NovoLIQ

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About

NovoLIQ

This software is designed for soil liquefaction analysis during earthquake and supports multi-layer stratigraphy. The results of the analysis are presented in form of:

- Safety Factor Against Soil Liquefaction
- Probability of Soil Liquefaction
- Post-liquefaction Site Movements Including:
  - Re-consolidation Settlement
  - Lateral Movement (Spreading)
  - Residual Strength

Although all efforts have been undertaken to ensure that this software is of the highest possible quality and that the results obtained are correct, the authors do not warrant the functions contained in the program will meet your requirements or that the operation of the program will be uninterrupted or error-free. The authors are not responsible and assume no liability for any results or any use made thereof, nor for any damages or litigation that may result from the use of the software for any purpose. All results to be verified independently by user.

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NovoTech software

Vancouver, Canada

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Getting Started ...

We recommend minimum 1024*768 screen resolution for using NovoLAB.
To call the help contents associated with each page of the software, click on the ? button on top-right corner of each page.
After the first installation on each computer, please open the *preferences* page and set the analyses methods, etc.
Please contact us at support@novotechsoftware.com with any questions or suggestions.

Units System

This version of NovoLIQ supports the following unit systems:

- Metric units (kg, m, cm)
- US CUstomary units (lb, ft, in)

You can set the unit system on the *preferences* page.

References

1- NCEER Workshop Report (1997)
2- Geotechnical Design Guidelines for Buildings on Liquefiable Sites in Accordance with NBC 2005 for Greater Vancouver Region, Canada, 2007
3- Estimating Liquefaction-Induced Lateral Displacements Using the Standard Penetration Test or Cone Penetration Test
G. Zhang; P. K. Robertson, M.ASCE; and R. W. I. Brachman, 2004
4- State Normalization of Penetration Resistance and the Effect of Overburden Stress on Liquefaction Resistance
R. W. Boulanger, I. M. Idriss, 2004
5- A Liquefaction Evaluation Procedure Based on Shear Wave Velocity
Ronald D. Andrus, Kenneth H. Stokoe
6- Earthquake-Induced Settlements in Saturated Sandy Soils
C. Y. Lee, 2007
7- Standard Penetration Test-Based Probabilistic and Deterministic Assessment of Seismic Soil Liquefaction Potential
K. Onder Cetin, M.ASCE; Raymond B. Seed, M.ASCE; Armen Der Kiureghian, M.ASCE; Kohji Tokimatsu; Leslie F. Harder Jr., M.ASCE; Robert E. Kayen, M.ASCE ; and Robert E. S. Moss, M.ASCE
8- Soil Liquefaction During Earthquake
I.M. Idriss, R.W. Boulanger
9- Revised Multilinear Regression Equations for Prediction of Lateral Spread Displacement
T. Leslie Youd, Corbett M. Hansen, Steven F. Bartlett
10- Guidelines on Foundation Loading and Deformation Due to Liquefaction Induced Lateral Spreading
DOT (February 2011)

Introduction

Evaluation of soil liquefaction hazard is an engineering art requiring judgment and experience in addition to testing and analysis. Important advancements have been made during the past few decades in developing tools to help assessing the potential of soil liquefaction, but still some aspects of the problem remain uncertain. A wide variety of methods from well respected researchers and practitioners have been implemented in NovoLIQ to carry out the soil liquefaction analysis. NovoLIQ has been designed to cover several world-wide known soil liquefaction analysis methods. As part of our policy for respecting our customers, NovoLIQ gives you options for choosing the analysis methods among all available recommended formulas (please see analysis methods for details).

