Help Instruction File:

Anoxic Limestone Drain Module

Provided by the Office of Surface Mining Reclamation and Enforcement (OSMRE), the Pennsylvania Department of Protection (PADEP), the U.S. Geological Survey's (USGS) and the West Virginia Department of Environmental Protection (WVDEP).

Anoxic Limestone Drain Module Overview

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1.0 Objective

An Anoxic Limestone Drain (ALD) is a passive treatment system (meaning that no machinery or daily chemical addition is required for its operation) that is typically used to treat net-acidic, anoxic mine drainage of low to moderate flow with low to moderate acidity and dissolved metals.

The objectives of this overview are to: (1) Provide a basic understanding of the theory and application of ALD and (2) Provide an overview of the ALD module to guide users in developing an estimate of the cost to construct, operate, and maintain ALDs for treating mine drainage. Therefore, this overview will be presented in two sections, **Treatment Component Overview** and **ALD Module Overview**.

2.0 Treatment Component Overview

The following section is organized into three sections, 1.) Physical and Hydraulic Description, 2.) Application and Treatment Chemistry, and 3.) Conceptual Treatment Module. The first section provides a physical description and hydraulic profile for a ALD to provide context for users of AMDTreat. The second section describes the common application of the ALD component. The third section describes a generalized conceptual model describing the treatment chemistry to help familiarize users with terms and concepts presented throughout the AMDTreat modules.

2.1 Physical and Hydraulic Description

An Anoxic Limestone Drain (ALD) is essentially a buried trench or basin filled with limestone overlain by a soil cover. The trench can be rectangular in shape with vertical side walls or can be constructed as an inverted trapezoidal prism (basin). The limestone is wrapped like a "burrito" in a synthetic liner to prevent water leaking, minimize the introduction of air and to prevent the surrounding soil from migrating into the limestone layer (Figure 7). However, the influent and effluent (upstream and downstream) ends of the ALD may or may not be wrapped with liner (only non-woven geotextile) and left open in order to accept the water to be treated depending on the type of hydraulic connection to the source of water. After the ALD is filled with limestone and wrapped in liner, a layer of soil (soil cover) is placed over the liner covering the limestone layer to bury or enclose the ALD. An influent pipe transports water into one end or side of the ALD and an effluent pipe discharges water from the opposite downstream end or side. The effluent pipe carries water to the surface and is positioned at an elevation to ensure the limestone layer remains fully submerged and anoxic (minimal or no headspace within the ALD).

An ALD can be conceptualized as having four distinct "material layers": soil cover, limestone, piping, and liner layers (Figures 2 and 3). Typically, an ALD is filled with limestone ranging from 1.0 to 3.5 inches in size (AASHTO #1 or #3) and is commonly 3.0-4.0 ft thick (AMDTreat default value is 4.0 ft). The soil cover is typically 1.0 to 3.0 ft thick on average. It is recommended to construct the soil cover with a peak or crown over the middle of the ALD and gently slope the final surface down and away from the crown to encourage surface runoff from precipitation events to flow off and away from the ALD. Historically ALDs were constructed as long narrow trenches but many modern ALDs are shorter and wider in more of a pond or basin shape with some even constructed in a square shape. The long narrow trench-like ALDs contain a small cross-sectional surface area (perpendicular to flow) and tend to quickly clog with metal precipitates and sediment resulting in short-circuiting or overall plugging and bypass of the ALD.

ALDs can be installed on underground or surface mine discharges. For underground mine discharges, typically an excavator is used to expose the underground mine void along a hillside and a pipe is installed as part of a wet seal structure to convey the water from the mine to the ALD. In many cases, a pressure relief pipe is installed at a higher elevation than the ALD inlet pipe so if the ALD clogs the rise in water within the mine will be controlled and allowed to discharge to the surface to prevent building up the head pressure that could create a mine blowout of the outcrop coal barrier. For ALDs installed on surface mine discharges, an excavator is used to excavate the discharge back into the hillside to collect the water and construct the ALD. In either case, water flows horizontally through the drain. The piping network is used to transport water in and out of the ALD and designed to provide pressure relief as the ALD clogs but is not typically used for flushing. ALDs are typically discharged to an oxidation and settling pond.

Figures 2 and 3 provide a perspective of the physical layout of an ALD and Figures 4 through 7 show various stages during construction of an ALD to treat mine water.

2.2 Application and Treatment Chemistry

An Anoxic Limestone Drain (ALD) is a type of "passive" treatment component used to treat circumneutral pH net-acidic mine drainage. The term "passive" refers to the inability to exert operational control to adjust treatment in response to changing influent or effluent conditions. Strictly speaking, circumneutral pH is defined as having a pH of 7, but the term is commonly used to describe mine drainage with a pH between 5.5 and 8.0. Net-acidic mine drainage describes solutions that contain more acid-producing than acid-consuming species when the water is "treated". Therefore, a net-acidic solution is one where the acidity of the solution is greater than the alkalinity (net acidity = acidity – alkalinity). Given the pH constraint and net acidic condition, circumneutral net acidic mine drainage typically contains ferrous iron and/or manganese in the Appalachian coal fields. ALDs are primarily used to treat circumneutral pH net-acidic mine drainage containing ferrous iron. The ferrous iron concentration will be at least 1.7 times the concentration of alkalinity (as $CaCO_3$) to create the net acidic condition.

The primary objective of ALDs is to impart alkalinity and turn the net-acidic mine water to net-alkaline (alkalinity > acidity) thereby allowing the ferrous iron to oxidize in a subsequent oxidation/settling pond and the pH will be buffered sufficiently and remain > 6.0. The combination of an ALD to impart alkalinity followed by an oxidation/settling pond(s) for iron removal has proven to be very effective and one of the lowest maintenance passive treatment strategies for mine water. In fact, some ALDs have operated for more than 20 years without intervention and consistently achieve water quality limits.

