Leadership in Sustainable Infrastructure
Leadership en Infrastructures Durables

Vancouver, Canada
May 31 – June 3, 2017/ *Mai 31 – Juin 3, 2017*

TUNNEL REPLACEMENT PROJECT: MORPHODYNAMIC MODELLING OF TRENCH MIGRATION

Robb, Daniel M.[1], Gellis, Matt S.[1,2], Vasquez, Jose A.[1] and Wang, Edwin C.[1]
[1] Northwest Hydraulic Consultants Ltd., Canada
[2] mgellis@nhcweb.com

Abstract: A highway tunnel passing under the main channel of the Lower Fraser River in British Columbia, Canada is nearing the end of its design life. Replacement with a new bridge has been proposed. The project includes decommissioning and removing the in-river segments of the tunnel. Preliminary plans do not propose backfilling after tunnel removal. This would result in a trench feature in the riverbed approximately 630 m long, 95 m wide, and 8 m deep. The tunnel is in a tidally-influenced reach of the river 5 km upstream from the sea. Because of the complex tidal conditions at the site, it was not feasible to assess the fate of the trench using analytical methods, especially the possibility that the trench could migrate upstream. In this paper, we use a three-dimensional hydrodynamic-morphodynamic model to investigate the alluvial channel response to the removal of the tunnel. The model used in the present study accounts for non-equilibrium effects; that is, the sediment concentration profile in the vertical direction does not adapt instantaneously to spatial and temporal changes in the flow. Non-equilibrium effects can influence the morphological evolution of a submerged trench. To validate the model, numerical results were first compared to existing experimental data from flume experiments on the morphodynamic development of dredged trenches. The numerical results agreed well with the experimental data over a range of initial trench dimensions. The model was then used to predict the morphological evolution of the trench resulting from the removal of the tunnel. The model results suggest that the trench will migrate downstream and will fill in within one or two freshet seasons.

1 INTRODUCTION

The highway tunnel analysed in this paper passes under the main channel of the sand-bedded Lower Fraser River between the municipalities of Richmond and Delta in British Columbia, Canada. During construction, each tunnel segment was floated into place and sunk into a shallow trench spanning the crossing. Since the tunnel is nearing the end of its useful life, replacement with a new bridge and removal of the in-river tunnel segments has been proposed. Decommissioning and removing the tunnel segments will result in a trench feature in the riverbed approximately 630 m long, 95 m wide, and 8 m deep. This study focuses on estimating the morphological evolution of the trench resulting from the removal of the tunnel.

The tunnel is in a tidally-influenced reach approximately 5 km upstream from where the river flows into the sea. The reach consists of deltaic distributary channels influenced by mixed semi-diurnal tides. Full flow reversal occurs in the winter months. Due to tidal effects, there was also the possibility that flow reversal would cause the trench to migrate upstream. To assess the fate of the trench, it is first important to correctly predict the hydraulic and morphological conditions in the study area. The complex tidal conditions present a challenge for many mathematical and numerical models. The problem is further complicated by the trench itself. The shape of the trench results in a relatively abrupt change in bed topography, which causes the sediment transport to be out of equilibrium with the flow conditions.

Early studies on trench migration proposed mathematical models for a few idealized cases (Galappatti and Vreugdenhil 1985; Lean 1980; Miles 1981). These studies focused on steady 1D or 2D approximate analytical solutions. For more complicated cases, involving flow reversal and tidal influence, these solutions have limited applicability. As a result, numerical models are often used for evaluating the hydraulic and morphological behaviour important for environmental assessment, navigation planning, and maintenance dredging in estuarine settings.

Experimental studies of trench migration have investigated bed evolution, velocity distribution and sediment concentration profiles (DHL 1980; Faraci et al. 2011; van Rijn 1986a; van Rijn 1986b). Many of these experimental studies produced datasets that have subsequently been used to validate numerical models. Of interest to this paper are sand-bed flume experiments described in van Rijn (1986a), in which suspended load was the dominant sediment transport mechanism. The bed evolution measurements from these experiments are used to validate the numerical model in this study.

Most river and coastal sediment transport models assume the bedload and suspended load are instantaneously in local equilibrium on each computational node (Sánchez and Wu 2011). That is, the vertical sediment concentration profile is assumed to adapt instantaneously to any spatial or temporal changes in the flow regime. As a result, the sediment flux between the bed and the water column is governed solely by the difference between the concentration of sediment in the water column and the equilibrium sediment concentration on the bed. These models are referred to as equilibrium or capacity transport models. Equilibrium models are usually adequate when modelling processes dominated by coarse bedload transport, but they may perform poorly when the deposition of suspended load is important. Assuming an instantaneous response of the sediment concentration profile to changes in the flow is invalid in many cases, for example, when there are changes in the flow conditions such as tidal variation, flow deceleration over the upstream edge of a dredged channel, or flow acceleration through a constriction. Because of inertial effects, it takes time for the velocity profile and the sediment concentration profile to adjust to the new flow conditions.

