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Hydraulic Transient and Steady State Flow Analysis Using the WHAMO Model For the Chicagoland Underflow Plan (CUP) Evaluations

by

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ATTACHMENT:

WHAMO Modeling Simulations of "A – Live" Revision,

Chicagoland Underflow Plan McCook Reservoir, Illinois

By CDM Camp Dresser & Mckee, October 2000

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I. INTRODUCTION

The purpose of this work is to review the WHAMO transient flow model with the independent MIXTRAN model. The MIXTRAN model also provides necessary boundary conditions for WHAMO model. The WHAMO model was used to analyze the small tunnel filling and dewatering system associated with final design analysis regarding the Chicagoland Underflow Plan (CUP). The subcontractor, CDM International Inc., carried out the WHAMO analysis and prepared a Technical Memorandum, which is attached to this report. The WHAMO analysis results were reviewed by the primecontractor, St. Anthony Falls Laboratory, The University of Minnesota.

The primecontractor also analyzed two cases, case 5 and case 5B of CDM report, using the MIXTRAN model and compared the results with that of the WHAMO model. Agreement between the results of WHAMO model and MIXTRAN model for these two cases is good.

II. GENERAL DESCRIPTION OF THE MODELS

WHAMO (water hammer and mass oscillation) model is a hydraulic transient flow model based on an implicit finite difference method. It applies to steady and unsteady fully pressurized closed conduit flows of various complexities and boundary conditions. In comparison, MIXTRAN model applies to more general steady and unsteady flows including, pressurized flows, free-surface flows and mixed flows in which two types of the flows coexist. MIXTRAN model is based on an explicit characteristic method. The shock surface, or the interface between pressurized flow and free-surface flow, is computed with the shock fitting method. The two methods should be expected to yield the same results when used to simulate a pressurized flow.

III. DESCRIPTION OF WHAMO ANALYSES CARRIED OUT BY CDM

CDM analyzed the pumping station system, the piping system downstream of the Mainstream Tunnel and the Des Plaines Tunnel but upstream of the sewage treatment plant and the Stage 1 McCook Reservoir, as shown in Figure 1 of the CDM report. They classified their analysis into groups as described below.

3.1 Operational Simulations

Six worst case scenarios, Case 1 to Case 6 were simulated. First four cases deal with the water hammer due to power failure occurring under four different steady flow conditions. Immediately after the power failure, the discharge valves at the pump houses were assumed to be closed in 15 seconds while the water levels at both ends of the system were kept unchanged. The computed pressure head and discharge at some key locations were shown graphically. The simulated results appear reasonable.

Case 5 is about the transient flow due to valve closure (in 5 minutes) when water in Des Plaines Tunnel is flowing to McCook Reservoir by gravity. This case is also simulated with MIXTRAN model and the results are compared as described later. Case 6 is about the transient flow due to valve closure when water in Des Plaines Tunnel is being pumped to McCook Reservoir.

3.2 Transient Main Tunnel Head – Cases 1A, 1B and 1C

These are the same as Case 1 except that the water depth at Des Plaines Tunnel was assumed to vary with time. The variable water depth used as a boundary condition by WHAMO model was the water depth at the downstream end of Des Plaines Tunnel simulated by the MIXTRAN model under a design storm condition. The WHAMO model indicated that the changing water depth at Des Plaines Tunnel affects the pressure every where by the same amount. In other words, there is no dynamic effect. This result is reasonable because the events in the tunnels are slow events as compared with water hammer events in the pump station system.

3.3 Modified Reservoir Operating Range – Cases 3A, 4A, 5A and 6A

These cases test the effect of different boundary water levels on water hammer pressure for the Cases 3, 4, 5 and 6. For Cases 3A, 4A and 6A, the water level of the reservoir was increased by 30 feet. For Cases 4A and 6A, the water level at Des Plaines Tunnel was also increased by 30 feet. For Case 5A the discharge was also increased from that of

Case 5. Here again the increased water level only served to increase the hydro static pressure without changing the hydrodynamic pressure due to water hammer. This result also agrees with our experience and should be correct. The water hammer pressure for Case 5A is higher than that of Case 5 because the initial flow rate was higher. This result is also reasonable.

3.4 Modified Valve Operation – Cases 5B, 5C, 1D and 1E

Case 5B is the same as Case 5 except that the valve closure time was increased from 5 minuets to 10 minuets. This case is also simulated with MIXTRAN model and the results are essentially the same as that of WHAMO. An interesting conclusion is that maximum pressure for Case 5B is about the same as that of Case 5. This can be explained by the fact that the natural periods (water hammer as well as surge) of the system are shorter than the valve closure time so that the dynamic effect of valve closure is small. For case 5C the valve closure time is staggered such that only one valve was closed over the first 5 minuets, followed by closure of the other valve over the next 5 minutes. The results were not much different from that of Case 5B as should be expected.

Cases 1D and 1E are the same as Case 1 except that the closing time for the pump discharge valves is varied to 10 seconds and 20 seconds, respectively. It is somewhat surprising to see that the results are about the same as those of Case 1. Normally one would expect substantial differences in the water hammer pressure when a valve closure time is changed from 10 seconds to 20 seconds.

3.5 Flow From One Main Tunnel to Another

This section describes an attempt to simulate the accident during the storm event of June 1999, when the Des Plaines Tunnel dewatering valve chamber sustained structural damage. Eleven different scenarios were considered and the results tabulated, Table 7 of the CDM report. For all cases analyzed, the effect of air content was not considered. The boundary conditions used in the WHAMO model was provided by the MIXTRAN model by simulating the interconnected Mainstream and Des Plaines tunnel system. The valve closure operation in the WHAMO model was based on a normal valve closure procedure.

