CHAPTER 1 – METHODOLOGY OF THE MODEL

INTRODUCTION

Soil nail walls are internally stabilized earth-retaining structures. The use of these structures has substantially increased in the United States in the last decade. Soil nail walls use a top-down construction method with installed reinforcing elements to support temporary or permanent excavations. In certain soil conditions, soil nail walls can be more feasible and cost-effective alternatives to conventional retaining structures. Soil nailing has been extensively used for highway applications as excavation support and for permanent retaining wall systems where top-down construction is advantageous. Soil nailing consists of installing closely spaced epoxy-coated steel bars (nails) which are subsequently encased in grout. As construction proceeds from top of cut to bottom, shotcrete is applied to the excavated face to provide stability. In certain conditions, soil nailing is a viable alternative to other ground anchor systems, considering technical feasibility, cost, and construction duration.

Although the use of soil nailing for highway applications has increased dramatically, computer programs for designing soil nail walls have not kept pace with the industry. Currently two computer programs are available for determining the length and specifications of the nail components. SNAIL (DOS-based, developed by CalTrans, 1991) and GOLDNAIL (Windows-based, developed by Golder and Associates, 1993) are the primary programs available for the designer. Both programs have limited use and are mainly designed for checking the soil nail wall stability by varying nail types and sizes, spacing and bond strengths. Neither program is capable of designing wall facing elements or shotcrete; global stability evaluation in both programs is done by limiting slip surfaces to those that pass the through the toe of the wall, and cannot evaluate a system with a complex slope profile above or below the wall. These programs also are used primarily with the Allowable Stress Design (ASD) method and older Load and Resistance Factor Design (LRFD) methods which may or may not be applicable to more recent guidelines.

Because of the advantages of soil nail walls, the Federal Highway Administration (FHWA) has sponsored and coordinated the development of several technical reports and research on soil nail wall projects since the early 1990s, including a comprehensive design and construction manual for soil nail walls (Manual for Design and Construction of Soil Nail Walls, Report No. FHWA-SA-96-069R), guidelines for analyzing, design, construction and monitoring of soil nail walls (Geotechnical Engineering Circular No. 7 - Soil Nail Walls, Report No. FHWA-IF-03-017), and a research project underway for developing LRFD Soil-Nailing Design and Construction Factors and Specifications (NCHRP Project 24-21). These technical reports, specifications, and research, together with engineering practice, provide highway engineers and contractors with a better understanding of the mechanisms, structural principles, and guidelines for soil nail retaining wall design and construction.

PURPOSE AND SCOPE OF THE PROGRAM

The objective of this work is to develop a computer program that follows the current State-of-Practice for designing the entire soil nail earth retaining structure. This includes the design of all soil nail system components such as 1) nail elements, 2) facing elements, 3) external stability, and 4) global stability for more complex slope geometries. All design and evaluation procedures were developed in general accordance with the FHWA guidelines presented in 1) The Manual for Design and Construction of Soil Nail Walls, Report No. FHWA-SA-96-069R, and 2) Geotechnical Engineering Circular No. 7 - Soil Nail Walls, Report No. FHWA-IF-03-017.

The computer program analysis follows the current service load design guidelines including internal and external stability evaluation for static and seismic loading. External failure modes include global stability, sliding, and bearing capacity analysis. Internal failure modes include nail pullout and nail tensile failure analysis, along with nail head and facing element analysis for temporary and permanent conditions.

LIMITATIONS

This program has been tested and is believed to be a reliable engineering tool. No responsibility is assumed by the authors, Yeh & Associates, Summit Peak Technologies LLC, FHWA, or any employees of the above for any errors, mistakes or misrepresentations that may occur from any use of this program.