The time for the suspended sediment to adjust to changes in the fluid velocity is referred to as a lag effect (Pritchard and Hogg 2003). In tidal systems, lag effects can result in the net flux of sediment over a tidal cycle in a direction over which there is no net flux of fluid. Lag effects can, therefore, introduce a hysteresis in sediment concentrations over a tidal cycle. Furthermore, for equal flow velocities, lag effects result in higher sediment concentrations in a decelerating flow than in an accelerating flow (Humphries et al. 2012). This result is applicable to trench migration, where the flow decelerates over the upstream edge of the trench and accelerates over its downstream edge. Since the study area is tidally influenced and includes a trench, lag effects are likely to influence the morphological evolution of this physical system. Therefore, we selected a non-equilibrium transport model to predict the spatial and temporal lags between the flow and the sediment transport.

In this paper, we use a hydrodynamic-morphodynamic model to investigate the channel response to a trench in the riverbed, resulting from the removal of a tunnel. The model accounts for non-equilibrium effects, which can influence the morphological evolution of a trench. The objective of this study is to simulate the channel response to a trench using a numerical model. The rest of the paper is organized as follows. Section 2 describes the hydrodynamic and morphodynamic components of the numerical model, including the key assumptions and the applicability of the model to simulate trench migration. A validation test case, presented in Section 3, compares the numerical results to existing experimental data from flume experiments on the morphodynamic development of dredged trenches. The model is then used to predict the morphological evolution of the trench resulting from the removal of the highway tunnel. Finally, in Section 4, we discuss the main outcomes of the study and summarize the key findings.

2 NUMERICAL MODEL DESCRIPTION

The numerical results presented herein were computed using the Telemac hydro-informatic system (Hervouet 2000; Villaret et al. 2013). The Telemac system contains several modules including 2D and 3D hydrodynamic models and a sediment transport (morphodynamic) model. This approach allows for the coupling of a hydrodynamic model (Telemac-2D or Telemac-3D) with the morphodynamic model (Sisyphe). At every time step, the hydrodynamic model calculates the flow field and sends the main hydrodynamic variables: water depth, velocity, and bed shear stress to the morphodynamic model. The morphodynamic model uses these hydrodynamic variables to compute the sediment fluxes and the changes in bed elevation. The bed levels are updated and this information is sent back to the hydrodynamic model for the following time step. All Telemac system modules use an unstructured triangular discretization with finite-element or finite volume algorithms, described in Hervouet (2007). The main features of the hydrodynamic and morphodynamic models are presented in this section.

2.1 Hydrodynamic Model

Telemac-2D is based on the solution to the shallow-water equations, which assume that the vertical velocities are significantly smaller than the horizontal ones. As a result, the pressure field is found to be hydrostatic. Various options for horizontal turbulent diffusivity exist including depth-averaged k-ε and constant eddy viscosity models. The shallow-water approximation is valid for many river and coastal applications and allows for faster computation times compared to a 3D model. Telemac-3D is based on the solution to the Reynolds-averaged Navier-Stokes (RANS) equations. The model uses an unstructured triangular grid in the horizontal plane, which is replicated in the vertical direction to create several layers, discretizing the vertical dimension. The replicated layers do not need to be equally spaced, which enables refinement near the bed, allowing for better accuracy of the turbulence models and a better estimation of the bed shear stress (Villaret et al. 2013). Either hydrodynamic model (2D or 3D) can be coupled with the morphodynamic model.

2.2 Morphodynamic Model

The morphodynamic model, Sisyphe, simulates erosion, deposition, bedload and suspended load transport. The sediment transport rates are calculated using one of several classical semi-empirical formulae which generally involve decomposing the sediment transport rates into bedload and suspended load. The bedload transport rate is calculated as a function of the excess bed shear above a threshold value for movement, for example, Meyer-Peter and Muller (1948) or van Rijn (1984). The vertical suspended sediment profile can be computed in Telemac-3D by treating the suspended sediment as a passive scalar and solving the classical advection-diffusion equation with an extra advection term to represent the effect of particle settling due to gravity. Sisyphe uses the depth-averaged form of the advection-diffusion equation, where the source term is expressed in terms of net vertical sediment flux; that is, erosion minus deposition.