Earlier study using MIXTRAN model considered the effect of air content, which is known to affect the pressure wave speed. It assumed that one of the valve in the Des Plaines valve chamber was closed in such a way that the valve opening area decreased linearly with time. The maximum pressure generated in the system predicted by WHAMO model is substantially smaller than that predicted by the MIXTRAN model. One of the reasons of the apparent differences due to the fact that different valve closing procedure assumed. Linear closure procedure is known to produce larger pressure than an optimized closing procedure. Apparently, the June 1999 event involved valve malfunctioning causing the valve to close almost instantaneously.

3.6 Steady State Operational Simulations

Steady state WHAMO simulations were conducted to estimate pumping capacity for a range of tunnel and reservoir stages. The results appear reasonable.

IV. SELECTED TESTS WITH MIXTRAN MODEL

4.1 Hydraulic Transients in the Interconnected Mainstream and Des Plaines Tunnel

The purpose of this run is to provide the information on the boundary conditions to be used by WHAMO model to analyze the effect of Tunnel Transients on the transients of pump station system. The filling process of the interconnected tunnels during a design storm condition was simulated. In the design storm, the peak inflow rate at each dropshaft is given using the design data for the tunnel systems, which are provided by the Metropolitan Water Reclamation District of Greater Chicago. Their distribution pattern is chosen based on the storm event of Oct. 18, 1985, in the same area. Fig. 1 shows the schematic of the Mainstream tunnel and Des Plaines tunnel for modeling purposes. Fig. 2 shows the changing water level at the ends of the two tunnels during the storm. Some instantaneous hydraulic grade lines in the tunnels are shown in Figs. 3 and 4 to indicate the filling process. The results were given to CDM to be used for the WHAMO analysis.

4.2 Simulation of Case 5

This is a case when the flow is going from Des Plaines Tunnel to McCook Reservoir by gravity and all valves associated with pumps are closed. Therefore, only the system directly connecting the reservoir to the Des Plaines Tunnel is isolated from the rest of the system and modeled. This simplified system is shown in Fig. 5. The boundary conditions are set the same as that of WHAMO model Case 5 and the valves V9 and V10 are closed in 5 minuets. The simulated water elevations at Nodes 1400(Des Plaines Tunnel), 400(Mainstream Tunnel), 2050(the junction between DSP and MS tunnels) and 2150(the bifurcation before the reservoir dewatering valves V9&V10) are shown in Fig. 6. The corresponding discharge at Node 1400 is shown in Fig. 7. When these figures are compared with the figures in the CDM report, it is clear that the results of the two models are quite similar.

4.3 Simulation of Case 5B

This case is the same as Case 5 except that the valve closure time is increased to 10 minuets. The results are shown in Figs. 8 and 9. These results are also seen to be essentially the same as the results of WHAMO model.

V. CONCLUSIONS

Following list of conclusions are offered based on the analysis described above.

1) WHAMO model, being based on one-dimensional dynamic equations of hydraulic transient flows, appears to be capable of simulating steady and unsteady pressurized flows accurately. Since the pump station system normally operates at pressurized condition, WHAMO model is suitable to the system. However, WHAMO model cannot be used for free-surface flows or mixed flows conditions.

2) For two cases selected for comparison, Cases 5 and 5B, the results of WHAMO model agree with the results of MIXTRAN model.

3) For most simulation purposes, the tunnel model and the pump station model need not be coupled. This is because the characteristic time of one system is much different from that of the other.

4) The impact force generated by the valve closure in the Des Plaines valve chamber during the failure event in June 1, 1999 is dependent on the valve closure time, and the wave speed, which is related to the air content in the storm sewer water. For a normal condition, it is assumed that the air content in water is about 0.5% to 2% (wave speed: a= 400 to 1000 ft/s) for a large storm event. If the first valve was slammed shut, the potential impact force,

$$F=aV/g=1.66a$$

Wave speed (ft/s)	400	1000	2000	3000	4000
Impact Force (ft)	664	1660	3320	4980	6640

In a normal valve closure operation, the valve operation procedure is also a very important factor to affect the impact force. WHAMO model was based on the standard valve closure procedure, while the earlier study using the MIXTRAN model used a linear valve opening (area) change with time. As a result, the impact forces based on WHAMO model are smaller than those using the MIXTRAN model when the first valve was not slammed shut.

