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The effect of subsurface military detonations on vadose zone hydraulic conductivity, contaminant transport and aquifer recharge

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ABSTRACT

Live fire military training involves the detonation of explosive warheads on training ranges. The purpose of this experiment is to evaluate the hydrogeological changes to the vadose zone caused by military training with high explosive ammunition. In particular, this study investigates artillery ammunition which penetrates underground prior to exploding, either by design or by defective fuze mechanisms. A 105 mm artillery round was detonated 2.6 m underground, and hydraulic conductivity measurements were taken before and after the explosion. A total of 114 hydraulic conductivity measurements were obtained within a radius of 3 m from the detonation point, at four different depths and at three different time periods separated by 18 months. This data was used to produce a three dimensional numerical model of the soil affected by the exploding artillery round. This model was then used to investigate potential changes to aquifer recharge and contaminant transport caused by the detonating round. The results indicate that an exploding artillery round can strongly affect the hydraulic conductivity in the vadose zone, increasing it locally by over an order of magnitude. These variations, however, appear to cause relatively small changes to both local groundwater recharge and contaminant transport.

1. Introduction

Contamination on military ranges is an international problem. By some estimates over 50 million acres have been contaminated in the United States alone by bombing and training (Armstrong, 1999) and similar problems exist in Canada (Bordeleau et al., 2008; Martel et al., 2009), Sweden (Wingfors et al., 2006) and the Netherlands (van Ham et al., 2007). During military training activities, explosive munitions are routinely used and the dispersion and fate of munitions-related contaminants has been the subject of considerable research (Bordeleau et al., 2008; Jenkins et al., 1999; Robertson et al., 2007, many others). It has been shown that mobilization of this contamination is most likely to occur when solid particles on the soil surface come in contact with precipitation, dissolves, and then leaches through the vadose zone (Lewis et al., 2009). If it reaches the underlying aquifer, it can be carried at considerable distances and has the potential to affect drinking water supplies, as it has at Camp Edwards in Massachusetts (Clausen et al., 2004).

The movement of dissolved constituents from the surface and through the vadose zone is therefore a key link in the fate and transport chain. There are numerous parameters that can affect the movement of dissolved constituents through the

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vadose zone. Eq. (1) shows Richard's equation, the governing equation for unsaturated flow.

$$\frac{\delta}{\delta x}\left[K(\psi)\frac{\delta\psi}{\delta x}\right]+\frac{\delta}{\delta y}\left[K(\psi)\frac{\delta\psi}{\delta y}\right]+\frac{\delta}{\delta z}\left[K(\psi)\left(\frac{\delta\psi}{\delta z}+1\right)\right]=C(\psi)\frac{\delta\psi}{\delta t}. \quad (1)$$

The variables in Richard's equation are ψ, the tension head; K, hydraulic conductivity; and C, the specific moisture capacity. A solution requires knowledge of the characteristic curves $K(\psi)$ and $C(\psi)$. Analytical solutions to Richard's equation are available for some simple and well-defined conditions, but in structured and variable soils numerical solutions are usually required.

Hydraulic conductivity is one of the few physical parameters in the natural sciences that extends over 13 orders of magnitude. It can vary from 1 m s^{-1} in coarse gravels to 10^{-12} m s^{-1} in compact glacial till, with even lower measurements applying to unfractured bedrocks. As the K variable in Eq. (1) implies, under unsaturated conditions, K is a function of the tension head of the soil. Such a wide spectrum of possible values means that small variations in local soil conditions could have a strong influence on movement of moisture and by extension the transport of soluble contaminants.

Some of the munitions used in a live fire context do not function as intended and either partially detonate or detonate at the wrong time. This can lead to soil and groundwater contamination by the explosive chemicals which are left un-reacted and available for leaching into the environment (Lewis et al., 2009). Failure rates are influenced by the weather, the type of fuze used to control the detonation and the soil hardness. They can vary significantly according to the type of munition and lot-number, but a commonly cited rate is between 1 and 5%.

In the case of indirect fire munitions such as air-to-ground bombs, artillery and mortar shells, different types of fuzes can be used to control where or when the munitions explode. These include timed or altitude fuzes which cause the munition to explode above the ground and are primarily intended to cause casualties through the wide dispersion of shrapnel, contact fuzes which cause the munition to detonate on impact and are typically deployed against defensive positions and obstacles, or delay fuzes which allow the munition to penetrate into the earth before exploding and are typically used against buried targets.