In the vertical direction, boundary conditions are needed at the free surface and at the interface between the bedload and the suspended load. At the free surface, the boundary condition is a zero sediment flux boundary through the free surface. The boundary condition at the bedload / suspended load interface is more challenging to define. Many models adopt the so-called *concentration boundary condition*, where the near-bed suspended load concentration is assumed to be at equilibrium. The other approach is to assume that the near-bed erosion rate (upward sediment flux) is at capacity under the given flow conditions. This approach is often called the *gradient boundary condition* (Wu 2008). Since it takes time for the suspended sediment load to adapt to spatial and temporal changes in the flow, the concentration boundary condition is only applicable to sediment transport conditions near equilibrium. However the near-bed erosion rate responds more readily to changes in the flow, so the gradient boundary condition is applicable to both equilibrium and non-equilibrium sediment transport.

In this study, we use a non-equilibrium model, applying the gradient boundary condition to simulate trench migration processes. To show the influence of non-equilibrium effects, we repeat a validation test case using the equilibrium, concentration boundary condition, approach. Non-equilibrium approaches are described further in Armanini and Di Silvio (1988), Galappatti and Vreugdenhil (1985), Miles (1981), and Wu (2008). The numerical results presented herein are based on the non-equilibrium approach proposed by Miles (1981) and included in recent versions of the Telemac system (version 6.3 or more recent). This approach has been recently applied to model trench migration processes in Tassi et al. (2011) and Knaapen and Kelly (2012).

3 NUMERICAL RESULTS

The numerical model described in Section 2 has been applied to two test cases. First, the migration of a trench in a laboratory was simulated and the results were compared to existing experimental data. The model was then applied to predict the morphological evolution of the trench resulting from the removal of the highway tunnel. The following section provides a description of each test and the corresponding numerical results.

3.1 Trench Migration Validation

As a first test case, the model was validated against flume data from experiments on the sediment transport processes associated with dredged trenches. The experiments are described in van Rijn (1986a). The purpose of selecting this test case was to assess the ability of the model to simulate trench migration.

3.1.1 Experimental Setup

Experiments were conducted at the Delft Hydraulics Laboratory in a straight rectangular flume 30 m long, 0.5 m wide, and 0.7 m high. The laboratory tests were carried out using sand of diameter, D_{50} (median diameter) of 0.16 mm and D_{90} (ninetieth percentile diameter) of 0.20 mm, supplied at a rate of 0.04 kg/s/m (total load) to maintain equilibrium conditions in the upstream section of the trench. During all tests, the mean flow velocity and water depth at the upstream section were $u_0 = 0.51$ m/s and $h_0 = 0.39$ m, respectively. The trench dimensions were varied using initial side slopes of 3H:1V, 7H:1V, and 10H:1V. Based on velocity and sediment concentration profile measurements, the equilibrium suspended sediment load in the upstream section was $q_s = 0.03$ kg/s/m (75% of total load), resulting in a bedload of $q_b = 0.01$ kg/s/m (25% of total load). From velocity profile measurements, the bed roughness (k_s) was found to be 0.025 m and based on suspended sediment samples, the settling velocity (w_s) of the suspended sediment was 0.013 m/s. The longitudinal bed profiles were measured at the beginning and end of the experiment. Further details on the experiment are provided in van Rijn (1986a).

3.1.2 Physical Description

In the upstream section of the channel, the steady uniform flow results in near equilibrium conditions for the sediment, as it is transported toward the trench. As the flow enters the trench, the velocity decreases due to the increase in water depth. This decrease in velocity results in a decrease in sediment transport capacity; therefore, particles from the bedload layer and some suspended particles will deposit in the trench. In the upstream (down-sloping) and middle regions of the trench, the dominant sediment process is the settling of sediment particles due to a decrease in transport capacity. The sediment trapped in the upstream and middle regions of the trench generate a deficit in sediment supply to the downstream region of the trench, which leads to erosion in this region.

The deposition in the upstream and middle regions of the trench and the erosion in the downstream region result in the trench migrating in the direction of flow. Figure 1 shows a schematic of this physical process for a trench oriented perpendicular to unidirectional flow. For bedload dominated conditions, the shape of the trench will remain relatively constant as it migrates downstream, whereas, under suspended load dominated conditions, the side slopes will smooth over time. Under tidal conditions, erosion may occur on both the upstream and downstream slopes.

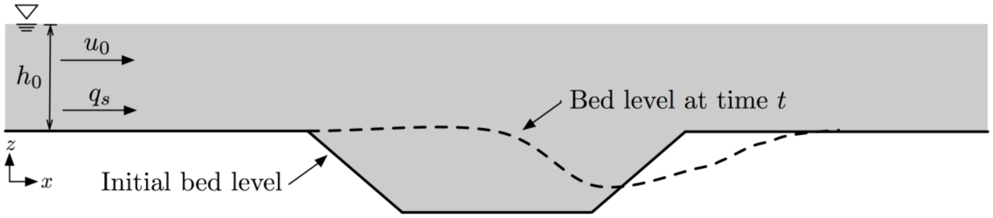

Figure 1: Problem definition sketch: trench migration

3.1.3 Model Setup

The coupled Telemac-2D/Sisyphe model was used to simulate trench migration. The model geometry, flow parameters, and sediment characteristics were selected to match the experimental setup in van Rijn (1986a). The computational domain was discretized into an unstructured triangular mesh with a resolution 0.1 m in the transverse direction and 0.2 m in the longitudinal direction, having 755 nodes and 1200 elements. A constant fluid and sediment discharge was imposed on the upstream boundary and a constant water level on the downstream boundary.