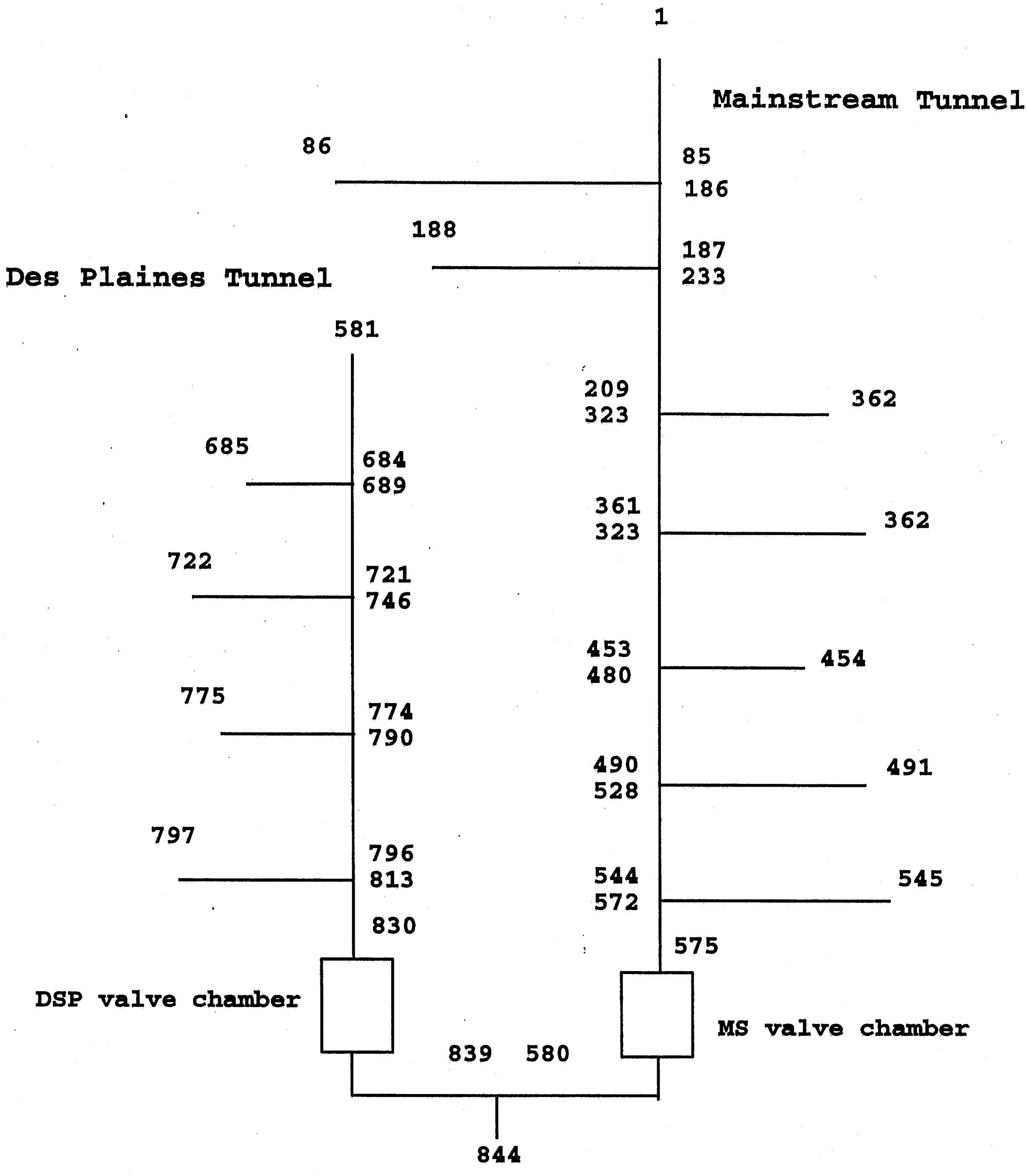

Fig. 1 Schematic of the Mainstream tunnel and Des Plaines tunnel systems for modeling purpose

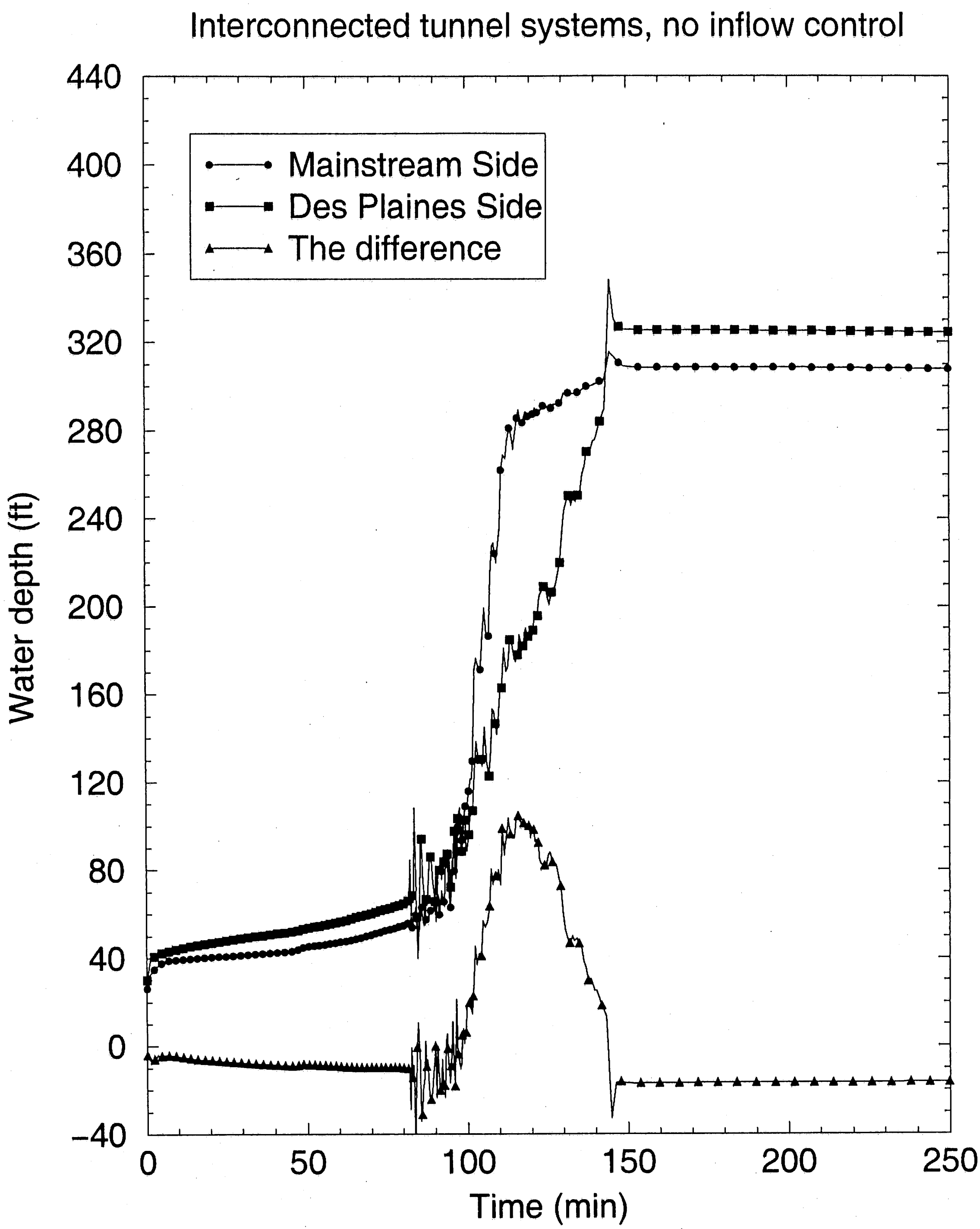

Fig. 2 Water depth changes with time at the Mainstream tunnel valve chamber and the Des Plaines chamber, and their difference.

