

UNIVERSITY OF MINNESOTA  
**ST. ANTHONY FALLS LABORATORY**  
Engineering, Environmental and Geophysical Fluid Dynamics

Project Report No. 439

# Hydraulic Transient Study of Narragansett Bay Commission CSO Storage Tunnel

by

Jianming He, Ph.D.  
Charles C.S. Song, Ph.D., P.E.



Prepared for

**CH2M HILL**  
25 New Chardon Street, Suite 500  
Boston, MA 02114

November 1999  
**Minneapolis, Minnesota**

UNIVERSITY OF MINNESOTA  
**ST. ANTHONY FALLS LABORATORY**  
Engineering, Environmental and Geophysical Fluid Dynamics

Project Report No. 439

# Hydraulic Transient Study of Narragansett Bay Commission CSO Storage Tunnel

by

Jianming He, Ph.D.  
Charles C.S. Song, Ph.D., P.E.

Prepared for

**CH2M HILL**  
25 New Chardon Street, Suite 500  
Boston, MA 02114

November 1999  
**Minneapolis, Minnesota**

# TABLE OF CONTENTS

|   |           |
|---|-----------|
| <b>LIST OF FIGURES .....</b>                                  | <b>ii</b> |
| <b>I. INTRODUCTION .....</b>                                  | <b>1</b>  |
| 1.1. Tunnel System.....                                       | 1         |
| 1.2. Study Objective.....                                     | 1         |
| <b>II. THE MIXED TRANSIENT FLOW MODEL.....</b>                | <b>2</b>  |
| 2.1. Modeling Equations of Hydraulic Transient.....           | 2         |
| 2.2. Modeling Configuration.....                              | 3         |
| 2.3. Inflow Hydrography.....                                  | 3         |
| 2.4. Inflow Gate Control .....                                | 4         |
| 2.5. Rating Curve for EOS .....                               | 4         |
| <b>III. GENERAL HYDRAULIC TRANSIENT CHARACTERISTICS .....</b> | <b>5</b>  |
| 3.1. Case 1: 1-Year Storm Event.....                          | 5         |
| 3.2. Case 2: Larger Storm Event .....                         | 6         |
| <b>IV. COMMENTS AND CONCLUSIONS.....</b>                      | <b>7</b>  |
| <b>REFERENCES.....</b>  | <b>8</b>  |

Tables 1 and 2  
Figures 1 through 22

The University of Minnesota is committed to the policy that all persons shall have equal access to its programs, facilities, and employment without regard to race, religion, color, sex, national origin, handicap, age or veteran status.

Prepared for: CH2M Hill  
Last Revised: 11/18/99i  
Disk Locators: (a:\Disk #250; PR439-fronts.doc; report.. CH2m)

# HYDRAULIC TRANSIENT STUDY OF NARRAGANSETT BAY COMMISSION CSO STORAGE TUNNEL

## I. INTRODUCTION

### 1.1 Tunnel System

The Narragansett Bay Commission CSO storage tunnel consists of the Main Spine tunnel, 7 dropshafts, and 2 work shafts. Each dropshaft has a short adit. The Main Spine tunnel is 16328.82-ft long and 26-ft in diameter with a pumping station in the vicinity of the Ernest Street Pump Station. Three longest adits (1295-ft, 805-ft, and 625-ft) connecting the main tunnel and three dropshafts (Seekonk, 032, and Woonasquatucket, respectively) are included in the model. There is an Emergency Overflow Structure (EOS) at Dropshaft 009/010. The layout of the tunnel system is displayed in Fig. 1. The detailed tunnel design data are shown in Tables 1 and 2.

### 1.2 Study Objective

One concern of the tunnel system is the potential for hydraulic transients during the tunnel filling process. Under some conditions, strong storm inflow to a tunnel may generate severe hydraulic surge in the tunnel, and consequently water may shoot up from the dropshaft like a geyser, which may result in structural damage to surface facilities and other environmental problems. For example, in Minneapolis, USA, a severe storm in 1997 caused a geyser 17 m above the ground from the storm water tunnel.

The purpose of this study is to examine the possibility of any geysering and other hydraulic transient problems during the tunnel filling process based on the proposed tunnel configuration design and inflow under different tunnel operating conditions using our well-established hydraulic transient computer simulation model (MXTRANS).

## II. THE MIXED TRANSIENT FLOW MODEL

### 2.1 Modeling Equations of Hydraulic Transient

The flow to be simulated is very unsteady and features highly dynamic phenomena such as pressurization surge and geysering. The transient flow model used, then, must be able to simultaneously calculate unsteady open channel flows and unsteady pressurized flows, including the abrupt change that occurs at the shock or the surge front.

The well-known St. Venant equations:

$$\frac{\partial y}{\partial t} + v \frac{\partial y}{\partial x} + \frac{c^2}{g} \frac{\partial v}{\partial x} = 0 \quad (1)$$

$$g \frac{\partial y}{\partial x} + \frac{\partial y}{\partial t} + v \frac{\partial v}{\partial x} + g(S_f - S_o) = 0 \quad (2)$$

are used to represent the unsteady open channel flow. In the above equations,  $y$  is the flow depth,  $v$  is the flow velocity,  $c$  is the gravity wave speed,  $S_o$  is the channel slope,  $S_f$  is the energy slope,  $g$  is the acceleration due to gravity,  $x$  is the distance along a tunnel, and  $t$  is time.

The corresponding equations for unsteady pressurized flow are:

$$\frac{\partial y}{\partial t} + v \frac{\partial y}{\partial x} + \frac{a^2}{g} \frac{\partial v}{\partial x} = 0 \quad (3)$$

$$g \frac{\partial y}{\partial x} + \frac{\partial y}{\partial t} + v \frac{\partial v}{\partial x} + g(S_f - S_o) = 0 \quad (4)$$

in which  $a$  is the pressure wave speed, while  $y$  takes the meaning of piezometric head measured from the tunnel invert. The systems of the equations (1) - (4) are solved by the method of Characteristics [3].

Because the transition from the open channel flow condition to pressurized flow condition must be abrupt, as in the case of a hydraulic jump, the special shock boundary conditions must be applied. It was shown by Cardle and Song [3], for a pressurization surge or a positive surge, that three characteristic equations plus two shock boundary conditions can be used to calculate five unknowns at the interface. These five unknowns are  $v$  and  $y$  on both sides of the interface and the speed of the interface movement. The model can also simulate the negative surge which occurs during the depressurization process. The detailed physical nature of the process has been discussed by Guo and Song [4].

A number of other boundary conditions representing junctions, dropshafts, upstream ends, downstream end, pump stations, and other accessories are also provided in the model. Inflow hydrographs, outflow conditions, and other active or passive control methods can be also included in the input data file. Flow velocity, depth, discharge, and other variables at any locations and any time may be specified as outputs.

For more than twenty years, the above dynamic transient mixed flow mathematical model has been applied to a number of large sewer tunnel systems as a problem solver or design tool. These tunnel systems include Rochester City Sewer System, NY [5], Chicago TARP Phase I [1, 6] and Phase II [7], Phoenix I-10 Tunnel System, AZ [8], Milwaukee Inline Storage System, WI [9, 10], New York Passaic River Flood Protection Tunnel, NY [11], Fall River Tunnel System, MA [12] and Narragansett Bay Commission Tunnel System, RI [13].

## 2.2 Modeling Configuration

For the mathematical modeling purpose, the simplified NBC CSO storage tunnel configuration, as shown in Fig. 2, is used. Numbers shown in Fig. 2 are the station numbers used in the model for the purpose of defining different segments of the system. Each junction is represented by three stations for identification of three connecting segments. The entire system is divided into 99 segments of 200 ft each. The locations of 7 dropshafts or inflow points are also shown in Fig. 2. The three relatively-long adits are included in the modeling configuration. The other 4 dropshafts are assumed to be directly attached to the tunnel.

## 2.3 Inflow Hydrographs

The basic inflow hydrograph to the tunnel in this study is the 1-year storm event, which has a peak inflow of 1821.0 cfs. The inflow hydrograph at each dropshaft and the total inflow is shown in Fig. 3. A larger storm is also simulated to study an extreme case. The larger storm is scaled up from the 1-year storm event to represent the conveyance capacity of the local collection system. The scaling factors at each dropshaft are as follows:

NBC CSO Tunnel Scaling Factors for System Capacity Hydrograph

| Location        | 1-year Design Flow rate (cfs) <sup>a</sup> | System Capacity Flow Rate (cfs) | Source for System Capacity Rates | Scaling Factor |
|-----------------|--|---------------------------------|----------------------------------|----------------|
| 067             | 671  | 991                             | b                                | 1.48           |
| 004/005/061     | 172  | 649                             | b                                | 3.77           |
| Seekonk         | 232  | 306                             | c                                | 1.32           |
| 006/007         | 146  | 216                             | b                                | 1.48           |
| 009/010         | 37   | 88                              | b                                | 2.38           |
| 032             | 82   | 103                             | c                                | 1.26           |
| Woonasquatucket | 488  | 744                             | c                                | 1.52           |

- Sources: a - CH2M HILL letter of 4/23/99 to St. Anthony Falls Laboratory – Alternative No. 11-1-year storm  
 b - St. Anthony Falls Project Report of 8/95 & CH2M HILL memo of 2/9/95 to St. Anthony Falls Laboratory  
 c - CH2M HILL memo of 2/16/99 to Sverdrup – Alternative No. 11 – 2-year storm

## 2.4 Inflow Gate Control

The total storage volume with appurtenances is about 67.5 MG. All the dropshaft gates except that of OF067 are assumed to be closed when the tunnel reaches its design capacity of 61.79 MG. The modeling scenario assumes that the gate at OF067 failed to close when the tunnel was nearly full, and thus the inflow is allowed to continue. The sketch of the inflow control hydrograph is shown in Fig. 4.

## 2.5 Rating Curve for EOS

The rating curve (as shown below) for the Emergency Overflow Structure is given by CH2M HILL. The curve accounts for backwater in the river and head losses through the tide gates, friction losses in the box culverts, and transition losses in the top of the dropshaft structure. This curve is used as a boundary condition at the EOS in the modeling.

| Flow (cfs) | Elevation (NGVD) |
|------------|------------------|
| 50         | 4.5              |
| 100        | 4.6              |
| 150        | 4.7              |
| 200        | 4.9              |
| 250        | 5.1              |
| 300        | 5.4              |
| 350        | 5.7              |
| 400        | 6.0              |
| 450        | 6.3              |
| 500        | 6.6              |
| 550        | 7.0              |
| 600        | 7.4              |
| 650        | 7.8              |
| 700        | 8.3              |
| 750        | 8.8              |
| 800        | 9.3              |

### III. GENERAL HYDRAULIC TRANSIENT CHARACTERISTICS

Based on the modeling configurations described previously, two scenarios are simulated in the study.

#### 3.1 Case 1: 1-Year Storm Event

Fig. 5 shows the temporal change in water surface elevations at five locations (Woonasquatucket, Foundry Workshaft, OF032, OF009/010, and OF006/007). The variation in water surface elevation at the other four locations (Seekonk, OF004/061/005, OF067, and Pump Station) is shown in Fig. 6. The start time in all the simulations is from 6:14, 1/1/99. Finer resolution graphs when the tunnel first becomes full and during the overfilling stages are presented in Figs. 7 to 10. Strong oscillations at the Woonasquatucket dropshaft are shown in Fig. 7, when the tunnel first becomes full. The gates are closed at  $t=3.75$  hours from the start time (6:14, 1/1/99). The remaining tunnel storage volume is filled by the inflow from OF067 where no gate control is assumed. It is known from the figures that it takes about 0.44 hour to fill the remaining tunnel storage capacity. From a hydraulic transient point of view, the water surface rise is slow after the main inflow to the tunnel was shut off, and the oscillations during the overfilling stage are mild. The peak water surface elevations at each dropshaft are listed below.

| Dropshaft        | Woonasquatucket | 032  | 009/010 | 006/007 | Seekonk | 004/005/061 | 067  |
|------------------|-----------------|------|---------|---------|---------|-------------|------|
| Peak HGL         | 10.3            | 9.7  | 7.8     | 7.2     | 10.8    | 9.9         | 13.3 |
| Ground Elevation | 10.4            | 24.0 | 7.0     | 7.2     | 11.0    | 14.0        | 21.6 |

Note that only the peak elevation at the EOS (009/010) is higher than its maximum surcharge elevation (ground elevation). Therefore, no overflow occurs at the dropshafts other than the emergency overflow structure. Fig. 11 shows the actual total inflow to the tunnel and the overflow from the Emergency Overflow Structure. The finer resolution details of the overflow oscillation are shown in Fig. 12. The peak overflow is about 651 cfs. After the tunnel becomes full, all the inflow from OF067 becomes overflow at the EOS. The overflow rate and the water surface elevation at EOS oscillate with decreasing amplitude after the initial surge.

The maximum rates of water surface rise at different stages for each dropshaft and the time when the maximum values occurred are listed in the following table.

| Dropshaft         | Max rise rate During just full Stage (ft/s) | Time Occurred (h) | Max rise rate During overfilling Stage (ft/s) | Time Occurred (h) |
|-------------------|---|-------------------|---|-------------------|
| Woonasquatucket   | 11.81                                       | 3.94              | 0.75  | 4.14              |
| Foundry Workshaft | 1.92  | 3.94              | 0.62  | 4.15              |
| 032               | 2.51  | 3.94              | 0.82  | 4.14              |
| 009/010           | 1.01  | 3.95              | 0.68  | 4.14              |
| 006/007           | 1.00  | 3.93              | 0.68  | 4.16              |
| Seekonk           | 1.95  | 3.92              | 1.21  | 4.16              |
| 004/005/061       | 1.13  | 3.93              | 0.73  | 4.13              |
| 067               | 0.69  | 3.96              | 0.54  | 4.17              |



The high maximum rise rate of water surface occurs when the tunnel first becomes full. It has no effect on structures near the ground. The peak flow velocity in the main tunnel is shown in Fig. 13. The high peak velocity between Woonasquatucket shaft and Foundry workshaft is due to the strong surge oscillations when the tunnel first becomes full and its small tunnel diameter.

