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Design of Mass Burial Sites for Safe and Dignified Disposal of Pandemic Fatalities

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Abstract

The huge number of fatalities due to COVID-19 pandemic has imposed an unprecedented pressure on existing burial facilities. Thus, mass burial is being used in different parts of the world to cope with this unusual situation. As a dead body might be contagious at least for hours, if not days, there is a need to manage/design/construct the mass burial considering the safe handling of coffins and other environmental, social, economical, and ethical/ dignity aspects. However, the guidelines of World Health Organization (WHO) do not thoroughly address the potential risk associated with groundwater pollution due to mass burial construction. Hence, the present study discusses the potential risk of groundwater pollution in the mass burial sites and sheds light on the factors that control the survival/retention of bacteria and viruses in porous media. Furthermore, using the available knowledge on designing/monitoring municipal/industrial waste disposal sites, cost-effective and simple construction method of mass burial is proposed to mitigate its potential environmental impact.

Keywords: Contaminated material; Environmental engineering; Geosynthetics; Pollution migration/control

Introduction

In the history of mankind, there were several pandemics similar to the COVID-19 pandemic where mass fatalities had resulted. A summary of past pandemics where fatalities exceed 100,000 is shown in Table 1. In such pandemics, cremation is the preferred method for disposal of the deceased. However, often the less desirable method of mass burial is selected due to insufficient capacity of crematories or religious beliefs. In the current COVID-19 pandemic, still as observed on April 10, 2020, in New York City, existing cemeteries may not have sufficient capacity or some deceased people may not be claimed by relatives, and therefore mass burial is used. However, this option might pose a potential risk to the environment through contamination of soil and the groundwater due to the excessive fluids (necroleachate) leaching out from decomposing bodies and coffin (Spongberg and Becks 2000 a,b; Oliveira et al., 2012). This necroleachate may contain bacteria and viruses that could pose a microbiological hazard and contaminate groundwater which may be used as a water source. The decomposition process of a typical body (70 kg) lasts up to three years after the death and produces about 30 to 40 litres of necroleachate with a unit weight of 12.06 kN/m^3 (Silva 1995; Swann et al., 2010; Schotsmans et al., 2014; Neckel et al., 2017). During this period, gases such as hydrogen sulfide, mercaptans, carbon dioxide, methane, ammonia and phosphine are also released (Całkosiński et al., 2015).

In connection to this, Bouwer (1978) listed several historical cases of contamination of groundwater in cemetery areas. For example, a 'sweetish taste and infected odour', was observed in water from sources close to cemeteries in Paris. Furthermore, a higher incidence of typhoid fever in communities near cemeteries was reported in Berlin. Pachecho et al. (1991) reported evidence of bacteria, ammonium and nitrite ions in a plume of decreasing concentration with distance from a cemetery, and indications of proteolytic and lipolytic bacteria in groundwater, accompanied by malodours. Recently, several cemeterial soil contamination cases have been reported in other regions of the world (Geleta et al., 2014; Całkosiński et al., 2015; Killgrove & Montgomery, 2016; Neckel et al., 2017).

Therefore, the construction of mass burial sites during pandemics need to be engineered to lessen the potential environmental/groundwater contamination risk (Young et al., 1999; Hart 2005; Williams et al., 2009). In this context, the World Health Organization (WHO) and Wisconsin Economic Development Corporation (WEDC) (2013) has recommended the minimum distances of burial sites from water sources based on the number of bodies to be buried. Wherein, Table 2 shows the minimum distance for mass burial should be at least 350 m from the nearest water source, and the bottom of the grave should be at least 2m above the groundwater table. It is believed that these recommendations are not enough to guarantee the containment of necroleachate within the burial site, especially if this necroleachate is expected to contain harmful bacteria and viruses. Therefore, pre- and post-assessment for mass burial site is proposed in this study and construction of the mass burial site using principles based on hazardous engineered landfill is recommended to reduce the environmental risk as well as risk to the operators of the site.