SYSTEM REQUIREMENTS

Minimum System Requirements:
2.0 GHz or faster processor
Intel Pentium 4, Penium M, Pentium D processor or better, or AMD K-8 (Athlon) or better
4 GB internal RAM
Windows 7, Windows Vista, Windows XP Professional or Windows XP Home
NVIDIA GeForce FX 5200, ATI Radeon 9600, or better graphics card

Recommended Requirements:
2.5 GHz or faster processor
Core 2 Duo or Athlon X2.
8 GB internal RAM
Windows 7, Windows Vista
NVIDIA GeForce 8000, ATI Radeon 9600, or better graphics card with 512 MB dedicated RAM

INSTALLATION

The SNAP (Soil Nail Analysis Program) can be installed from the accompanying CD ROM disk, or installed from an internet web link. Either way, some files will be copied to your location during the installation process. Before installing SNAP, ensure that you have at least a minimum recommended free space of 300 MB.

CD Installation

From your CD drive, select and double click the file named *"SNAP 1.0 Self Extracting Executable.exe"*. A window will open asking to where you wish to extract the executable files. A suggestion would be C:\SNAP. This will download all the files to a folder called SNAP on the root directory of your C drive. To run the SNAP program, click on *"SNAP.exe"* in C:\SNAP or whatever directory you chose. For convenience you can create a desktop shortcut to SNAP.

Internet Installation

This public version of SNAP 1.0 can be found at www.cflhd.gov/programs/techDevelopment. Navigate to *"Completed Projects"* under the *"FHWA CFLHD Technology Development"* website. From under the *"Geotechnical"* section, select *"SNAP (Soil Nail Analysis Program) - 2010."* Click on *"Self-Extracting Executable Program – SNAP (Soil Nail Analysis Program)"* and *"save"* it onto your hard drive. Once downloaded, follow the *CD Installation* directions shown above.

BASIC THEORY

SNAP (Soil Nail Analysis Program) evaluates the internal (facing and nail) components of a soil nail wall, external stability, and global stability. The calculations are based primarily on two FHWA publications: 1) The Manual for Design and Construction of Soil Nail Walls, Report No. FHWA-SA-96-069R, and 2) Geotechnical Engineering Circular No. 7 - Soil Nail Walls, Report No. FHWA-IF-03-017. The differences and similarities between these two manuals are diverse. The primary differences include methods for calculating the active earth load for internal stability and facing design, overall (global) stability, and external stability failure modes. Further discussion related to the two publications can be found in Appendix A.

The following sections discuss how each component including groundwater is treated.

Wall Facing Analysis

SNAP (Soil Nail Analysis Program) evaluates the internal stability of a soil nail wall for both a shotcrete-only facing type and a permanent cast-in-place (CIP) concrete facing type. Calculations are based on FHWA Report No. FHWA-SA-96-069R, “The Manual for Design and Construction of Soil Nail Walls,” and on AASHTO Standard Specifications for Highway Bridges, 17th Edition.

For a shotcrete-only facing, the program determines the nominal nail head strength by evaluating “Flexure” and “Punching Shear” failure modes, based on input from the user. SNAP will calculate the nominal nail head strength for both failure modes, and use the appropriate (controlling) value in subsequent global stability calculations. Input parameters include information on the wire mesh, horizontal waler bars, vertical bearing bars, bearing plate, and shotcrete. Permanent applications of shotcrete facing can be troweled to an acceptable façade or faced with pre-cast panels (Figure 1).

For a cast-in-place (CIP) facing type, typically soil nail walls are constructed with a temporary shotcrete facing only, then the permanent CIP concrete facing is installed and connected after completion of the wall. When a CIP concrete facing is evaluated in SNAP, the strength of the shotcrete facing is neglected under the assumption that the shotcrete is a temporary facing only and its long-term strength cannot be relied upon. In addition to flexure and punching shear failure modes, headed stud tension failure is also evaluated for a permanent cast-in-place facing type. The program will calculate the nominal nail head strength for all three failure modes in the permanent facing, and use the appropriate value in subsequent global stability calculations. Input parameters include information on cast-in-place concrete, horizontal and vertical reinforcement bars, and the headed-stud connection system.