### 3.2 Case 2: Larger Storm Event

It is useful to study the hydraulic transient characteristics for a larger storm event. The larger storm event that was modeled is scaled up based on the 1-year storm event as described previously. Similar to Case 1, it is assumed that the tunnel is initially empty. In order to see how high the water surface elevation can reach at each dropshaft without any overflow, it is also assumed that the dropshafts are high enough to prevent any overflow.

Similar to Case 1, the modeled results are plotted in Figs. 14 to 22. Since overflow starts at near the peak of the inflow hydrograph at OF067, as shown in Fig. 20, the peak water surface elevations at each dropshaft (as shown below) are much higher than those in Case 1,

| Dropshaft        | Woonasquatucket | 032  | 009/010 | 006/007 | Seekonk | 004/005/061 | 067  |
|------------------|-----------------|------|---------|---------|---------|-------------|------|
| Peak HGL         | 15.4            | 13.7 | 13.0    | 12.6    | 13.7    | 12.0        | 14.9 |
| Ground Elevation | 10.4            | 24.0 | 7.0     | 7.2     | 11.0    | 14.0        | 21.6 |

Note that the peak water surface elevations at the Woonasquatucket, OF009/010, OF006/007 and Seekonk dropshafts are higher than their ground elevations.

The peak overflow rate from the EOS is about 1170 cfs, as shown in Fig. 21.

The maximum rates of water surface rise at different stages for each dropshaft and the time when the maximum values occurred are listed in the following table.

| Dropshaft         | Max rise rate During just full Stage (ft/s) | Time Occurred (h) | Max rise rate During overfilling Stage (ft/s) | Time Occurred (h) |
|-------------------|---|-------------------|---|-------------------|
| Woonasquatucket   | 0.85  | 3.35              | 0.61  | 3.51              |
| Foundry Workshaft | 0.76  | 3.35              | 0.60  | 3.51              |
| 032               | 0.75  | 3.35              | 0.62  | 3.51              |
| 009/010           | 2.49  | 3.33              | 0.46  | 3.51              |
| 006/007           | 0.73  | 3.36              | 0.59  | 3.50              |
| Seekonk           | 1.70  | 3.34              | 0.59  | 3.50              |
| 004/005/061       | 0.77  | 3.34              | 0.96  | 3.50              |
| 067               | 0.66  | 3.34              | 0.67  | 3.49              |

It has no effect on structures near the ground. The peak flow velocity in the main tunnel is shown in Fig. 22.

#### IV. COMMENTS AND CONCLUSIONS

In this study, one basic tunnel operation case and one more conservative scenario (larger storm event) are examined using a well established hydraulic transient computer model (MXTRANS) to investigate any potential geysering and other transient problems. Based on the analyses of the simulation results, the main hydraulic transient characteristics are summarized as follows.

1. No potential geysering and other hydraulic transient problems are identified in the normal 1-year storm event case based on the current tunnel design configuration and operation procedures. The peak water surface elevations at each dropshaft are all below their maximum surcharge elevations except at the 009/010 dropshaft (EOS). The peak overflow from the EOS is 651 cfs.

2. For the larger storm event, the hydraulic surge is still very mild. But, the peak water surface elevations at the Woonasquatucket, OF009/010, OF006/007 and Seekonk dropshafts are higher than their maximum surcharge elevations. Should this be of concern, one way to prevent it is to close the gates early to avoid the overflow from occurring at the peak inflow of OF067.

3. Strong oscillations at the Woonasquatucket dropshaft when the tunnel first becomes full ( $t=3.88$  hours) are identified during the 1-year storm event. The magnitude is as high as 80 ft. During the overfilling stage, however, the oscillation is much weaker. At the Woonasquatucket dropshaft, the largest magnitude of the oscillations is about 13 ft over a period of about 3 minutes when the tunnel is overfilled.

## REFERENCES

1. Song, C.C.S., Guo, Q., and Zheng, Y., "Hydraulic Transient Modeling of TARP Systems," St. Anthony Falls Hydraulic Laboratory, University of Minnesota, Project Report No. 270, March 1988.
2. Guo, Q., and Song, C.C.S., "Hydraulic Transient Analysis of TARP Phase II O'Hare System," St. Anthony Falls Hydraulic Laboratory, University of Minnesota, Project Report No. 276, July 1988.
3. Cardle, J.A., and Song, C.S.C., "Mathematical Modeling of Unsteady Flow in Storm Sewers," *International Journal of Engineering Fluid Mechanics*, Vol. 1, No. 4, 1988.
4. Guo, Q., and Song, C.C.S., "Surging in Urban Storm Drainage Systems," *Journal of Hydraulic Engineering, ASCE*, Vol. 116, No. 12, June, 1989.
5. Song, C.C.S., Cardle, J.A., and Gavali, S., "Mathematical modeling of the Genesee River Storage - conveyance System Rochester, NY," St. Anthony Falls Hydraulic Laboratory, University of Minnesota, Project Report No. 215, July 1982.
6. Song, C.C.S., Lin, W., and Gong, C., "Hydraulic Transient Modeling of TARP Systems," St. Anthony Falls Hydraulic Laboratory, University of Minnesota, Project Report No. 332, March 1992.
7. Song, C.C.S., He, J., Liu, Y., and Gong, C., "Hydraulic Transient Study of Mainstream & Des Plaines TARP Phase II Systems," St. Anthony Falls Hydraulic Laboratory, University of Minnesota, Project Report No. 353, July 1994.
8. Song, C.C.S., "Mathematical Modeling of I-10 Inner Loop Drainage System," St. Anthony Falls Hydraulic Laboratory, University of Minnesota, Project Report No. 235, Aug. 1984.
9. Song, C.C.S., and Lin, W., "Study of Potential Hydraulic Transient for Milwaukee Inline Storage System," St. Anthony Falls Hydraulic Laboratory, University of Minnesota, Project Report No. 297, July 1990.
10. Lin, W., and Song, C.C.S., "Hydraulic Transient Analysis of Tunnels and Dropshafts for Milwaukee Inline Storage System," St. Anthony Falls Hydraulic Laboratory, University of Minnesota, Project Report No. 340, July 1993.
11. He, J., Song, C.C.S., and Liu, Y., "Hydraulic Transient Study of Passaic River Flood Protection Tunnel," St. Anthony Falls Hydraulic Laboratory, University of Minnesota, Project Report No. 354, July 1994.

12. He, J., Song, C.C.S., and Liu, Y., "Hydraulic Transient Study of Fall River Tunnel System," St. Anthony Falls Hydraulic Laboratory, University of Minnesota, Project Report No. 365, Dec. 1994.

13 . He, J., Song, C.C.S., and Liu, Y., "Hydraulic Transient Study of Narragansett Bay Commission Tunnel System," St. Anthony Falls Hydraulic Laboratory, University of Minnesota, Project Report No. 368, August 1995.

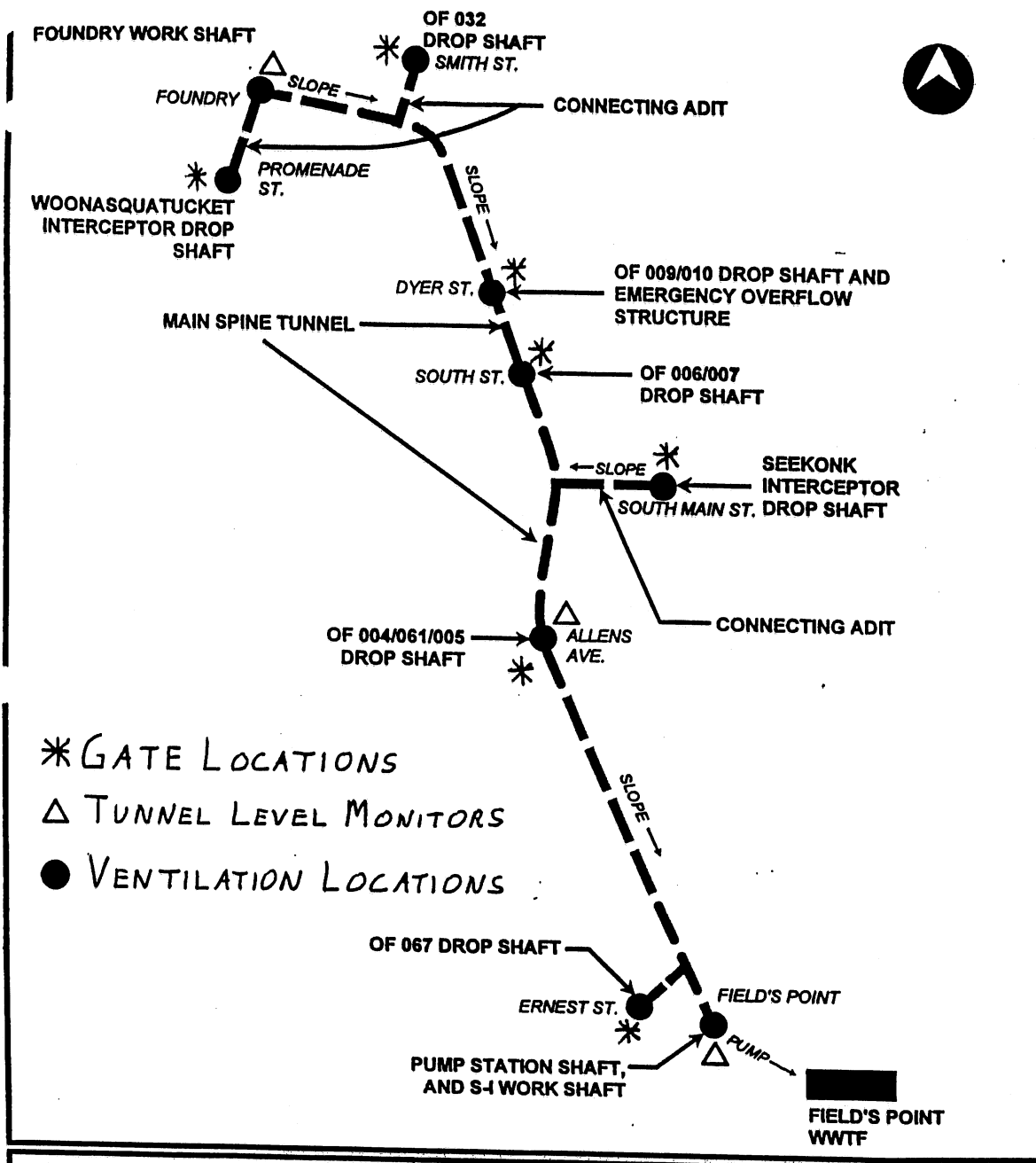
14. Guo, Q., and Song, C.C.S., "Dropshaft Hydrodynamics under Transient Conditions," *Journal of Hydraulic Engineering, ASCE*, Vol. 117, No. 8, June, 1990.

| <b>NBC CSO TUNNEL PRELIMINARY DESIGN<br/>Data for Transient Analyses</b>  |   |                      |   |                         |   |
|---|---|----------------------|---|-------------------------|---|
| <b>Main Spine Tunnel Data<br/>From drawings dated April, 1999<sup>1</sup></b>   |   |                      |   |                         |   |
| Station (ft)  | Location  | Tunnel Invert (NGVD) | Work or Ventilation Shaft Diameter (ft) | Dropshaft Diameter (ft) | Maximum Surcharge Elevation <sup>2</sup> (NGVD) |
| 472.62  | Pump Station Shaft                                  | -236.59              |   |                         |   |
| 842.98  | S-1 Workshaft                                       | -236.15              | 30                                      |                         |   |
| 882.98  | 067   | -236.10              |   | 9                       | 21.6  |
| 6286.32   | 004,005,061   | -229.62              |   | 5                       | 14.0  |
| 9029.07   | Seekonk   | -226.33              |   | 5                       | 11.0  |
| 9652.61   | 006,007   | -225.58              |   | 5                       | 7.2   |
| 10751.94  | 009,010   | -224.26              |   | 9                       | 7.0   |
| 14539.18  | 032   | -219.71              |   | 5                       | 24.0  |
| 16801.44  | Foundry Workshaft / Woonasquatucket                 | -217.00              | 30                                      | 6                       | 10.4  |
| <sup>1</sup> Station number for 067 was estimated; inverts of tunnel at 067 and Seekonk were calculated. All other stations numbers and inverts taken directly from drawings. |   |                      |   |                         |   |
| <sup>2</sup> Lowest ground elevation at either gate/screening structure or dropshaft.   |   |                      |   |                         |   |
| <b>Emergency Overflow Structure (EOS) data</b>  |   |                      |   |                         |   |
| 2.5   | Weir crest elevation (ft, NGVD)                     |                      |   |                         |   |
| 48.0  | Weir length (ft)                                    |                      |   |                         |   |
| -5.0  | Upstream invert of box culverts (ft, NGVD)          |                      |   |                         |   |
| -5.1  | Downstream invert of box culverts (ft, NGVD)        |                      |   |                         |   |
| 6.0   | Dimensions of box culverts (ft H or W)              |                      |   |                         |   |
| 0.1%  | Slope of box culverts                               |                      |   |                         |   |
| 96  | Length of box culverts (between weir and river, ft) |                      |   |                         |   |