Survival/retention of Bacteria and Viruses

To assess the possible environmental impact of mass burial site on groundwater pollution, a thorough understanding of survival/retention of bacteria and viruses in porous media is required. Unfortunately, limited studies have been conducted in this field (Abu-Ashour et al., 1994, Bosch et al., 2006, Kuzyakov and Mason-Jones 2016; LaRosa et al., 2020; Tang et al., 2020). Reddy et al. (1981) and Rao et al. (1986) show that both survival and retention behaviour depends on the types of soil and microorganism, ionic strength, pH, ground temperature and flow rate. Bacteria and virus's die-off rate increase as the ground temperature and acidity increases. Adsorption of bacteria and viruses by the soil particles is the major factor controlling virus retention. Clayey soils with small pore size and large surface area have a higher adsorption capacity of viruses. Lance and Gerba (1980) have mentioned that soil adsorption to viruses could also be affected by the strength of the negative charge on the virus particle; where viruses with a net negative charge below a certain level are immediately adsorbed while viruses with a stronger negative charge move farther in the soil pores; wherein active mineralogy and organic contents present in the soil neutralize the surface charge on the virus and shows adsorption process. Bosch et al. (2006) provided a summary of the factors influencing virus transport in the soil as shown in Table 3. Although studies on other environmental surfaces can be found, no study of the infectivity of coronaviruses in soils is currently available. As SARS-CoV-2 is enveloped, it is less stable in the environment compared to non-enveloped human enteric viruses (WHO 2020). Experimental evidence by van Doremalen et al. (2020) indicates that survivability of SARS-CoV-2 on surfaces is similar to that of SARS-CoV-1. The coronaviruses (CoVs), SARS-CoV (Duan et al. 2003), 229E and OC43 (Sizun 2000), can retain their infectivity for several hours on porous and non-porous environmental surfaces which include glass, mosaic, paper, metal, plastic, cloth, filter paper and autoclaved soils. The SARS-CoV could be detected in decholrinated tapwater and hospital wastewater at 20^{o}C for up to three days and could be detected in urine at 20^{o}C for up to 17 days (Wang et al. 2005). The SARS-CoV-2 could be detected in aerosols up to 3 hours post aerosolization, up to 4 hours on copper, up to 24 hours on cardboard and up to 2-3 days on plastic and stainless steel (van Doremalen et al. 2020).

Proposed Engineered Lining System for Mass Burial Sites

The World Health Organization (WHO) recommended guidelines for mass burials (WHO/WEDC 2013) have not incorporated rigorous requirements to address the potential groundwater pollution risk. It is believed that the requirement of at least 2m above the highest groundwater table from the bottom of grave is not enough precautionary measure since experimental studies indicated that the virus might survive for a certain period of time in unsaturated porous media before reaching into the groundwater (Chu et al., 2003; Rajsekhar et al., 2016). Hence, it is believed that the mass burial sites need to be engineered to mitigate its potential environmental risk (Mather 1989; Williams et al., 2009). The engineering design of the mass burial site should guarantee minimum rainwater infiltration into the burial site to reduce the amount of necroleachate. Furthermore, it should provide an opportunity to maximize virus retention by adsorption process.

As the mass burial site can be considered as a special type of hazardous landfill wherein available engineering technologies can be used for constructing the safe mass burial sites. In this context, sealing of the burial sites and virus retention can be significantly improved if geosynthetics clay liners are used to encapsulate the bodies. Moreover, a capillary barrier cover system can be employed to reduce the possibility of rainwater from infiltrating the burial site.

Geosynthetics clay liners

Geosynthetic clay liners (GCLs) are thin (typically 5 to 10 mm) manufactured hydraulic barriers having a very low hydraulic conductivity ($k \leq 10^{-10}$ m/s). They are increasingly used as components of barrier systems in waste containment facilities (Bouazza, 2002; Bouazza and Bowders, 2010). In this respect, there is a wide range of work available on GCLs hydraulic/gas barrier performance (Shackelford et al., 2000; Gates and Bouazza, 2010; Abuel-Naga et al. 2013; 2014; Rowe 2014; Lu et al., 2018 and 2020). To improve GCL's barrier performance in mass burial context, it is recommended to modify its clay layer composition to be able to inactivate or kill any viruses pass through it.

It has been reported that CoVs are highly vulnerable to acidic and basic-pH conditions (Tang et al., 2020). Hence, the survivability of COVs in mass burial sites is reduced with the use of high acidic and/or basic pH industrial by-products viz., fly ash zeolites, red mud. As fly ash zeolite is known for high surface acidity, very fine pores, negatively charged channels, cages, and high cation exchange capacity ranging from 250-850 meq/100g (Jha and Singh, 2011, 2016), replacing the bentonite clay layer of GCL by a mixture of bentonite and zeolite may improve the barrier performance of GCL against viruses. A similar solution has been suggested by Arif et al. (2021) to use flyash zeolite to seal small pit for disposal of medical and healthcare waste. However, research is needed to assess the optimum mixing ratio of bentonite and zeolite clay layer of GCL in terms of its hydraulic properties and retention capacity of bacteria and viruses.