Interconnected MS tunnel, No inflow control

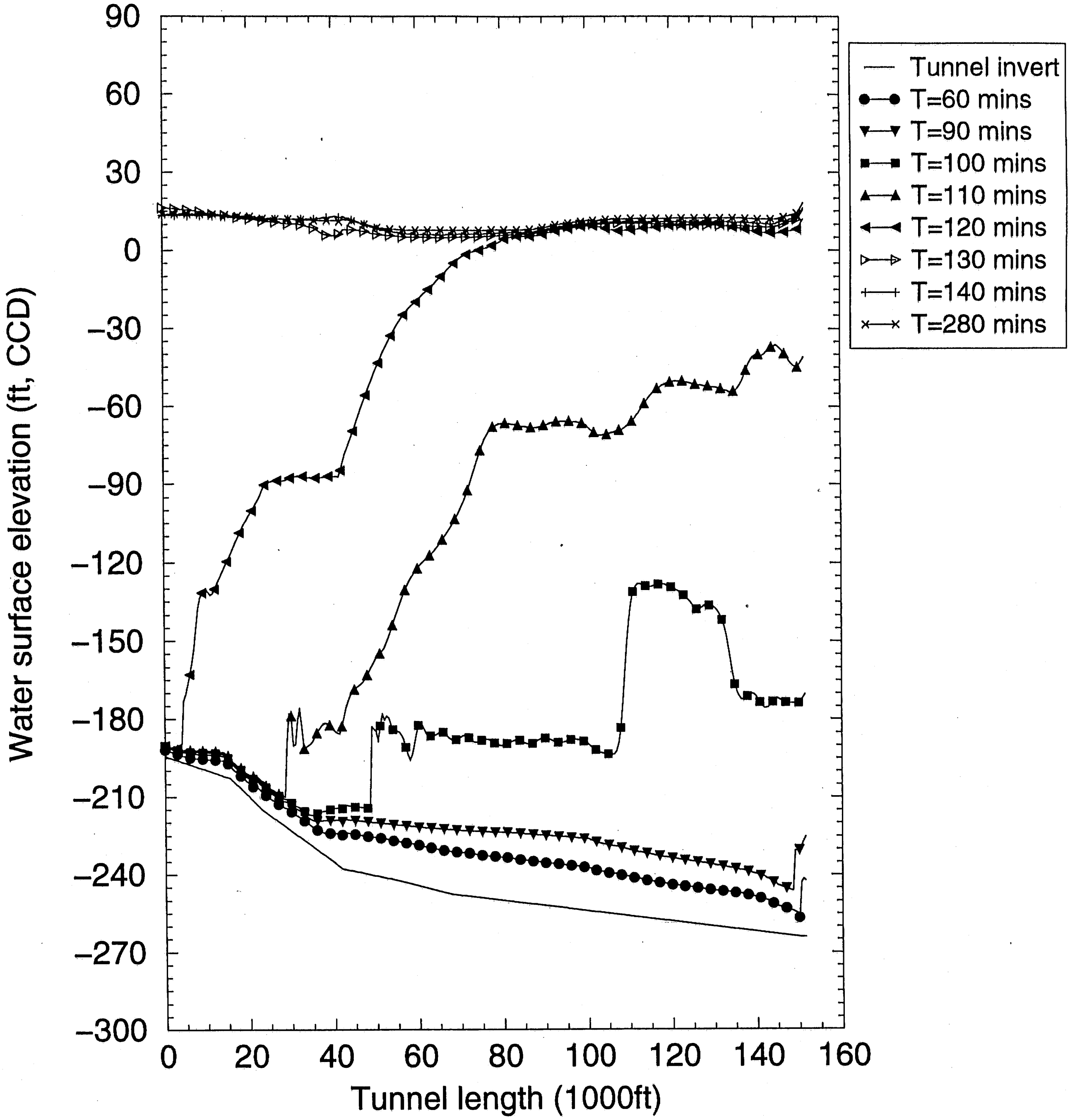

Fig. 3 Instantaneous hydraulic grade lines along the Mainstream tunnel.

