Pennsylvania's Land Recycling Program

Vapor Intrusion Technical Guidance

Appendix Y: Vapor Intrusion Modeling Guidance

The Department recommends the use of EPA's Johnson & Ettinger model (U.S. EPA, 2004) for analyzing vapor intrusion under the Statewide health and site-specific standards. Remediators should use the Department's versions of the model which are based on EPA's advanced model version 3.1 spreadsheets. These versions are posted on the Department's website, and they will be updated periodically with current scientific information when Ch. 250 MSCs are revised.

This appendix describes key assumptions and limitations of the J&E model, acceptable adjustments to default input values, and the use of alternative models for petroleum hydrocarbons.

2.1. Background

The Johnson & Ettinger (J&E) model solves for the transport of vapor-phase contaminants into a building above the source (Johnson and Ettinger, 1991; U.S. EPA, 2004). There are three spreadsheets for the different source types: groundwater, soil, and soil gas. The model calculates the vaporization of dissolved or adsorbed contaminants, the diffusion of these vapors toward the surface, their advection through the foundation or slab into the occupied space, and their dilution in indoor air. The calculations rely on five sets of parameters integral to this process and the inhalation risk assessment:

- source description (e.g., depth)
- chemical properties
- toxicological properties
- capillary and vadose zone properties (e.g., soil type)
- building characteristics (e.g., air exchange rate).

The J&E model is an approximation that is dependent on many parameters, not all of which are well known. It is not easily calibrated; therefore, the user should input conservative values to avoid underestimating inhalation risks. Users submitting J&E models to the Department are expected to be familiar with EPA's *User's Guide* and should understand the model's assumptions and limitations (U.S. EPA, 2004).

Several studies have compared J&E model results to field data (Hers et al., 2003; Provoost et al., 2009, 2010) and to numerical analyses (Yao et al., 2011). This research indicates that J&E gives reasonable, conservative results in most cases, within about one order of magnitude. These studies reinforce the need to use J&E with caution because the model is highly sensitive to some parameters. It is essential to have adequate site data and a strong conceptual site model when modeling vapor intrusion.

The objective of vapor intrusion modeling is to determine if an Act 2 standard is attained. Although the EPA spreadsheets can calculate screening values, models submitted to the Department should not be used in this manner. Users must instead input the contaminant concentration on the DATENTER worksheet to calculate the incremental risk. The Department versions give results in two forms, depending on the Act 2 standard selected for the contaminant.

- For Statewide health standard evaluations the user compares the predicted indoor air concentration on the RESULTS sheet to the Statewide health standard indoor air screening value (SV_{IA}) (VI Guidance, Table 5).
- For site-specific standard risk assessments the user obtains the incremental carcinogenic and noncarcinogenic inhalation risks from the RESULTS sheet, determines the cumulative risks for all site-specific standard contaminants of concern, and compares the cumulative risks to the Act 2 thresholds (Section 250.402(b)).

Under appropriate conditions predicted indoor air concentrations can be compared to occupational limits (OSHA PELs).

2.2. Assumptions

Users are referred to EPA's J&E *User's Guide* for a complete description of the model (U.S. EPA, 2004). It has several critical assumptions and limitations that all users must be aware of.

- The source extent is horizontally and vertically infinite. Source mass does not diminish with time. These are conservative assumptions.
- No separate phase or non-aqueous phase liquid (SPL, NAPL) is present for soil and groundwater modeling.
- The solution is one-dimensional, meaning that lateral transport of vapors is ignored.
- Soil properties are homogeneous.
- There is no biodegradation of contaminant vapors in the vadose zone, a conservative assumption.
- There are no preferential pathways between the source and the building.
- The system is in steady state; that is, vapor transport is in equilibrium.
- The model does not account for the combined effects of multiple contaminants.

In addition, see U.S. EPA (2004) Sections 2.11 and 5.

2.3. Statewide Health Standard Parameter Adjustments

Key input parameters and allowable changes to these values for Statewide health standard modeling are explained in this section. The Department's conservative default model parameter values, as input on the DATENTER sheet of the J&E spreadsheet, are given in Table Y-1. Most input values used are EPA's defaults.