Since most types of munitions have a great deal of kinetic energy when fired, if the fuze fails the munition will often become deeply buried when it lands. Depth of penetration is dependent on the type of munition, the charge used to fire it and the soil type. Empirical evidence from World War II suggests that unexploded artillery munitions can be found at a depth of over 4.6 m (Blackburn, 1995). In the chalk soil of northern France, an unexploded (dud) 155 mm artillery shell from World War I was found in a 7 m deep tunnel at the Vimy battlefield.

It is therefore reasonable to assume that some of the munitions which fail to detonate properly will deeply bury themselves. Some of these will subsequently detonate, either through subsurface impact with a rock or sympathetic detonation caused by other munitions exploding nearby. Furthermore, during large scale demilitarization of munitions by open detonation, the burial of the charges to be detonated is a common practice to improve the confinement of the detonation process (Ampleman et al., 1998).

The purpose of this experiment is to test the hypothesis that subsurface explosions may affect the hydraulic conductivity, groundwater recharge characteristics and contaminant transport behavior in the vadose zone.

2. Materials and methods

Tests were conducted on the Bofors test range in Karlskrona, Sweden, at Lat. N 59° 25′ 30″ Long. E 14° 54′ 17″. The study area is characterized by a deep, homogeneous quaternary sand deposit of glacial origin. The climate is typical of northern Sweden, with approximately 600 mm annual precipitation of which up to half (Laudon et al., 2007) falls as snow. Between April and May, this snow melts, producing a large groundwater recharge event. Similar groundwater recharge characteristics are to be found in Canada and in the northern United States (Döll and Fiedler, 2008).

The area used for the experiment had not been used previously for military training involving explosives and the soil and subsurface were undisturbed. The hydraulic conductivity of the undisturbed vadose zone was assessed at multiple depths using a Guelph permeameter (Soilmoisture Equipment Corp. Santa Barbara, California). Surface measurements were taken using a tension disk attached to the Guelph Permeameter. A manual auger (3 cm radius) was used to bore the test holes. This apparatus was first used to characterize an area 2 m×2 m prior to the test in order to obtain background measurements of the local hydraulic conductivity. The locations of these measurements are identified by triangles in Fig. 1.

At each point of measurement, three discrete hydraulic conductivity readings were taken at depths of 0 m (surface), 1 m and 2 m. Measurements were obtained at heads of −1 cm and −3 cm. The water table was over 4 m below the surface. All points in Fig. 1 were characterized in the same way,

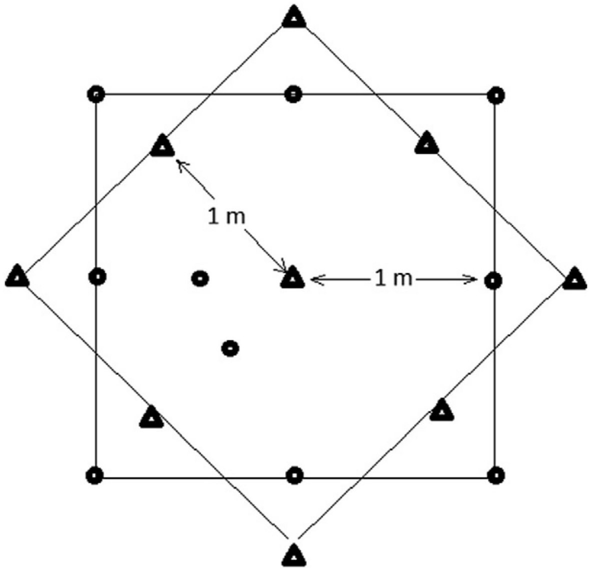

Fig. 1. Characterization grid for hydraulic conductivity. Triangles represent points of measurement before detonation. Circles represent points of measurement after detonation.

producing a 3 dimensional representation of the hydraulic conductivity. In addition, several measurements were taken 3 m away from the point of detonation (not shown in diagram). Twenty seven hydraulic conductivity measurements were taken prior to detonation, 54 were taken immediately following detonation, and 33 were taken 18 months following detonation, for a total of 114 measurements.