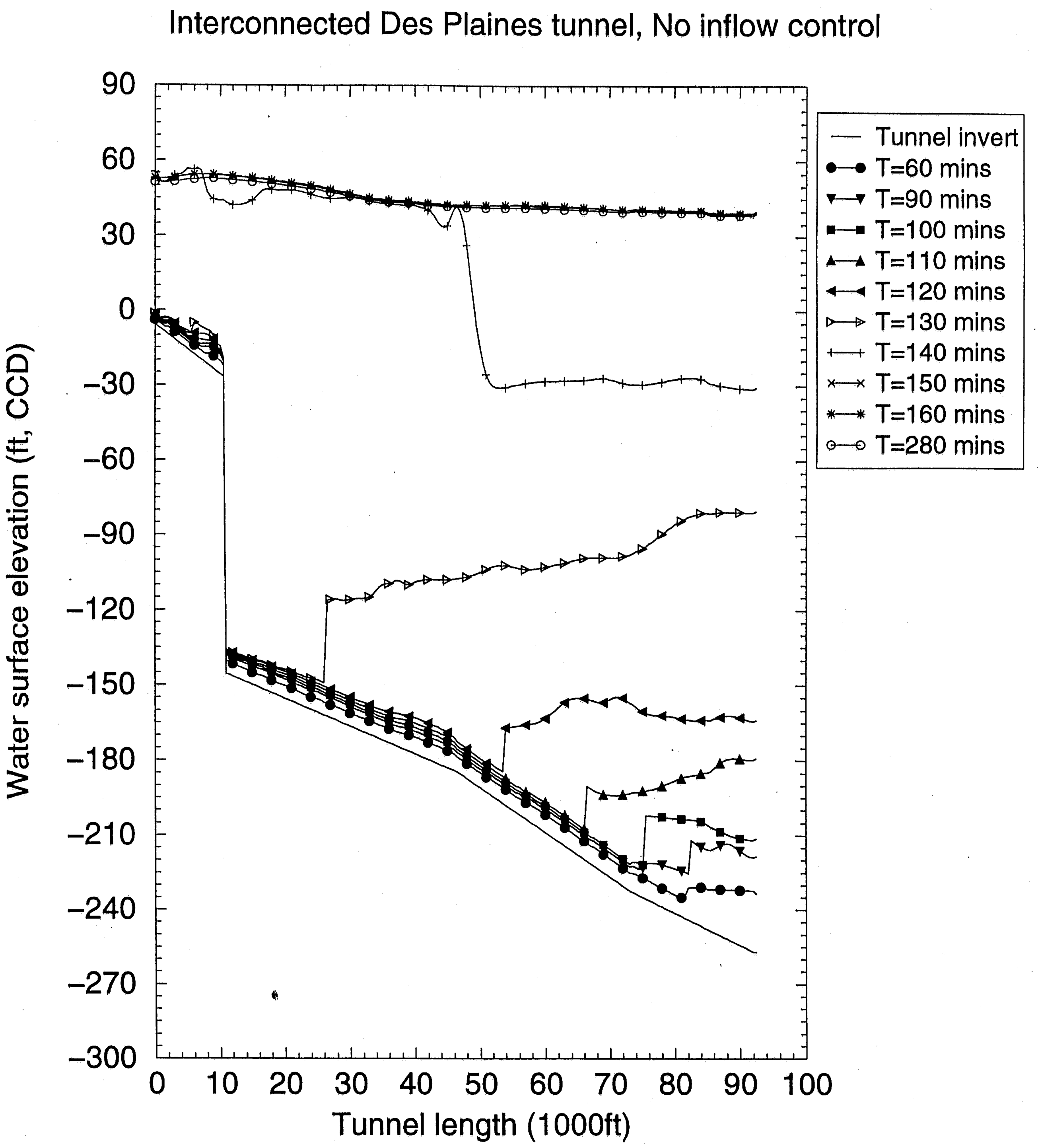

Fig. 4 Instantaneous hydraulic grade lines along the Des Plaines tunnel.