The primary reason why ALDs are so successful when applied to the appropriate mine water chemistry, i.e. mine water containing low dissolved oxygen and low aluminum concentration, is because the ferrous iron remains soluble in the ALD. The circumneutral pH water quality criteria avoids aluminum and ferric iron-rich waters that would precipitate within the ALD and cause hydraulic failure. If properly designed and constructed, the ALD will be anoxic (free of oxygen) and ferrous iron will remain dissolved as limestone dissolves and the pH and alkalinity increases. In addition, manganese treatment/removal is not expected or observed in properly functioning ALD's as anoxic conditions prevent the presence of manganese oxidizing bacteria and that pH constraints limit abiotic manganese removal mechanisms

Since ALDs are primarily utilized on circumneutral pH mine water and ferrous iron remains soluble, ALDs lack pH and mineral acidity to drive limestone dissolution like in most passive treatment systems. Instead, dissolved carbon dioxide is the primary driving force of limestone dissolution and the amount of alkalinity that can be generated from the ALD is directly related to the carbon dioxide concentration in the raw mine water. Thus, it is important to characterize the raw mine water carbon dioxide concentration and calculate whether the ALD can generate the alkalinity to produce net alkaline conditions as part of the design evaluation process. Otherwise, a net acidic condition leaving the ALD or within the subsequent oxidation/settling pond will result in iron oxidation consuming all the available alkalinity and the excess iron acidity will decrease the pH below 6.0 and decrease the rate of iron oxidation. As a result, the settling pond will discharge low pH and net-acidic water containing unoxidized (dissolved) ferrous iron.

The solubility of aluminum is largely pH dependent, so the geochemical behavior of aluminum will be similar in Vertical Flow Ponds, Limestone Beds, and ALDs. As the mine water pH is increased to ~ 5.5, most of the aluminum will precipitate and cause hydraulic issues by clogging the limestone void spaces. However, Vertical Flow Ponds and Limestone Beds are much more suitable for treating aluminum-rich mine water since they have much larger cross-sectional area perpendicular to flow and are also capable of periodically flushing some of the precipitates as part of their normal operating conditions. Aluminum will still precipitate, but the larger surface area and flushing will allow the beds to function longer before hydraulic failure. In addition, Vertical Flow Ponds and Limestone Beds contain freeboard that allows the build up of hydraulic head to continue to force the flow of water through the bed as aluminum precipitate accumulates in the limestone layer and impact the permeability of the bed. Since ALDs have no freeboard layer they lack the ability to increase hydraulic head without causing the rerouting of water around the ALD in surface mine discharges or increasing the mine pool elevation in underground mine discharges. Thus, ALDs are better suited for treating waters void of ferric iron, aluminum, and dissolved oxygen.

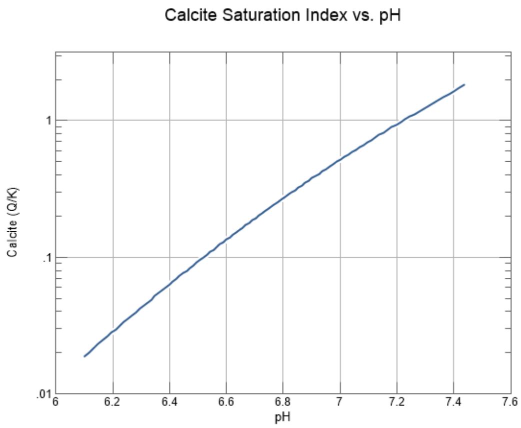
2.3 Anoxic Limestone Bed Conceptual Treatment Module

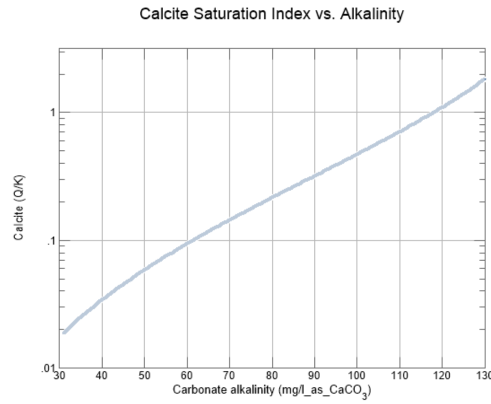
The following discussion presents a conceptual treatment model for ALDs treating net acidic circumneutral pH mine drainage containing ferrous iron and manganese.

2.3.1 Soil Cover Layer: The soil cover layer is the top layer and is to serve as a barrier to keep atmospheric oxygen from entering the limestone layer. This is done in order to create anoxic conditions necessary for the limestone drain to function properly.

2.3.2 Limestone Layer: The following mine drainage flows from an underground coal mine and into an ALD: pH = 5.8, Alkalinity = 31.8 mg/L as $CaCO_3$, Ferrous iron = 170 mg/L, Dissolved Oxygen < 0.1 mg/L, and Temperature = 11 °C. Performing chemical speciation of the water shows the mine drainage contains 52 mg/L of $CO_{2(aq)}$ and 21 mg/L of Total Inorganic Carbon (TIC).

As this mine water flows into the ALD, the dissolved carbon dioxide will react with the limestone and produce bicarbonate alkalinity and increase pH. The dissolution of limestone will increase the TIC concentration along the flow path within the ALD. Ferrous iron will remain soluble since the water lacks an electron acceptor, such as dissolved oxygen, to facilitate oxidation. Assume the ALD is constructed with enough retention time to bring the water into equilibrium with calcite ($CaCO_3$). At equilibrium, the pH will have increased to 7.2 and the alkalinity will be 118 mg/L (as $CaCO_3$). It is important to note that very few ALDs are constructed large enough to bring the water into equilibrium (saturation index = 0) with calcite and many only achieve a saturation index of -1.5 to -0.5. Nevertheless, for the purpose of this discussion assume the water discharged from the ALD is in equilibrium with calcite.





The water flows from the ALD down a turbulent rock-lined ditch to an oxidation/settling pond. The turbulence within the ditch dissolves 6.0 mg/L of dissolved oxygen (O_2) into the water and the oxic-rich and increased pH environment facilitates ferrous iron oxidation. The 170 mg/L of ferrous iron will generate 300 mg/L of acidity (as $CaCO_3$) after oxidation and hydrolysis of the ferrous iron. Thus, even if the ALD is constructed large enough to bring the water into equilibrium with calcite, the generation of 118 mg/L of alkalinity will be insufficient to neutralize the 300 mg/L of iron acidity and the water will remain net acidic. Approximately 69 mg/L of the 170 mg/L of ferrous iron would oxidize and precipitate before turning the water net acidic again. Further iron oxidation will produce excess acidity and cause the pH to decrease and minimize further oxidation. The settling pond will discharge low pH water (< 4.0) with a lower but still elevated dissolved ferrous iron concentration.

3.0 Anoxic Limestone Bed Module Overview

3.1 Layout and Workflow

In general, inputs are on the left-hand side of the module and calculated outputs are on the right. The module inputs on the left-hand side are arranged into five sections: (1) Water Quality and Flow Input, (2) Sizing Methods, (3) System Properties, (4) Layer Materials, and (5) Other Items. The workflow for the module is for users to start at the top left-hand side. Enter the *Design Flow* and *Net Acidity*, then select a method to determine the amount of limestone contained in the limestone layer of the ALD. Next, users specify design parameters such as the depth of the soil cover and limestone layers, and unit costs for items affecting the capital cost to construct the ALD. Finally, users can enter any capital cost not captured by the module into the *Other Items* section.