3.1.4 Model Results

Figure 2 shows the measured and computed bed levels after 15 hours for initial side slopes of 3H:1V, 7H:1V, and 10H:1V. The computed bed levels are in good agreement with the measured values. The maximum depth of the trench is predicted very well. Figure 2b shows that for initial side slopes of 7H:1V the computed results slightly under-predict the infilling of the trench at the upstream end, and the trench does not migrate as far downstream as in the laboratory experiments. For all three trench geometries, the computed results slightly under-predict the erosion at the downstream end of the trench as it migrates downstream.

To show the influence of non-equilibrium effects on the model results, Figure 3 compares computed bed levels using both the equilibrium and non-equilibrium approaches for the 3H:1V trench condition. The equilibrium approach results in a behaviour like that expected for a bedload dominated problem in which sediment deposits practically instantaneously when entering the trench. This behaviour forms an avalanching front at the upstream face of the trench that migrates downstream like the leeside of a dune or delta front entering a reservoir. Because all the sediment is deposited on the avalanching front, with no sediment depositing downstream of it, the bottom elevation of the trench downstream of the front remains unaltered. For the non-equilibrium case, suspended load deposits farther downstream inside the trench, causing the minimum bed elevation to gradually rise. The results demonstrate that to correctly model trench migration when suspended load is dominant (for example, in a fine sand river), a non-equilibrium model is needed. The equilibrium model results do not agree with the observations in terms of maximum depth of the trench, rate of infilling, or the general shape of the trench, as it migrates downstream.

Overall, the non-equilibrium model correctly predicts the migration and infilling of the trench over a range of trench geometries. The trench resulting from the removal of the tunnel is expected to have initial side slopes of approximately 4H:1V on the upstream slope and 5H:1V on the downstream slope. These slopes are similar to those modelled in the trench migration validation simulations presented herein. While these flume experiments are not necessarily representative of the field conditions in the study area, the validation shows that the model reproduces the laboratory simulations of an alluvial channel's response to an excavated trench. Also, in the laboratory experiments, 75% of the total load moves in suspension; in the field case this ratio is higher, making non-equilibrium conditions more relevant. Church and McLean (1994) found that, on average, 98.4% of the total sediment load in the Fraser River at Mission moved in suspension.

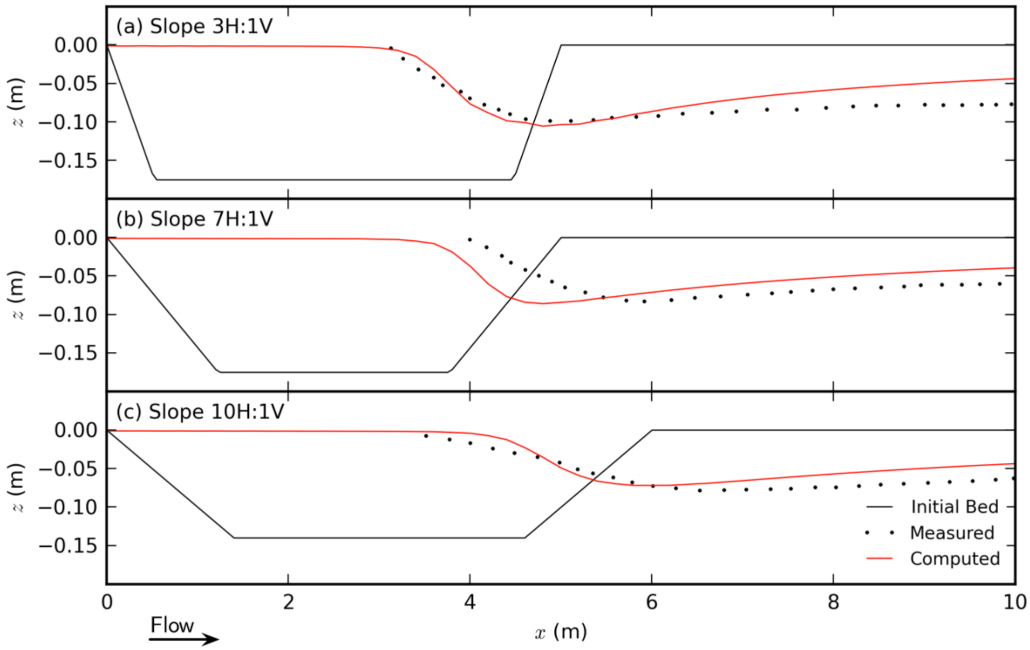

Figure 2: Computed and measured bed level profiles after 15 hours for a trench initially sloping at (a) 3H:1V, (b) 7H:1V, and (c) 10H:1V