Capillary barrier system

A capillary barrier system is a two-layer cover system consisting of a fine-grained layer and a coarse-grained layer having distinctly different hydraulic properties to create an unsaturated soil system to prevent rainwater infiltration (Stormont, 1996; Rahardjo et al. 2006). The contrast in unsaturated hydraulic properties, which are soil-water characteristic curves and permeability functions, as shown in Figure 1, serves to minimize water infiltration into the underlying soil. At high suction, the hydraulic conductivity of the coarse-grained soil layer is lower than the hydraulic conductivity of the fine-grained soil layer resulting in the infiltrated water being stored in the fine-grained soil layer and ultimately removed by evaporation and transpiration. Lateral diversion through the fine-grained layer is possible if the cover capillary barrier system has a small slope. There are three controlling parameters that must be considered in selecting the fine-grained and coarse-grained materials, which are: the ratio between the water-entry value of the fine-grained layer and the coarse-grained layer (ψ_w-ratio), the ψ_w of the coarse-grained layer and the saturated coefficient permeability of the fine-grained layer (Rahardjo et al. 2006). The minimum ψ_w -ratio should be 10 to create the capillary barrier effect between the fine-grained and the coarse-grained layers and to minimize the infiltration of rainwater into the coarse-grained layer. The coarse-grained layer must have a low water-entry value (preferably less than 1 kPa) in order to maintain the effectiveness of the capillary barrier system for a longer duration rainfall. The saturated coefficient of permeability of the fine-grained layer should preferably be higher than 10^{-5} m/s to allow water to flow out from the fine-grained layer by lateral drainage and enhances the effectiveness of the capillary barrier system. The fine-grained layer should also have low fines content so that the SWCC of the soil for the fine-grained layer will be steep and the soil is able to drain a large amount of water during a rainfall as well as minimizing the possibility of crack developments in the fine-grained layer during dry period when matric suctions are high (Tami et al., 2007).

For mass burial sites, construction of cover capillary barrier system will be problematic as the required type of soils might not be available at the site and using heavy equipment to compact the capillary barrier soils above the buried coffins is not allowed for religious/dignity reasons. To overcome this problem, the coarse-grained layer of the proposed cover capillary barrier system can be replaced by a geocomposite capillary barrier that comprises nonwoven geotextile drainage e.g., Secudrain (Rahardjo et al. 2013) or drainage geonet (Zornberg et al., 2010) and the fine-grained layer can be replaced with fine recycled concrete aggregrates or fine recycled asphalt pavement (Rahardjo et al., 2019).

Proposed construction procedures

Mass burial site should be organized so that burial can be conducted in an orderly and efficient fashion to cope with demand. The grave shall be dug as a long trench that is at least 1.5 to 2 m below the ground surface and consists of at least 0.7 m of unsaturated soil zone (WHO 2005). The unsaturated soil layer provides a line of defence against the transport of necrolechate into the groundwater below the burial site. One end of the trench can be made with a slope access to enable a forklift to operate (Figure 2a). The trench can then be lined with GCL, and the coffins can be placed at some uniform spacing as indicated in Figure 2a. When the trench is full of coffins, the trench is sprayed with 1000 ppm sodium hypochlorite solution as suggested by Chen et al. (2018) for two purposes: (1) to disinfect the coffins, and (2) to hydrate the GCL but does not change its hydraulic conductivity. Sodium hypochlorite at 1000 ppm (0.1%) was found to be effective against transmissible gastroenteritis virus, TGEV (Wood and Payne 1998), bovine coronavirus (Maris 1990) and 229E (Sattar et al. 1989) irrespective of test conditions. WHO (2017) recommended using 0.5% chlorine solution for disinfection of objects possibly contaminated by victims of Ebola and Marburg virus. The SARS-CoV-2 can be inactivated effectively within one minute using common disinfectants, such as 70% ethanol or 0.1% sodium hypochlorite (Kampf et al., 2020). Hydration of the bentonite layer in the GCL may increase the hydraulic conductivity of the GCL (Didier and Comeaga, 1997). However, hydrating the bentonite layer in GCL causes the bentonite to swell and self-heal meaning that it forms a continuous mat of bentonite in contrast to an unsaturated bentonite layer which may have "holes" where the leachate can flow out of the site. Lee and Shackelford (2005) found that $CaCl_2$ at concentration of less than 50 mM has no effect on the hydraulic conductivity of GCL, and Rout and Singh (2020) found that polyvalent cations have more impact than those of monovalent cations. The concentration of 1000 ppm sodium hypochlorite (NaOCl) solution is 13.4 mM and gives a monovalent cation. Hence, the use of 1000 ppm sodium hypochlorite solution to hydrate the GCL will not have an effect on the hydraulic conductivity of the GCL. Soil is then backfilled into the trench until it covers the top of the coffins. Another layer of GCL is then placed, and the soil is then backfilled to the ground surface. To develop the capillary barrier effect, coarse-grained soil is first laid, followed by fine-grained soil. Alternatively, a layer of nonwoven geotextiles or drainage geonet can be used in place of the coarse-grained soil. The in-situ soil is then placed on top of the fine-grained soil. The capillary barrier system should be sloped to create a gentle gradient for surface runoff and lateral diversion (Rahardjo et al. 2006). The surface drains should be constructed around the boundary of the mass burial site to collect surface runoffs from the surroundings and the lateral diversion flow from the capillary barrier cover system. Vertical bentonite-type cutoff wall (Evans 2002) can be installed around the periphery of the mass burial site if it is deemed that the amount of necroleachate reaching and being carried in the groundwater may become an issue. Effectiveness of the cutoff wall depends greatly on the hydraulic conductivity of the wall material relative to the soil, chemical stability of the wall material, contaminants and groundwater condition (U.S. Army Corp of Engineers 1996, U.S. Environmental Protection Agency 1998).