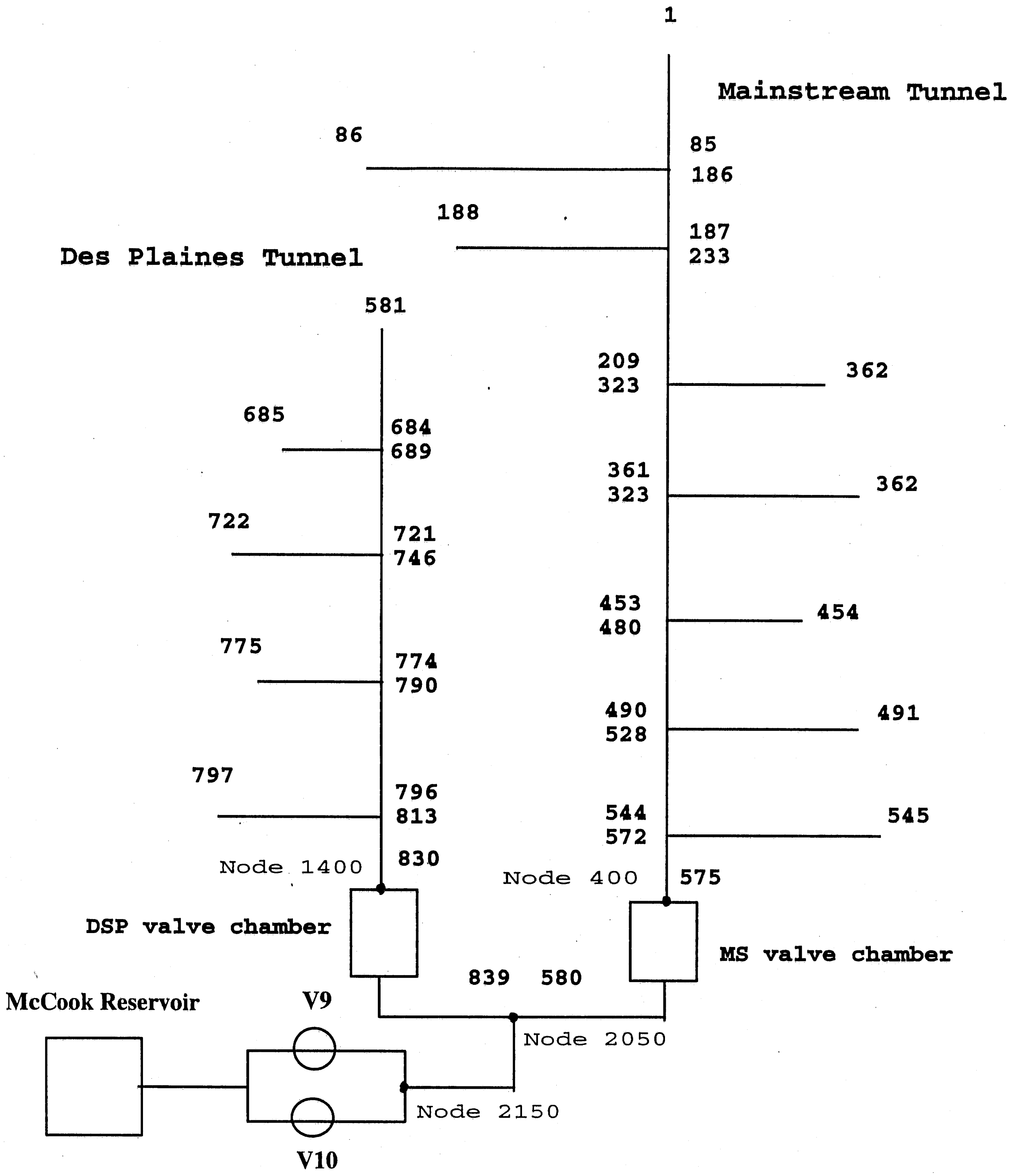

Fig. 5 Schematic of the Mainstream tunnel and Des Plaines tunnel systems with the McCook Reservoir for modeling purpose

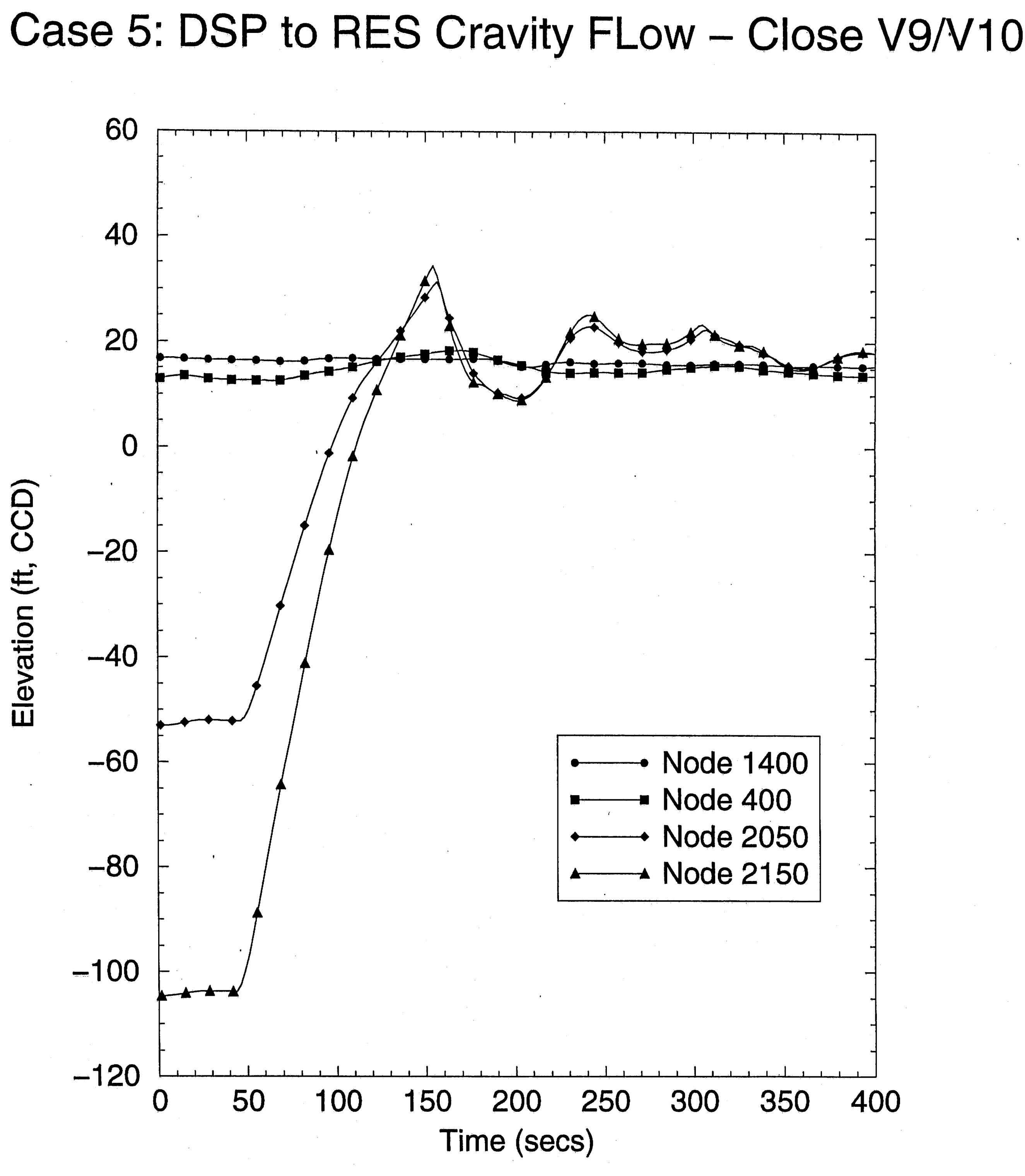

Fig. 6 Water elevation variations with time at four locations (Node 1400, Node 400, Node 2050, and Node 2150 of the WHAMO model), valve closure time = 300 seconds (Case 5 of the WHAMO simulations).