Table 1 NBC CSO tunnel design data

| NBC CSO TUNNEL PRELIMINARY DESIGN   |           |        |         |                    |          |                              |          |                  |                   |
|---|-----------|--------|---------|--------------------|----------|------------------------------|----------|------------------|-------------------|
| Data for Transient Analyses   |           |        |         |                    |          |                              |          |                  |                   |
| All elevations in ft, NGVD  |           |        |         |                    |          |                              |          |                  |                   |
| Subsurface Facilities Data  |           |        |         |                    |          |                              |          |                  |                   |
| Dropshaft   | Dropshaft |        |         | Deaeration Chamber |          | Connecting Adit <sup>1</sup> |          |                  | Drawing           |
|   | Diameter  | Ground | Invert  | Length             | Diameter | Length                       | Diameter | Invert at Tunnel | Date <sup>2</sup> |
| 067   | 9         | 22.0   | -217.86 | 112.5              | 15.75    | 7                            | 8.00     | -218.10          | 4/14/99           |
| 004/005/061   | 5         | 14.0   | -207.96 | 62.5               | 8.75     | 16                           | 4.50     | -208.12          | 4/14/99           |
| Seekonk   | 5         | 11.0   | -202.11 | 62.5               | 8.75     | 1295                         | 4.50     | -204.83          | 4/12/99           |
| 006/007   | 5         | 7.2    | -203.88 | 62.5               | 8.75     | 37                           | 4.50     | -204.08          | 3/24/99           |
| 009/010   | 9         | 7.2    | -206.01 | 112.5              | 15.75    | 14                           | 8.00     | -206.26          | 4/12/99           |
| 032   | 5         | 24.0   | -196.48 | 62.5               | 8.75     | 805                          | 4.50     | -198.21          | 4/12/99           |
| Woonasquatucket   | 6         | 10.4   | -194.85 | 75.0               | 10.50    | 625                          | 5.25     | -196.25          | 4/15/99           |
| <sup>1</sup> Assume slope of connecting adits and deaeration chambers is 0.2% |           |        |         |                    |          |                              |          |                  |                   |
| <sup>2</sup> Date of drawing from which length of connecting adit was scaled  |           |        |         |                    |          |                              |          |                  |                   |

Table 2 NBC CSO tunnel and dropshaft design data





|   |   |                                |
|---|---|--------------------------------|
|  LOUIS BERGER & ASSOCIATES, INC.   | <b>PHASE I CSO - LAYOUT OF UNDERGROUND STRUCTURES</b> | FIG<br>#1                      |
|  NARRAGANSETT BAY COMMISSION<br>COMBINED SEWER OVERFLOW CONTROL FACILITIES |   | <small>File: PIC-1.prs</small> |
| <small>Source: LDM</small>  | <small>NOT TO SCALE</small>                           | Tk 10                          |

Fig. 1 Layout of the NBC CSO storage tunnel

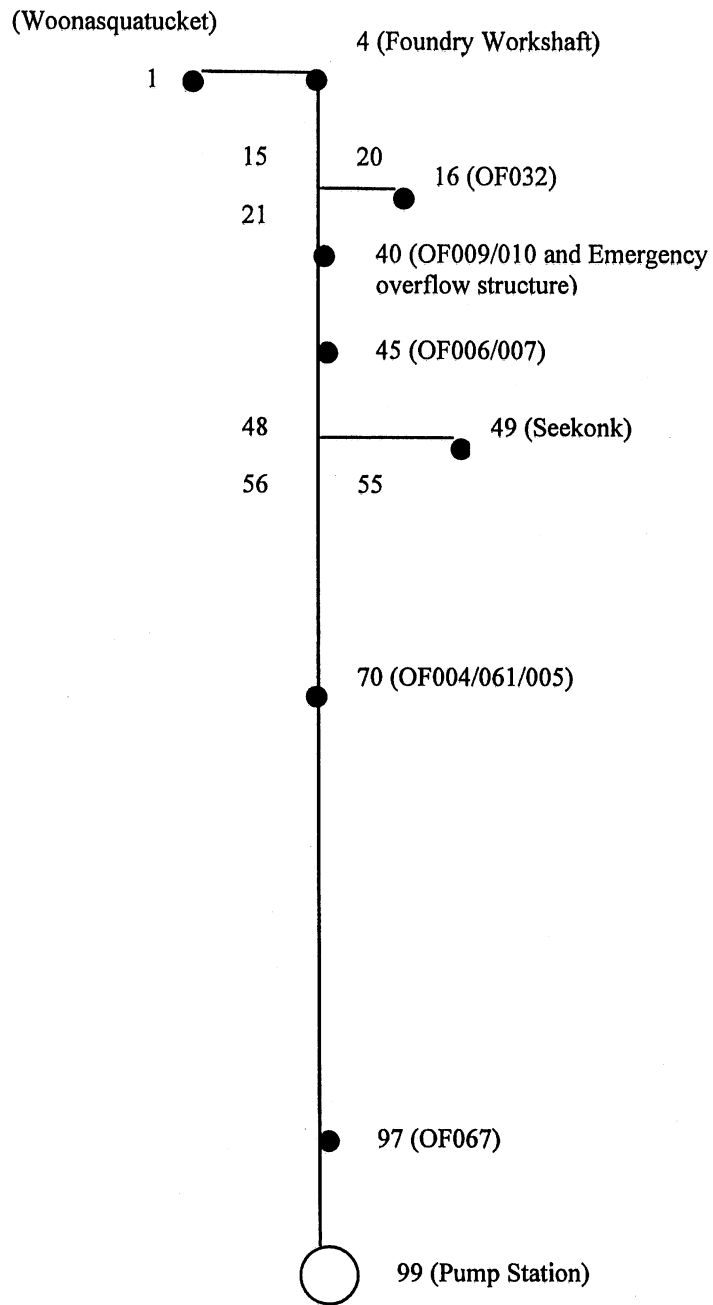


Fig. 2 Simplified configuration of the NBC CSO storage tunnel for modeling purposes.



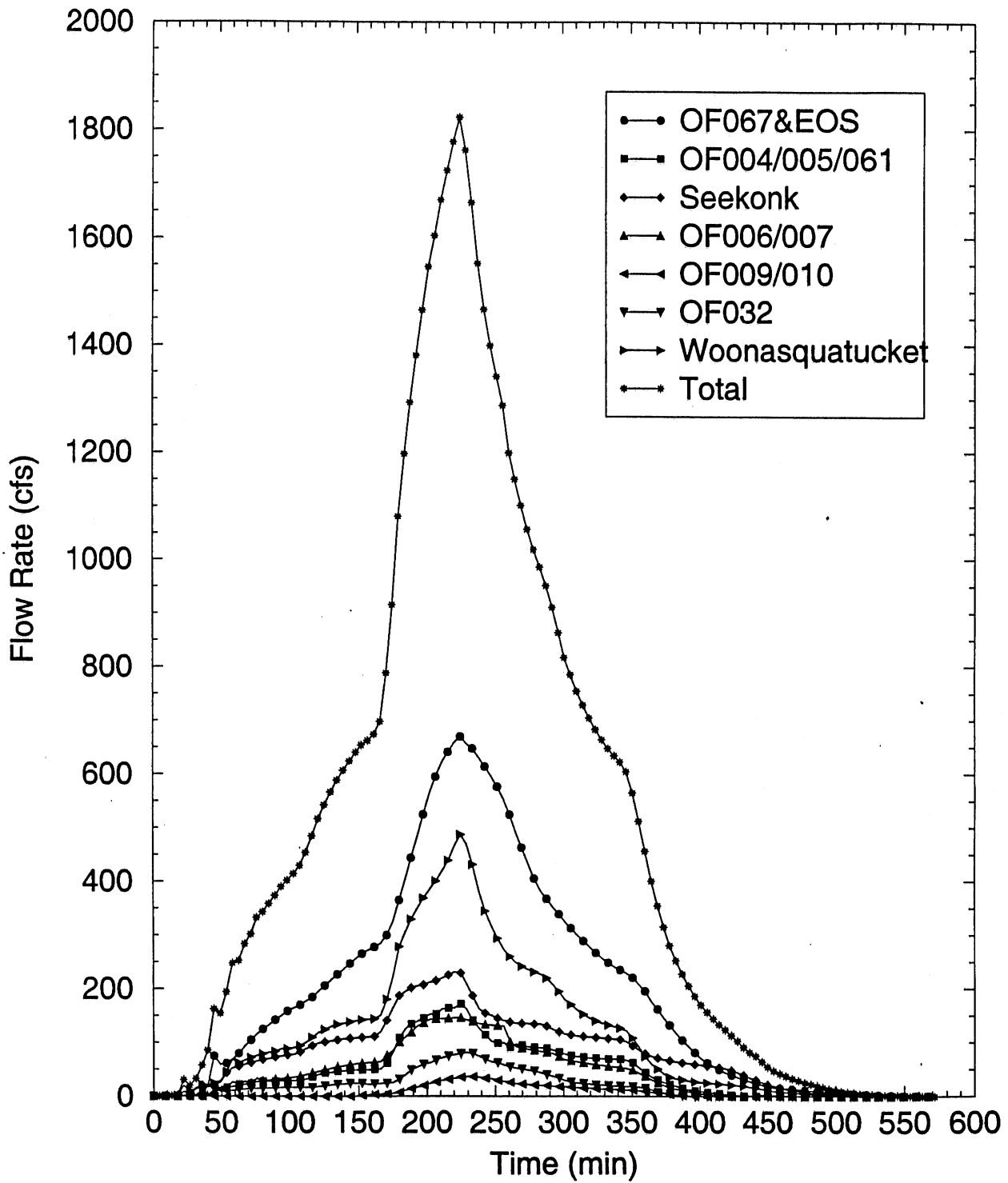


Fig. 3 1-year storm inflow hydrographs at each dropshaft and the total inflow.

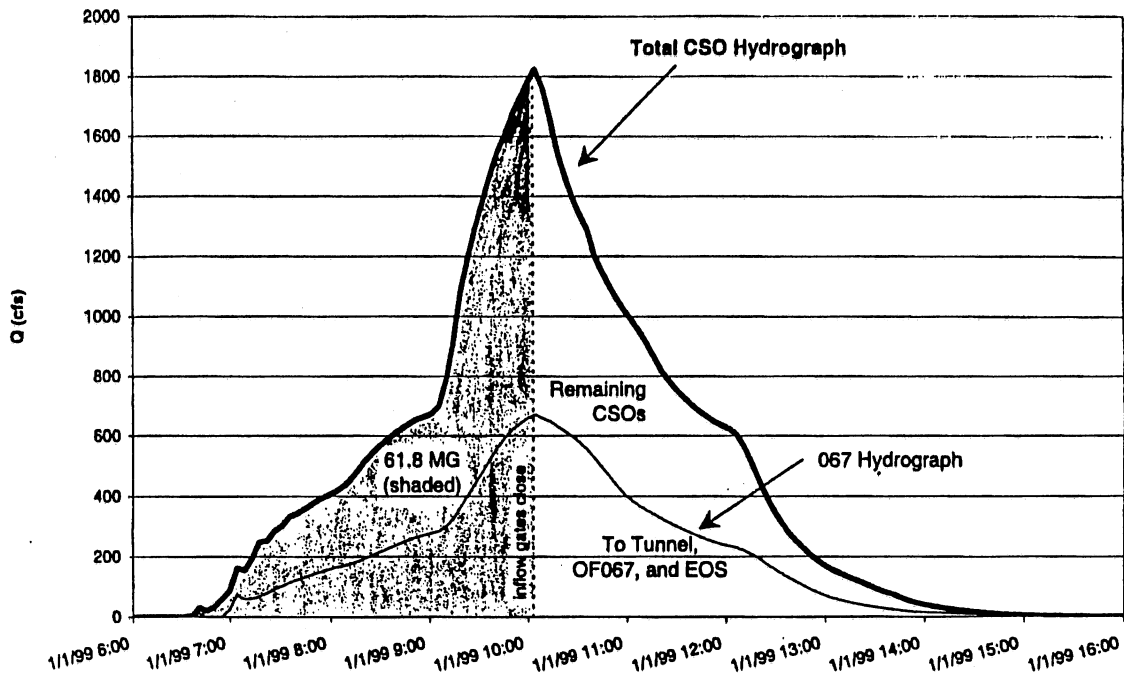


Fig. 4 Inflow control schedule

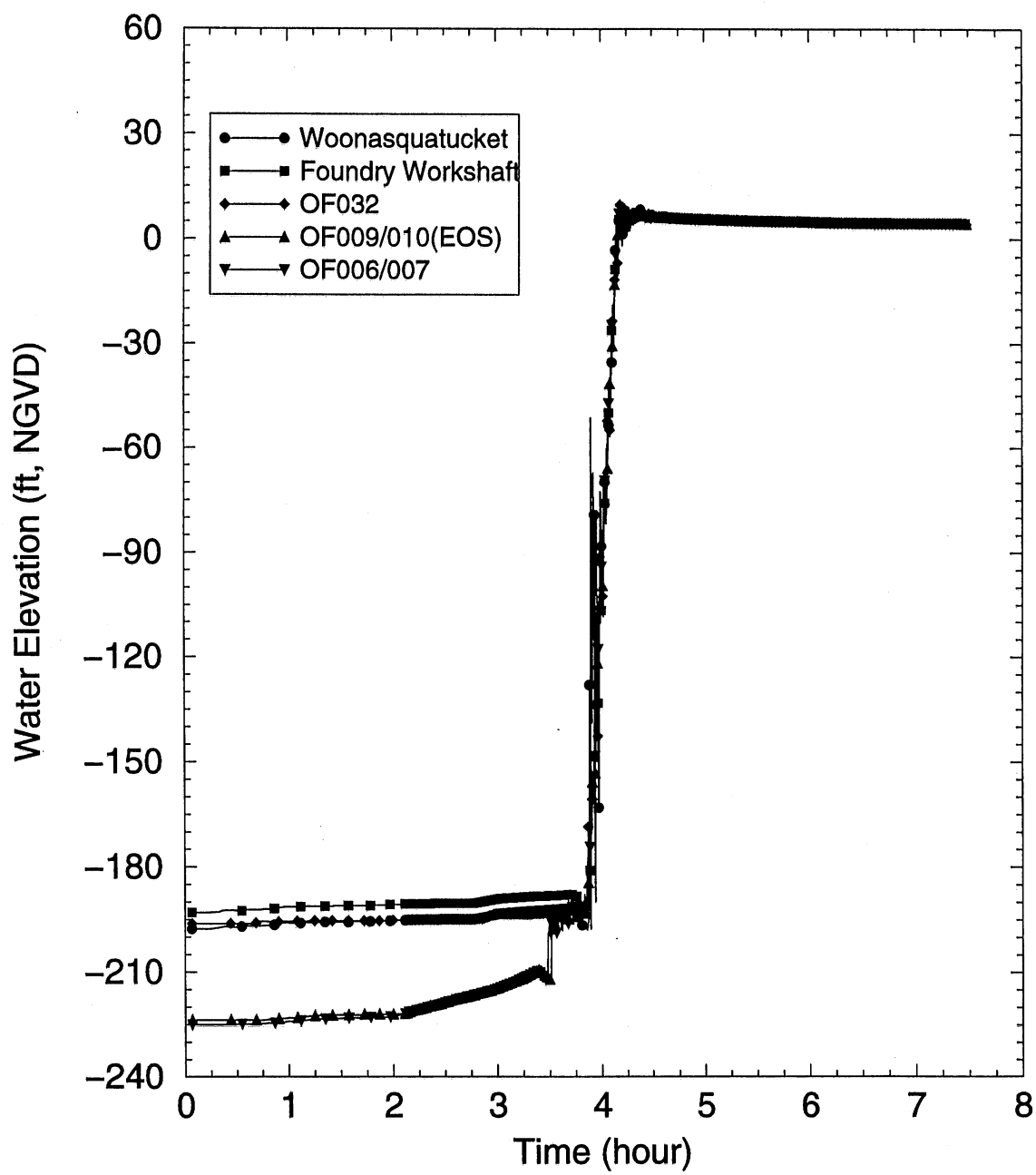


Fig. 5 Water surface elevation variations with time at the five upstream locations (Woonasquatucket, Foundry workshaft, OF032, OF009/010, and OF006/007), 1-year storm event (Case 1).