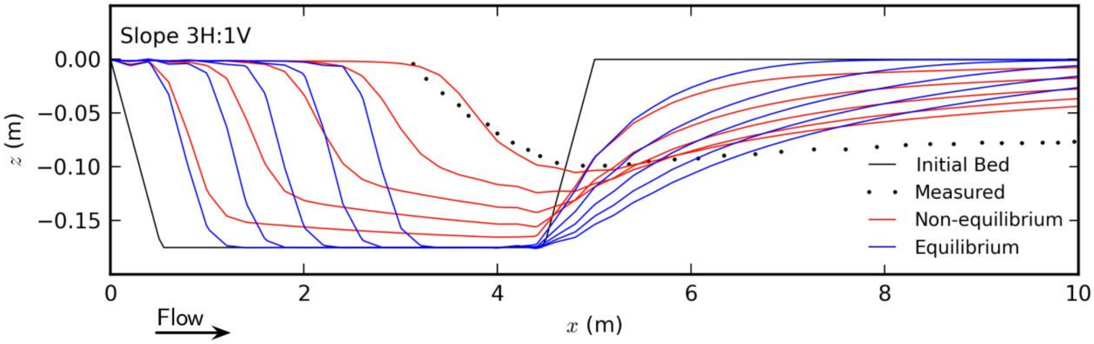

Figure 3: Comparison of equilibrium and non-equilibrium models when 75% of the sediment load is transported in suspension: computed and measured bed level profiles at t = 3 hr, 6 hr, 9 hr, 12 hr, and 15 hr for a trench initially sloping at 3H:1V

3.2 Tunnel Removal Simulation

3.2.1 Physical Description (hydraulic and morphological conditions)

The tunnel crosses the tidally-influenced main channel of the Fraser River between the municipalities of Richmond and Delta in British Columbia, about 5 km from the sea. The river's hydrologic regime is snowmelt-dominated, with the discharge typically rising in April, peaking between May and July (the freshet period) and then receding during the autumn and winter months. Near the mouth of the river, the mean tidal range is 3.1 m, with extremes of over 5.4 m (Villard and Church 2003). Full reversal of flow occurs in the study area during the winter months, when tidal amplitudes are large and freshwater discharges are small. During freshet, the flow remains tidally-influenced but does not fully reverse.

Suspended sediment load in the river averages 16.5 million tonnes/year, and ranges from 12.3 million to 31.0 million tonnes/year (McLean et al., 1999; McLean and Tassone, 1988; NHC, 2002; Tywoniuk, N., 1972). Fine sediments moving as washload remain in suspension without settling on the riverbed and therefore have little effect on sedimentation patterns. Of primary importance is the bed-material load, which includes the bedload and the suspended load capable of depositing in the river. These sediment fractions exert an influence on the river morphology. The bed-material load in the crossing reach is composed of sand with diameter larger than 0.18 mm; the estimated average annual bed-material load is 2.9 million tonnes/year, and ranges from 1.2 million to 8.9 million tonnes/year (NHC 2002).

A substantial amount of in-river infrastructure exists near the crossing. Of particular interest is a water main crossing about 600 m downstream of the tunnel, shown in Figure 4. Due to a relatively long history of industrial development, the river banks near the crossing are hardened by riprap and river training works, resulting in a narrower and deeper estuary than existed in the 19th century. Extensive dredging for navigation has also had a notable effect on the river. Bed degradation on the order of two to three metres occurred between 1951 and 1988 (NHC 2002). During the height of dredging activity in the 1970s and 1980s, about 15% of the total annual sediment removal was from the reaches adjacent to the tunnel, resulting in bed degradation of about 25 cm/year in the reach upstream of the tunnel.

3.2.2 Model Setup

A coupled Telemac-3D hydrodynamic model and Sisyphe morphodynamic model was used to evaluate changes in river hydraulics and morphology associated with the tunnel removal. The model mesh has on the order of 11,000 nodes, 21,000 elements and 10 levels in the vertical. The element lengths vary from 20 m near the upstream boundary to 5 m near the tunnel. Upstream and downstream boundary conditions were flow and water level, respectively.