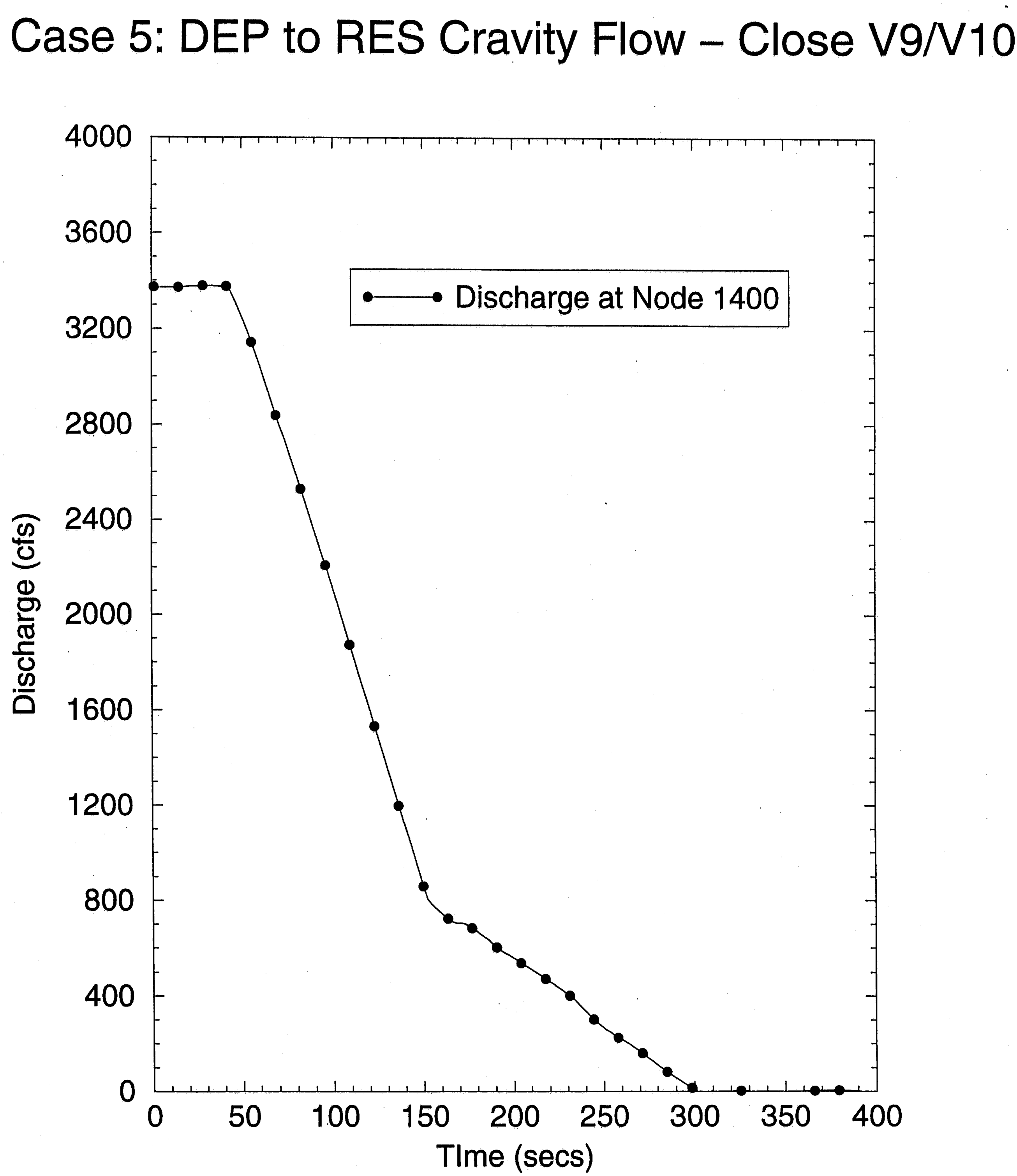

Fig. 7 Flow rate change from the DSP tunnel to the McCook reservoir, valve closure time = 300 seconds (Case 5 of the WHAMO simulations).