The empty shell of a 105 mm artillery with all explosives removed was modified by welding a 4.5 cm outer diameter tube assembly onto its back end and drilling a hole through the shell (Fig. 2). This modified shell was driven into the ground using a jackhammer and 5 cm diameter steel pipe sections that were each 1 m long. The steel pipe sections were machined to slide over the tube assembly that was welded to the shell. This allowed the shell to be placed at a depth of 2.6 m without seriously disturbing the surrounding soil, closely imitating how such a shell would be buried upon impact. The shell was then filled with 3 kg of granulated TNT (trinitrotoluene) explosive by pouring it through the pipe and tube assembly extending to the surface. An electric detonator was set in approximately 100 g of plastic explosive as a booster charge, and the steel pipes were removed by jacking them out of the ground. The buried 105 mm round was then detonated.

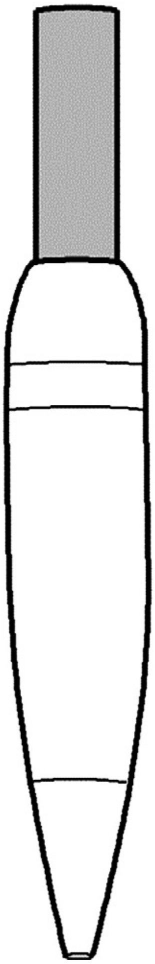

Fig. 2. 105 mm diameter artillery shell with steel tube assembly (shaded) welded in place.

Following the detonation, the Guelph permeameter was again used to characterize the hydraulic conductivity in the pattern shown by the circles in Fig. 1. As for the initial sampling, the characterization was done at depths of 0 m (surface, using the disk permeameter assembly), 1 m and 2 m. Eighteen months following the detonation, the site was re-assessed to determine transient changes to the hydraulic conductivity, this time at depths down to 4 m.

Data analysis for the Guelph permeameter was carried out using the two-head method described in Soilmoisture Equipment Corp. (2010) using the excel spreadsheet provided by Soilmoisture Inc. Analysis of the disk permeameter data was performed using proprietary software available from the senior author of Reynolds and Zebchuk (1996).

The results of the 3-D hydraulic conductivity characterization from before and after the 105 mm artillery shell was detonated were used to construct two numerical models in the hydrogeological modeling program FEFLOW 6.0 (DHI-WASY GmbH). These before and after models allowed an evaluation of how the recharge characteristics and transport behavior of soil water changed after the detonation.

3. Results and discussion

The grain size of the soil at the test site is shown in Fig. 3. Over 60% of the soil by mass is found in the range of 0.2 mm to 0.6 mm, which according to ISO 14688 is classified as medium sand. In fact, over 95% of the soil is classified as sand, falling in the range 0.075 mm to 2 mm, which includes both fine and coarse sand fractions. Little layering was observed at the site, with the exception of a thin silty lens at a depth of 1 m which was found 3 m directly west of the detonation. All of the saturated hydraulic conductivity measurements that were taken prior to the detonation fell in the range of 1×10^{-4} m s$^{-1}\pm7\times10^{-5}$ m s^{-1} which is consistent with a homogeneous, medium sand formation.

In contrast, the hydraulic conductivity of the sand after detonation varied by over an order of magnitude, with the highest reading measuring 25×10^{-4} m s^{-1}. Fig. 4 shows a 3-D regionalized image of the hydraulic conductivity after detonation. The hydraulic conductivity at the exact point of detonation could not be measured because the hole created by the jacked-in tubing assembly precluded augering the precisely-dimensioned hole necessary for the Guelph permeameter. For the purposes of the regionalization, it was assumed that the hydraulic conductivity at the point of detonation was equivalent to the highest proximate measured value.

The field data suggests that the volume of soil that was affected by the detonation was relatively limited. There was a sharp gradient between areas that were strongly affected by the detonation and the surrounding soil that was unaffected. Measurements taken 3 m away from the point of detonation (data not shown) indicated no measurable differences in hydraulic conductivity before and after detonation.