- **Source concentration (C_W, C_R, C_g):** The user enters an appropriate contaminant concentration for groundwater (µg/L), soil (µg/kg), or soil gas (µg/m^3). Source data should conform to the conditions in Table 6 of the VI Guidance. Input concentrations should generally be the maximum from recent sampling in the vicinity of current or potential future buildings. If sufficient data are available, a 95% upper confidence limit of the mean may be a suitable value. The data selected for determining the source concentration may have been collected for the site characterization and/or the demonstration of attainment. When the vapor source is a groundwater plume, fate-and-transport modeling may be used to estimate groundwater concentrations at downgradient receptors if monitoring well data is unavailable. The model should be calibrated, conservative, and applied in a manner consistent with the Department's Quick Domenico user's guide (DEP, 2014). For the soil gas J&E model only near-source soil gas data may be used, and the source may include SPL.

- **Depth below grade to source** (L_{WT}, L_t, L_s)**:** The default value is 5 feet (150 cm). The user enters the actual minimum depth based on the site characterization and/or monitoring data. For groundwater it should be the seasonally high water table depth of the contaminated aquifer (L_{WT}). For soil it should be the depth to the top of contaminated soil (L_t). The Department recommends using the shallowest depth that either exceeds the soil screening value (SV_{SOIL}) or that is contaminated as indicated by field screening. For soil gas the source depth is the top of the screen in the soil gas probe (L_s).

  Acceptable soil or soil-like material should be present between the building foundation and the contaminant source. This material cannot be "contaminated." The Department considers soil with any of the following characteristics to be contaminated with respect to the vapor intrusion evaluation: visual or olfactory indications of contaminants, field instrument readings in the jar head space above soil samples greater than 100 ppmv, evidence of separate phase liquids (NAPL), or exceedences of PQLs. The thickness of acceptable soil or soil-like material may be less than 5 feet.

  Where there is a basement, the source must be entirely below the foundation as J&E does not model lateral vapor transport. Contaminated soil or groundwater cannot be in contact with the foundation. J&E simulates vapor diffusion through homogeneous, isotropic porous media. Therefore, it cannot determine vapor migration through fractured bedrock. If the water table is below the bedrock interface, then the groundwater source depth should be input as the depth to bedrock. A continuous layer of acceptable soil or soil-like material should be present between the bedrock surface and the building foundation.

- **Soil type:** It is the user's responsibility to assess soil boring logs to select an appropriate soil type for input to the model. Field logging of borings should be performed by a qualified environmental professional (i.e., a geological scientist or a soil scientist). Where the soil is heterogeneous or there are different interpretations of the soil type, professional judgment must be used, but the best practice is to select the soil type with the greatest vapor intrusion potential. This may require sensitivity testing of the model. The default entry in the Department's model versions is a loamy sand as a conservative extreme.

  EPA categorized soil using the U.S. Department of Agriculture's Soil Conservation Service (now the Natural Resources Conservation Service) soil types. To select the soil type, the environmental professional interprets boring logs based on the Unified Soil Classification System (ASTM D2487) in terms of the SCS classifications. A gradation analysis of soil samples is the best means to select the proper soil type in J&E (ASTM D422). Table Y-2 can also assist the user with this selection, and Figure Y-1 shows the SCS soil types in terms of the proportions of clay, silt, and sand.

If artificial fill is present then the user must be cautious in applying the J&E model to the site. The fill might have characteristics sufficiently close to a USDA soil type to be acceptable for modeling; if so, the user can choose an appropriate soil type with justification in the report.

- **Building foundation:** The default foundation type is slab-on-grade construction. This choice establishes the value of the depth below grade of the enclosed space floor (L_F). For slab-on-grade foundations the EPA default is L_F = 15 cm (0.5 feet); for basements it is L_F = 200 cm (6.6 feet). This value may be altered with supporting documentation for the site building.

- **Building dimensions** (L_B, W_B, H_B)**:** The EPA default residential floor space area is 1080 ft^2 (100 m^2) for a 10- by10-m home. Default enclosed space heights (H_B) are 244 cm (8 feet) for slab-on-grade buildings and 366 cm (12 feet) for structures with basements. The user may input the actual (or planned) building dimensions.

- **Floor thickness** (L_{crack})**:** The EPA default value is 10 cm (4 inches). This may be changed by the user if the actual (or planned) slab thickness is known.