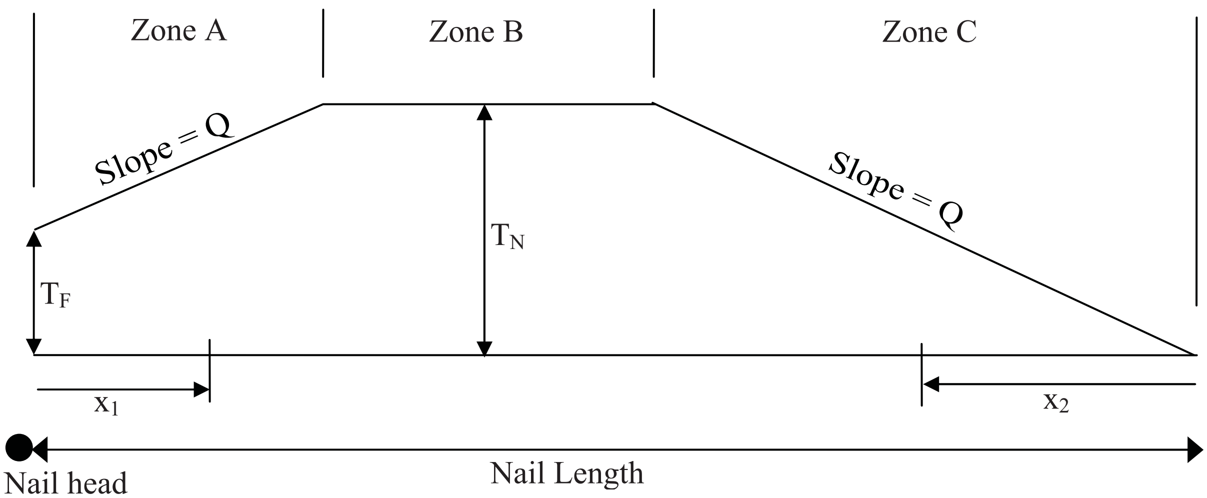
In addition to determining the nail head strength, SNAP performs required design and serviceability checks for both shotcrete and CIP facings as outlined in FHWA Report No. FHWA-SA-96-069R and AASHTO Standard Specifications for Highway Bridges, 17th Edition.

Figure 1. Photo. Installation of a permanent pre-cast concrete facing over a structural shotcrete soil wall.

Internal Stability Analysis

SNAP evaluates maximum nail loading along the length of each nail using methods outlined in FHWA-SA-96-069R. This method is based on applying the Coulomb active earth load uniformly at the back of the wall facing. The program uses the nail head strength determined from the facing analysis, the nail tendon strength entered by the user, the grout-ground pullout strength entered by the user, and the reduction factors entered by the user to generate a nail support diagram for each nail (Figure 2). The reduction factors should be selected by the user based on Tables 4.4 and 4.5 in FHWA-SA-96-069R.

SNAP then uses the nail support diagram for each nail in the global stability calculations. For each slip circle evaluated for global stability, the program determines the nail loads at the locations where the slip circle intersects each nail, according to each nail's support diagram. These loads are applied as "resisting forces" to their respective slices in the global Factor of Safety calculations for each slip circle.



T_F = Allowable Nail Head Load = $T_{FN}*\alpha_F$
T_N = Allowable Nail Tendon Load = (bar area)*(bar F_y)*α_N
Q = Allowable Pullout Resistance, force per unit length

Nail support to slip circles intersecting the Nail in Zone A at point $x_1 = T_F + Q \cdot x_1$
Nail support to slip circles intersecting the Nail in Zone B = T_N
Nail support to slip circles intersecting the Nail in Zone C at point $x_2 = Q \cdot x_2$

Figure 2. Schematic. Nail Support Diagram used in SNAP, reproduced from publication FHWA-SA-96-069R.

External Stability Analysis

External stability of a retaining structure refers to the potential failure or deformation modes which are typically associated with conventional gravity or cantilever retaining structures. These failure modes include horizontal sliding of the retaining wall along its base, and foundation bearing failure of the retaining wall associated with overturning. FHWA Report No. FHWA-SA-96-069R recommends use of the "slip surface" limiting equilibrium technique, which does not entail separate evaluation for sliding stability or overturning stability about the toe of the wall; these failure modes are accounted for in the general slip surface evaluation, which also includes global stability analysis. Foundation bearing failure is evaluated separately, but a complete evaluation as per AASHTO Section 4.4.7.1 is not required for all soil conditions.