We modelled a trench migration scenario to examine the channel response to the proposed tunnel removal. The validation case described in Section 3.1 supported the idea that the Telemac system could predict the non-equilibrium processes involved in trench migration. Existing conditions were modelled and validated against measured water levels and velocities. The model geometry was then altered to represent the proposed removal of tunnel segments, resulting in a trench 95 m wide at the top of slope, 630 m long and 8 m deep. Modelled initial bed elevations for existing and proposed conditions are shown in Figure 4. Sediment sizes in the model were based on measurements of the riverbed material. The model sediment had a D_{50} = 0.25 mm and D_{90} = 0.45 mm (McLaren and Ren 1995). The van Rijn (1993) formula was used to compute bedload and suspended load transport. The model was run for a 210 day period during low flow conditions, between 16 August 2012 and 13 March 2013. This was the most likely time frame for tunnel removal considering fisheries and constructability, and was expected to yield a conservative (i.e. long) estimate of the time required for the trench to fill in.

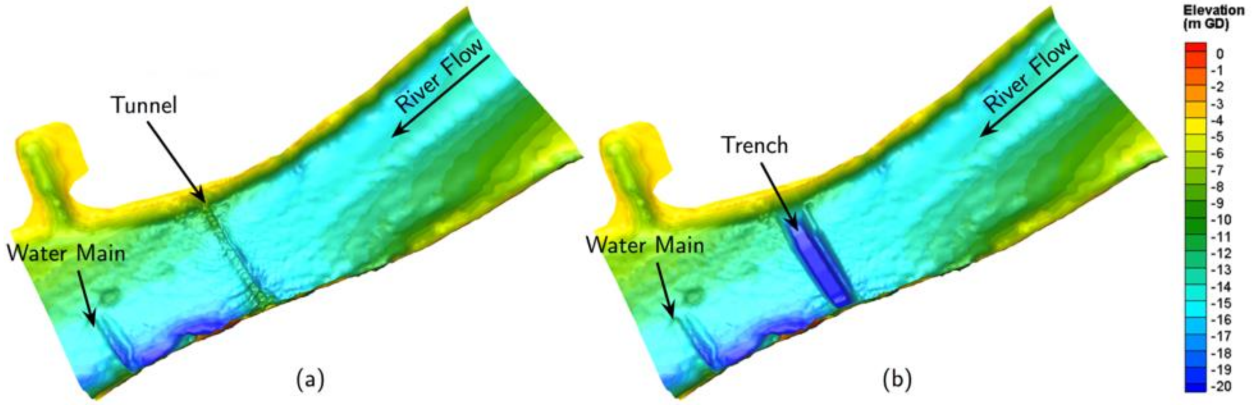

Figure 4: Initial bed elevations for (a) existing conditions and (b) proposed conditions (tunnel removal).

3.2.3 Model Results

The model results show flow decelerating and sediment depositing over the upstream region of the trench and erosion where flow accelerated over the downstream region of the trench. Figure 5 shows a time sequence of riverbed profiles along the navigation channel centreline. After 210 days of simulation, the trench has mostly filled in and we expect it to fill in completely by the end of the following freshet season. The model results support the hypothesis that the trench will migrate in the seaward direction and will have very little impact on upstream riverbed levels. The model predicts bed lowering of 1 to 2 m in the region between the tunnel and the water main. Over the same simulation period, a model of the existing conditions showed about 1 m of bed lowering; therefore, the incremental change in bed elevation due to the tunnel removal is roughly 1 m. The water main crossing is protected with riprap in the southern half of the channel, and bed elevations there remain unchanged throughout the model run. Figure 6 shows a time sequence of the trench evolution. While the trench is oriented perpendicular to the channel, the velocity distribution across the channel is asymmetric; therefore, the trench on the right side of the channel fills in faster than on the left side of the channel.

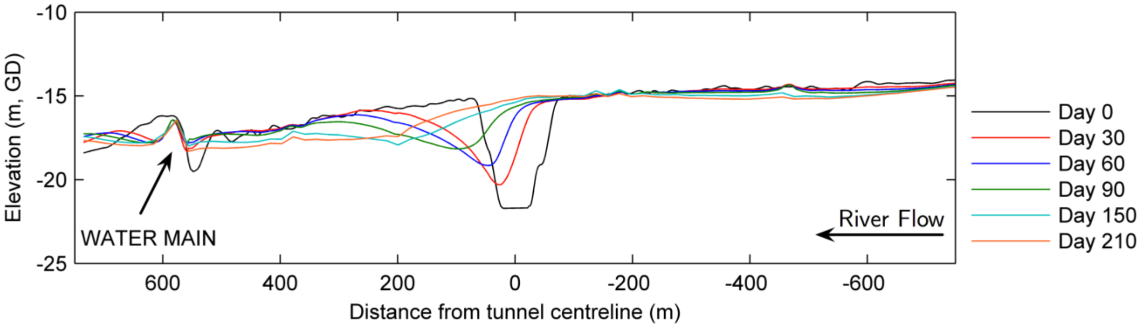

Figure 5: Riverbed profile along the centreline of the navigation channel from 750 m downstream to 750 m upstream of the tunnel with the tunnel removed.

