Evaluating Surge Potential in CSO Tunnels

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Tunnels are being proposed to control combined sewer overflow (CSO) in numerous cities in the United States and Canada. The tunnels are intended to capture and store CSO for later dewatering to a wastewater treatment plant (WWTP). These tunnel systems may also provide relief to the interceptor system and transport the captured CSO to a downstream interceptor, pumping station or WWTP.

When a CSO tunnel is filled slowly, the surge waves that are created intuitively are small and there is no established guidance as to the breakpoint filling rate required to create significant surges. In this chapter, some guidance is provided that relates the surging potential to tunnel diameter, tunnel slope and the maximum filling rate expected. These results may be used as a screening tool to decide whether surges and surge control measures need to be evaluated in further detail for proposed CSO tunnel projects. The surge modeling results are not intended to be used to provide absolute answers of potential surge heights. Also, ventilation requirements to prevent geysering should be considered and have been studied by others (Vasconcelos, 2005).

Rapid filling of CSO tunnels, such as from large and intense rain storms, can result in surges, in pockets of air being trapped and pressurized, and in geysers occurring to grade at tunnel manholes and shafts. When open channel conditions exist and the filling creates a pipe filling bore, surges can rise to unacceptably high levels (including grade) which can cause basement flooding, damage structures, and spill sewage to the environment. Surge control measures that are commonly considered for CSO tunnels include

orifices on connections that limit the peak filling rates and inlet gates that close once the tunnel reaches a target part full level. Surge relief can also occur through tunnel outfalls or into surge tanks.

The Transient Analysis Program (TAP) was used to simulate worst-case surge conditions in hypothetical tunnel systems and develop relationships that provide the breakpoint filling rates below which the potential for surges is small. TAP has been shown to be a proper computational hydraulics program for simulating surges in one-dimensional pipelines and TAP model results have compared favorably with laboratory surge data (Ridgway and Kumpula, 2006, 2007). TAP is useful in analyzing water supply, storm water, drainage, irrigation, combined sewer, sanitary sewer systems, and does an excellent job of calculating detailed steady-state gradually-varied flow profiles through channels/conduits and water/wastewater treatment facilities. TAP can be used to simulate flood routing in open channel/conduit systems as well as evaluate operation and control schemes.

14.1 TAP Model Set-Up

Sets of TAP model runs were made for a range of hypothetical CSO tunnels with three diameters, three design slopes, and a range of initial sewage levels and filling rates. From these runs, the maximum surge levels were calculated, tabulated, and plotted so relationships between the tunnel diameter, tunnel slope, filling rate, initial sewage level and maximum surge level were observed.

A hypothetical CSO tunnel model was created using TAP. There was one tunnel segment in the model with a riser shaft at the upstream end and an overflow shaft at the downstream end as shown on Figure 14.1.

Figure 14.1 TAP model schematic.

A filling hydrograph was introduced at the overflow shaft to generate surges at the riser shaft. A higher level outfall conduit with free discharge to a water body (such as a river) also was connected to the overflow shaft. The filling rate was linearly increased to a maximum value over ten seconds and held at the maximum flow rate over the remainder of the model run. Sensitivity model runs were made which show that the maximum surge level reached and the breakpoint filling rate were not significantly influenced by the ramp time.

Surges were calculated and the maximum surge levels that were predicted at the riser shaft were taken from the results. Model runs were made with varying initial (static) levels in the tunnel in order to determine the initial level that provides the maximum surge level for each filling rate.

The highest surges were predicted when the tunnel was partly full, rapid filling occurs and a pipe filling bore that moves in an upslope direction toward the riser shaft was formed. When the pipe filling bore reached the riser shaft, a rapid rise or surge in level occurred. The surge was then reflected back downstream as an open or closed conduit wave.

Three alternative TAP model set-ups were made as given on Table 14.1. The crown elevation of the tunnel at the riser shaft was held at elevation 120 ft (36.6 m) for all three model set-ups and the three tunnel slopes evaluated. The overflow elevation to the river was 130 ft (39.6 m) for all three set-ups and all three slopes.

Table 14.1 TAP model set-up parameters.