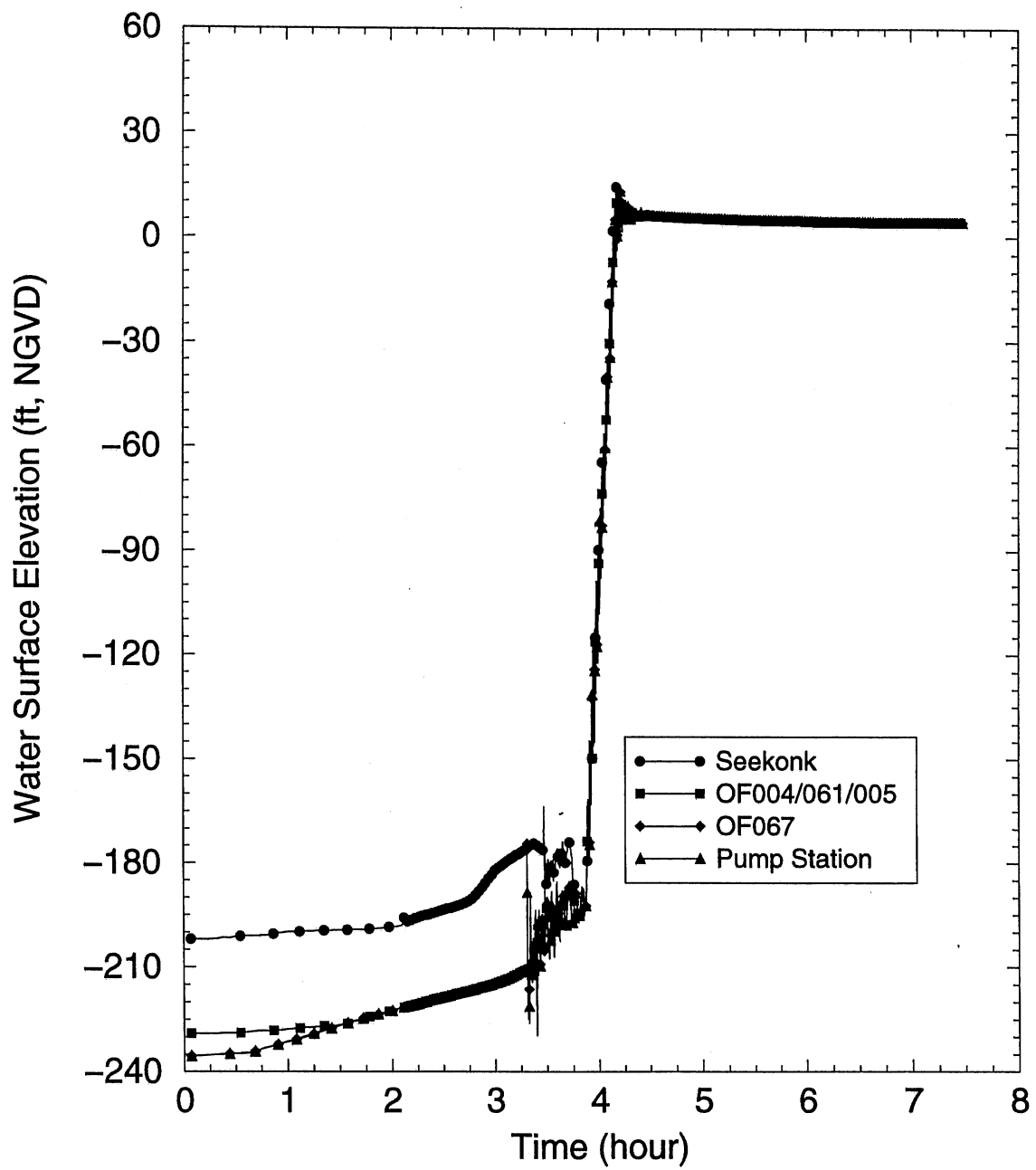


Fig. 6 Water surface elevation variations with time at the four downstream locations (Seekonk, OF004/005/061, OF067, and Pump station), 1-year storm event (Case 1).

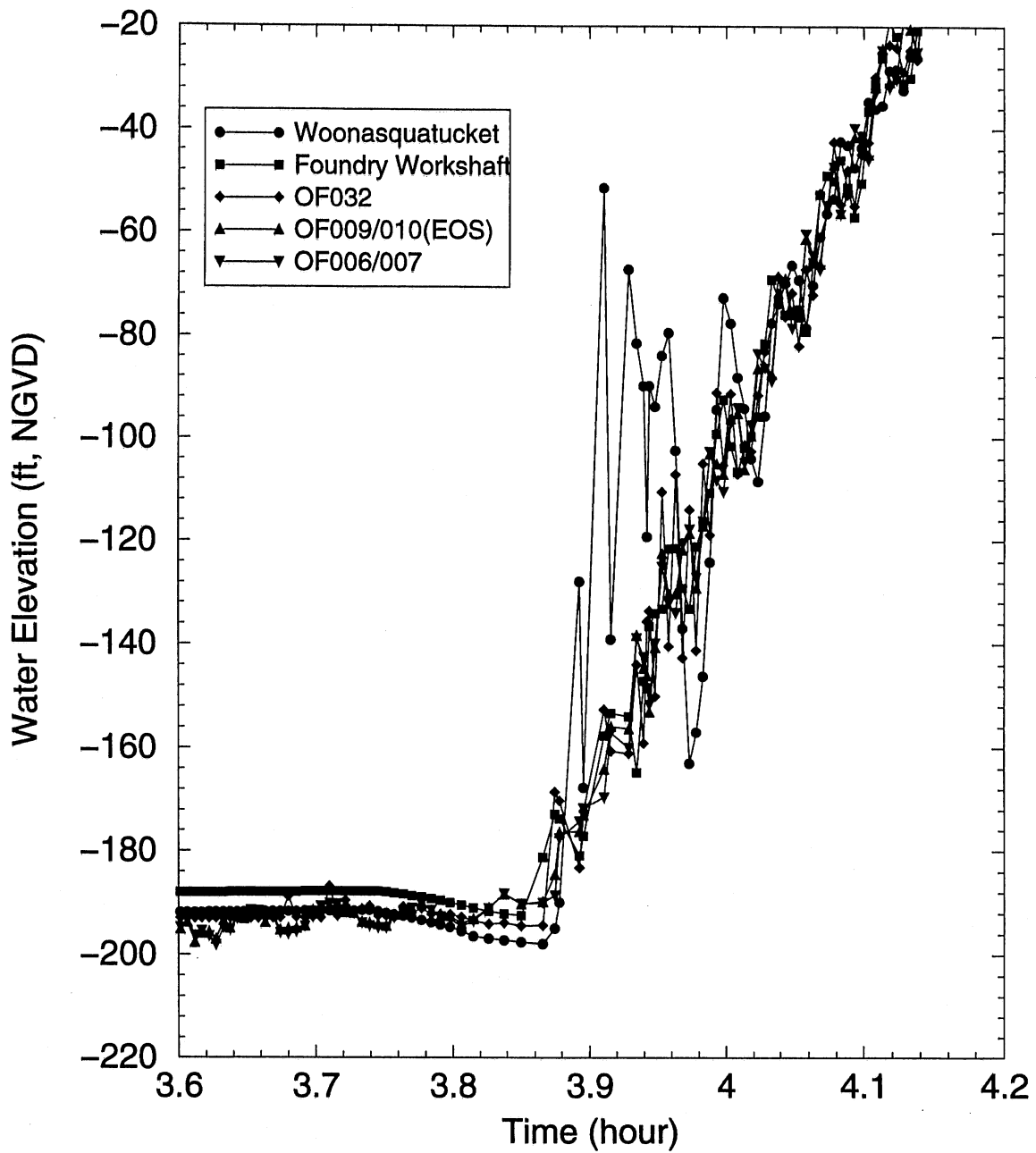


Fig. 7 More detailed water surface elevation variations with time when the tunnel first becomes full at the five upstream locations (Woonasquatucket, Foundry workshaft, OF032, OF009/010, and OF006/007), 1-year storm event (Case 1).

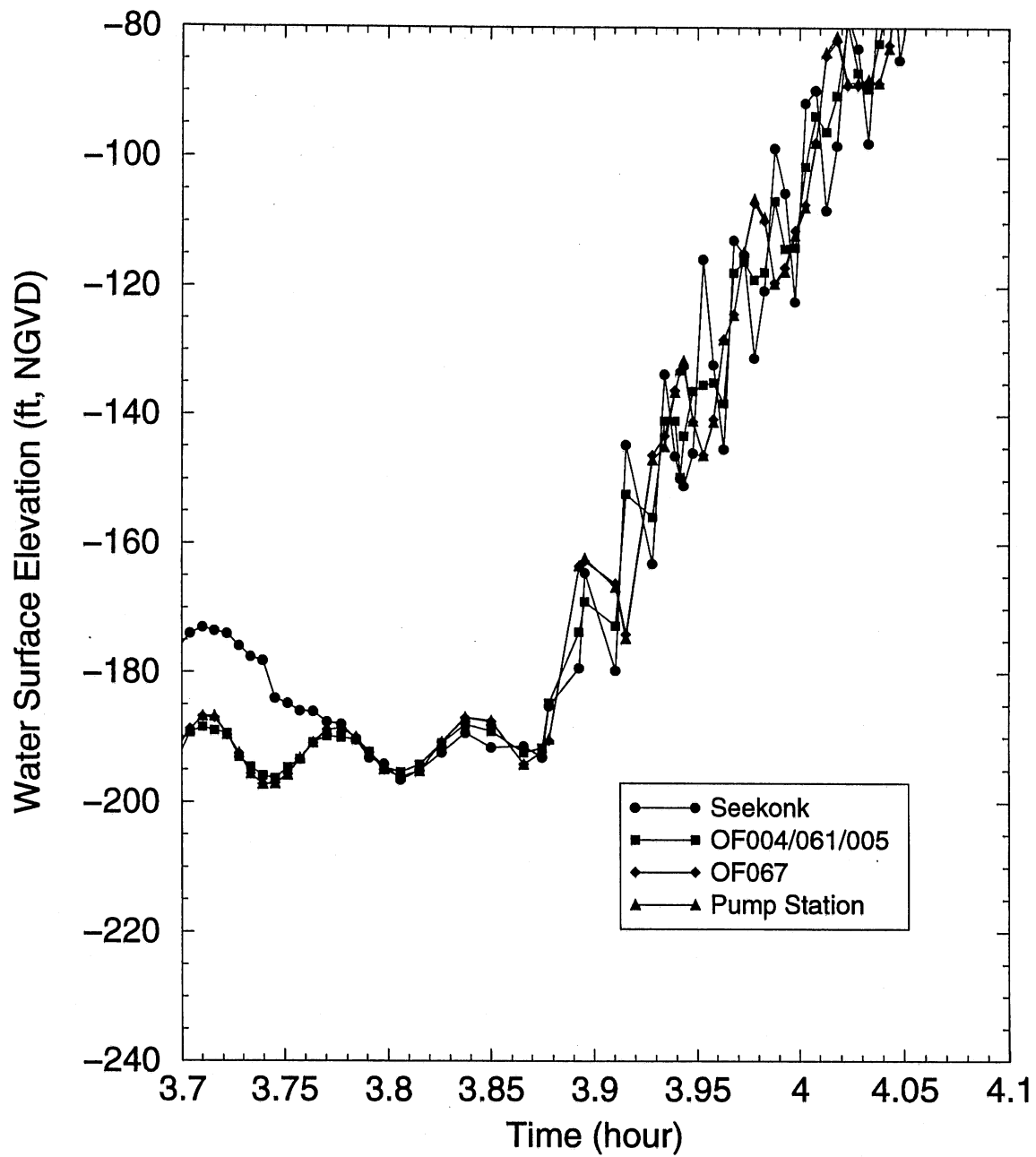


Fig. 8 More detailed water surface elevation variations with time when the tunnel first becomes full at the four downstream locations (Seekonk, OF004/005/061, OF067, and Pump station), 1-year storm event (Case 1).