SNAP performs a complete bearing capacity evaluation for all cases, rather than the rough initial check outlined in FHWA-SA-96-069R. Sliding failure along the base of the wall and overturning about the toe of the wall are also evaluated, based on guidelines for Mechanically Stabilized Earth (MSE) walls given in the AASHTO Standard Specifications for Highway Bridges, 17th Edition. These failure modes are highly unlikely to control stability of a soil nail wall, and are provided primarily for the designer's own information and conformance with the AASHTO. For bearing capacity evaluation, FHWA publication No. FHWA-SA-96-069R points the designer to AASHTO 15th Edition, which is more than 15 years old; the more recent 17th Edition was used for the purposes of this program to evaluate bearing capacity as well as sliding and overturning failure modes.

The user may choose to include the effects of seismic forces in external stability calculations. Seismic forces are taken into account by including, in addition to the static forces, a horizontal inertial force and a dynamic horizontal thrust force, as outlined by AASHTO 17th Edition, Section 5.8.9.1. The dynamic horizontal thrust force (shown in SNAP as P_{AE}) is calculated with the use of the Mononobe-Okabe method (Mononobe , 1929; Okabe, 1926), rather than the equation given in AASHTO. This method is applicable to all values of the friction angle, ϕ, and introduces an additional angle into the calculations for the active earth pressure coefficient, K_a, based on the horizontal and vertical seismic coefficients. The user input for seismic loading can either be the peak ground acceleration, A, or the horizontal seismic coefficient, k_h. For conservative calculations, SNAP always assumes that the vertical seismic coefficient, k_v, is zero, for both external and global stability calculations. This is common for pseudo-static analysis, and is done because the vertical component of seismic forces is generally significantly smaller than the horizontal component, and may act upwards on the nailed soil mass. This would decrease the loads on the wall and result in a less conservative analysis.

For all external stability calculations, the active earth pressure behind the nailed soil mass is calculated using Coulomb's earth pressure coefficient, K_a. The wall-soil interface friction angle is taken to be 2/3 of the friction angle, ϕ. The surface on which active earth pressure acts (the back surface of the wall) is always assumed to be vertical. SNAP evaluates external stability for the long-term drained case rather than the short-term undrained case; therefore, saturated unit weight of the reinforced soil and groundwater uplift forces are not incorporated into the external stability calculations.

Sliding stability is evaluated along the base of the nailed soil mass. Since SNAP has the capability to evaluate both uniform and non-uniform soil nail lengths and vertical spacings, the base width of the wall is taken as the horizontal distance between the toe of the wall and the average end of nail, as shown in Figure 3. This method allows the calculation to be consistent whether the user selects uniform or non-uniform nail geometry. The cohesive strength of the foundation soil is included in the resisting forces, but not the shear strength of any nails that may extend below the base of the wall.