Alternative	Tunnel Diameter (ft)	Riser Shaft Invert Elevation (ft)	Overflow Conduit Dimensions (ft)
1	10	110	10H by 10W
2	20	100	10H by 40W
3	30	90	10H by 90W

14.2 10 ft (3.05 m) Diameter Tunnel

A hypothetical CSO tunnel system with a 10 ft (3.05 m) diameter tunnel and slope of 0.1% was created using TAP. The riser and overflow shaft diameters were set at 15 ft (4.57 m) which is 1.5 times the tunnel diameter. The outfall conduit width was set at 10 ft (3.05 m). A tunnel profile is shown in Figure 14.2. The filling rates were varied from 25 to 1000 cfs (708 to 28320 L/s).

The initial levels were first set at 130 ft (39.6 m), which was overflow elevation at the downstream end of the tunnel, and were subsequently dropped at constant intervals of 0.5 ft (0.152 m) until the maximum surge level was determined for each filling rate.

The maximum surge level results are plotted on Figure 14.3 along with the final steady-state level and initial level that produced the maximum surge level. For lower filling rates, the maximum surge level occurred with a surcharged initial level, but there also was a nearly full open channel initial level that provided a similar maximum surge result.

As shown on Figure 14.3, the maximum surge level and the steady-state level increase with the filling rate, and the maximum surge level is relatively small below a breakpoint filling flow rate. The breakpoint filling rate occurred at about 200 cfs (5660 L/s). For filling rates below this breakpoint, the maximum surge level at the riser shaft results from closed conduit transients.

The effect of tunnel slope on the breakpoint filling rate was then determined. Additional TAP model runs were made for two different tunnel slopes, 0.05% and 0.2%, with filling rates around the breakpoint filling rate of 200 cfs (5660 L/s). This limited the number of model runs required, but still allowed the new breakpoint filling rates to be found. The breakpoint filling rates are about 220 and 180 cfs (6230 and 5100 L/s) for tunnel slopes of 0.05% and 0.2%, respectively.

Figure 14.2 Hypothetical 10 ft (3.05 m) diameter tunnel at 0.1% slope.

Figure 14.3 Results for 10 ft (3.05 m) diameter tunnel at 0.1% slope.

14.3 20 ft (6.1 m) Diameter Tunnel

A hypothetical CSO tunnel system with a 20 ft (6.10 m) diameter tunnel and slope of 0.1% was created using TAP. The riser and overflow shaft diameters were set at 30 ft (9.14 m) which is 1.5 times the tunnel diameter. The outfall conduit width was set at 40 ft (12.2 m) since a 20 ft (6.10 m) diameter tunnel has about four times the capacity of a 10 ft (3.05 m) diameter tunnel. A tunnel profile is shown in Figure 14.4. The filling rates were varied from 100 to 4000 cfs (2830 to 113000 L/s).

The initial levels were started at 130 ft (39.6 m), which is overflow elevation at the downstream end of the tunnel, and were dropped at constant intervals of 1 ft (0.305 m) until the maximum surge level was determined for each filling rate.

The maximum surge level results are plotted on Figure 14.5 along with the final steady-state level and initial level that produced the maximum surge level. For lower filling rates, the maximum surge level occurred with a surcharged initial level, but there also was a nearly full open channel initial level that provided a similar maximum surge result.

As shown on Figure 14.5, the maximum surge level and the steady-state level increase with the filling rate, and the maximum surge level is relatively small below a breakpoint filling flow rate. The breakpoint filling rate occurs at about 880 cfs (24900 L/s). For filling rates below this breakpoint, the maximum surge level at the riser shaft results from closed conduit transients.

The effect of tunnel slope on the breakpoint filling rate was then determined. Additional TAP model runs were made for two different tunnel

slopes, 0.05% and 0.2%, with filling rates around the breakpoint filling rate of 880 cfs (24900 L/s). This limited the number of model runs required, but still allowed the new breakpoint filling rates to be found. The breakpoint filling rates are about 920 and 810 cfs (26000 and 22900 L/s) for tunnel slopes of 0.05% and 0.2%, respectively.

Figure 14.4 Hypothetical 20 ft (6.10 m) diameter tunnel at 0.1% slope.