Module output is provided on the right-hand side of the module. Module outputs on the right-hand side are arranged into four sections: (1) Sizing Summary, (2) Capital Cost, (3) Annual Cost, and (4) Net Present Value. The sizing summary provides dimensional details for the system. The estimated cost to construct and operate the ALD is provided under the *Capital Cost* and *Annual Cost* headings. Lastly, users can opt to conduct a Net Present Value (NPV) to obtain the total cost to operate and maintain a treatment system for a defined time period.

A general overview of the module input and output sections are presented below, however, users are directed to the numerous tool tips located in the module that provide additional detailed information, such as definitions of terminology. In most cases, the tool tips are accessed by clicking on the information icon ( ) in each of the subheadings in the module.

3.2 Module Inputs

3.2.1 Water Quality and Flow Input: The Water Quality and Flow Input section is where users specify the design flow and net acidity to size the passive treatment system component. The definitions for the required input can be found in the tool tip for this section. Click on the information icon ( ) on the right side of the Water Quality and Flow subheading.

3.2.2 Sizing Methods: Users can select from five different methods to size the ALD: Retention Time, Bureau of Mines, User-specified Limestone Quantity, and User-specified Dimensions. The module offers two different approaches to sizing ALDs. The first approach calculates the mass of limestone (tons) in the limestone layer before determining other dimensions. The Retention Time, Bureau of Mines, and User-Specified Limestone Quantity methods utilize this approach. The first approach is the most common as it relates the sizing of the treatment system based on flow and water quality characteristics. The second approach requires users to specify the length and width of the freeboard layer (User-specified Dimensions method) before calculating the remaining dimensions of the ALD. The second approach is often used when the land area available for treatment is restricted, when reverse engineering, or when developing a cost estimate for an existing treatment system.

Calculate Mass of Limestone in Limestone Layer

3.2.2.1 Retention Time – The user enters the desired time to retain the water in the void spaces between the individual pieces of limestone. The mass of limestone required to achieve the user-specified retention time is calculated by multiplying the *Design Flow* rate by the *Retention Time* to determine the volume required to retain the water (Equation 1). The calculated volume is then divided by the porosity of the limestone layer to calculate the total volume of the limestone layer (Equation 2).

$$\begin{aligned} &Volume\ Required\ for\ Water\ (yd^3) = \\ &\qquad Design\ Flow\ (gpm) \times \frac{60\ min}{1\ hr} \times Retention\ Time\ (hrs) \times \frac{1\ yd^3}{201.974\ gal} \end{aligned} \qquad \textbf{(1)}$$

$$Limestone\ Layer\ Volume\ (yd^3) = \frac{Volume\ Required\ for\ Water\ (yd^3)}{Limestone\ Porosity\ (\%)} \qquad \textbf{(2)}$$

The porosity represents the percent (%) of void space in the limestone layer (volume of the voids in between individual pieces of limestone/total volume of the voids and the limestone).

Users can specify a value for porosity to match the gradation of limestone they plan to use in the limestone layer. Users can specify the porosity value under the *Limestone* section, which is located under the *Layer Materials* subheading. Based on the user-specified porosity value, AMDTreat calculates the *Bulk Density* of the limestone. The mass of the limestone required in the limestone layer is calculated by multiplying the limestone layer volume by the *Bulk Density*.

$$Limestone\ Mass\ (tons) = Limestone\ Volume\ (yd^3) \times \frac{27\ ft^3}{1\ yd^3} \times Limestone\ Bulk\ Density\ \left(\frac{lbs}{ft^3}\right) \times \frac{1\ ton}{2000\ lbs} \qquad \textbf{(3)}$$

Results from bench-scale testing indicate that a retention time of 16 hours is a good balance between maximizing alkalinity production and the size of the treatment system (mass of limestone). Some professionals conduct "cubitainer" testing to determine the amount of time required to achieve net alkaline conditions. A cubitainer is filled with limestone and mine drainage, with care taken to prevent off-gassing of carbon dioxide (CO_2) from the mine drainage, and alkalinity is measured over time. Some professionals find it appropriate to add a safety factor to the retention time since the retention time and contact between limestone and mine drainage will change as soon as limestone starts to dissolve.

See Section 3.2.2.5 to 3.2.2.7 for volume calculations for the other layers.

3.2.2.2 Bureau of Mines - The Bureau of Mines was an agency in the U.S. Department of Interior that is now retired but was instrumental in conducting some of the early research in how to design passive treatment systems (Hedin and Watzlaf, 1994). A method they developed to determine the mass of limestone needed in passive treatment systems was to perform two calculations. The first calculation is to determine the mass of limestone required to retain the water for a given retention time. This calculation is the same as Equation 3, described above for the retention time sizing method.

A second calculation (Equation 4) is used to determine the mass of limestone required to neutralize the acid loading of the mine drainage for a specified time frame (*Neutralization Period*). The mass of limestone required to neutralize the acid loading is determined by multiplying the user-specified *Design Flow* by the *Net Acidity* and the *Neutralization Period*. The resultant value is divided by both the *Purity* and *Dissolution Efficiency* of the limestone to correct for the portion of limestone that will not dissolve to produce alkalinity and account for the fact that larger pieces of limestone are not likely to efficiently dissolve due to a loss of surface area from weathering and mineral precipitate coatings (i.e. iron hydroxide) that form on the surface and disrupt dissolution. A *Dissolution Efficiency* of less than 100% will increase the mass of limestone required in the LB to compensate for the mass of limestone that is unlikely to dissolve. Users can specify the *Purity* and *Dissolution Efficiency* of limestone under the *Limestone* section, which is located under the *Layer Materials* subheading.

$$Limestone\ Mass\ to\ Neutralize\ Acid\ (tons) =$$

$$\frac{Design\ Flow\ (gpm) \times \frac{1\ ft^3}{7.48\ gal} \times \frac{525600\ min}{1\ year} \times Net\ Acidity \times \frac{1\ lb}{453592\ mg} \times \frac{28.3168\ L}{1\ ft^3} \times Neut.Period\ (yrs) \times \frac{1\ ton}{2000\ lbs}}{Purity\ (\%\ CaCO_3\ by\ weight) \times Dissolution\ Efficiency\ (\%)} \quad \textbf{(4)}$$

The mass of limestone required to retain the water for a specified time (*Retention Time*) is added to the mass of limestone required to neutralize the acidity loading for the *Neutralization Period* to determine the total mass of limestone required for the ALD limestone layer (Equation 5). This method ensures the user-specified *Retention Time* is preserved, to generate maximum alkalinity, at the end of the user-specified *Neutralization Period* when the limestone mass dedicated to neutralizing the acidity load is nearly depleted.

$$Total\ mass\ of\ limestone\ (Bureau\ of\ Mines\ method) =$$

$$Retention\ Time\ Limestone\ mass\ (Eq.3) + Limestone\ mass, neutralization\ (Eq.4) \quad \textbf{(5)}$$

See Section 3.2.2.5 to 3.2.2.7 for volume calculations for the other layers.