Safe Handling of Coffins and Dignity Aspect

Unlike mass fatalities in natural disasters, identification is rarely a problem in a pandemic as those who died are either at home or in a healthcare facility (Scanlon and McMahon 2011). Hence, even in the mass burial site, efforts should be made to keep a register of the deceased and location of the grave. For fatalities arising from infectious disease, the commonly used procedures is to seal the bodies in watertight body bags. The New South Wales (NSW) Ministry of Health (2020) guidelines for funeral directors is to double bagged the body if suspected of infection by COVID-19. The body bag has specifications to disintegrate in soils within 5 to 8 years (e.g. Hong Kong, 2014; Scheerlinck, 2015). This process of bagging the deceased is usually done by healthcare workers in full-body personal protective equipment. The body bag is then sprayed with 1000 ppm sodium hypochlorite solution, and then placed into the coffin when available. For safe disposal, it is recommended that the coffin can be specially made with extra plinths which can be picked up using a forklift, thus minimizing the risk of infection through manual handling. Furthermore, the spraying of GCL by 1000 ppm sodium hypochlorite solution can be sprayed from a truck along the trench to minimize infection risk to the operators (Figure 2b). Similarly, backfilling and construction of the capillary barrier can be mechanized as much as possible to minimize infection risk to the operators as well as to increase efficiency.

Considering the possible high number of bodies that may be buried in a day during a pandemic, it is proposed that an expedient method of marking the graves be adopted: Coordinates of two points of the trench at the start and end can be located using global positioning system (GPS) and marked using pegs as indicated in Figure 3a. The GPS coordinates of the trench ensure that the record is permanent as the pegs may be lost over time. The register of the deceased in interred in each trench, together with the GPS coordinates of the trench and the uniform spacing of the coffins will allow identification of the grave and setting up of tombstone by family members or relatives in future, after the pandemic. A schematic of the completed burial site is shown in Figure 3b.

Monitoring of Mass Burial Sites

It has been recognized that cemeteries released contaminants at levels that pose environmental risks for the population (Üçisik. and Rushbrook 1998; Oliveira et al., 2012; Geleta et al., 2014; Całkosiński et al., 2015). Compared to the standard cemeteries, higher environmental risk can be expected of mass burial sites during pandemics due to; (i) its high burial load (area per body), (ii) pathogens can be carried in the necroleachate that may reach the groundwater, and (iii) embalming of the body is not performed (absence of the toxic embalming chemicals), but there may be a high level of disinfectants being used. If the proposed construction procedures for the mass burial mentioned above is adopted, the GCL encapsulating the bodies will be able to contain the necroleachate while the capillary barrier system will reduce or eliminate the amount of rainwater infiltrating into the burial site. Nonetheless, it is still prudent to implement a monitoring programme for the burial site to assess the possible spread of CoV and other pathogens as well as other contaminants from mass burial sites. Guidance for monitoring of groundwater contamination from cemeteries is available, for example, UK Environment Agency Guidance for Cemeteries and Burials: Prevent Groundwater Pollution (2020) and UK Environment Agency Guidance on Monitoring of Landfill Leachate, Groundwater and Surface Water (2014). The number of monitoring points depends on the area of the mass burial site, and the monitoring points should be representative points around the mass burial site. The location of the monitoring points should be between 10 to 100 m from the edge of the mass burial site. In addition, a couple of monitoring wells are recommended to be installed at the upstream side to monitor background water quality as a reference baseline monitoring. Further, the full decomposition of a body is expected to take up to 10 years, and hence, the monitoring programme should last at least 10 years from the time of the last burial.