During the excavation of the augured boreholes for the Guelph permeameter analyses, highly porous, loosely packed voids were encountered at several locations close to the point of detonation at depths between 0.7 m and 1.5 m. The measurements and field observations suggest that at the

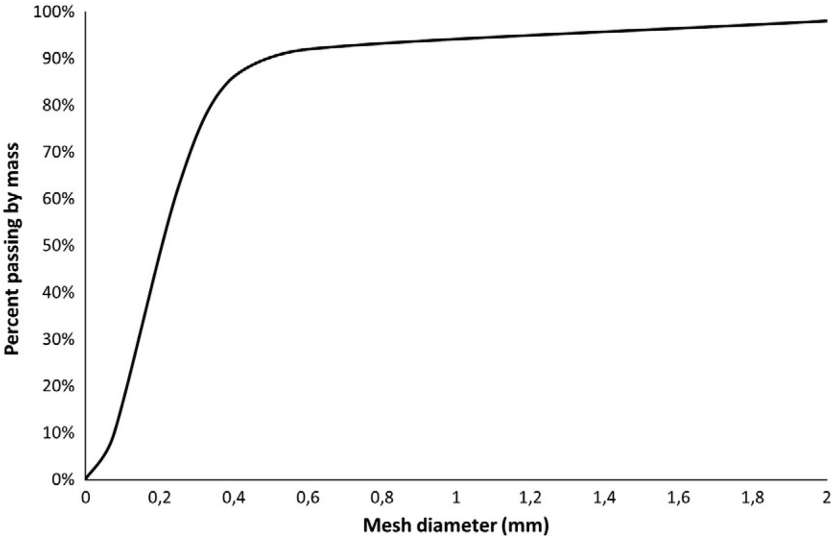

Fig. 3. Grain size curve of soil at the test site showing predominance of well sorted, medium sand (mesh diameter 0.2 mm to 0.6 mm).

point of detonation, an underground zone of highly disrupted, highly porous soil was created that measured approximately 1.5 m in diameter and was approximately 0.5 m thick. Subsequent measurements taken 18 months following the detonation suggested that such a disrupted zone was created over, but not under the detonated round.

A numerical FEFLOW model was constructed around a 3-D kriged regionalization performed by the Geovariances' software package Isatis version 2012.4. This regionalization was based on the measured post-detonation hydraulic conductivities (Fig. 4). For the purposes of the model, this regionalization was also applied to the parameters of unsaturated flow porosity, residual saturation, and the fitting coefficient and exponent of the capillary-head curve. The FEFLOW parameters that were used in the model are given in Table 1.

The mass transport properties in FEFLOW only allow the use of the simplest of adsorption models, based on the Henry isotherm. This is a special case of the Langmuir isotherm that assumes linear adsorption behavior when surface coverage of the contaminant approaches zero. Linear adsorption behavior has been shown to be appropriate for RDX (hexahydro-1,3,5-trinitro-1,3,5-triazine) (Brannon and Pennington, 2002) with

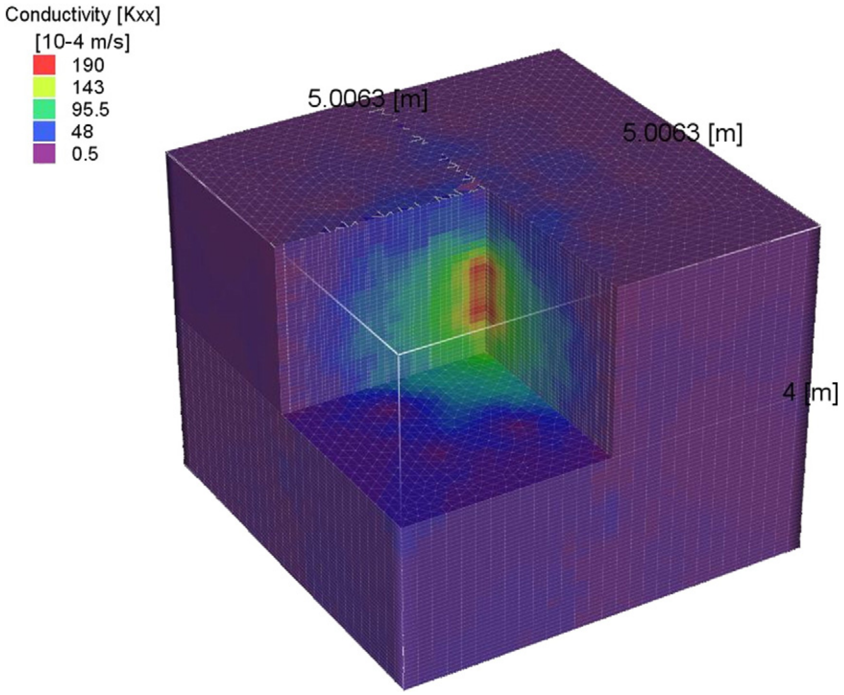

Fig. 4. Hydraulic conductivity following detonation, kriged in three dimensions.