3.2.2.3 User-Specified Limestone Quantity (tons) - If users have their own method for determining the mass of limestone, the user-specified limestone method can be used to calculate the dimensions of the limestone layer and remaining layers of the ALD. The mass of limestone is entered, and the user-specified porosity value for the limestone layer is used to calculate the volume and retention time of the limestone layer. See Section 3.2.2.7 for volume calculations for the other layers.

3.2.2.4 User-Specified Dimensions – Mine drainage discharges often emerge at the base of hillsides. The available land area for constructing a treatment system between the point of emergence and the receiving stream can be limited. The use of other sizing methods may produce an ALD that is larger than the available land area. A smaller ALD can be designed for the site, but it will most likely require more maintenance and prematurely plug due to high metal loading per unit area/volume. Alternatively, a smaller ALD could be designed to treat only a portion of the mine drainage while bypassing the rest. To use this sizing method, enter the top length and width of the limestone layer. AMDTreat then uses the user-specified side slopes and depths to calculate the dimensions and volumes of the ALD layers.

Volumetric Calculations

3.2.2.5 Volumetric Calculations –AMDTreat models all passive treatment systems, including ALDs, as an “inverted” trapezoidal prism (Figure 1). AMDTreat calculates the overall dimensions of a passive treatment system by first breaking up the system into individual soil cover and limestone layers. Each individual layer and the geometric shape of the overall system is modeled as an inverted trapezoidal prism. AMDTreat sizing methods fall into one of two categories: (1) users input information that is used to calculate a layer volume or surface area is calculated or users specify the mass of limestone, or (2) users specify the top width and length of the limestone layer. In either case, AMDTreat uses the information generated by the sizing method, along with user-specified depths, side slopes, and length-to-width ratios to determine the dimensions of a layer shaped as an inverted trapezoidal prism. What differs is the approached used to calculate the geometry. The two approaches are provided below

3.2.2.6 Calculations for Retention Time, Bureau of Mines, and User-Specified Limestone Sizing Methods –

The equation for an inverted trapezoidal prism is:

$$V = \left(\frac{W_T L_T + W_B L_B}{2}\right) D \quad \mathbf{(6)}$$

Where:
V = Volume of trapezoidal prism
$L_T W_T$ =Length & Width of top of prism
$L_B W_B$ =Length & Width of bottom of prism
D = Depth

These sizing methods determine the volume of the limestone layer. Therefore, AMDTreat calculates the volume of the limestone layer and users are required to specify the depth of the limestone layer, inside slope, and length-to-width ratio for the bottom of the limestone layer. The unknowns are the length and width of the top and bottom dimensions of the trapezoidal prism for the limestone layer. Since the depth and inside side slope of the ALD is known, the top width and length of the limestone layer can be written in terms of the bottom length and width to reduce unknowns in the equation. Furthermore, since the bottom length-to-width ratio is known, the bottom width can be written in terms of the bottom length. Now Equation (8) is rearranged to solve for the bottom length of the limestone layer. The resultant equation is a quadratic:

$$L_{BLL} = \frac{-\left(\frac{2DR}{S} + \frac{2D}{S}\right) \pm \sqrt{\left(\frac{2DR}{S} + \frac{2D}{S}\right)^2 - 4(2R)\left(\frac{4D^2}{S^2} - \frac{2V}{D}\right)}}{2(2R)} \quad \mathbf{(7)}$$

Where:
V = Volume of Limestone Layer
L_{BLL} = Bottom Length of Limestone Layer
D = Depth of Limestone Layer
S = Inside Side Slope of ALD
R = Length to Width Ratio of Bottom of Limestone Layer

Once the bottom length is known, the bottom width of the limestone layer (W_{BWL}) is calculated by dividing the bottom length by the user-specified value for length-to-width ratio for bottom of the ALD:

$$W_{BWL} = \frac{L_{BLL}}{R} \quad \mathbf{(8)}$$

The two remaining unknown dimensions of the limestone layer are the top length and width. The top length of the limestone layer is calculated by:

$$L_{TLL} = L_{BLL} + 2 * S * (D_{LL}) \quad \mathbf{(9)}$$

Where:
L_{TLL} =Top Length of Limestone Layer
L_{BLL} = Bottom Length of Limestone Layer
D_{LL} = Depth of Limestone Layer
S =Inside Side Slope of ALD (rise/run)

The top width of the limestone layer is determined by the same approach. Now that all the dimensions of the limestone layer are known, the dimensions of the water and freeboard layers can be determined using a similar approach:

Soil Cover Layer

The bottom length of the soil cover layer (L_{BSCL}) is equal to the top length of the limestone layer (L_{TLL}).

$$L_{BSCL} = L_{TLL} \quad \mathbf{(10)}$$

The top length of the soil cover layer (L_{TSCL}) is calculated by:

$$L_{TSCL} = L_{BSCL} + 2 * S * (D_{SCL}) \quad \mathbf{(11)}$$

Where:
S =Inside Side Slope of ALD (rise/run)
D_{SCL} = Depth of Soil Cover Layer

Equation (8) is used to calculate the volume of the soil cover layer.

In addition to assuming all passive treatment systems are constructed as an inverted trapezoidal prism, an additional assumption is that the excavation volume is equal to the summation of the limestone and soil cover layer volumes:

$$ALD\ Exavation\ Volume = Soil\ Cover + Limestone\ Volume \qquad \mathbf{(12)}$$

3.2.2.7 Calculations for User-Specified Dimensions Sizing Method – When users specify top width and length of the limestone layer for a system, AMDTreat uses the user-specified values for inside side slope, and the soil cover and limestone layer depths to calculate the dimensions and volumes of the individual layers of the ALD.

The bottom length of the limestone layer (L_{BLL}) is calculated by:

$$L_{BLL} = L_{TLL} - 2 * S * (D_{FL}) \quad \mathbf{(13)}$$

Where:
L_{BLL} = Bottom Length of Limestone Layer
L_{TLL} =User-Specified Top Length of Limestone Layer
D_{FL} = Depth of Freeboard Layer
S =Inside Slope of ALD (Run/Rise)

The bottom width of the limestone layer is calculated using the same approach.