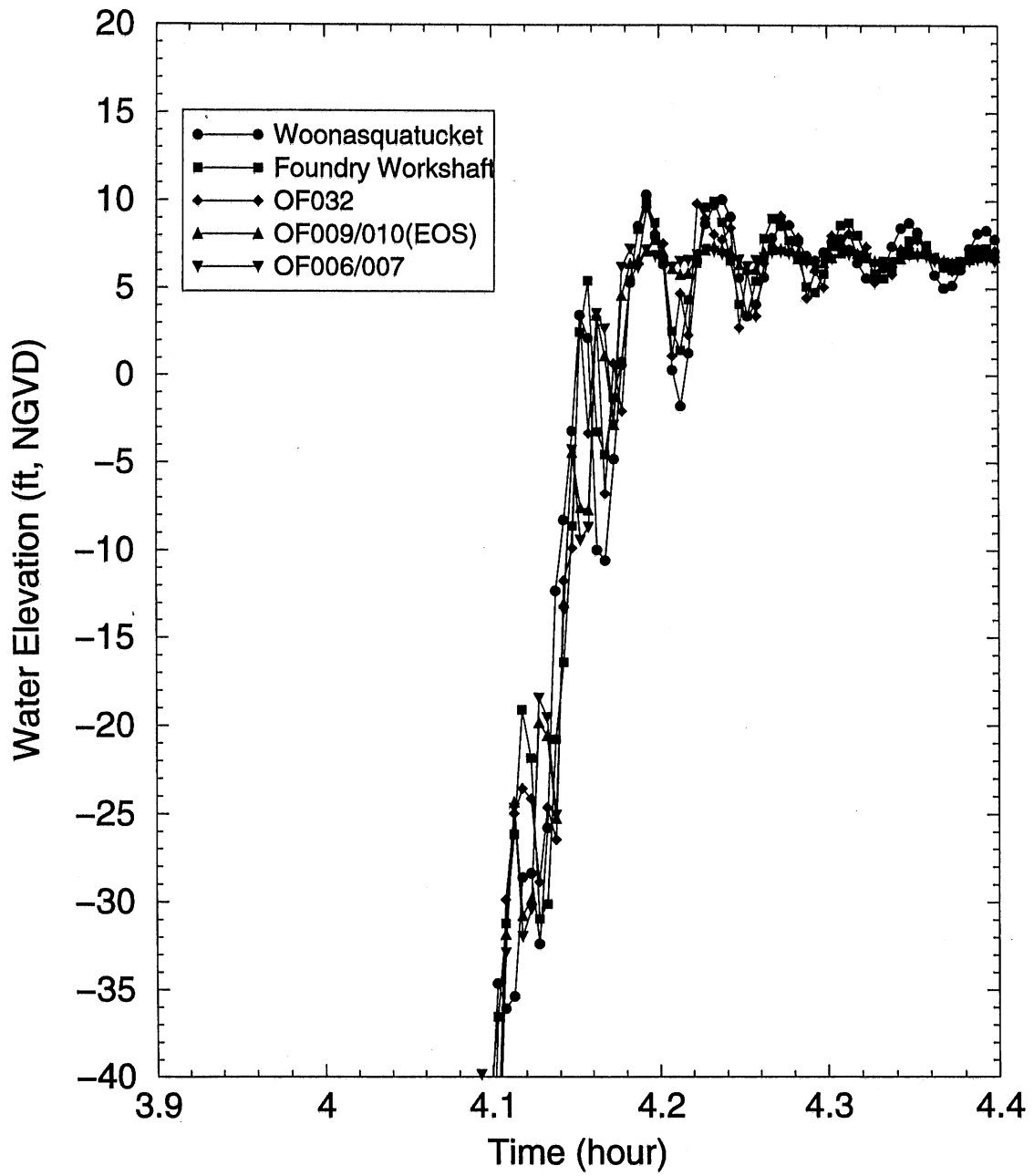


Fig. 9 More detailed water surface elevation variations with time during the overfilling stage at the five upstream locations (Woonasquatucket, Foundry workshaft, OF032, OF009/010, and OF006/007), 1-year storm event (Case 1).

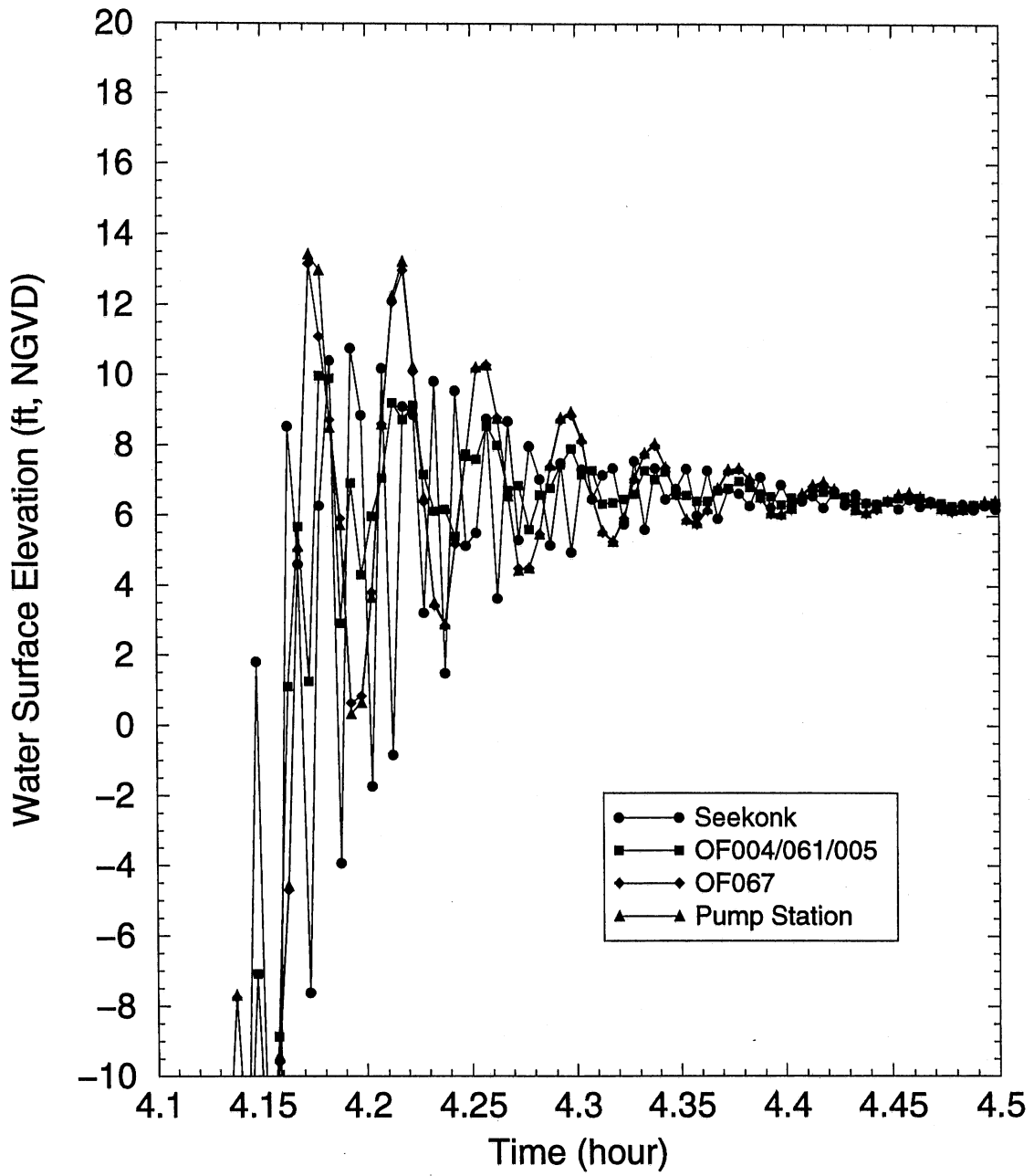


Fig. 10 More detailed water surface elevation variations with time during the overfilling stage at the four downstream locations (Seekonk, OF004/005/061, OF067, and Pump station), 1-year storm event (Case 1).



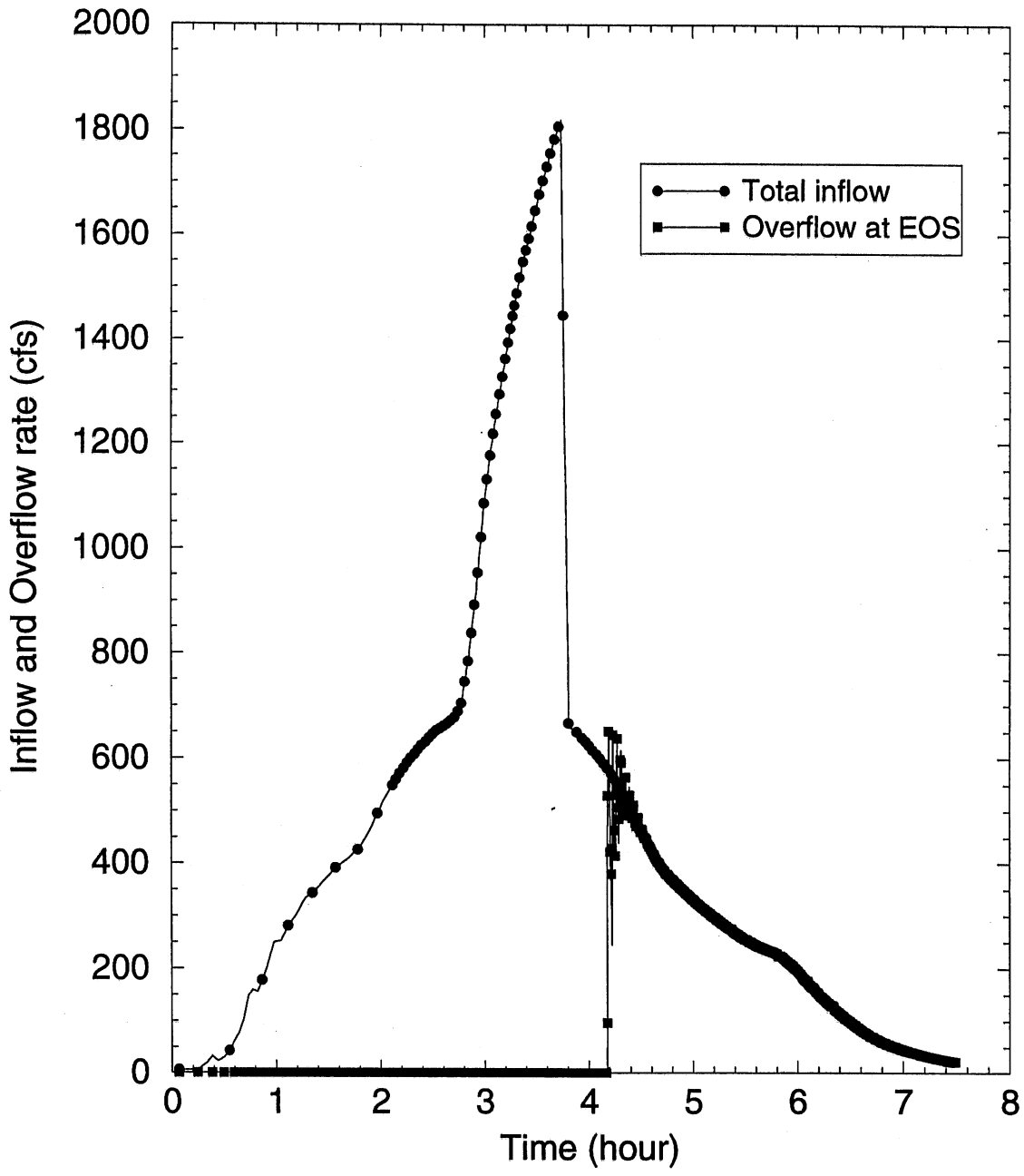


Fig. 11 The total inflow hydrograph to the tunnel system and the computed overflow from the EOS, 1-year storm event (Case 1).