Conclusion

Previous case histories have indicated that the construction of mass burial during pandemics or mass disasters requires extra precaution to mitigate any possible negative environmental impact on groundwater. The geoenvironmental engineers, with their extensive experience in landfill construction and management, can play a major role in designing environmentally safer mass burial site. However, it must be admitted that time constraints and cultural sensitivity aspects when dealing with the disposal of dead bodies add significant engineering challenges compared to the case of the waste landfills. In this note, construction and management approach of mass burial sites during pandemics are proposed where the safety and health of personnel handling the bodies are considered, and commercially available geosynthetic materials are recommended to seal off the decomposing dead bodies from the surrounding environment. Capping the mass burial site with a capillary barrier system minimizes the amount of rainwater infiltrating into the burial site and hence the amount of necroleachate that may escape from the burial site. The use of GCL and drainage geotextiles offer cost-effectiveness and simplify the construction process in terms of the required construction equipment and time. However, more research is needed to assess the survival/retention of bacteria and viruses through GCL, which is amended by zeolites.

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Table 1. Pandemics where fatalities ≥ 100,000

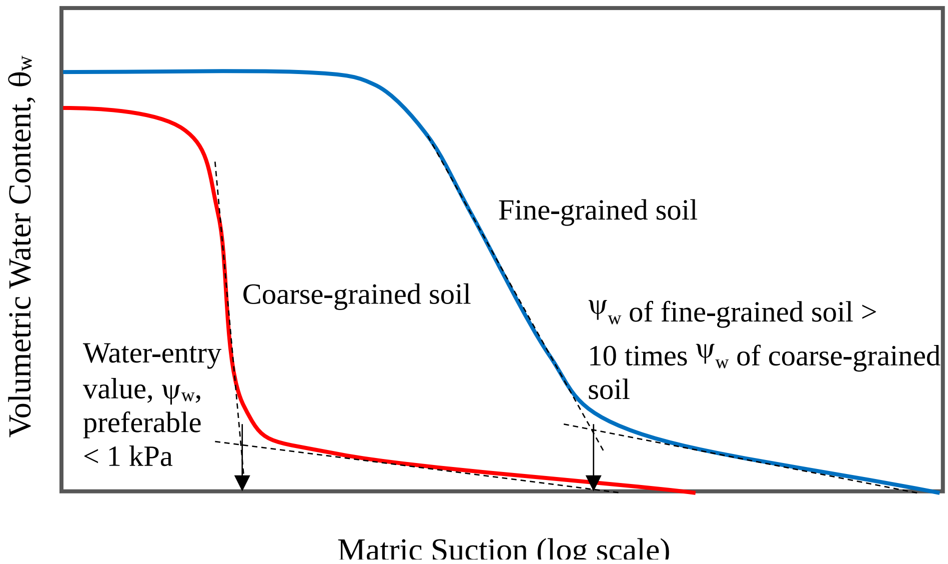
Pandemic	Dates	Estimated fatalities
Plague of Athens	430 B.C.	100,000
Antonine Plague	A.D. 165-180	5,000,000
Plague of Justinian (Bubonic)	A.D. 541-542	25,000,000
The Black Death (Bacterium *Yersinia pestis*)	1346-1353	75,000,000 to 200,000,000
Cocoliztli epidemic (Bacterium *S. paratyphi C*)	1545-1548	15,000,000
Great Plague of London	1665-1666	100,000
Great Plague of Marseille	1720-1723	100,000
Third Cholera Pandemic	1852–1860	1,000,000
Flu pandemic	1889-1890	1,000,000
Sixth Cholera Pandemic	1910-1911	> 800,000
Spanish Flu	1918-1920	20,000,000 to 50,000,000
Asian Flu	1957-1958	2,000,000
H1N1 Swine Flu pandemic	2009-2010	151,700 to 575,400

Table 2. Minimum distances to water sources (information from WHO/WEDC 2013)

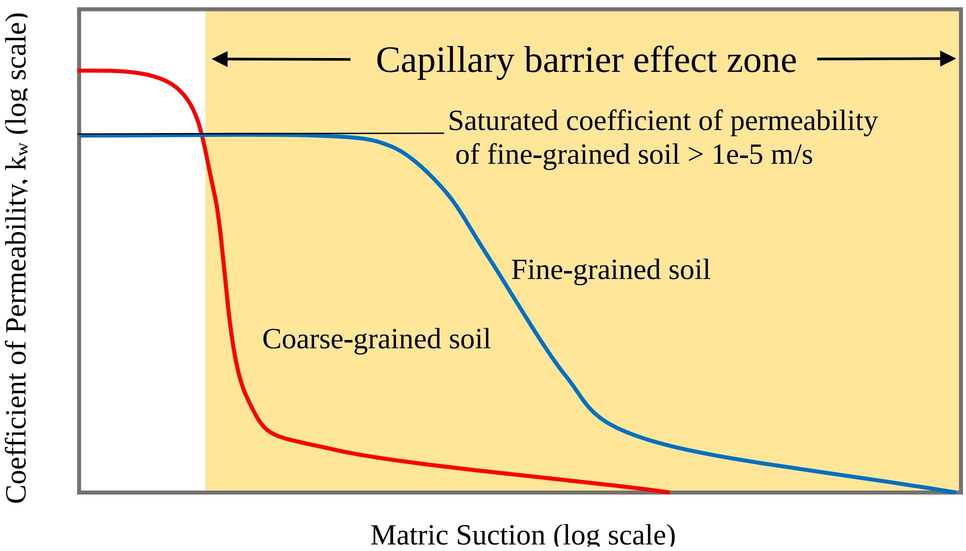
Number of bodies	Distance from water source (m)
4 or less	200
5 to 60	250
60 or more	350
120 bodies per $100m^2$	350
Note: The bottom of grave should be at least 2.0m above the highest groundwater table.	