The volume of the limestone layer is determined by:

$$V_{LL} = \left(\frac{W_{TLL}L_{TLL} + W_{BLL}L_{BLL}}{2}\right) D_{LL} \qquad \mathbf{(14)}$$

Where:
V_{LL} = Volume of trapezoidal prism-shaped Limestone Layer
W_{TLL} = Top Width Limestone Layer
L_{TLL} = Top Length Limestone Layer
W_{BLL} = Bottom Width Limestone Layer
L_{BLL} = Bottom Length Limestone Layer
D_{LL} = Depth of Limestone Layer

Soil Cover Layer
The bottom length of the soil cover layer (L_{BSCL}) is equal to the top length of the limestone layer (L_{TLL}).

$$L_{BSCL} = L_{TLL} \qquad \mathbf{(15)}$$

Now that the bottom width and length of the soil cover layer is known, the user-specified values for inside slope and depth of soil cover layer are used in Equation (13) to calculate the top width and length of the soil cover layer. Equation (14) is used to calculate the volume of the soil cover layer.

Lastly, the excavation volume is determined by adding the volumes for the soil cover and limestone layers (Equation 12). The model assumes that the excavated earth excess material is disposed of on-site.

3.2.3 System Properties:
The Systems Properties section allows the user to specify the inside slope of the ALD, the limestone layer bottom length-to-width ratio, and the excavation unit cost.

3.2.4 Layer Materials:
Unlike active treatment systems which require the continuous addition of chemicals to maintain treatment of mine drainage, passive treatment systems typically consist of impoundments filled with enough reagent (e.g., limestone) to provide treatment for many years. For some passive treatment system components, such as ALDs, limestone is used within the impoundment to manipulate the geochemistry and control oxidation/reduction and solubility reactions as the mine drainage flows through the system. AMDTreat considers each reagent or material as a "layer" in the impoundment. Both "reagent" and "material" are used to describe layers because not all layers are comprised of reagents or materials meant to manipulate water chemistry. For example, the liner layer is designed to prevent leakage from the constructed impoundment feature and also to provide a separation material between the excavated soil face and the treatment media (e.g., limestone). The *Layer Materials* section is where users can control the depth and other characteristics of the materials used in an ALD.

3.2.4.1 Soil Cover Layer: Users specify the depth of the soil used to cover the ALD. A typical soil depth is between 1.0 and 3.0 feet. The soil cover layer is most likely not a uniform depth in order to construct a crown in the middle of the ALD and then to gradually slope down away (<1%) from the crown to promote positive drainage of surface runoff off of the ALD to minimize infiltration.

3.2.4.2 Limestone Layer: The limestone layer is the main source of alkalinity generation in an ALD. Users can specify the depth, purity, dissolution efficiency, porosity and unit cost for both the material and placement of limestone in this section. A typical limestone depth is 4.0 feet and limestone used in passive treatment system components such as ALDs normally have purity greater than 85% calcium carbonate ($CaCO_3$) by weight. The dissolution efficiency is used to compensate for limestone losing surface area and becoming less reactive as it dissolves/weathers and as a safety factor for additional limestone to compensate for potential plugging or coating (a.k.a. armoring) issues.

3.2.4.3 Pipe Layer: The piping layer considers the piping required to convey the water into and/or out of the ALD. The piping layer may be situated between the limestone and liner layers or within the limestone layer and is necessary to distribute the water and promote flow horizontally and vertically through the treatment media and collect the water and discharge it out of the ALD. The ALD module offers users two methods to estimate the cost to purchase and install the piping network, the AMDTreat Piping Calculator or User-Specified Piping Layout. The default design of the AMDTreat Piping Calculator for ALDs is different than for Vertical Flow Pond, however, it is very similar to Limestone Beds. Similar to the Limestone Bed piping default design, the ALD default piping layout includes a perforated header pipe installed at both the influent and effluent ends of the limestone layer to transport water in and out of the ALD. The perforated header pipes are intended to evenly distribute the raw mine water across the width of the limestone bed and to draw water both horizontally and vertically through the treatment media into the effluent pipe for discharge from the LB. The exact placement of the influent and effluent perforated header pipes within the limestone layer of an ALD is at the discretion of the designer, but Figures 1 and 2 show typical locations for both header pipes. The header pipe is attached to the influent/effluent pipes using a "Tee" or Elbow coupler depending upon the pipe orientation. Users can also opt to enter custom pipe lengths, diameter, and unit costs to develop a custom piping design by selecting the User-Specified Piping Layout.

3.2.4.4 Liner Layer: Many mine sites lack the soil characteristics required to prevent leaky passive treatment system components. AMDTreat offers three types of liner systems that prevent water from leaking out of the impoundment including Clay, Synthetic (i.e. PVC), and Geosynthetic Clay (GCL) liners (Figure 4, 5, and 6). The volume of clay required is calculated from the entire inside sloped area of the limestone layer and multiplying it by the user-specified thickness (typically 0.5 to 1.0 foot after compaction) and unit cost to purchase and install the clay liner. However, since an ALD has a soil cover over the limestone layer, no clay liner is placed between the soil cover and the limestone so it is highly recommended that if the user selects clay liner that they also select the non-woven geotextile in order to at a minimum provide the separation material (non-woven geotextile) between the soil cover and limestone layers as well as around the bottom and sides of the ALD to keep the limestone from penetrating into the clay liner. The area required for Synthetic or Geosynthetic Clay (GCL) liners is determined by calculating the inside sloped area of the limestone layer and the bottom area of the ALD similar to the clay liner and adding the top surface area of the limestone layer in order to provide sufficient line material to enclose the entire limestone layer and also provide separation between the soil cover and limestone. AMDTreat provides the option of adding Non-woven Geotextile as a separate material for all liner systems. Non-woven geotextile separation material is commonly used to protect the Synthetic or GCL liner from the excavated inside surface of the pond and/or the limestone layer. The non-woven geotextile is also important to provide separation between limestone layer and the soil cover for an ALD.

3.2.5 Other Items: The *Other Items* section allows users to consider the capital cost of inlet and outlet structures, valves, and flow distribution structures. **AMDTreat suggests default quantities and unit costs for construction of a single ALD component.**

3.3 Module Outputs

3.3.1 Sizing Summary: The Sizing Summary section contains all the calculated module outputs, such as the dimensions, volumes, and plug flow retention times for the applicable layers. The mass of limestone required for the limestone layer is provided on the right-hand side of the Sizing Summary heading.

3.3.2 Capital Cost: This section provides the estimated costs for the various user-specified components and the total estimated cost to construct the entire ALD component of the passive treatment system.