- **Air exchange rate** (ER)**:** Air exchange rates exhibit a large range for different buildings and seasons. EPA's residential default value was 0.25 hr^{-1}. The Department adopts the current 10th percentile figure of 0.18 hr^{-1} (U.S. EPA, 2011, Ch. 19). The measured range in a study of 100 office buildings was approximately 0.2–4.5 per hour (Persily and Gorfain, 2009). A 10th percentile nonresidential value is 0.60 hr^{-1} (U.S. EPA, 2011, Ch. 19). The user should input these 10th-percentile values for residential and nonresidential buildings. The actual air exchange rate of an existing or planned building may be input to the J&E model if it has been measured or is documented in the HVAC system design and settings.

- **Vapor flow rate** (Q_{soil})**:** The soil gas flow rate into buildings is highly uncertain, and it depends on the material in contact with the foundation, the arrangement of cracks and other foundation openings, the pressure differential, and other factors. The EPA default value is 5 L/min based on tracer gas studies at five sites summarized by Hers *et al.* (2003). In the absence of better information on this parameter, the Department's default Q_{soil} is 5 L/min for Statewide health standard modeling. If the user changes the building dimensions (L_B and W_B) then the value of Q_{soil} should be scaled correspondingly. Assuming vapor entry through foundation perimeter cracks, the scale factor is the ratio of the building perimeters. The default perimeter for the 10- by 10-m building is 40 m (130 ft). For example, if the building dimensions are 50 ft by 100 ft, the perimeter is 300 ft, the scale factor is 2.3, and Q_{soil} = 11.5 L/min. The Q_{soil} field should not be left blank in Statewide health standard models.

Default chemical, physical, and toxicological properties and default residential or nonresidential exposure factors cannot be changed in Statewide health standard modeling. (Model-predicted indoor air concentrations for the Statewide health standard do not depend on the exposure factors on the DATENTER sheet.)

2.4. Site-Specific Standard Parameter Adjustments

A remediator performing site-specific standard risk assessment modeling may adjust any of the Statewide health standard parameters listed in the previous section as well as those in this section.

- **Soil/groundwater temperature** (T_S)**:** The Department's default value for the average temperature is 11°C (52°F). This may only be changed if sufficient seasonal subsurface temperature data is collected at the site.

- **Depth below grade to bottom of contamination** (L_b)**:** A finite source calculation is allowed for the soil model if the depth to the bottom of the contaminated soil has been delineated.

- **Soil properties:** The Department has adopted the EPA default values for bulk soil density ($\square_b$) and total porosity (*n*), which depend on the soil type. These values should not be altered unless properly collected samples (e.g., in thin-walled tubes) have been analyzed for these parameters (ASTM D2937, D7263). The Department does not consider the EPA default water-filled porosity values (θ_w□ to be sufficiently conservative because soil beneath buildings is relatively dry. The Department's default value is 0.1 or the residual saturation (θ_r), whichever is greater for the soil type. The user can change θ_w only based on laboratory analyses of the moisture content of properly collected soil samples collected under the building or an intact paved area large enough to be representative of a future inhabited building (ASTM D2216). The user may define up to three soil layers in the model if sufficient data has been obtained to support this option.

- **Fraction of organic carbon** (f_{oc})**:** The default value is 0.0025 from EPA and Section 250.308(a). The user may change this value for soil modeling only with laboratory measurements of f_{oc} in site soils (e.g., the Walkley–Black method). However, the f_{oc} may be set to zero if the material is not believed to contain any organic carbon.

- **Vapor flow rate** (Q_{soil})**:** The Department adopts EPA's default value of 5 L/min, which should be modified based on the building surface area as described above.

  The J&E model will calculate an estimated Q_{soil} rate if this field is left blank. The calculation will depend on the permeability of the soil in contact with the foundation. Most buildings are assumed to have a relatively coarse-grained material beneath the foundation, and 5 L/min is an appropriate minimum value. If the user has detailed knowledge of the native soil type that is present beneath and in contact with the foundation, this soil type may be entered in the "Soil stratum A SCS soil type (used to estimate soil vapor permeability)" field and the Q_{soil} field may be left blank. The report should justify this selection with descriptions of soil samples collected from beneath the foundation and described by an environmental professional (i.e., a geological scientist or a soil scientist).