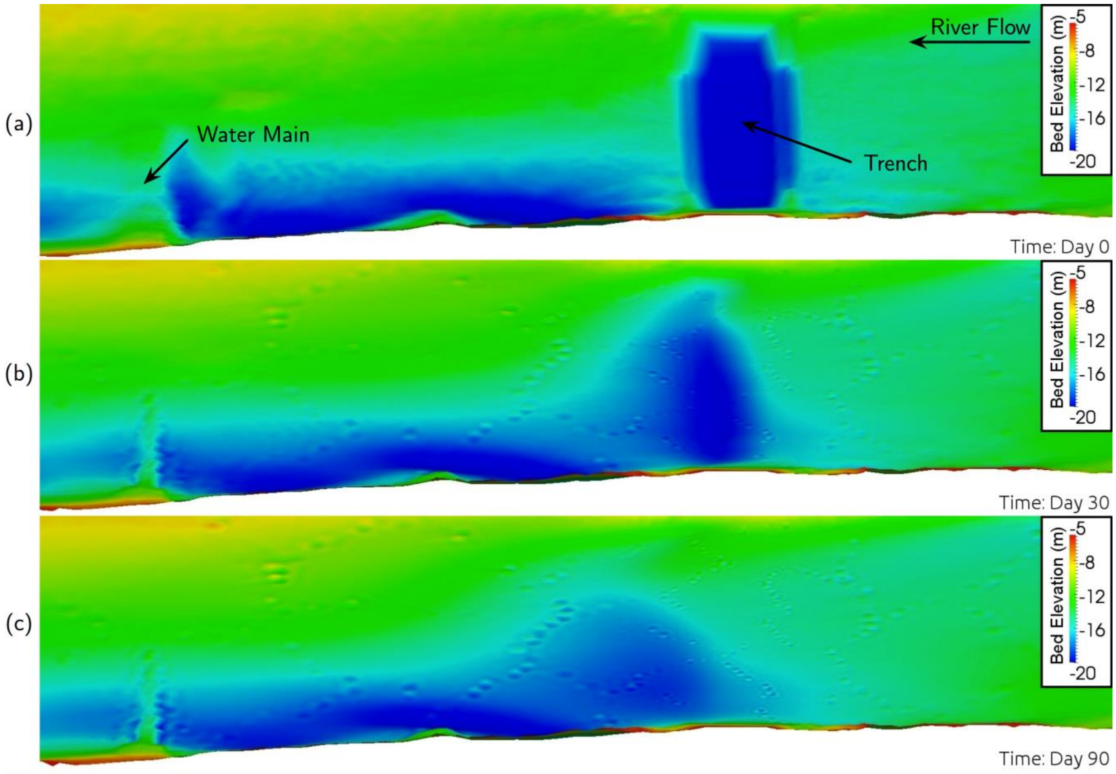

Figure 6: Three-dimensional view of trench migration at (a) *t* = 0 days, (b) *t* = 30 days, and (c) *t* = 90 days

4 SUMMARY AND CONCLUSIONS

In alluvial rivers, bed-material sediment is transported as bedload along the riverbed or as suspended load in the water column. Bedload sediment responds almost immediately to changes in flow conditions and sediment transport capacity; that is, the sediment remains in equilibrium with the flow. On the other hand, suspended sediment requires a finite distance to settle and deposit on the riverbed due to its small vertical fall velocity. Therefore, suspended sediment may not be in equilibrium with local flow conditions, causing lag effects. This distinction is important when studying sedimentation processes in sand bed rivers where suspended load is the main mode of sediment transport, as is the case in the Lower Fraser River.

The proposed removal of a highway tunnel passing under the Lower Fraser River would lead to the formation of a large trench where sediment would deposit. In contrast to other depositional features such as reservoirs or sand traps, which are fixed in placed by non-erodible material, trenches can migrate, potentially affecting nearby structures. Due to tidal effects, there was also the possibility that flow reversal would cause the trench to migrate upstream. To assess the trench dynamics, we used a numerical model with capabilities for unsteady flow and sediment transport with non-equilibrium effects.

We verified the numerical model by simulating the trench dynamics observed in flume experiments under suspended-load dominated conditions. We found that non-equilibrium effects play an important role in accurately reproducing the shape of the migrating trench, especially the gradual rising of the trench's bottom due to suspended load deposition.

Once verified, we applied the model to simulate the trench dynamics in the Lower Fraser River over a period of 210 days representing seasonal low flow conditions. Because tidal effects were not strong enough, the trench migrated downstream towards the sea. By the end of the simulation, the original trench was almost completely filled with sand. Due to its downstream migration, approximately 1 m of scour was predicted 600 m downstream at the location of a buried water main crossing.