NovoLIQ supports the following field tests for soil liquefaction triggering:

- Standard Penetration Test (SPT)
- Becker Denseness Test (BDT)
- Shear Wave Velocity (Vs)

In addition, you can take advantage of power features for:

- Unlimited soil layers
- Cyclic Resistance Ratio CRR (**10** methods)
- Probability of soil liquefaction (Youd and Noble 2001, Cetin et al. 2004)
- Depth (overburden) correction factor Cn for SPT (**9** options)
- Several SPT/BDT/Vs corrections (>**6** options)
- Direct conversion of Becker Density Test to SPT (**2** methods, including friction effect)
- Magnitude Scaling Factor (**8** options)
- Fines content correction (**2** options)
- Depth Reduction Factor Rd (**4** options)
- Relative Density (**5** options)
- Assessment of structure surcharge on soil liquefaction

Note: Recently there has been technical discussions (by Dr Boulanger and Dr Idriss, 2010) about the accuracy and reliability of Cetin et al (2004) method. Therefore it is recommended that this method is used with cautious and full understanding of the risks associated.

Data Entry

In NovoLIQ, all input data for soil liquefaction analysis is categorized as below:

Soil Stratigraphy

Use this table (located at the top of the page) for entering Soil Layers data. This data may be entered manually (line by line) or can be imported from text file.

Layer Thickness : represents thickness of the layer.
Soil Type : can be Clay, Silt, Sand or Gravel and is only for user's information. This means that NovoLiq does not take any specific action based on the soil type. For example if you select Clay as the soil type for a layer and you don't consider this layer to be liquefiable (see "Prone to Liquefaction" below), you should remove this layer from liquefaction assessment by un-selecting the last column of the table ("Prone to liquefaction?").
Unit Weight :represents the unit weight of the layer.
Fines Content (%): is the percentage of soil particles passing through sieve #200 (clay and silt).
D_{50} (mm) : is the particle diameter corresponding to 50 percent passing, in sieve analysis curve. D_{50} is only used for Japanese Bridge Code method.
Check for Liquefaction : if selected, liquefaction analysis will be carried out for this layer. For example if there is a clay layer in the subject site, which is not essentially prone to liquefaction, you can remove the checkbox for this layer; in this case a gap will appear on the output graphs corresponding to this layer (because NovoLIQ just skips the liquefaction assessment for this layer).

Field Test Data

Three type of field tests are supported in NovoLIQ for soil liquefaction analysis: SPT, BDT and Vs. For more information on theoretical background of each method please read this article. Each dataset obtained from a field test requires additional corrections. You can enter the test data manually, or import from Text files, or import from gINT database files. In any case, the test data will be entered in the table located at the left side of the page. The graph on the right-hand side of the page will be automatically updated based on the data in this table. It will also show the variation of field test results in depth of subsurface soil layers.

Corrections

The settings for corrections are displayed at the bottom-left portion of screen. If the test type is SPT or DCPT, the following corrections will be applied on SPT blows (N) in order to obtain N_{60} and $N1_{(60)}$:

- Energy level (Ce): this will adjust the SPT equipment energy to standard 60% energy.
- Borehole diameter (Cb): size of the borehole affects the SPT blow counts.
- Sampling method (Cs): specifies whether the sampler has a liner.
- Rod length (Cr): this correction factor depends on length of SPT rods which is approximately equal to the depth of the test. The following formula proposed by Dr. Cetin is used in NovoLiq:

$$C_R = \frac{1}{0.989860781 + \frac{4.31663223}{z^2}} \quad for \quad z >= 3$$

- Overburden stress (Cn): this corrections is usually called "depth correction/normalization factor" and depends on overburden stress due to the weight of the soil above the testing depth.

Please choose your favorite method for each correction factor. The following equations are used to calculate the actual correction factor at each depth:

$$C=Ce.Cb.Cs.Cr \qquad N_{60}=C.N \qquad N1_{(60)}=Cn.N_{60}$$

All the above-mentioned factors (including N_{60} and $N1_{(60)}$) are plotted versus depth and presented on the screen.

Schematic Soil Profile

An schematic soil profile is presented on the "Start Analysis" page, based on data entered in soil layers table (read more).