  Another option is to enter a soil vapor permeability and allow the model to calculate Q_{soil}. This is permitted only if the user performs vapor permeability testing of the soil in contact with the foundation (ASTM D6539).

- **Pressure differential** (□P)**:** The pressure differential only affects the model calculation of Q_{soil}. EPA's default residential value is 4 Pa (40 g/cm-s^2). The ventilation system design of commercial buildings typically results in less under-pressurization than in homes (Hers *et al.*, 2001). The Department allows a value of 2 Pa (20 g/cm-s^2) for nonresidential modeling. If the remediator can document the actual or planned ventilation system design for a building, that information may be used in a site-specific standard model.

- **Crack width** (w)**:** The crack width only affects the model calculation of Q_{soil}. EPA's default value is 0.1 cm. This value may be changed only with a documented study of the foundation cracks in the modeled building.

Chemical, physical, and toxicological properties for substances with vapor intrusion potential are found in the VLOOKUP sheet. The Department's default values are listed in Table X-5. The user should not change these parameters, with rare exceptions described below for the site-specific standard only.

- **Organic carbon partition coefficient** (K_{oc})**:** The default values are from Chapter 250, Appendix A, Table 5A. The values may be changed only if the user undertakes laboratory testing of soil samples collected at the site.

- **Toxicity parameters** (IUR, RfC_i)**:** The inhalation unit risk (or unit risk factor, URF) and the inhalation reference concentration are from Chapter 250, Appendix A, Table 5A. For a site-specific standard risk assessment, the user should determine if there is more recent toxicity information available. Current values should be substituted for the Ch. 250 values.

Exposure factors are entered on the DATENTER sheet for site-specific standard risk assessments. The default values are listed in Table Y-3. Residential factors should not be changed. The user may adjust nonresidential factors based on conditions at the site. For instance, the daily exposure time could depend on the workplace shift length. EPA currently recommends a residential exposure duration of 26 yr (U.S. EPA, 2014), which may be used in site-specific standard models. (The Department's versions of the J&E spreadsheets include a field for the exposure time (ET), allowing it to be altered from the residential default of 24 hr/day.)

The EPA J&E models do not account for the effect of mutagenic chemicals on the cancer risks for residential exposure scenarios. The inhalation risk equations for mutagens are provided in Appendix X. The Department's versions of the spreadsheets include a mutagenic risk adjustment factor (MRF) that is applied when the exposure time is entered as 24 hr/day. For the default conditions, MRF = 1.4 for trichloroethylene, 3.4 for vinyl chloride, and 2.5 for other mutagens.

2.5. Petroleum Hydrocarbons

The Department can accept the use of models that account for biodegradation when evaluating petroleum hydrocarbon vapor intrusion. An example is the American Petroleum Institute's BioVapor (API, 2010).

BioVapor has several additional parameters that must be assessed in the modeling. The user should test the model sensitivity to these values.

- **Oxygen boundary condition:** The user should normally select a constant air flow rate (Q_f), and this is typically set equal to the vapor flow rate through the foundation (e.g., Q_{soil} = 5 L/min). If site data is collected to determine vertical profiles of oxygen, carbon dioxide, and methane concentrations, then the user may estimate the depth of the aerobic zone for model input.

- **Baseline soil oxygen respiration rate:** The model scales this rate with the fraction of organic carbon (f_{oc}), which is not typically known for the site.

- **Biodegradation rate constants** (k_w)**:** BioVapor selects default first-order, aqueous phase, aerobic decay rates. Actual degradation rates are extremely variable. Vertical profiling of contaminant concentrations in soil gas may allow the user to estimate the decay rates.

2.6. Attenuation Factor Risk Calculations

Site-specific standard screening and risk assessments may also be performed under certain conditions with near-source soil gas and sub-slab soil gas data by using conservative attenuation factors (α). An attenuation factor is the ratio between the contaminant concentration in indoor air and the equilibrium soil gas concentration in the medium ($\alpha \equiv C_{IA}/C_{SG}$). Therefore, conservative indoor air concentrations may be estimated using a measured or calculated soil gas concentration and an appropriate attenuation factor. Refer to Appendix X for the relevant equations and Table X-4 for the Department's default attenuation factors. The conditions for using near-source soil gas attenuation factors are the same as those listed for the screening values in the VI Guidance, Table 6.