References

Armanini, A. and Di Silvio, G. 1988. A one-dimensional model for the transport of a sediment mixture in non-equilibrium conditions. *Journal of Hydraulic Research*, **26**(3), 275-292.

Church, M. A., and McLean, D. G. (1994). Sedimentation in Lower Fraser River, British Columbia: Implications for Management. *The variability of large alluvial rivers* (pp. 221–241). American Society of Civil Engineers press.

Delft Hydraulics Laboratory (DHL). 1980. *Computation of Siltation in Dredged Trenches*. Report 1267-V/M 1570.

Faraci, C., Foti, E., Marini, A. and Scandura, P. 2011. Waves plus currents crossing at a right angle: sandpit case. *Journal of Waterway, Port, Coastal, and Ocean Engineering*, **138**(5), 339-361.

Galappatti, G. and Vreugdenhil, C. 1985. A depth-integrated model for suspended sediment transport. *Journal of Hydraulic Research*, **23**(4), 359-377.

Hervouet, J.-M. 2007. *Hydrodynamics of free surface flows: modelling with the finite element method*: John Wiley & Sons.

Hervouet, J.-M. 2000. TELEMAC modelling system: an overview. *Hydrological Processes*, **14**(13), 2209-2210.

Humphries, R., Venditti, J.G., Sklar, L.S. and Wooster, J.K. 2012. Experimental evidence for the effect of hydrographs on sediment pulse dynamics in gravel-bedded rivers. *Water Resources Research*, **48**(1).

Jurbin, T. 2006. Seismic upgrade for Massey Tunnel. *Tunnels & Tunnelling international*, (MAR).

Knaapen, M.A. and Kelly, D.M. 2012. Lag effects in morphodynamic modelling of engineering impacts. *33rd International Conference on Coastal Engineering (ICCE)*, Santander, Spain.

Lean, G. 1980. *Estimation of maintenance dredging for navigation channels*. Report by HR Wallingford Ltd.

McLean, D. G., Church, M. A., and Tassone, B. (1999). Sediment transport along lower Fraser River 1: Measurements and hydraulic computations. *Water Resources Research*, **35**(8), 2533–2548.

McLean, D. G., and Tassone, B. (1988). Budget of the Lower Fraser River. *Federal Inter-Agency Committee on Sedimentation,* 5th International Conference, Las Vegas, Nevada, pp. 16.

Meyer-Peter, E. and Müller, R. 1948. Formulas for bedload transport. *2nd International IAHR Congress*, Stockholm, Sweden.

NHC (2002). *Review of Lower Fraser River Sediment Budget*. Prepared by Northwest Hydraulic Consultants for Dredge Management Advisory Committee, Fraser River Estuary Management Program.

Miles, G. 1981. *Sediment transport models for estuaries*. Report by HR Wallingford Ltd.

Pritchard, D.T. and Hogg, A.J. 2003. Models of settling lag in coastal and estuarine settings. 3rd Symposium on River, *Coastal and Estuarine Morphodynamics*, Barcelona.

Sánchez, A. and Wu, W. 2011. A non-equilibrium sediment transport model for coastal inlets and navigation channels. *Journal of Coastal Research*, 39-48.

Tassi, P., Villaret, C., Huybrechts, N. and Hervouet, J. 2011. Numerical modelling of 2D and 3D suspended sediment transport in turbulent flows. *7th IAHR Symposium River Coastal and Estuarine Morphodynamics*, Beijing, China.

Tywoniuk, N. (1972). Sediment budget of the lower Fraser River. *American Society of Civil Engineering*, **Proc. 2**, 1105–1122.

van Rijn, L.C. 1984. Sediment transport, part I: bed load transport. *Journal of Hydraulic Engineering*, **110**(10), 1431-1456.

van Rijn, L.C. 1986a. Mathematical modeling of suspended sediment in nonuniform flows. *Journal of Hydraulic Engineering*, **112**(6), 433-455.

van Rijn, L.C. 1986b. Sedimentation of dredged channels by currents and waves. *Journal of Waterway, Port, Coastal, and Ocean Engineering*, **112**(5), 541-559.

Villard, P. and Church, M. 2003. Dunes and associated sand transport in a tidally influenced sand-bed channel: Fraser River, British Columbia. *Canadian Journal of Earth Sciences*, **40**(1), 115-130.

Villaret, C., Hervouet, J.-M., Kopmann, R., Merkel, U. and Davies, A.G. 2013. Morphodynamic modeling using the Telemac finite-element system. *Computers & Geosciences*, **53**, 105-113.

Wu, W. 2008. *Computational river dynamics*: CRC Press.