equilibrium sorption coefficient values in sand having been found to be approximately 0.3 L/kg (Brannon et al., 1992; Pennington et al., 1999). RDX is an explosive that is commonly found in artillery rounds and has been detected in the groundwater at several military installations (Bordeleau et al., 2008; Clausen et al., 2004). TNT was not used in the model because it has more complex degradation and sorption behavior than RDX (Brannon and Pennington, 2002).

Figs. 5 and 6 show graphically the results obtained from the numerical model of fluid flow and RDX transport through the base of the model. This is analogous to the aquifer recharge and mass influx of RDX into the aquifer. The results suggest that although the detonation caused order-of-magnitude changes in the local hydraulic conductivities, there is a minimal effect on either local aquifer recharge or contaminant transport. The figures reveal small but reproducible differences in the behavior of the models pre- and post-detonation. To evaluate reproducibility, each model was re-built around the same regionalization three times and run independently. When the same number of nodes and layers were used in each model, the differences in the resulting curves were less than the thickness of the heavy lines shown in Figs. 5 and 6.

When the full, 5 m × 5 m model area is considered (thick lines in Figs. 5 and 6), the post-detonation model shows a small but noticeable increase in both the fluid flux and RDX transport. This is interesting, considering that the detonation zone acted like a capillary barrier and prevented the unsaturated flow of fluid through it (Fig. 7). These results are likely due to an increase in the saturation in the soil immediately proximate to the detonation zone caused by the diversion of water around the capillary barrier. This increase in saturation leads to a localized increase in the hydraulic conductivity of the soil around the detonation.

When the analyses are restricted to the 1.5 m diameter footprint zone immediately under the detonation zone (thin lines in Figs. 5 and 6), the results are the opposite. In this situation, the detonation causes lower fluid flux and RDX transport. The detonation zone causes a capillary barrier "shadow" which forces preferential fluid flux and RDX transport to the edges of the model, illustrated in Fig. 7. One consequence of this is that any residual solid explosives that are deposited in the high conductivity zone by the detonation itself should be immobile as long as the capillary barrier holds, because little fluid flows through it.

Another consequence of the capillary barrier is that moisture builds up on the upper surface of the high conductivity zone on a seasonal basis. This zone of increased moisture reaches a steady state saturation of 0.52 after 22 days of infiltration (data not shown). It was hypothesized that such a transient and seasonal build-up of moisture (and mass) will lead to the eventual collapse and compaction of the existing high-porosity voids. This was investigated in a follow-up analysis performed 1.5 years following the original experiment. Augering revealed that the highly porous subsurface voids were still present and the size of the disrupted zone based on hydraulic conductivity measurements was not

Table 1
FEFLOW modeling parameters.

FEFLOW parameter	Before detonation model	After detonation model
Material and transport properties		
Bulk saturated hydraulic conductivity (K)	1×10^{-4} m s^{-1}	Kriged, 1×10^{-4} m s^{-1} to 25×10^{-4} m s^{-1}
Unsaturated flow porosity	0.41	Kriged, 0.41 to 0.9
Maximum saturation	1	1
Residual saturation	0.0025	Kriged, 0.0025 to 0.0001
Fitting coefficient in capillary-head curve (α)	3.65 m^{-1}	Kriged, 3.65 m^{-1} to 500 m^{-1}
Fitting exponent in capillary-head curve (n)	2	Kriged, 2 to 1.1
In/outflow on top/bottom	6 mm/day	6 mm/day
Henry sorptivity coefficient for RDX	0.3	0.3
Longitudinal dispersivity	2 cm	2 cm
Horizontal dispersivity	0.5 cm	0.5 cm
Decay-rate constant	0	0
Mesh and model properties		
Problem class	Transient unsaturated	
Time integration scheme	Forward Adams–Bashforth/backwards trapezoid, with step size limited to 0.01 days	
Initial time step length	0.001 days	
Area of modeled soil block	5 m × 5 m	
Depth of modeled soil block	4 m	
Mesh elements in model	237,600	
Number of layers	80	
Initial hydraulic head	−4 m, then allowed to come to steady state after 4 months of zero infiltration (winter conditions)	
Initial mass concentration	0 g/kg	
Flow boundary conditions		
Sides of soil block	No flow	
Surface of soil block	Steady state inflow on top 1 cm day^{-1} (see in/outflow parameter)	
Base of soil block	Constant head boundary condition −4 m	
Mass flux boundary conditions		
Surface of soil block	0.1 g/m^2/day RDX	