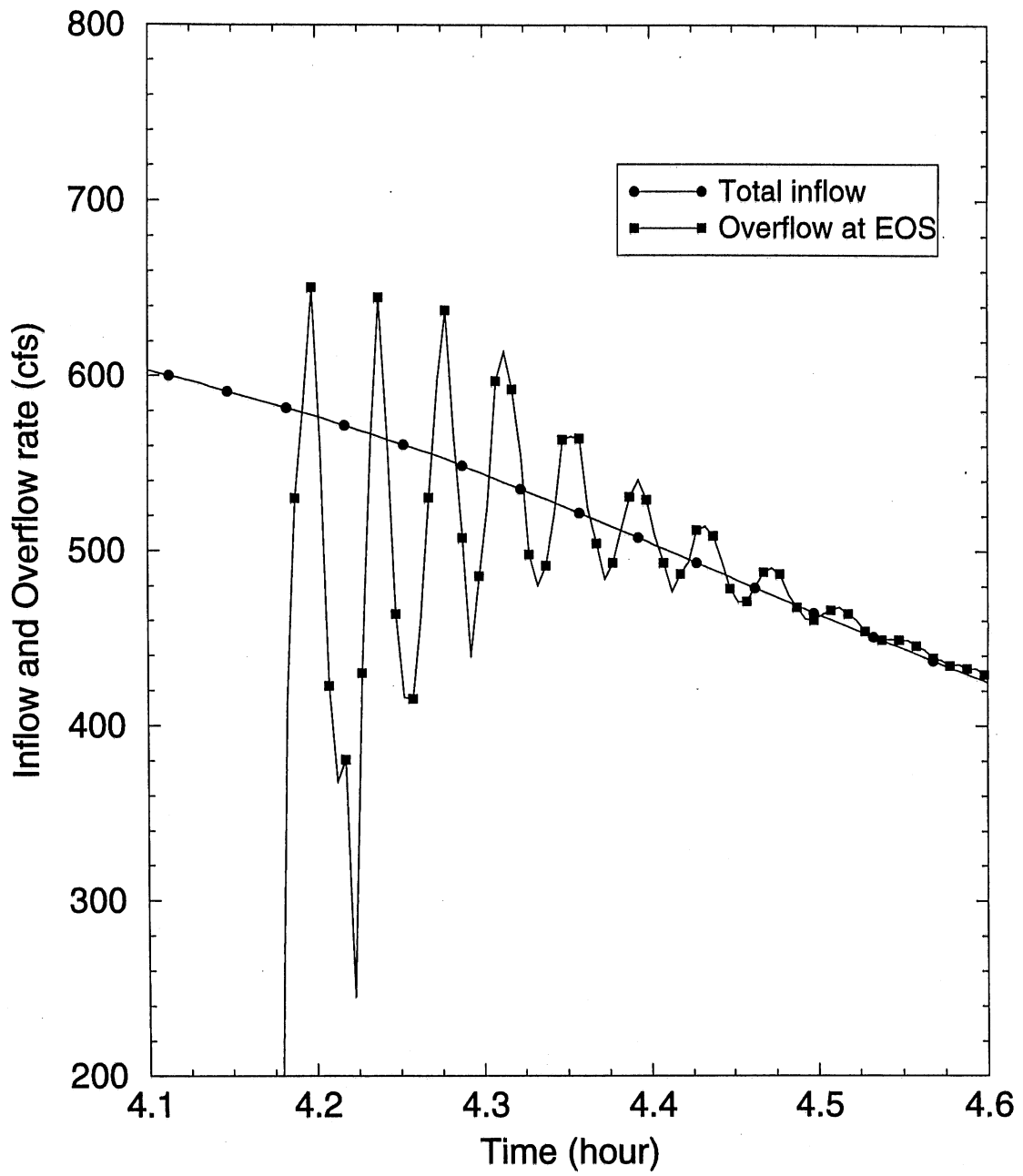


Fig. 12 More detailed overflow oscillations at the EOS, 1-year storm event (Case 1).

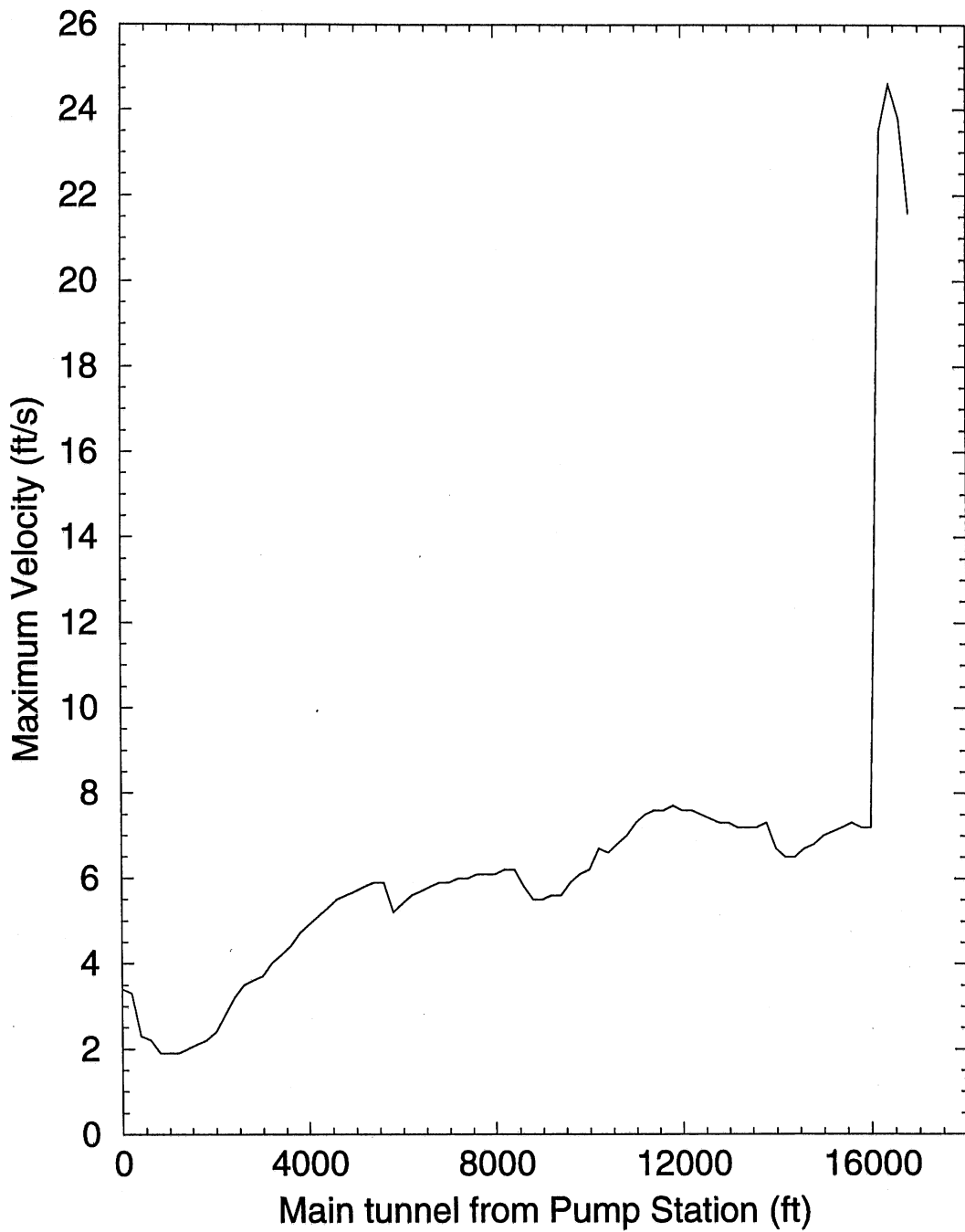


Fig. 13 Maximum flow velocity along the main tunnel from the Pumping station to the Woonasquatucket dropshaft, 1-year storm event (Case 1).

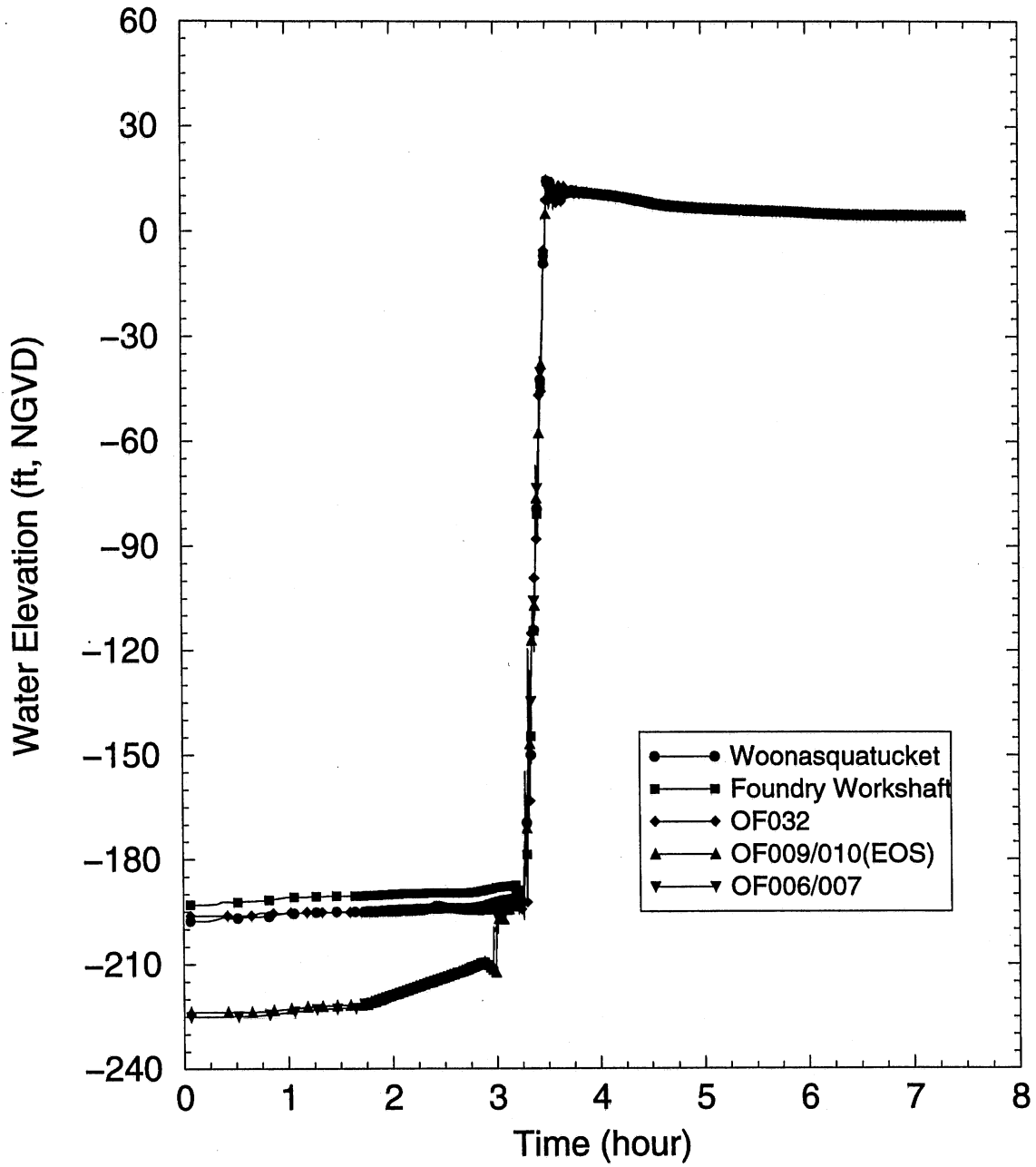


Fig. 14 Water surface elevation variations with time at the five upstream locations (Woonasquatucket, Foundry workshaft, OF032, OF009/010, and OF006/007), larger storm event (Case 2).

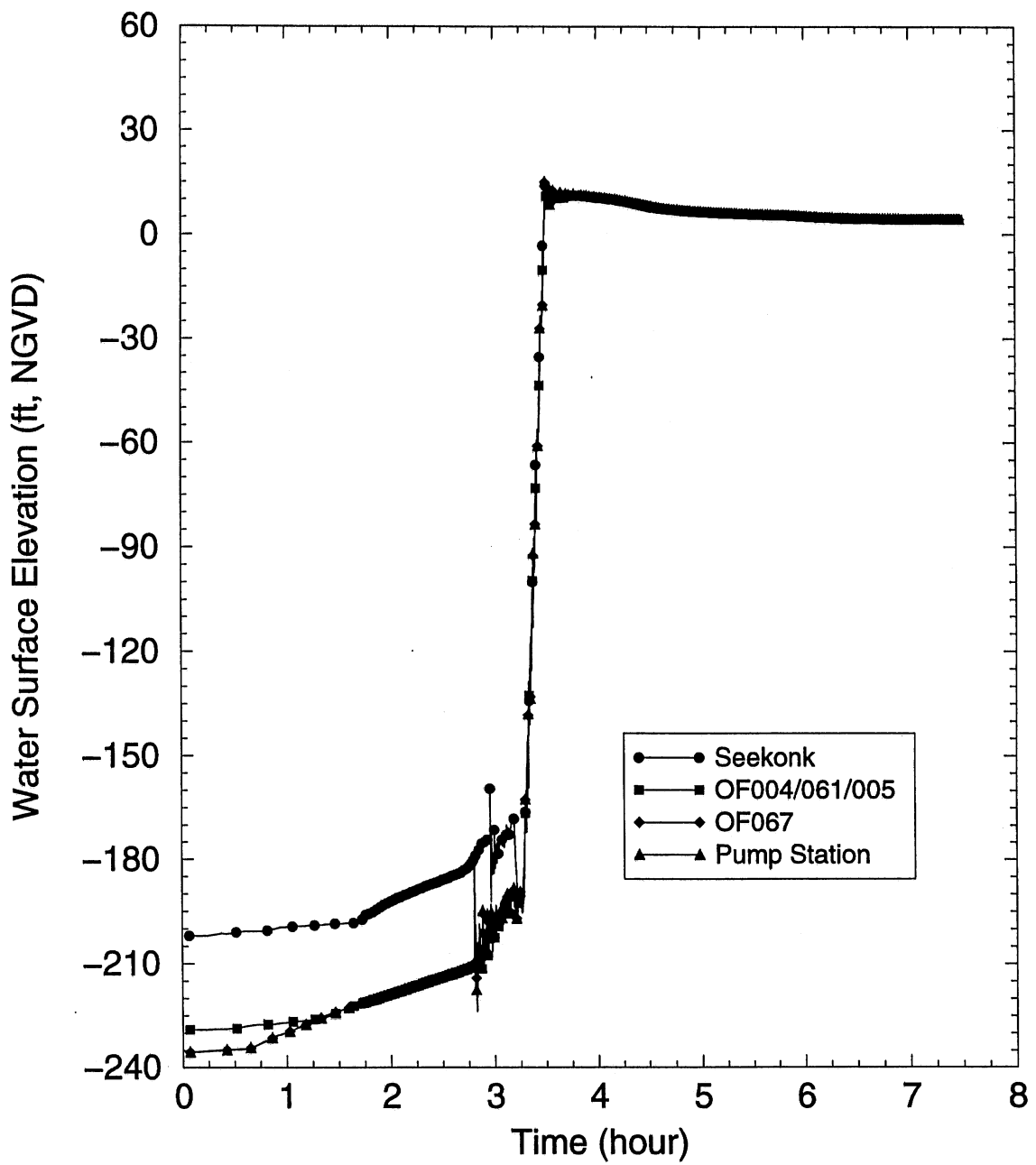


Fig. 15 Water surface elevation variations with time at the four downstream locations (Seekonk, OF004/005/061, OF067, and Pump station), larger storm event (Case 2).