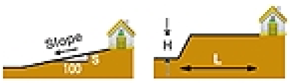
Analysis Settings

On the left portion of the screen, you can choose various methods for liquefaction analysis. Particularly, you can enter site-specific seismic data by clicking on Site's Seismic Data button:

Maximum Earthquake Acceleration (a_{max}) : is the maximum ground acceleration caused by the earthquake.

Earthquake Magnitude: is the magnitude of the earthquake and affects the MSF factor.

Cyclic Resistance Ratio (CRR1) method: NovoLIQ supports **10** methods for calculating CRR1 (for an earthquake magnitude of 7.5). User may select more than one method of analysis and NovoLiq will provide comparison of all selected methods in outputs. Please click on each method to toggle on/off. In order to estimate the settlement and lateral spreading of the site during and after the liquefaction, the following information are required:



Distance From Fault : is the distance (km) of the subject site from the fault causing the design earthquake.

Site Topography : site slope condition is one of the most important parameters in estimation of post-liquefaction lateral displacement. Zhang & Robertson (2004) recommend using S≥0.6% (for gently sloped ground) and 40≥L/H≥4 (for free face ground).

Other Analysis Settings

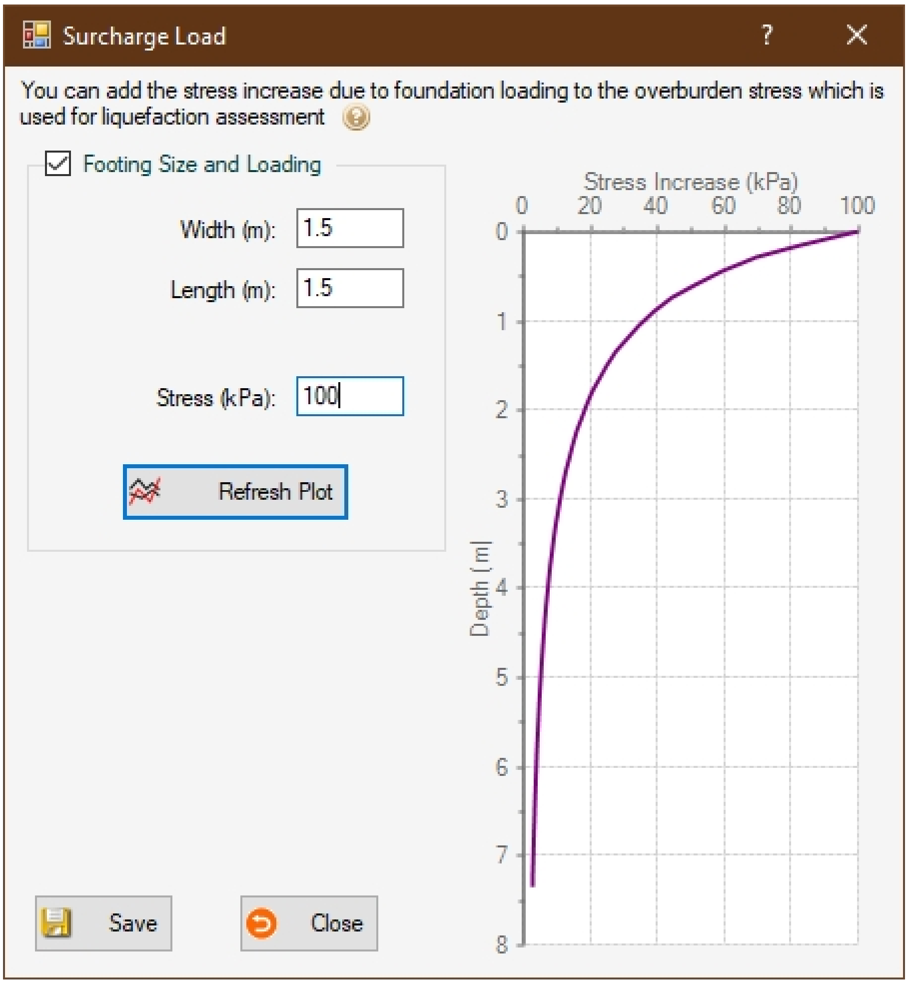
Surcharge Load: This feature will consider the effect of the structural load (stress below the footing) on mitigation of liquefaction potential (more information).