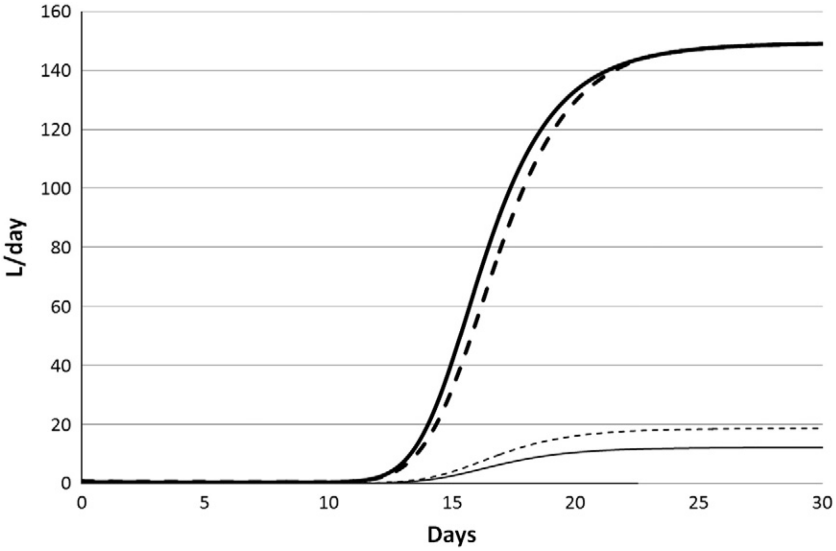

Fig. 5. Numerical modeling results of fluid flux through the bottom boundary of the model. Pre-detonation results (dashed lines); post-detonation results (solid lines); entire model area (thick lines); and footprint of detonation-affected area (thin lines).

significantly different to the observations obtained immediately following the detonation. Follow-up assessments will be performed periodically to monitor how the system changes, but it is clear that the soil disruption caused by the detonation is more stable than was expected. Hydraulic conductivity measurements were also obtained at a depth of 4 m below the surface, immediately below the point of detonation. These measurements were not statistically different from the background values obtained prior to detonation.

Overall, despite the changes to hydraulic conductivity the effects on fluid flux and RDX transport caused by the subsurface detonation are minor and are unlikely to be of much significance at the field scale. The modeled effects are so small that it is doubtful that field measurements of groundwater chemistry would have a high enough precision to detect them. However, extending these experimental results to active (or legacy) ranges where tens of thousands of rounds have been fired is problematic. The cumulative effects of repeated bombardment are unlikely to be a linear interpolation of the results obtained from this experiment. Our results do suggest that a limited number of rounds detonating underground in sandy soil are unlikely to have serious effects on groundwater recharge or contaminant transport from the surface. Other effects of large-scale bombardment, such as the destruction of vegetation and the resultant reduction in evapotranspiration will probably have a more significant effect on hydrogeological