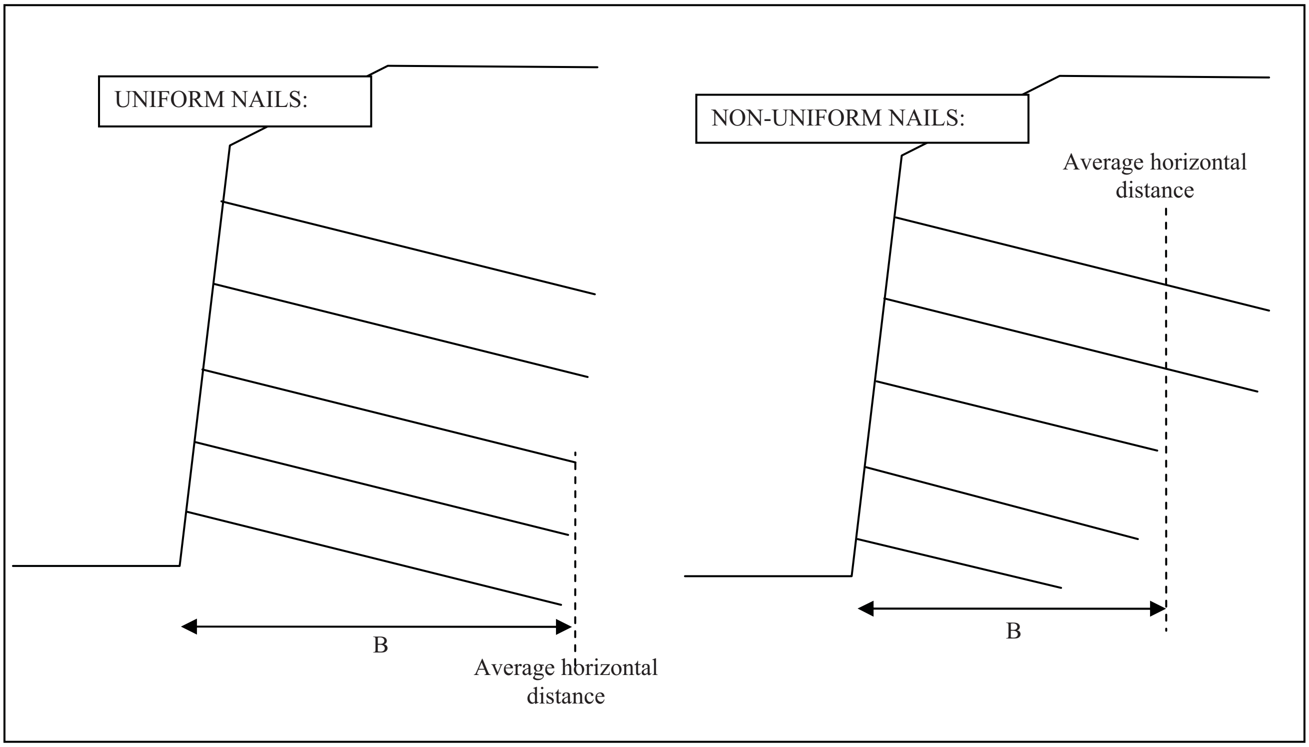


Figure 3. Schematic. Wall base length, B, used for external stability calculations.

Overturning (moment) stability is evaluated about the toe of the wall, at the ground surface. Although this is not generally considered for soil nail walls, it has been included for the wall designer's information and conformance with AASHTO. This failure mode is highly unlikely to control stability of a soil nail wall.

Bearing capacity is evaluated using the method outlined in AASHTO Standard Specifications for Highway Bridges, 17th Edition, Section 4.4.7.1. The user must enter bearing capacity factors N_c, N_γ, and N_q, on the Soil input tab. This allows the user to adjust the bearing capacity calculation to account for sloping ground in front of the wall. At this time, groundwater below the base of the wall is not accounted for in the ultimate bearing capacity calculations; if groundwater is anticipated below the soil nail wall, SNAP accounts for this condition in the global stability evaluation.

Global Stability Analysis

SNAP evaluates limit-equilibrium global stability using Bishop's Simplified (Modified) Method (Bishop, 1955). This method accounts for interslice normal forces but ignores interslice shear forces, and satisfies vertical force equilibrium for each slice and overall moment equilibrium about the center of the slip circle. SNAP evaluates circular-shaped failure surfaces only. The soil mass is divided into approximately 100 vertical slices, and stability is assessed for an average of 5,000 slip circles to find the 100 most critical failure surfaces and Factors of Safety (FS). SNAP can evaluate stability under seismic loading conditions using a pseudo-static analysis. This is done by multiplying the mass of each slice by the horizontal seismic coefficient and modeling this as an applied horizontal force at the centroid of each slice.

The slip circles for which SNAP calculates a Factor of Safety (FS) are generated automatically by the program, with some minimal user control of the search limits. Slip circle centers are located inside a pre-defined grid area, which is located above the top nail and to the left of the wall face at the top of wall, as shown in Figure 4 below. Circle center points have equal horizontal and vertical grid spacing. The spacing is scaled according to the height of the wall. For this reason, the number of total center points varies for different walls. Slip circles are generated when SNAP selects various *radius values, in 1-foot increments*, for each center point. The radius range for each center point can *either* be automatically limited to the slope geometry entered *or* the user can control the search by choosing a permissible X-coordinate range for the top and bottom of each failure circle. When *the radius range is automatically calculated*, the *minimum radius* for each center point must pass *only* through the top nail of the wall, and the *maximum radius* passes through the point on the ground surface furthest from the center point which will still result in the circle passing through both the toe slope and the backslope of the wall (Figure 4).