3.3.3 Annual Cost:

Since an ALD is a passive treatment system component, the only annual cost considered is the cost for maintenance. Annual costs, such as sampling, labor, and access road maintenance are "project-wide" costs since they apply to an entire treatment site, not each individual treatment component. Sampling, Labor, and Site Development (i.e. snow plowing) modules are located under the "Project Modules" section of the Main User Interface and capture these types of annual costs.

Annual maintenance costs for ALDs can include periodic "flushing" of the piping network to evacuate metal hydroxide precipitates from the limestone layer, maintaining clear influent and effluent piping, and manipulating the water level control structure (e.g. Agri drain) to change the water level in the ALD. However, it is important to note that it is not recommended to flush ALDs due to the introduction of air into the limestone layer, which will compromise the anoxic conditions for some period within the ALD, which could result in iron precipitation and plugging of the limestone. It is assumed that some years will not require the full amount of funds set aside for maintenance but will eventually be used over the system life. Users can estimate the annual maintenance costs by assuming a percentage of the capital cost (more expensive the system, the more expensive the maintenance) or specify an annual maintenance cost amount. ALDs have one of the lowest annual maintenance requirements of any passive treatment component when applied to the appropriate water chemistry and implemented properly.

3.3.4 Net Present Value:

The Net Present Value (NPV) section determines the cost to operate a treatment system component over a specified time frame. The NPV calculates the present-day financial investment required to generate the income to pay for future operation and equipment/materials replacement costs. Both **Financial Variables** and **Cost Categories** are required to calculate the NPV.

3.3.4.1 Financial Variables

- The *Term of Analysis*, *Inflation Rate*, and *Rate of Return* are three variables used in the NPV calculations. The default values for these terms are shown under the Net Present Value section of each module. Users must access the Net Present Value menu at the top of the main user interface to change the default values as they would apply to all modules used for an entire treatment system. While NPV is determined for each AMDTreat module activated by the user, the goal is to determine a total NPV for an entire mine drainage treatment system project (a collection of cost estimates for individual modules creates a treatment system project in AMDTreat). Therefore, a single value for *Term of Analysis*, *Rate of Return*, and *Inflation Rate* is applied to all modules and cannot vary between modules.

- Term of Analysis: The time period used for the NPV calculation is to determine the financial investment required to pay for all future costs of the treatment system components.
- Inflation Rate: Represents the average price increase of goods and services over time. AMDTreat uses the inflation rate to calculate the future cost of the annual operation and maintenance (O&M) and recapitalization items (e.g., limestone).
- Rate of Return: Describes the expected profit on an investment.

3.3.4.2 Cost Categories

- For each treatment module, AMDTreat provides a list of recommended equipment and materials that require recapitalization. In addition, AMDTreat provides recommendations (default values) for life cycle and replacement percentage. Users can click on the default values for *Life Cycle* or *Replacement Percentage* and use the +/- buttons to change the default values. In addition, users can select *Custom Cost* and enter a new cost to represent the current cost of the equipment. Users can add new recapitalization items or deactivate/delete existing items for calculating the NPV.

An example of how the recapitalization variables are used to determine NPV is to consider the following hypothetical scenario. Assume a vertical turbine pump has a life cycle of 50 years but requires the motor component of the pump to be rebuilt every 20 years. Let's assume the present-day cost to purchase the pump is $500,000 and the cost to remove, rebuild, and reinstall the pump motor is only $20,000. Now assume we want to determine the amount of investment required today (NPV) to generate the income to pay for the future cost of rebuilding the pump motor over a 50-year Term of Analysis, which is also equal to the life cycle of the pump. In addition, let's assume an inflation rate of 5.0% and Rate of Return of 8.1%. The goal is to place the money in a relatively secure investment vehicle to generate 8.1% annually. The NPV will tell us the size of investment required to generate the income to pay for the future costs over 50 years.

There are several ways to model the replacement cost. One way is to replace 4% of the present day cost of the pump (4% of $500,000 = $20,000) with a life cycle of every 20 years. If the Term of Analysis is 50 years, then the entire pump would not require recapitalization since the life cycle of the pump is 50 years. However, the motor would require two replacements (50 years / 20 years = 2.5 rounded down to 2).

To determine the NPV to recapitalize rebuilding of the motor, AMDTreat calculates the future cost to rebuild the motor at each life cycle, 20 and 40 years. The program uses the Inflation Rate to inflate the present day default cost to rebuild the motor in 20 and 40 years from now. While the present day cost to rebuild the pump motor is $20,000, the future cost to rebuild the motor in 20 years at a 5.0% Inflation Rate is $53,065 and $140,799 in 40 years (Equation 8). Assuming an 8.1% Rate of Return, the 50-year NPV for the pump is $17,422. In other words, an initial investment of $17,422 is needed at an annual Rate of Return of 8.1% to generate the investment income required for the two motor rebuilds over the 50-year life cycle of the pump.

$$\begin{aligned}&\textit{Cost to rebuild motor in 20 years} =\\ &\textit{Present Day Cost} \times (100\% + \textit{Inflation Rate})^{20} = \$20{,}000 \times (100\% + 5\%)^{20} = \$53{,}065 \quad \textbf{(16)}\end{aligned}$$

- Annual Operation and Maintenance Cost: By default, AMDTreat transcribes the annual O&M cost from the Annual Cost section to the Net Present Value section. The program assumes the module is being used to first estimate the annual cost for a treatment system component, so it automatically transcribes the annual cost to the NPV section. If this is not the case or the user wants to use some other annual cost, the "Use Custom" box can be selected to allow the user input of a different annual cost to utilize in the NPV calculation.

- Recapitalization Cost: Certain treatment system components, especially mechanical and water conveyance equipment, require periodic replacement. The recapitalization cost of an item is an estimate of the amount of money required to pay for future replacement costs for the item. In addition to the Financial Variables described above, three additional values are required to calculate the NPV of recapitalization costs, the Present-Day Equipment Cost, the Life Cycle, and the Replacement Percentage.

- Default Cost: This represents the current cost to purchase the equipment or material.

- Life Cycle: The time span between equipment or material replacement is termed as its Life Cycle. Some equipment manufacturers provide recommended life cycles for their equipment to provide consumers with an estimate of how long the equipment is expected to be operational. Some life cycles, such as those used for treatment media (limestone), are based on best professional judgement. Some operators prefer to periodically purchase and replace equipment before failure to preserve the continuity of operations, while others wait until failure to replace an item.