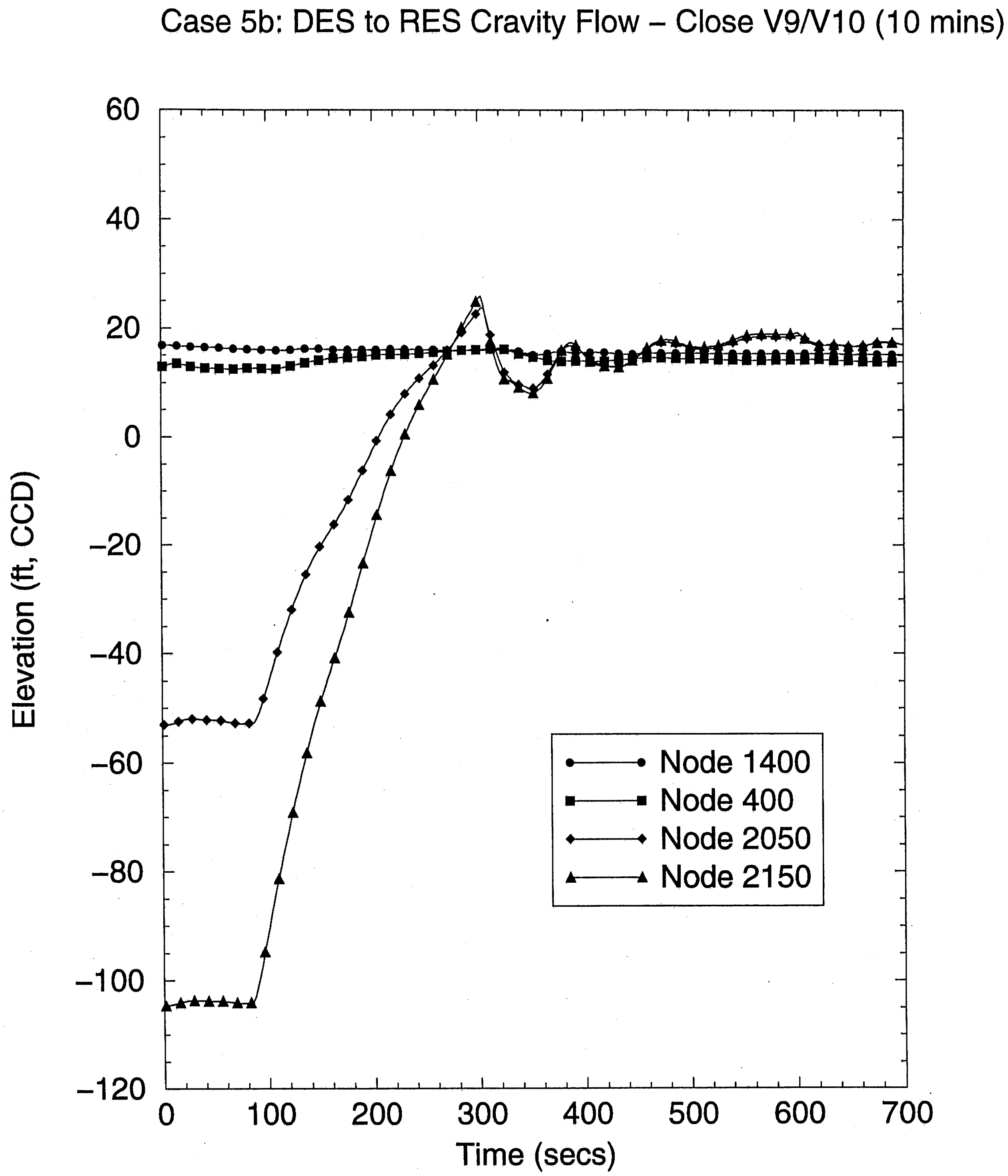

Fig. 8 Water elevation variations with time at four locations (Node 1400, Node 400, Node 2050, and Node 2150 of the WHAMO model), valve closure time = 600 seconds (Case 5b of the WHAMO simulations).

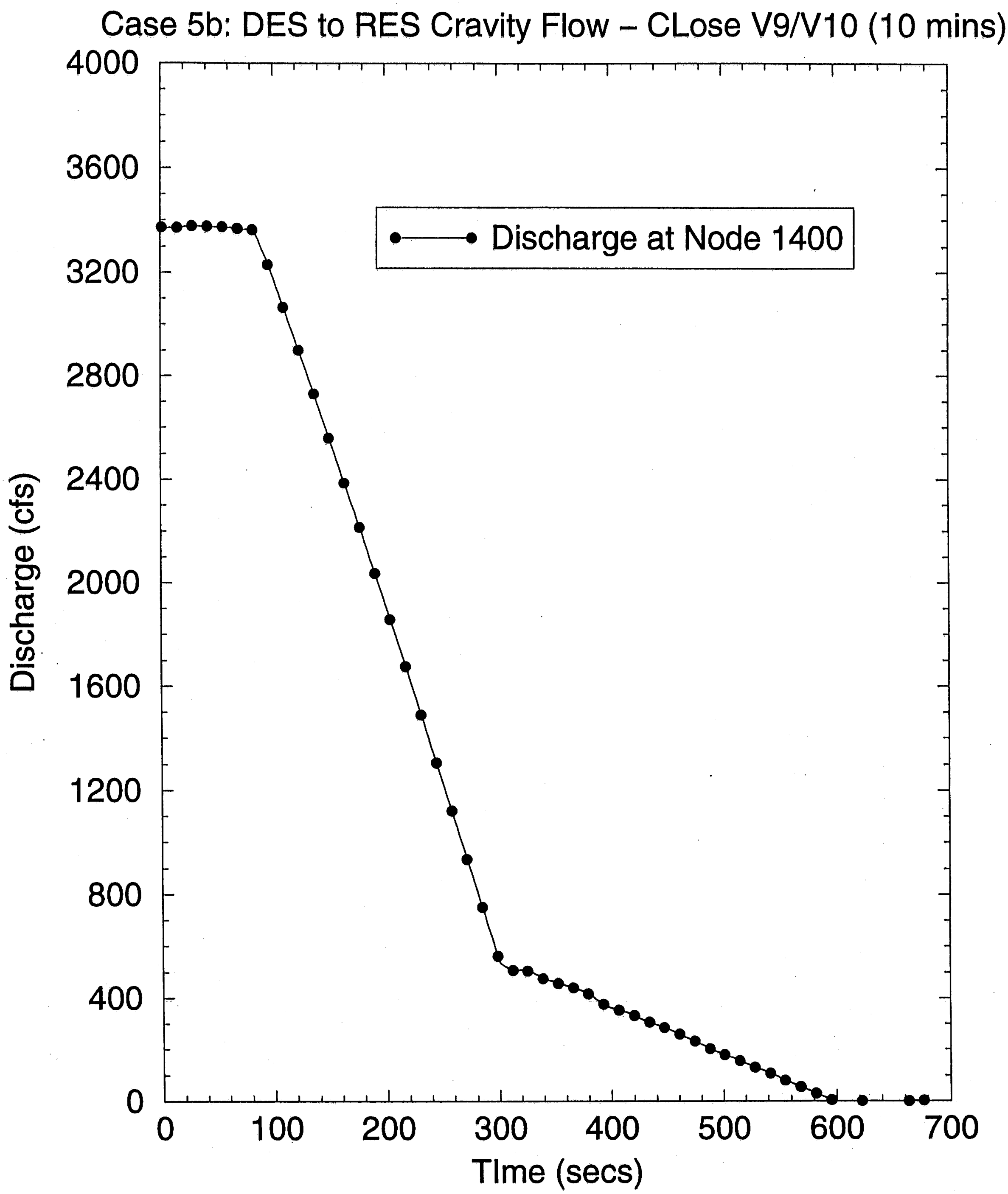

Fig. 9 Flow rate change from the DSP tunnel to the McCook reservoir, valve closure time = 600 seconds (Case 5b of the WHAMO simulations).