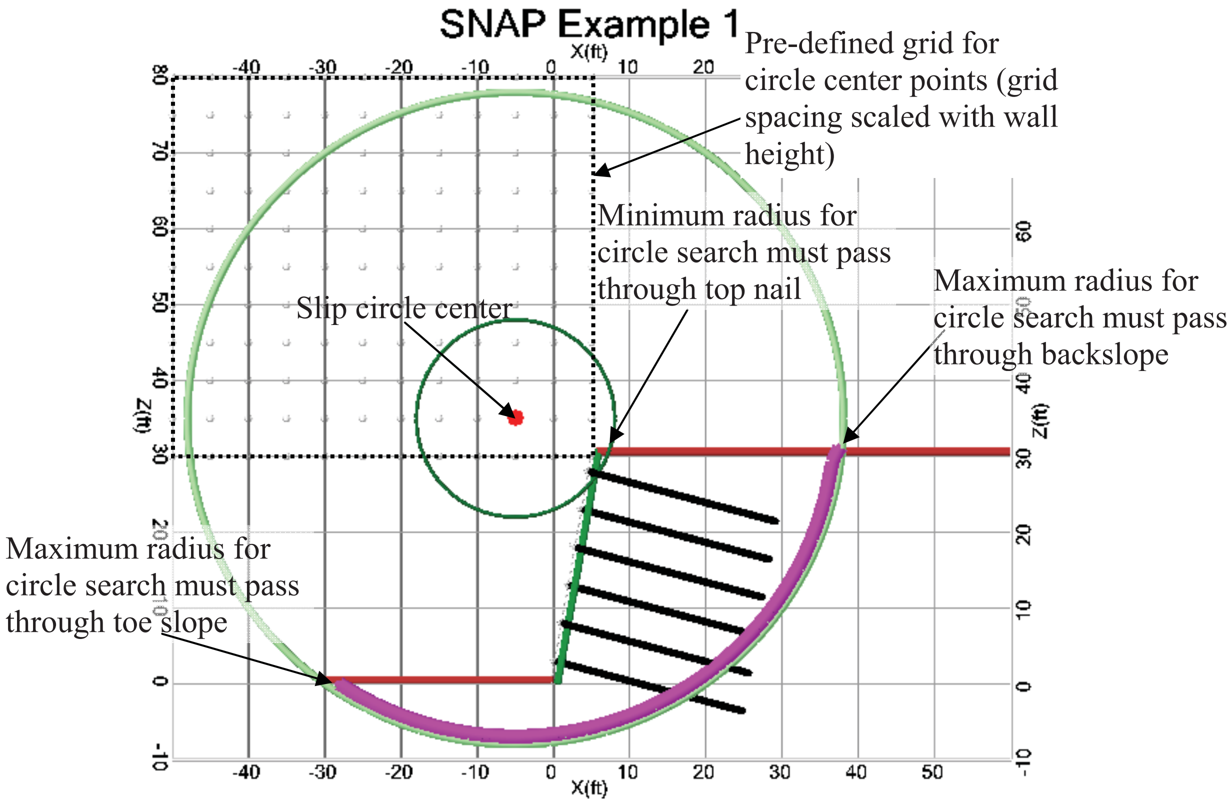


Figure 4. Schematic. SNAP generates slip circles (green) using a grid of center points and a range of radii. (Only the pink portion of the circle is actually relevant to FS calculations.)

SNAP calculates a FS using Bishop's Simplified Method for all radii at all center points generated in this manner.

For Bishop's Simplified Method, and the interslice force assumptions, each FS calculation is iterative; SNAP chooses an initial "guess" FS of 1.0 for each slip circle evaluated. The global stability calculation includes surcharge loading, nail support loads, pseudo-static seismic loads (if selected), and uplift force at the base of each slice due to groundwater.