- Replacement Percentage: The Replacement Percentage is an adjustment factor to the Default Cost to accommodate situations where the entire piece of equipment or all of the material does not require recapitalization. For example, a passive treatment component may be designed to contain enough limestone to neutralize the acidity load for 20 years, however, the accumulation of metal hydroxide precipitates within the void space of the limestone layer may require that 25% of the limestone be replaced every 7 years to prevent hydraulic failure such as plugging or short-circuiting. For this scenario, the initial cost of the limestone making up the limestone layer is discounted by 75% and assigned a life cycle of 7 years to determine the amount of money required to cover the cost of replacing 25% of the limestone layer every 7 years over the Term of Analysis.

3.3.4.3 Rationale for Recapitalization Recommendations:

Recapitalization recommendations are based on professional experience of the AMDTreat Team and may not apply to all situations. Users are encouraged to customize the recapitalization assumptions to their treatment scenario. AMDTeat Team members are located in Pennsylvania and West Virginia and have collective experience in design, funding, and/or operation/maintenance for over 100 passive treatment systems. Most passive treatment systems constructed in Pennsylvania and West Virginia are less than 15 years old, thus the industry is still gaining experience in lifecycles for various components. However, the AMDTreat Team held discussions on personal experience to develop a list of recapitalization recommendations. Users may have different experience and opinions.

By default, AMDTreat includes a list of five recapitalization items for Limestone Bed. The items are listed even if they are not selected for the treatment system. The purpose of this is to inform the user of items they should think about recapitalizing or including in their treatment design. For example, Liner is listed as a recapitalization item even if no liner is selected in the cost estimation. In this case the recapitalization cost is set to $0.00 but the item is still shown as a reminder to the user that a Liner is a common item that should be considered. If a liner is included in the cost estimation, the estimated liner cost is used to calculate a recapitalization cost for liner. Users can delete or modify any of the default Recapitalization items by either deselecting the item or by setting the Replacement % to zero. If the item is deselected the Total Cost for the item will still be shown but the cost will be subtracted from the Net Present Value Cost, shown in the Net Present Value Heading.

Limestone: The limestone can require maintenance and periodic partial replacement, mostly due to clogging from metal precipitate. Therefore, the default recommendation in AMDTreat is to replace 50% of the limestone every 10 years.

Liner: Often liners are destroyed, especially synthetic, while conducting maintenance on passive treatment systems, if the equipment operator is inexperienced with passive systems. Thus, AMDTreat recommends planning to replace a portion of the liner while the Limestone is being replaced. The default assumption is to replace 50% of the Limestone every 10 years, so the same assumptions are recommended for Liner recapitalization.

Pipe: Piping is often exposed at the surface and can become damaged by vandalism, falling trees, and other factors. AMDTreat assumes 50% of the piping will require replacement after 25 years of service.

Other Items: The Other Items section in AMDTreat includes Flow Distribution Structures, Water Level Control Structures, and Outlet Protection Structures. These structures are often durable, and many treatment systems have never experienced replacement of these items, however, AMDTreat Team members have had at least one experience of each of these items requiring replacement, thus the Team wanted to include these items for replacement consideration.

3.4 Assumptions of Design Sizing and Costs: AMDTreat is a cost estimation model that uses assumptions to provide treatment sizing and both capital and annual cost estimates. While there are many assumptions in the program, the ones provided below are important to consider for the LB module.

1. The Limestone bed is assumed to be constructed on a flat surface, where the water and limestone layers are excavated at or below the existing or original ground. A portion of the excavated material is then used to construct the freeboard embankments above the existing or original ground (see Figure 2). AMDTreat assumes an on-site balance of cut and fill material. However, if this is not the case, the user can modify excavation cost default values to reflect the anticipated conditions based on the site characteristics.

2. The geometric shape of a ALD is an inverted trapezoidal prism (Figure 1). The volumetric equation for a trapezoidal prism is used to calculate the ALD layer volumes.

3. None of the sizing methods provide a "design life" that properly accounts for both: A) the amount of limestone required to neutralize the acidity loading for a defined time frame, and B) hydraulic and treatment issues caused by the accumulation of metal hydroxide precipitates within the void spaces of the treatment media. Some sizing methods, such as the *Bureau of Mines*, account for reagent requirements.

4. In general, the goal of the ALD sizing methods is to provide an estimate of the limestone mass required to generate net alkaline conditions. None of the sizing methods are based on achieving effluent water quality criteria or requirements. With that said, a properly sized ALD treatment system should generate pH > 6.0 and net alkaline water, which in theory will decrease aluminum and ferric iron solubility to less than 1.0 mg/L.

4.0 References

Hedin, R.S. and Watzlaf, G.R., 1994. The effects of anoxic limestone drains on mine water chemistry. Proceedings of the 3rd International Conference of the Abatement of Acidic Drainage, Volume 1, Pittsburgh, PA. U.S. Bureau of Mines SP 06B-94, p. 185–194.

Rose, A. W., 2004. Vertical flow systems – Effects of time and acidity relations. Proceedings, American Society of Mining and Reclamation, Morgantown, WV, April 18-24, 2004, p. 1595-1615. https://www.asrs.us/Portals/0/Documents/Conference-Proceedings/2004/1595-Rose.pdf