Ground Improvement: NovoLIQ assumes that when ground improvement (stone column or similar) is carried out at a site, soil liquefaction will not be likely to occur within that specific depth range. If this is applicable to your site, enter depth of ground improvement. All settlement and lateral displacement will be ignored within the ground improvement area and soil liquefaction will not be assessed in that depth range (a gap in the output tables and graphs).

Additional Settings: This will show the Analysis Methods tab from the Preferences page.

Surcharge Effect (Optional)

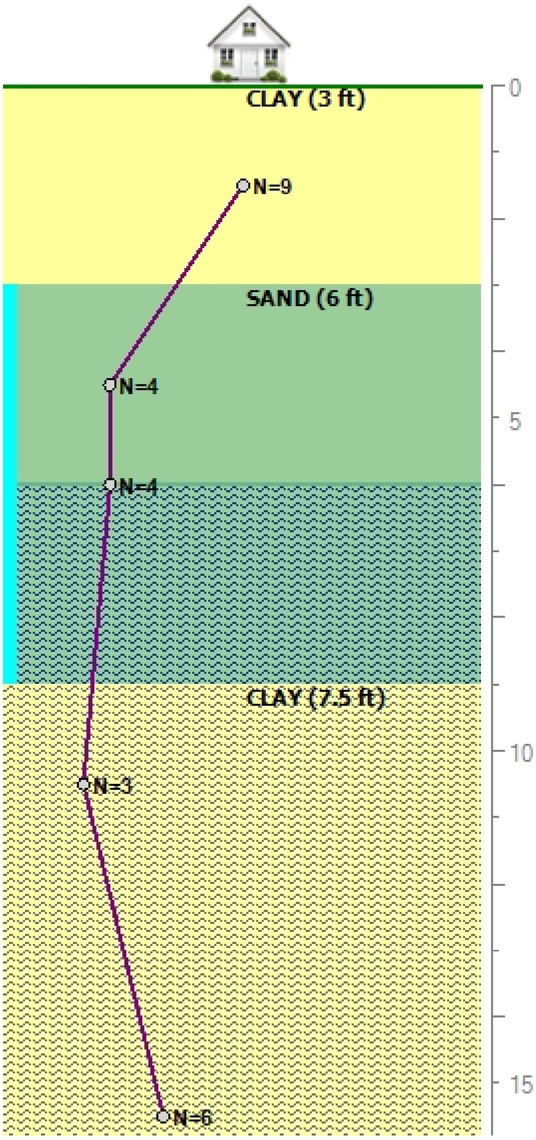
When a structure applies the load on a footing, total and effective stress increases in the soil mass. If you like to consider the effect of surcharge loads on soil liquefaction assessment (read more here), click on Input→ Surcharge Loads menu to access this page:



To activate this feature, simply click on "Footing Size and Loading" checkbox and enter footing (surcharge) size and the bearing pressure. If you uncheck this checkbox, the effect of surcharge will not be considered in soil liquefaction analysis.

