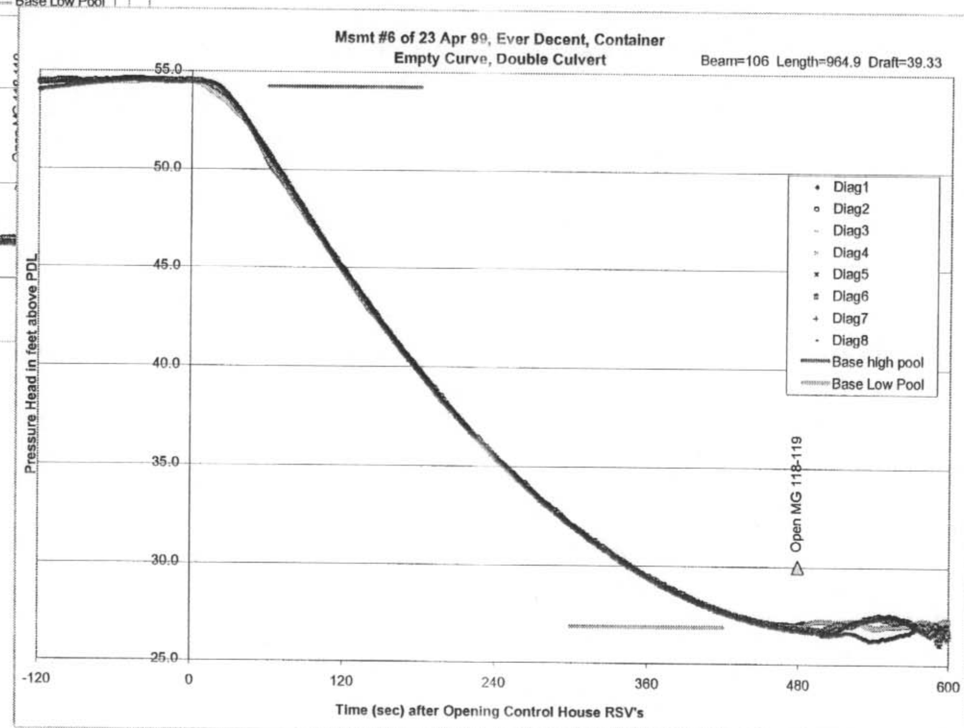


- **Double culvert filling 8 minutes**

Locks Chamber Emptying Curves



- Single culvert emptying 13 minutes



- Double culvert emptying 8 minutes

SECTION 6. CONCLUSIONS AND RECOMMENDATIONS

6.a. CONCLUSIONS

The following general conclusions can be drawn from the study:

1. Pressures in a deep draft lock as affected by ship movements can be accurately measured using transducers and battery powered data loggers that are relatively easy to install. The equipment is durable enough to operate in a consistent manner for several continuous days. However, cables attached to the sensors are vulnerable to damage if not kept very taught.

2. The fact that gages mounted in close proximity tended to track each other indicates that pressures are hydrostatic and nearly always reflect local water surface levels in the vicinity of the gages. The only obvious exception observed was the effect of turbulence generated by ships' propellers. However, the effects of a boat moving over a sill on the pressure beneath it could not be measured because the only sill-mounted gage was damaged and rendered inoperable early in the testing period.

3. Large ships entering a lock temporarily trap water in between the bow and miter gates creating surcharges. The highest surcharges (measured up to 2.35 feet) occur with southbound vessels. Southbound ships with blockage ratios exceeding 0.5 tend to produce surcharges exceeding 0.5 feet. The surcharge pattern generally consists of two peaks, one occurring 1.5 to 3 minutes after the bow passes the northwest knuckle, with a second lower peak 2 to 3 minutes later. Faster moving ships cause higher surcharges.

4. Surcharges associated with northbound ships were roughly half the magnitude of southbound ships with similar blockage ratios. The maximum observed northbound surcharge was 1.22 feet. Again, the surcharge is multi-peaked but in the southbound case is superimposed on a pre-existing oscillation created by overemptying of the chamber.

5. Ships exiting the lock create "suction drawdown" behind them. Water rushing past the ship to fill the suction void causes "velocity drawdown" in the confined flow region. Maximum observed suction drawdown of a northbound exiting ship was 1.44 feet. Velocity drawdown exceeds suction drawdown, with measured maximums of 3.93 feet northbound and 3.23 feet southbound. Velocity drawdown is also evident in the case of northbound entering ships.

6. Surcharge and suction drawdown can be estimated by fitting a function of blockage ratio and ship speed (V&BR' Function) to the experimental data. The function is derived from a simplified analysis relating rate of volume displacement by a moving ship to flow escaping around the ship. A modified blockage ratio, BR', which takes into account flow escaping through filling culverts as well as around the ship should be used rather than the ordinary blockage ratio. The form of the equation is:

$$\text{Surcharge or Drawdown} = C1 + C2 * (\text{Vship} / (1/\text{BR}' - 1))^2$$

where C1 and C2 are constants as follows:

Surcharge, southbound entering	-	C1 = 0.32 feet,	C2 = 0.0225
Surcharge, northbound entering	-	C1 = 0 ,	C2 = 0.0155
Drawdown, northbound exiting	-	C1 = 0 ,	C2 = 0.0236

Southbound exiting drawdown correlations were not investigated.

7. Conservative maximum surcharges and drawdowns can be estimated with the above relationships but using the highest probable blockage ratios and associated ship speeds, and adjusting for the maximum deviations between observed and predicted values. The estimated maximums with the present system are:

Surcharge, southbound entering	-	4.34 feet
Surcharge, northbound entering	-	2.41 feet
Drawdown, northbound exiting	-	3.25 feet

8. No significant correlation was found between surcharge and type of vessel as represented by its characteristic Block Coefficient (Cb). This implies that net available flow area as represented by blockage ratio is dominant with the degree of hull streamlining being relatively unimportant.

6.b. RECOMMENDATIONS

Recommendations on how this the results of this study should be used and how the understanding of the effects of ship movements on pressures in lock chambers can be improved are as follows:

1. Additional field testing would increase the sample size, thereby refining and improving the reliability of results. If such testing is done, more than one gage should be installed on gate sills and the sill-mounted gages should be well protected from high turbulence of propellers and possibly debris clinging to the underside of ships.

2. If additional field testing is done and safety would not be compromised, consideration could be given to closing the west wall RSV's in addition to the centerwall CV's for some measurements with large ships. This would eliminate all culvert bypass flow, maximize the blockage ratio, and better define the extreme condition.

3. Correlation analyses could be performed on the existing data using more sophisticated techniques. Other statistical tools may be available that consider different functions and relationships between variables which may produce better predictive methods for surcharge and drawdown.

4. The problem may have an analytical solution. Displacement, buoyancy, open channel flow, closed conduit flow and wave theory are all involved. A university or research lab may be able to sort out and develop the important relationships using the existing data for verification.

5. Surcharges and drawdowns can be estimated for design of structures using equations and graphs presented herein. The ship speed and blockage ratio, which should include any bypass culvert area in the computation, must be known. The Upper Limit curves of BR' versus Speed and V&BR' Function versus Surcharge/Drawdown should be used for conservative design.