Table 3. Factors influencing virus transport in soil (information from Abu-Ashour et al. 1994, Bosch et al. 2006)

Factor	Effects
Flow rate	Higher flow rate of water increases the rate of movement.
Hydraulic condition	Rate of movement is higher in saturated soils than in unsaturated soils.
Soil texture	Coarse-grained soils retain less viruses than fine-grained soils.
Soil solution	Greater ionic strength implies higher adsorption of viruses.
pH	Higher pH leads to greater adhesion to soil. Generally shorter survival time in acidic soils (pH: 3-5) than in alkaline soils.
Temperature	Longer survival at lower temperature.
Virus type	Adsorption varies depending on the strain and type of virus.
Humic substances	Organic content may retard virus adhesion to soil.
Cations	Presence of cations increases adsorption.

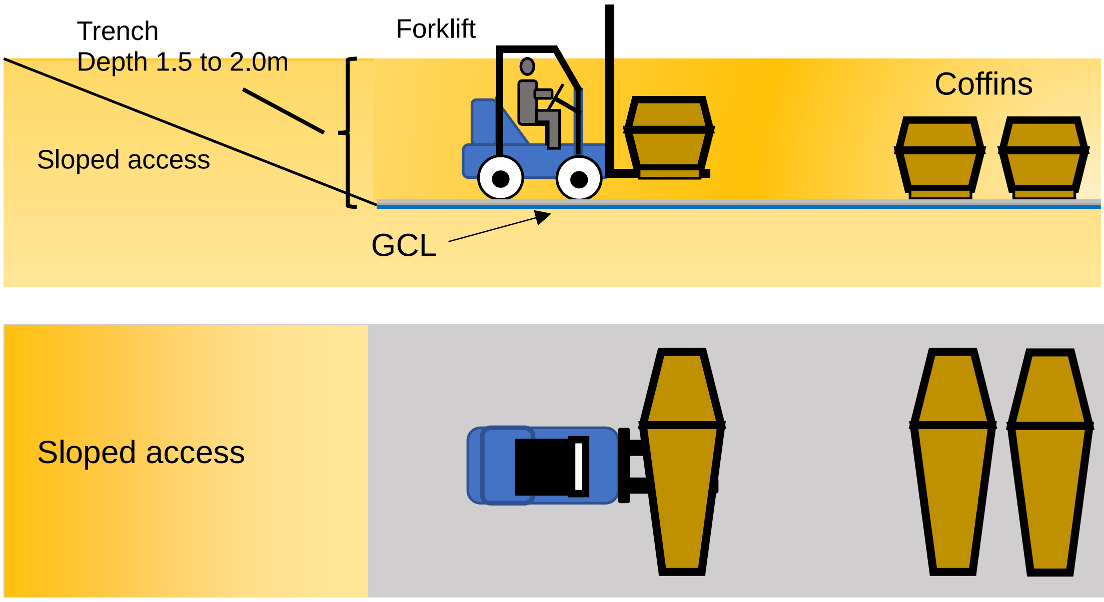


(a) Soil-water characteristic curve

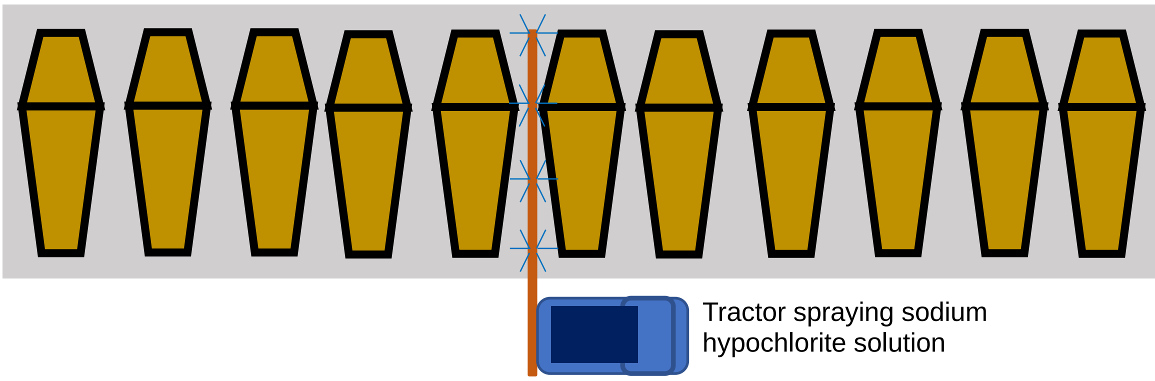


(b) Permeability function

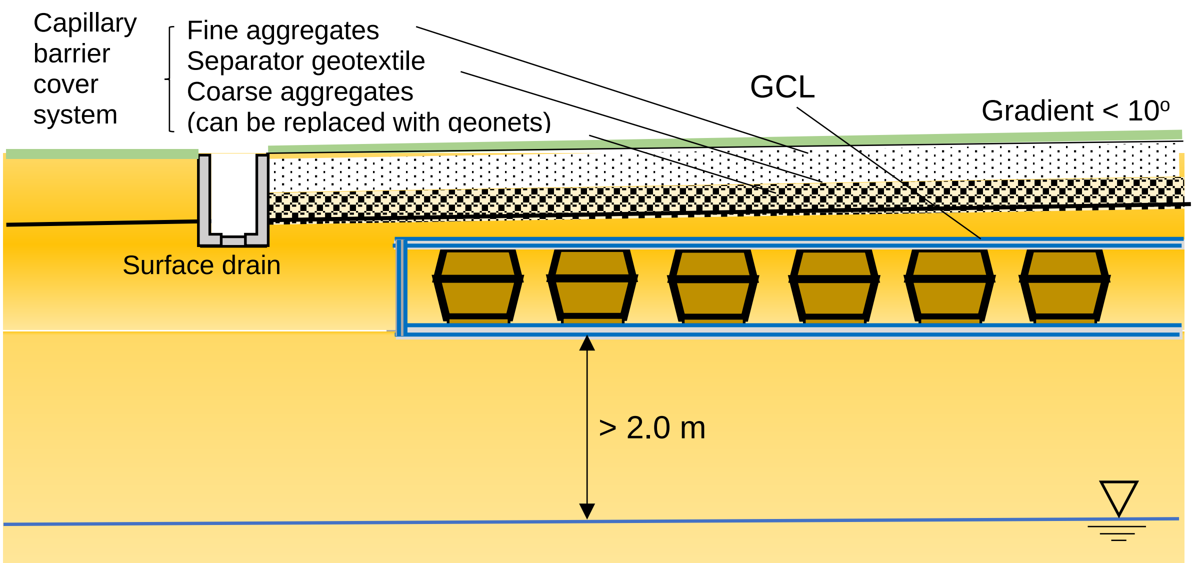
Figure 1. Soil-water characteristic curves and permeability functions of coarse- and fine-grained soils of the capillary barrier system