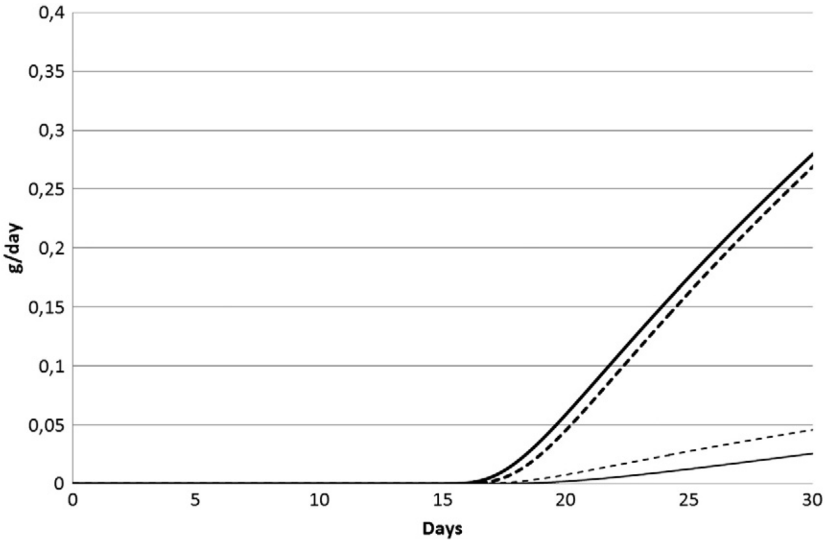

Fig. 6. Numerical modeling results of RDX transport through the bottom boundary of the model. Pre-detonation (dashed lines); post-detonation (solid lines); entire model area (thick lines); and footprint of detonation-affected area (thin lines).

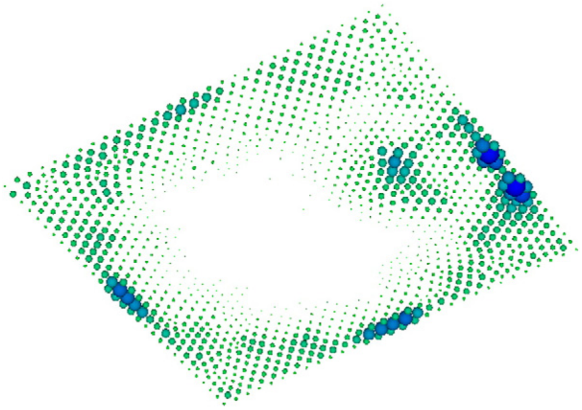

Fig. 7. Flow distribution vertically downwards at the base of the model, where the size of the sphere is indicative of the flux. The figure shows the lack of flow at the center of the area caused by the overlying detonation-disrupted soil.

parameters of the vadose zone than the disrupted hydraulic conductivity.

The results of this experiment were obtained on a sandy soil. It is possible that in soils with a lower natural hydraulic conductivity – such as silts or clays – a subsurface detonation could have different effects on fluid flow and contaminant transport through the vadose zone. The capillary barrier effect could be quickly overcome in such situations which could make the high-conductivity zone of disrupted soil a preferential flow pathway instead of a barrier to flow.

The size and angle of impact of the munition are also probably key variables in determining how a subsurface detonation will affect the hydraulic properties of the vadose zone. The current experiment was performed with a modified 105 mm artillery shell that was oriented with its nose straight down. There are multiple other types of shell in common use, both larger (155 mm artillery) and smaller (most mortars). The type of munition will determine both the mass of explosive that is being delivered and the angle at which it will strike the surface, with mortars typically using a higher angle of attack (between 45° and 90°) than artillery. Higher angles of attack will reduce the likelihood of ricochet and maximize the amount of kinetic energy directed downwards, allowing the munition to be buried deeper all else being equal. However, mortars also have much lower velocities than artillery rounds, and therefore have less kinetic energy with which to become buried. Since most indirect-fire munitions are designed to explode radially, the angle at which they are buried will undoubtedly affect the pattern of subsurface soil disruption. The amount of explosive that is delivered underground will also undoubtedly affect the degree of soil disturbance.

4. Conclusions

The subsurface detonation of a simulated 105 mm artillery round filled with 3.1 kg of high explosives caused a localized, order-of-magnitude increase in the hydraulic conductivity of the vadose zone. This effect was restricted to a radius of approximately 1 m from the point of detonation and no changes to hydraulic conductivity were observed 3 m away from the explosion. This localized increase in hydraulic conductivity was used to build two models using the software FEFLOW: one that represented the undisturbed soil pre-detonation and one that represented the soil post-detonation. The models were subjected to the largest groundwater recharge of the year in Sweden, which occurs during the springtime snowmelt. The results from these models suggest that a subsurface detonation of a 105 mm artillery round will have a small effect on both the groundwater recharge and contaminant transport characteristics of the vadose zone. In practice, the effects on recharge and transport are so small and localized that they are unlikely to be measureable in the field.

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