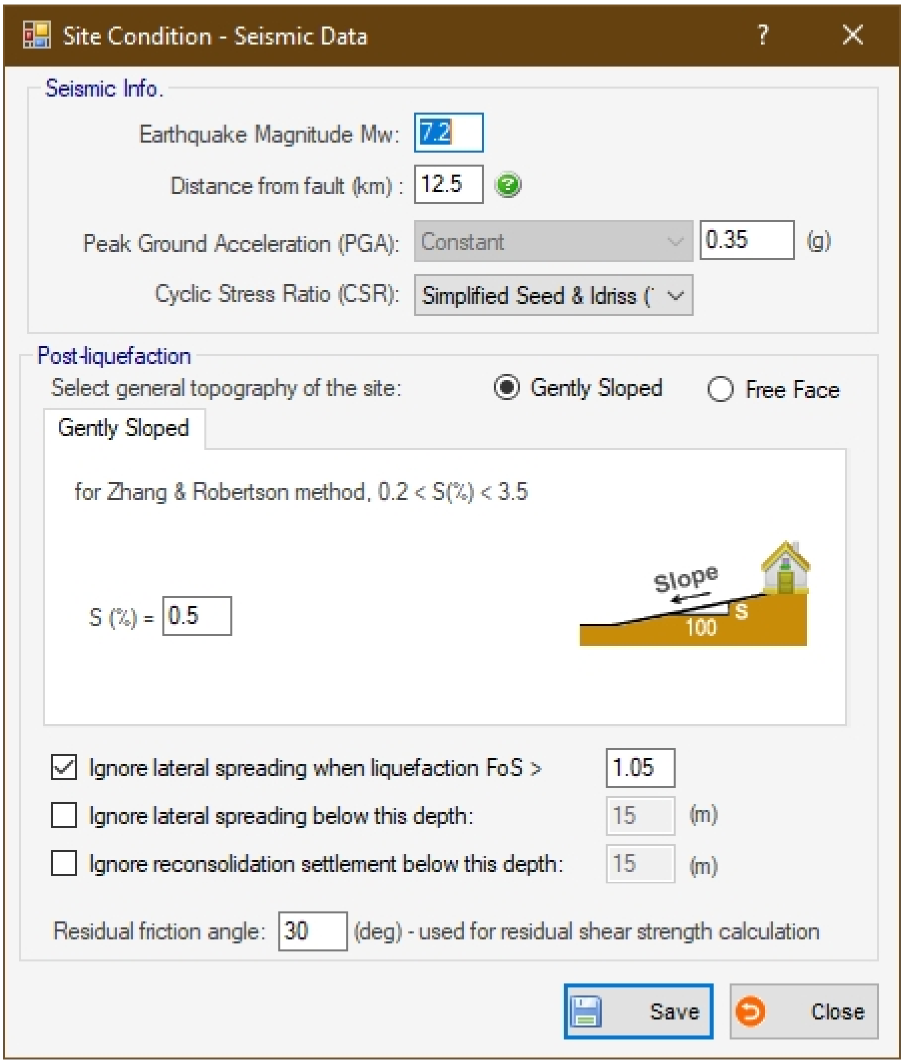
Schematic Soil Profile

NovoLIQ draws the schematic soil stratigraphy based on the data entered in soil layers table. Each soil type is shown in a specific color to ease differentiating between soil types. You can save this drawing as image file (BMP format), by click on Save as image link at the top-right corner of the page. Please notice that ~~~~~ shading on this schematic soil profile is indicative of groundwater level.



Site's Seismic Data

Seismic condition of the site can be entered from Input ▸ Site's Seismic Data button from the top toolbar. This data is required for each project and includes the following sections:



Seismic Info

This data is directly used during the soil liquefaction assessment analysis and consists of PGA and Magnitude of the design earthquake. Distance from fault is used for lateral spreading estimation based on Youd et al 2002 method.

CSR can be either calculated based on Simplified Seed (1974) equation or can be entered manually by user. If Shake, Shake 2000 or Pro Shake programs are used for response spectrum analysis and CSR data is available, please select "User-defined data" from the corresponding list and click on ... button. CSR data can be entered manually in the table or may be imported from text file (comma or tab delimited). When done click on Save button.

Post Liquefaction

Site topography determines the response of the site to post-liquefaction lateral spreading and settlement.

