

structure is also a factor. Whereas frost heave expands the soil skeleton, clayey soils will consolidate under sustained high suction, thereby reducing effective permeability and void ratio.

The introduction of a fluid phase contaminant will alter fluid migration, even before one considers effects of contaminant sorption or desorption on particle surfaces, although the nature of the changes remains largely unknown at present. This first level of change is due to effects the contaminant may have on pore fluid density, viscosity, surface tension, and threshold temperatures for changes in state that will influence the response to every one of the six factors listed above.

Henry (1988) considered the various effects solutes might have on migration of water and solutes, as they relate to frost heave. She pointed out, first, that concentration gradients will induce migration of solutes. Second, ions that become attached to particle surfaces may reduce or increase the thickness of the unfrozen seepage conduits on the particle surfaces, and at the same time change chemical potential and freezing point. Third, a solute may act to disperse soil particles, or it may cause them to flocculate, which will change permeability of the soil. Fourth, thermal dispersion may propel ions away from the cold front, or attract them toward it. And fifth, depending on the rate of freezing, solutes will be expelled from the pore solution, thereby increasing in concentration as freezing proceeds; they may even reach a threshold concentration that then causes them to precipitate.

Henry concludes the discussion of individual effects by pointing out that a single solute may have effects that work against each other, and the net result may depend on solute concentration and other environmental factors. Indeed, contaminants may be propelled either toward or away from the advancing cold front. They may become concentrated, infiltrate ice rich zones, and lead to ice erosion, which can undermine the usefulness of either naturally frozen or artificially frozen soil barriers to contain contaminants on a temporary basis. Alternatively, the temperature gradient could attract the now concentrated contaminant to an amended soil barrier either to capture the contaminant for removal or for accelerated insitu remediation.

Immiscible contaminants with properties that are temperature sensitive, especially in their viscosity, and that change state at a higher temperature than water, may choke off seepage. For example, the viscosity of oil increases as it is cooled, and as cooling continues, waxes may crystallize, blocking off seepage passages. Even

without crystallization, it may become trapped in pores, thereby blocking seepage. The result may be that transport is retarded, redirected, or even halted in place by the freezing/cooling process.

Contaminants with densities and viscosities that are greater than water will be more difficult to draw toward the freezing front. In the absence of water in the soil, this may lead to development of greater suctions, and in compressible (clayey) soils, this may lead in turn to freeze consolidation due to that suction. Alternatively, at shallow depth, where overburden pressures are small, freeze induced fissuring may develop that increases effective permeability of the soil. This may be a problem when the soil is frozen, but it will especially be a problem when the soil is thawed.

Consider now the factors that govern sorption and desorption processes, discussed in the previous section for unfrozen soils, which may also be significantly altered. Pollutant concentration, C , in equation 1 may be greater if freezing causes pure water to be extracted from the contaminant solution. In addition K_F is likely to be temperature sensitive, increasing as temperature decreases due to the fact that sorption is generally an exothermic process. Together these would predict greater solid phase concentration, q , which could be ideal if the contaminant is attracted to an amended soil barrier for accelerated insitu remediation, provided there is sufficient contact time to develop sorption equilibrium. Alternatively, partitioning into the solid phase may increase and the pollutant may become more mobile during the thawing process due to possible increase in colloidal matter.

In reconsidering equation 6 developed for unfrozen soil, the sorption process may become discontinuous in freezing soils (i.e it is no longer a two phase process) and sorption/desorption may have to be represented by a model other than the Freundlich isotherm. For instance, it may be necessary to use a two-pronged approach where equation 5 is used to model sorption in unfrozen soil, and a different, as yet undetermined, representation is used (equation 7) when the soil is freezing. In this equation, the function representing the amount sorbed at any time ($f_{q_{freez}}$) is expected to be a function of time (t), temperature (T), and fluid phase concentration (C).

$$\frac{\partial q}{\partial t} = f_{q_{freez}}(t, T, C) \quad [7]$$

Application of Geoenvironmental Centrifuge Modelling

It is clear, then, that fluid phase contaminants