Figure 14.5 Results for 20 ft (6.10 m) diameter tunnel at 0.1% slope.

14.4 30 Ft (9.14 m) Diameter Tunnel

A hypothetical CSO tunnel system with a 30 ft (9.14 m) diameter tunnel and slope of 0.1% was created using TAP. The riser and overflow shaft diameters were set at 45 ft (13.7 m) which is 1.5 times the tunnel diameter.

The outfall conduit width was set at 90 ft (27.4 m) since a 30 ft (9.14 m) diameter tunnel has about nine times the capacity of a 10 ft (3.05 m) diameter tunnel. A tunnel profile is shown in Figure 14.6. The filling rates were varied from 100 to 9000 cfs (2830 to 254900 L/s).

The initial levels were started at 130 ft (39.6 m), which is overflow elevation at the downstream end of the tunnel, and were dropped at constant intervals of 1 ft (0.305 m) until the maximum surge level was determined for each filling rate.

The maximum surge level results are plotted on Figure 14.7 along with the final steady-state level and initial level that produced the maximum surge level. For lower filling rates, the maximum surge level occurred with a surcharged initial level, but there also was a nearly full open channel initial level that provided a similar maximum surge result.

As shown on Figure 14.7, the maximum surge level and the steady-state level increase with the filling rate, and the maximum surge level is relatively small below a breakpoint filling flow rate. The breakpoint filling rate occurs at about 2100 cfs (59500 L/s). For filling rates below this breakpoint, the maximum surge level at the riser shaft results from closed conduit transients.

The effect of tunnel slope on the breakpoint filling rate was then determined. Additional TAP model runs were made for two different tunnel slopes, 0.05% and 0.2%, with filling rates around the breakpoint filling rate of 2100 cfs (59500 L/s). This limited the number of model runs required, but still allowed the new breakpoint filling rates to be found. The breakpoint filling rates are about 2200 and 1840 cfs (62300 and 52100 L/s) for tunnel slopes of 0.05% and 0.2%, respectively.

Figure 14.6 Hypothetical 30 ft (9.14 m) diameter tunnel at 0.1% slope.

Figure 14.7 Results for 30 ft (9.14 m) diameter tunnel at 0.1% slope.

14.5 Breakpoint Filling Rates

The breakpoint filling rate results are given in Table 14.2. These results show that the breakpoint filling rate increases with tunnel diameter nearly in proportion to the diameter squared. This result is expected based on dynamic similarity. Also, the breakpoint filling rate is higher for milder sloping tunnels.

Table 14.2 Breakpoint filling rate data.

Tunnel Diameter (feet)	Breakpoint Filling Rate (cfs) Versus Tunnel Slope		
	S = 0.05%	S = 0.1%	S = 0.2%
10 (3.05 m)	220 (6230 L/s)	200 (5660 L/s)	180 (5100 L/s)
20 (6.10 m)	920 (26100 L/s)	880 (24900 L/s)	810 (22900 L/s)
30 (9.14 m)	200 (62300 L/s)	2100 (59500 L/s)	1840 (52100 L/s)

The breakpoint filling rate data is plotted on Figure 14.8. The best-fit equation for the breakpoint filling rate versus tunnel diameter for a 0.1% tunnel slope is given as follows.

$$Q = 2.7 * D^2 - 13 * D + 60 \quad (14.1)$$

where:

D = Tunnel Diameter (in feet), and
Q = Breakpoint Filling Rate (in cfs).

Figure 14.8 Breakpoint flow rate versus tunnel diameter and slope.

14.6 Conclusions

Worst-case surge potential in CSO tunnels is shown to be related to tunnel diameter, tunnel slope, and the maximum filling rate expected. If the maximum filling rate expected for a CSO tunnel project is small relative to the tunnel diameter, the potential for creating strong surges is shown to be small and detailed surge analyses may not be needed. For filling rates below the breakpoint, no strong pipe filling bore can be created and the maximum surge occurs from closed conduit transients. For filling rates above the breakpoint, a pipe filling bore may be created and detailed surge analyses are recommended to be made and surge control measures may need to be evaluated and included in the CSO tunnel project.

References

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