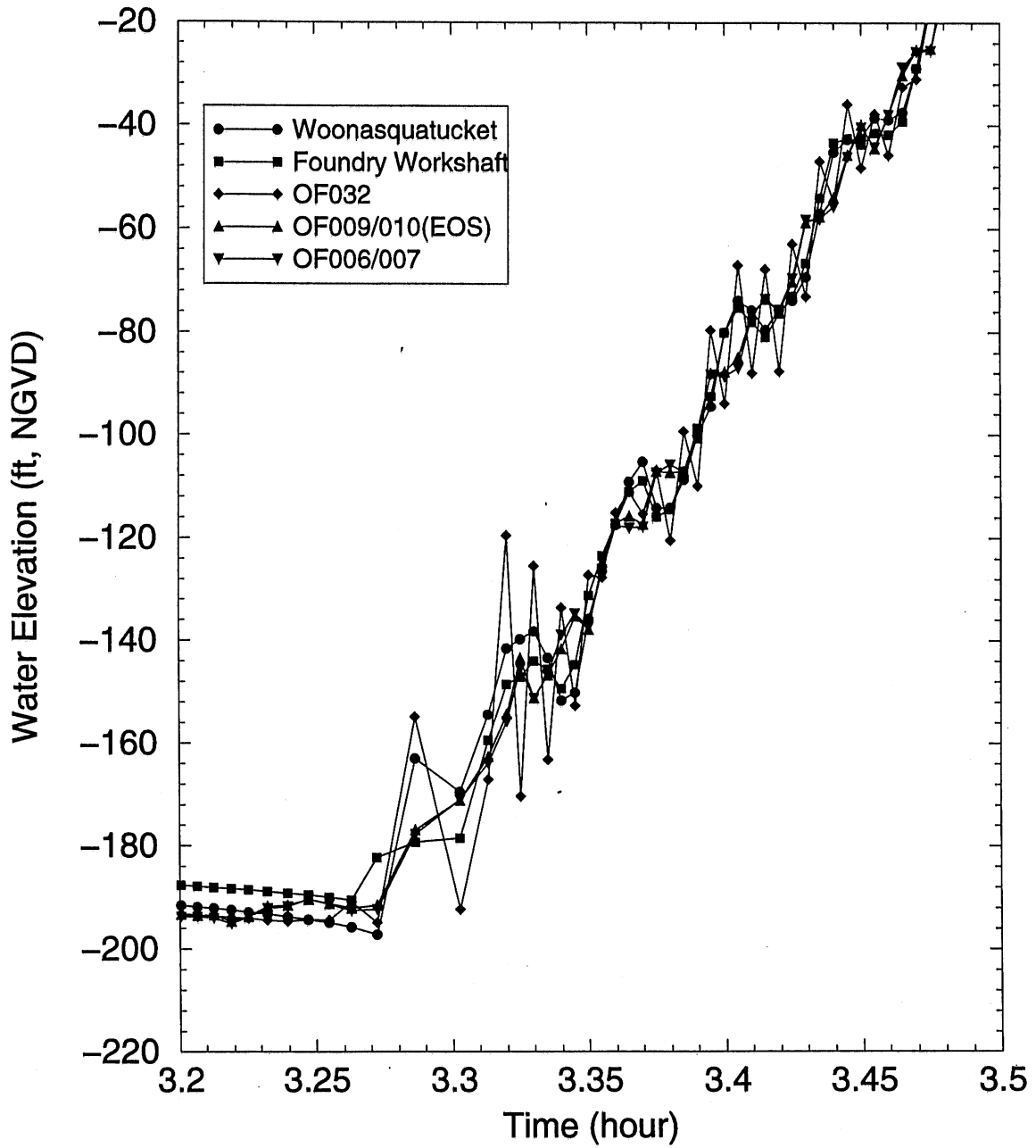


Fig. 16 More detailed water surface elevation variations with time when the tunnel first becomes full at the five upstream locations (Woonasquatucket, Foundry workshaft, OF032, OF009/010, and OF006/007), larger storm event (Case 2).

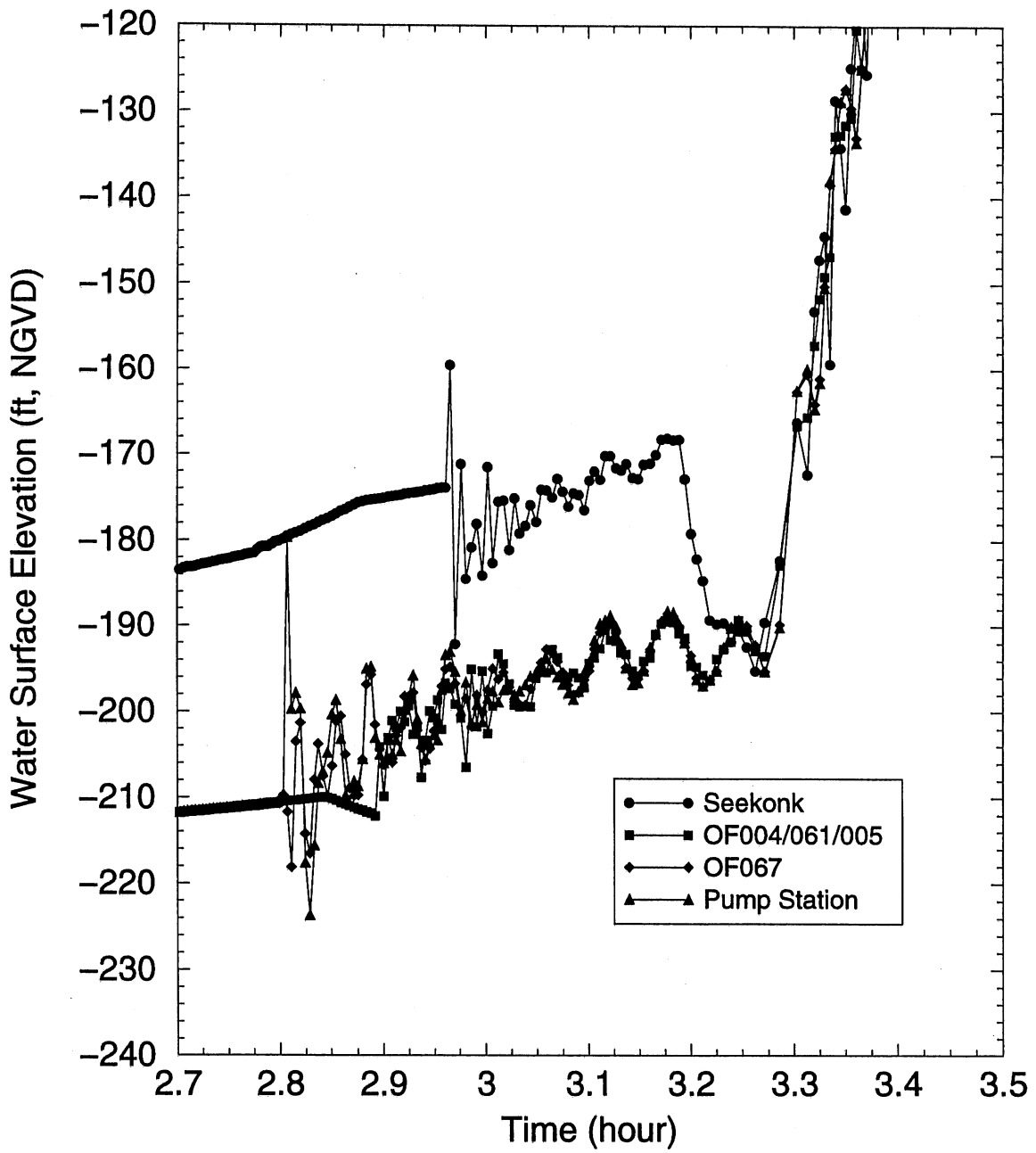


Fig. 17 More detailed water surface elevation variations with time when the tunnel first becomes full at the four downstream locations (Seekonk, OF004/005/061, OF067, and Pump station), larger storm event (Case 2).

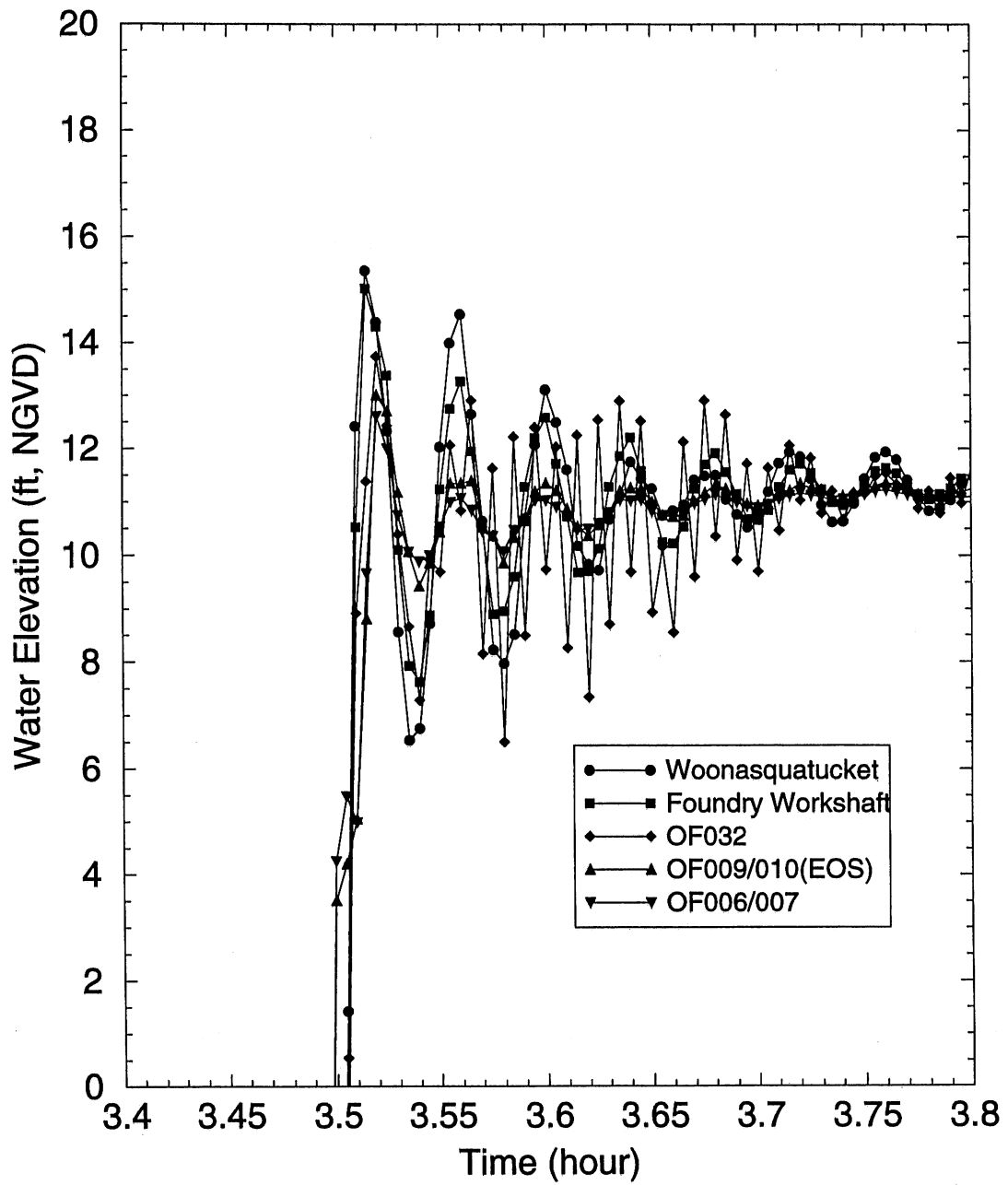


Fig. 18 More detailed water surface elevation variations with time during the overflowing stage at the five upstream locations (Woonasquatucket, Foundry workshaft, OF032, OF009/010, and OF006/007), larger storm event (Case 2).