Other soil gas attenuation factors may be used with adequate justification for the site-specific standard. For instance, a tracer test could be used to determine a sub-slab attenuation factor (α_{SS}) for the building. The default attenuation factors may be scaled with actual air exchange rates (AER) for the building. The Department's default indoor air exchange rates are 0.18 hr^{-1} for residential properties and 0.60 hr^{-1} for nonresidential facilities. The adjusted attenuation factor (α') is the product of the default attenuation factor and the ratio of the default AER and the actual AER. For example, if a nonresidential building has a measured air exchange rate of 1.2 hr^{-1}, then the sub-slab attenuation factor may be reduced as follows:

$$\alpha'_{\mathrm{SS,NR}} = \alpha_{\mathrm{SS,NR}} \frac{0.60\ \mathrm{hr}^{-1}}{1.2\ \mathrm{hr}^{-1}} = (0.0078) \frac{0.60\ \mathrm{hr}^{-1}}{1.2\ \mathrm{hr}^{-1}} = 0.0039$$

2.7. Report Contents

The Johnson & Ettinger modeling should be fully documented in the submitted report. The information provided should be sufficient for the Department to understand how the modeling was performed and reproduce the results. The model description should include the following.

- An explanation for how the model is being used to evaluate the VI pathway; that is, for a Statewide health standard prediction of indoor air concentrations or a site-specific standard human health risk assessment.

- A list of the contaminants of concern being modeled and the input source concentrations.
- An explanation of how source concentrations were selected (for example, the maximum groundwater concentrations from monitoring well data).
- A table of all input parameters, such as source depth and soil type.
- The reasoning for any changes to default input values.
- References for any changes to toxicological values in site-specific standard models.
- A table of the predicted indoor air concentrations or risks for each contaminant of concern and the cumulative VI risk.
- A figure showing the source area, the locations of sample points used for the source concentrations, any preferential pathways, and potentially impacted buildings.
- An appendix with J&E worksheet printouts for the modeling. The DATENTER and RESULTS sheets should be provided for each contaminant of concern. One copy of the VLOOKUP sheet can be included.

2.8. References

American Petroleum Institute (API), 2010, *BioVapor Users Manual*, Washington, DC. http://www.api.org/environment-health-and-safety/clean-water/ground-water/vapor-intrusion/biovapor-form

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U.S. Environmental Protection Agency (EPA), 2014, Human health evaluation manual, Supplemental Guidance: Update of Standard Default Exposure Factors, Office of Solid Waste and Emergency Response, Washington, DC, OSWER Directive 9200.1-120, February 6, 2014.
http://www.epa.gov/oswer/riskassessment/pdf/superfund-hh-exposure/OSWER-Directive-9200-1-120-ExposureFactors.pdf

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Table Y-1. Adjustable Johnson & Ettinger model input parameters and default values.

Parameter	**Symbol**	**SHS[1]**	**Residential**	**Nonresidential**
Average soil/groundwater temperature (°C)	T_s		11	11
Depth below grade to bottom of enclosed space floor (cm)	L_F	✓	15[2]	15[2]
Depth below grade to source (cm)	L_{WT}, L_t, L_s	✓	150	150
Thickness of soil strata (cm)	h	✓	150	150
Capillary and vadose zone USDA soil types		✓	SL[3]	SL[3]
Soil dry bulk density (g/cm^3)	$\square_b$	[4]	1.62	1.62
Soil total porosity	n	[4]	0.390	0.390
Soil water-filled porosity	$\square_w$	[4]	0.1	0.1
Enclosed space floor thickness (cm)	L_{crack}	✓	10	10
Soil–building pressure differential ($g/cm\text{-}s^2$)	$\square P$		40	20
Enclosed space floor length (cm)	L_B	✓	1000	1000
Enclosed space floor width (cm)	W_B	✓	1000	1000
Enclosed space height (cm)	H_B	✓	244[5]	244[5]
Floor–wall seam crack width (cm)	w		0.1	0.1
Indoor air exchange rate (hr^{-1})	ER	✓	0.18	0.60
Average vapor flow rate into building (L/min)	Q_{soil}	[6]	5	5

Notes

[1] Only the indicated parameters may be modified in Statewide health standard modeling.
[2] Default is 200 cm for buildings with basements.
[3] sandy loam
[4] The values shown are for a sandy loam. Statewide health standard models must use the J&E default values associated with the selected soil type.
[5] Default is 366 cm for buildings with basements.
[6] Adjust default based on building size; see text.