5.0 Figures

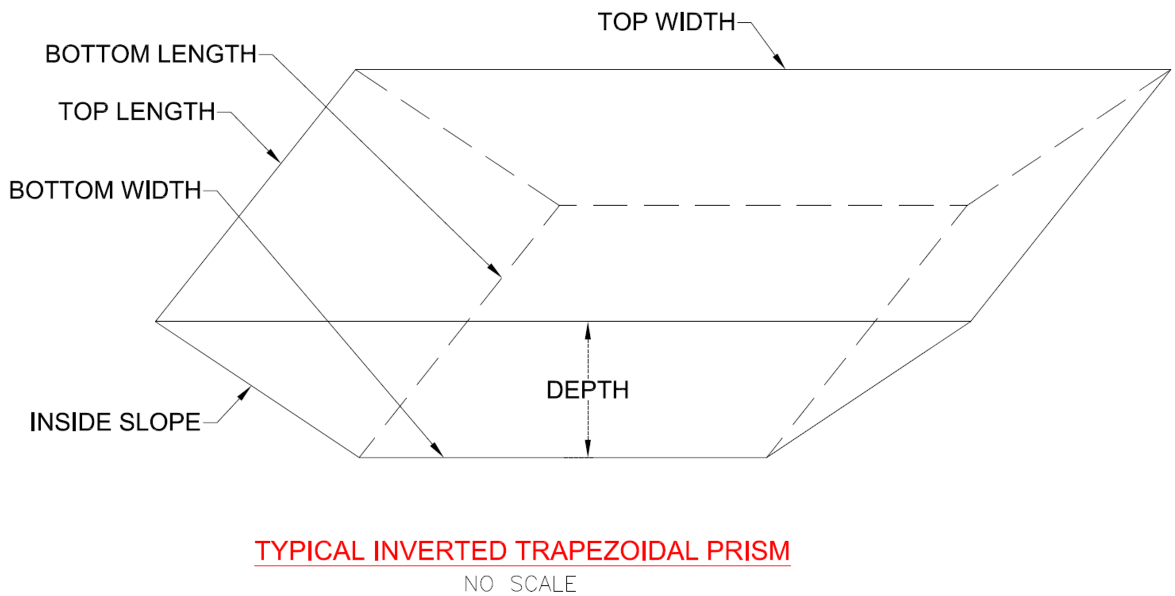


Figure 1: Typical Inverted Trapezoidal Prism

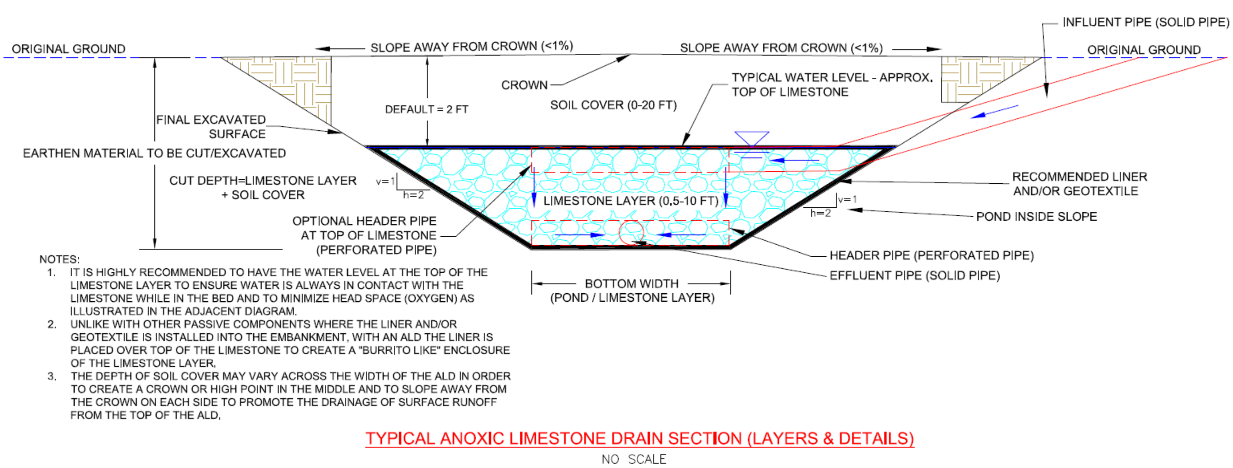


Figure 2: Typical Cross Section View of an Anoxic Limestone Drain (ALD) with a water layer.

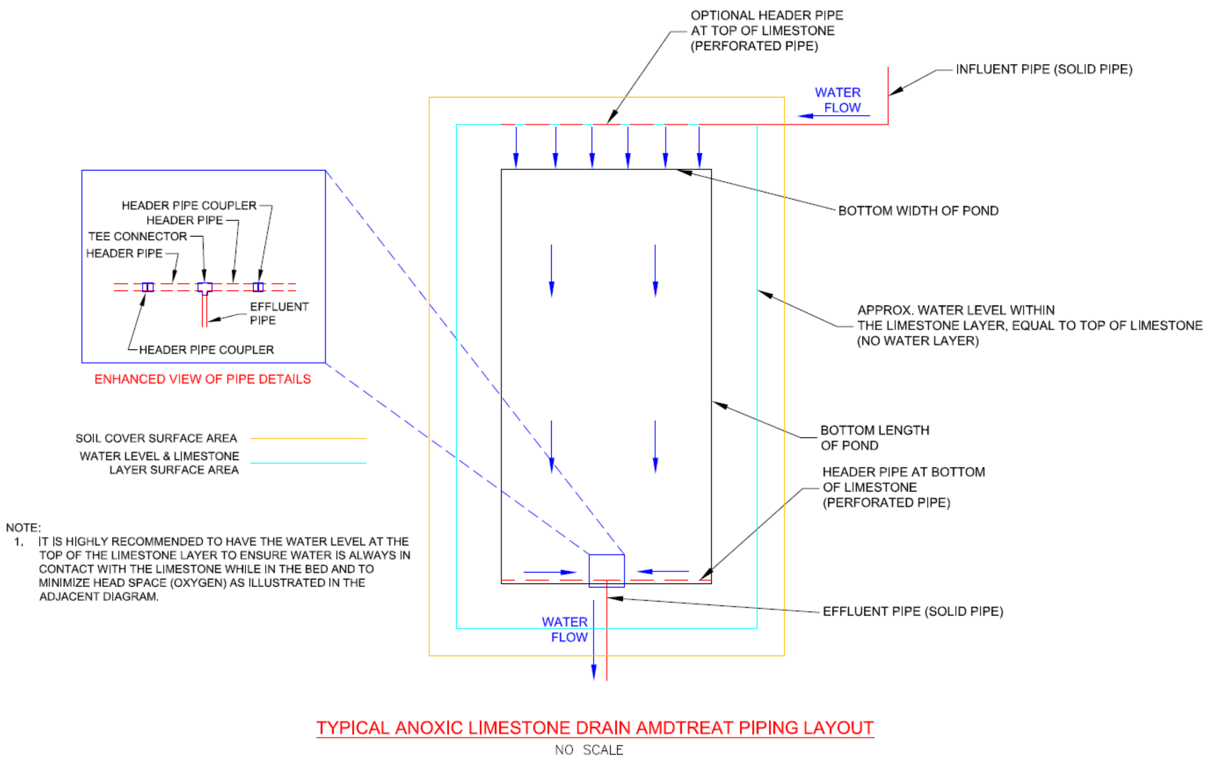


Figure 3: Plan View of the ALD to Illustrate Common Piping Layout and Components (Used in AMDTreat Piping Calculator) and the Layer Surface Areas

Figure 4: Excavator unrolling Non-woven Geotextile to act as a protective barrier between soil and synthetic liner as part of constructing an ALD.

Figure 5: Excavator unrolling synthetic liner overtop of a layer of non-woven Geotextile.

Figure 6: Triaxle truck dumping limestone on top of synthetic liner during ALD construction.

Figure 7: Long narrow ALD. Workers wrapping the limestone with synthetic liner before burial. Vertical pipes are used to measure head loss caused by the gradual accumulation of precipitate within the porosity of the limestone.

Figure 7: Completed and operating ALD.