(a) Placement of coffins at regular spacing by forklift

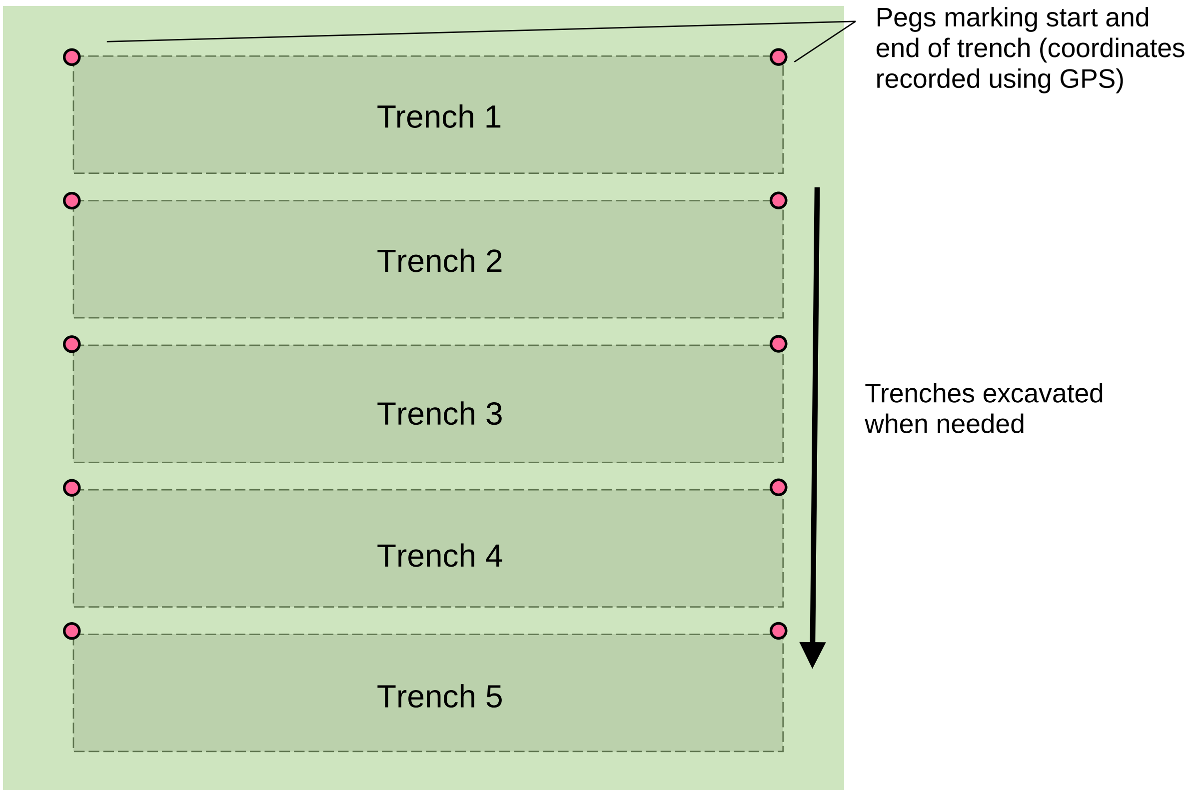


(b) Spraying of 1000 ppm sodium hypochlorite solution

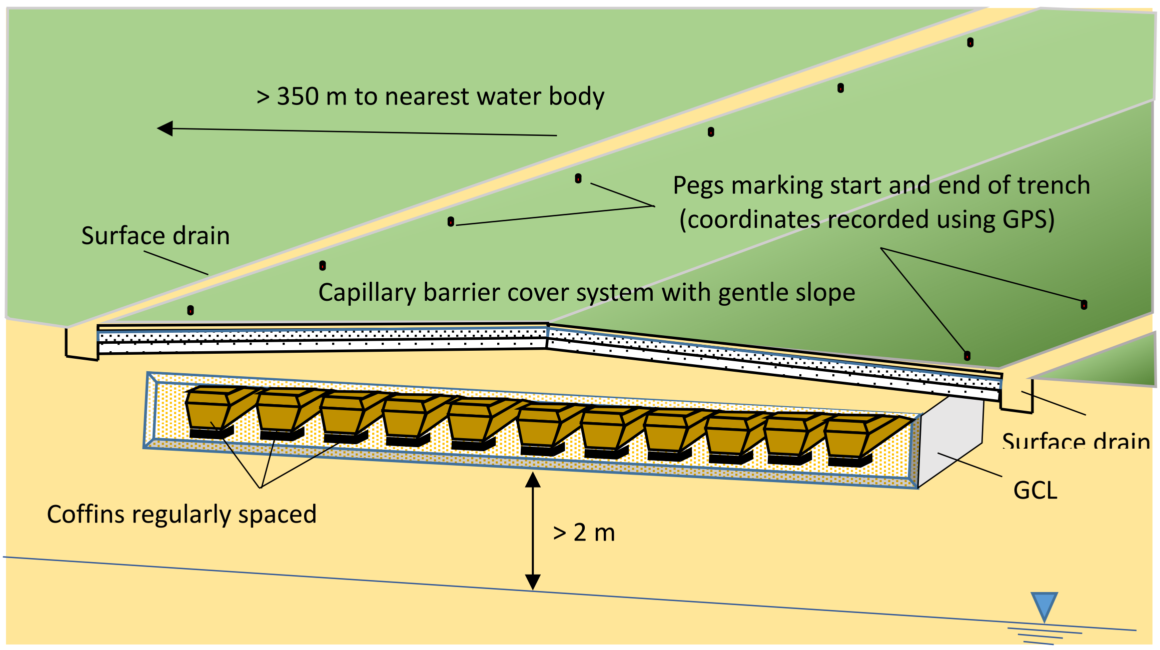


(c) Encapsulation of coffins using GCL with a capillary barrier cover system

Figure 2. Proposed construction procedures for mass burial site.



(a) Marking of trench for future location of grave by family members and relatives.



(b) Completed mass burial site

Figure 3. Schematic drawing of marking of trenches and completed mass burial site.