Table Y-2. Guidance for the selection of the J&E model soil type.

Predominant Soil Types in Boring Logs	**Recommended Soil Classification**
• Sand or Gravel or Sand and Gravel, with less than about 12% fines, where "fines" are smaller than 0.075 mm in size.	Sand
• Sand or Silty Sand, with about 12% to 25% fines	Loamy Sand
• Silty Sand, with about 20% to 50% fines	Sandy Loam
• Silt and Sand or Silty Sand or Clayey, Silty Sand or Sandy Silt or Clayey, Sandy Silt, with about 45 to 75% fines	Loam
• Sandy Silt or Silt, with about 50 to 85% fines	Silt Loam

Source: U.S. EPA (2004), Table 11

Table Y-3. J&E model default exposure factors.

Symbol	Term	Residential	Nonresidential
AT_{nc}	Averaging Time for systemic toxicants (yr)	30	25
ET	Exposure Time (hr/day)	24	8
EF	Exposure Frequency (days/yr)	350	250
ED	Exposure Duration (yr)	30	25
AT_c	Averaging Time for carcinogens (yr)	70	70

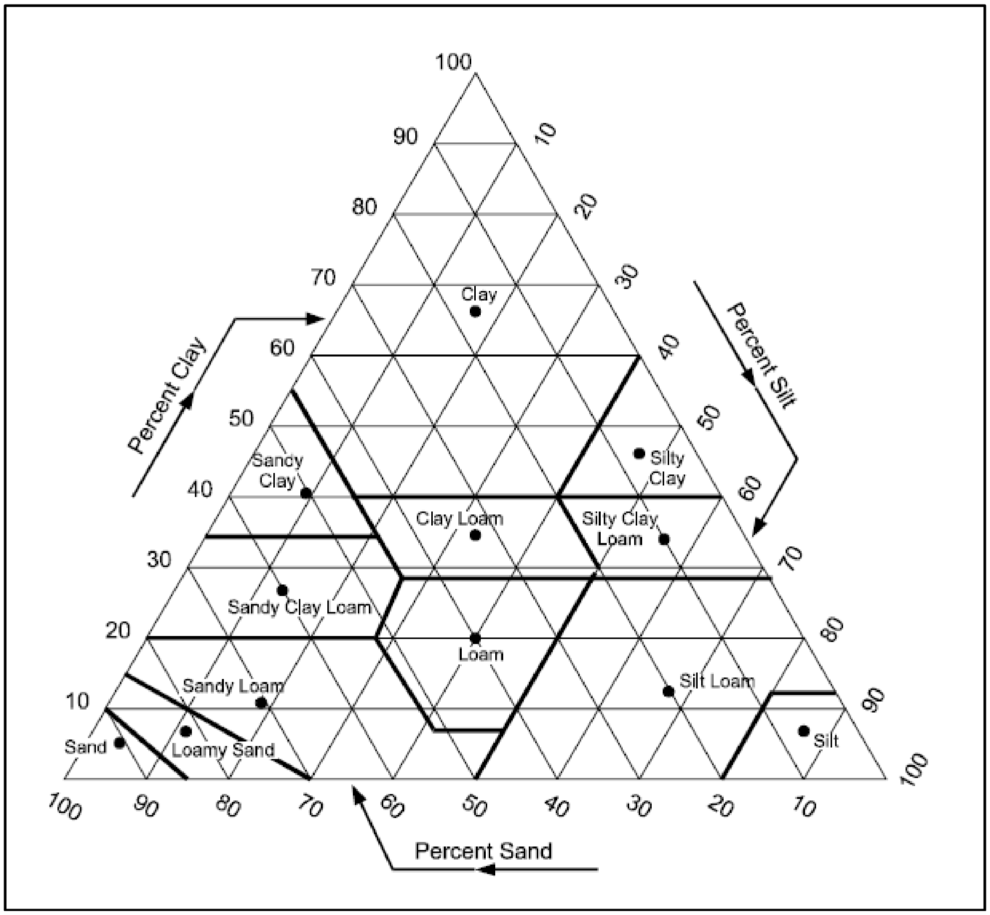

Figure Y-1. USDA SCS soil classification chart.