SNAP uses the Nail Support Diagram discussed above to determine how the nails contribute to global stability of the wall. For each slip circle, the program determines where along each nail the circle and nail intersect, and in which slice the circle and nail intersect. Then the program pulls the corresponding nail support load for each nail from its nail support diagram, and applies that force as a resisting force to the appropriate slice, oriented in the direction of the nail inclination. In this way, the global stability calculation incorporates a resisting force based on the allowable nail bar tensile strength where circles intersect the nail closer to the facing, but for nails that are intersected near the back end of the nail, the calculation will reduce the resisting force according to the allowable pullout strength. The effects of lengthening particular nails can thus be seen directly in the program display.

Groundwater

SNAP uses a phreatic surface (water table) groundwater model (as opposed to a piezometric model). The pore pressure from any point is computed from the difference in head between that point and the phreatic surface. Figure 5 illustrates a phreatic pore pressure calculation. SNAP only uses pore water pressure for calculating global stability. Global stability calculations use the buoyant unit weight (saturated unit weight - water uplift force) for soil below the phreatic surface. SNAP can only accommodate an unconfined aquifer groundwater model. *Groundwater is not accounted for in facing, internal, or external stability calculations, including bearing capacity*.

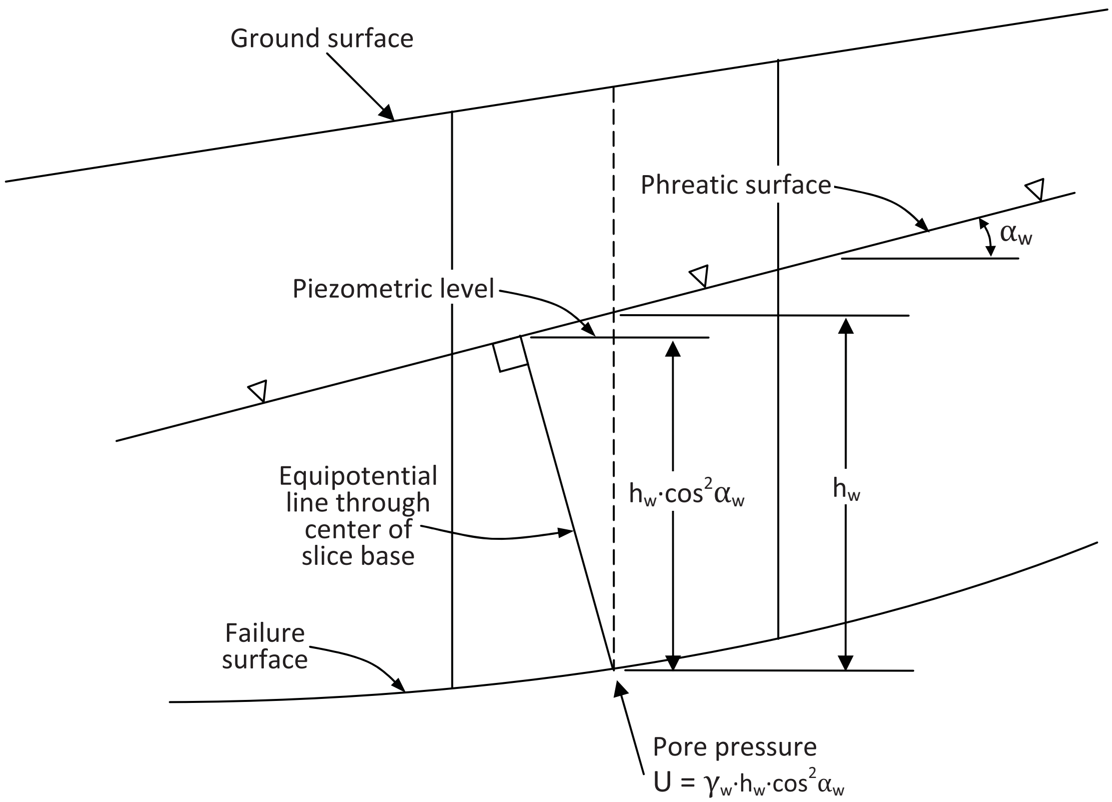


Figure 5. Schematic. Method of pore pressure calculation in SNAP (from Abramson et al., 1996)