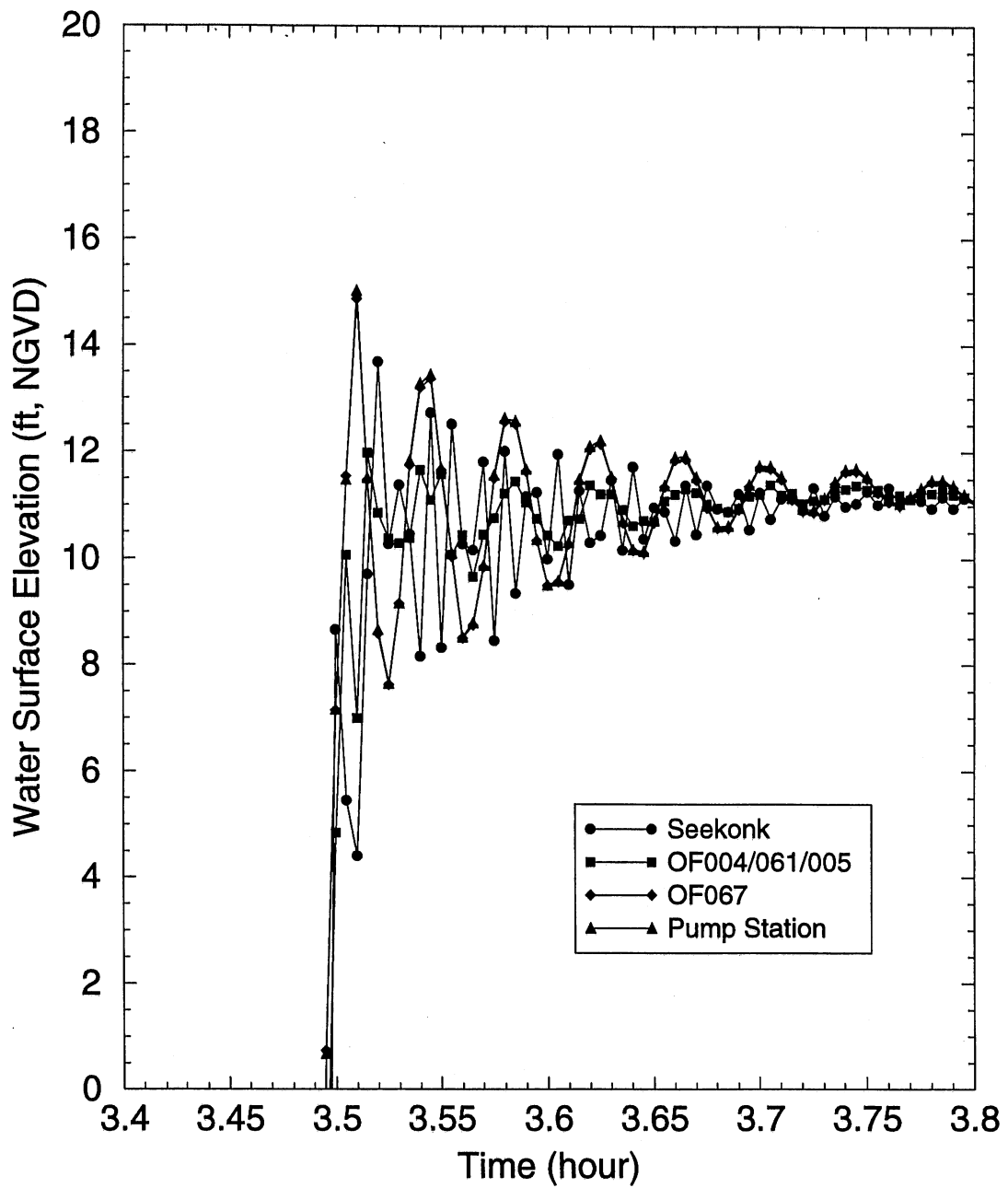


Fig. 19 More detailed water surface elevation variations with time during the overflowing stage at the four downstream locations (Seekonk, OF004/005/061, OF067, and Pump station), larger storm event (Case 2).

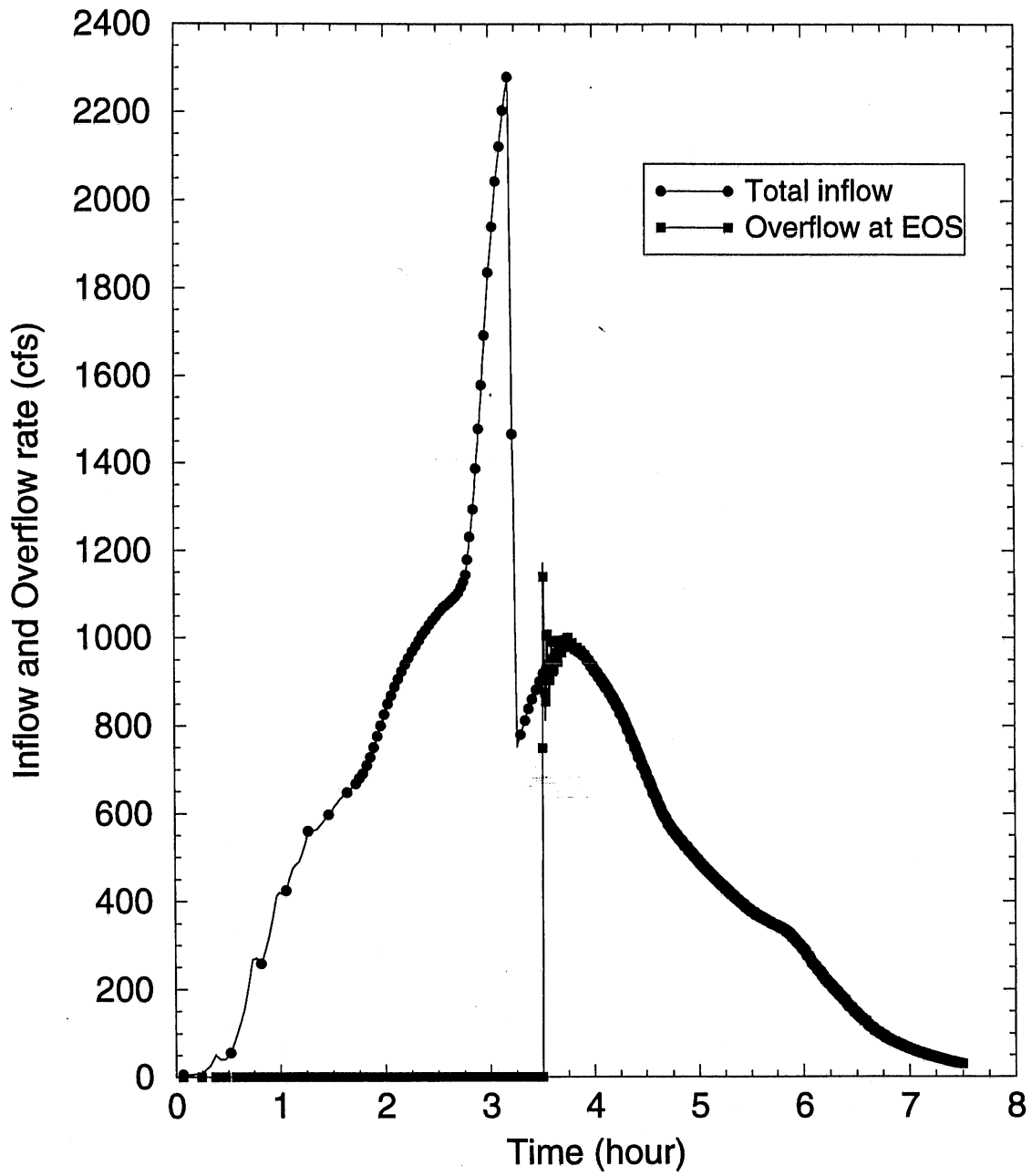


Fig. 20 The total inflow hydrograph to the tunnel system and the computed overflow from the EOS, larger storm event (Case 2).

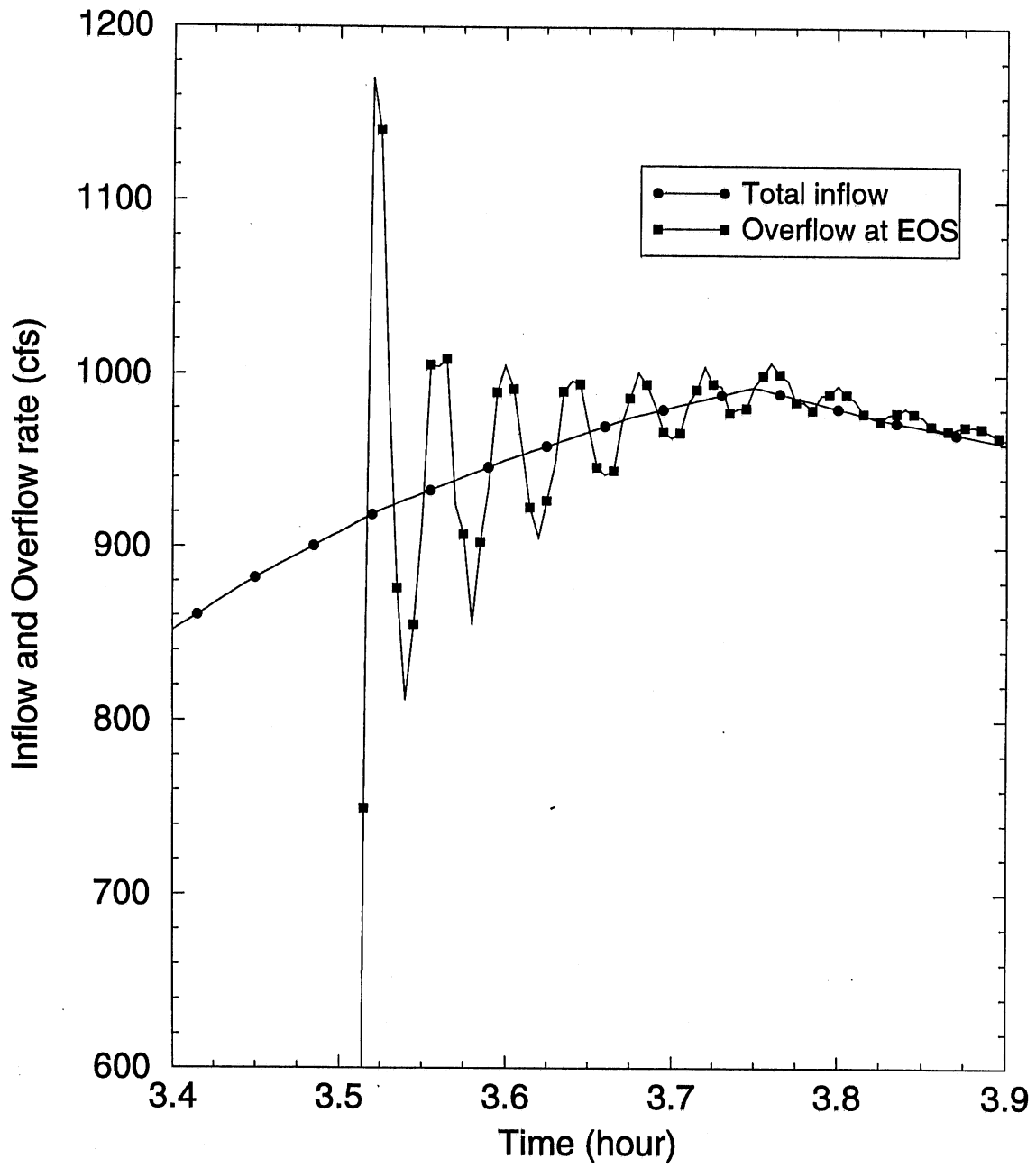


Fig. 21 More detailed overflow oscillations at the EOS, larger storm event (Case 2).

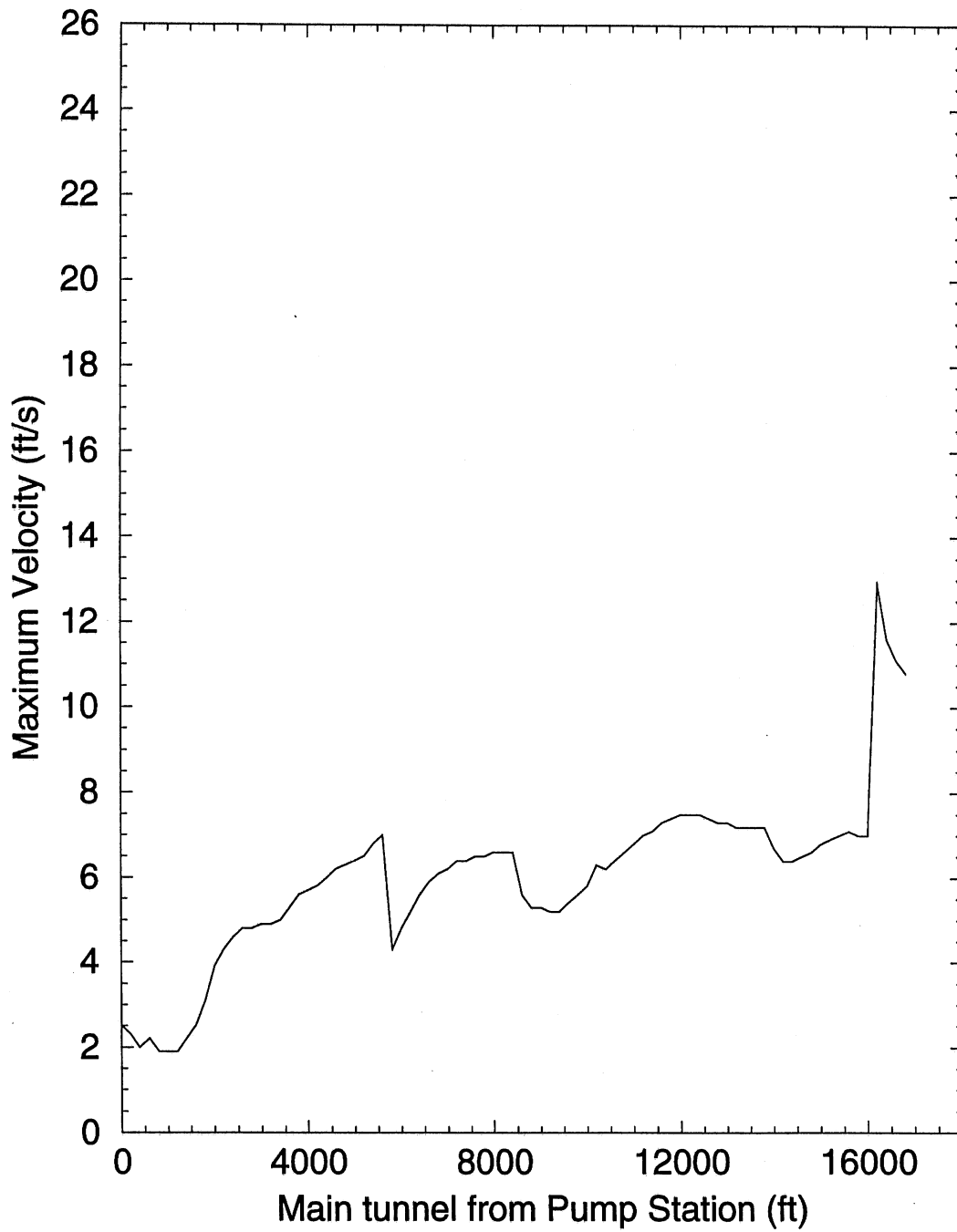


Fig. 22 Maximum flow velocity along the main tunnel from the Pumping station to the Woonasquatucket dropshaft, larger storm event (Case 2).