Ignore lateral spreading below 2H: If selected, when site has 'free face' topography, any lateral spreading below the depth of 2H will be ignored.
Ignore lateral spreading when FoS≥: In some methodologies such as Zhang et al (2004), even a factor of safety greater than 1 corresponds to small cyclic shear strains. If selected, user can specify a cut-off for factor of safety beyond which, cyclic shear strain (and lateral spreading) will be ignored.
Ignore lateral spreading below this depth: If selected, any lateral spreading below this depth

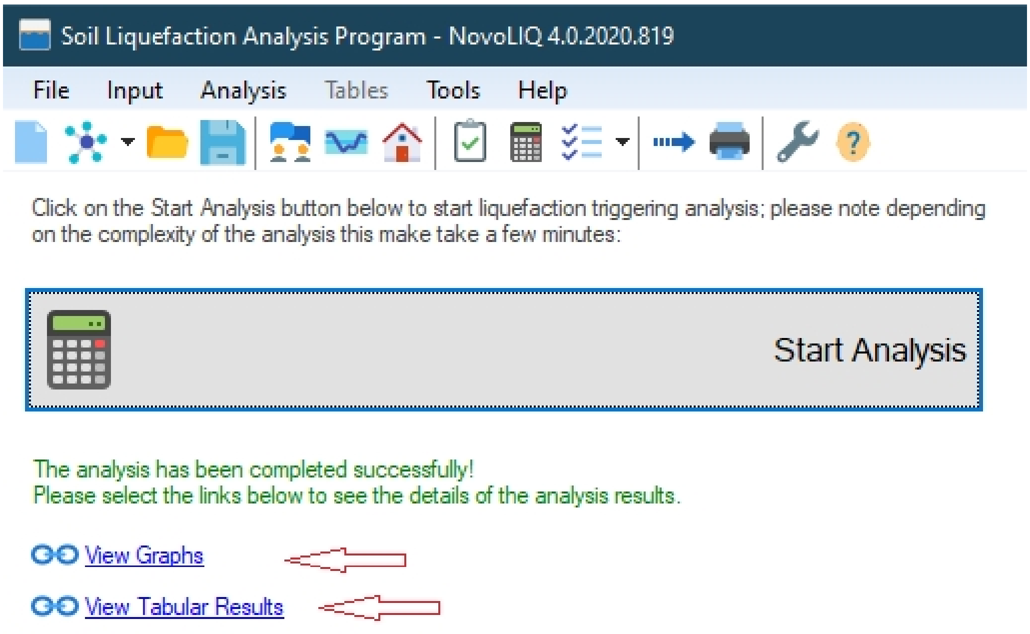
will be ignored.
Ignore re-consolidation settlement below this depth: If selected, any re-consolidation settlement below this depth will be ignored.
Residual shear strength friction angle: The upper limit for post-liquefaction residual shear strength ratio (S_r/σ'_v) is defined by tan(Φ) where Φ is internal friction angle of sand. Here you can specify the friction angle Φ.

Working with Charts

Please read the most up-to-date article from our website.

Analysis Results

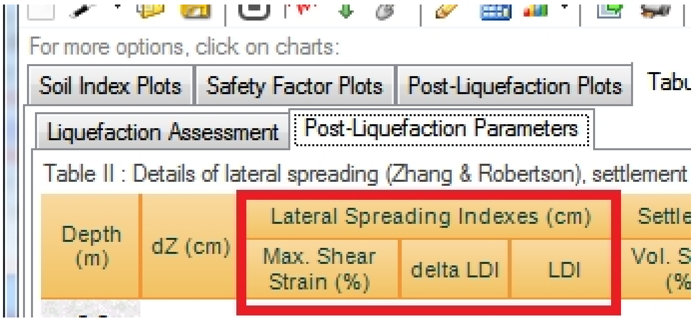
NovoLiq analysis results is shown when Start Analysis button in pressed. Results of the soil liquefaction analysis is presented in form of tables and graphs:



Graphs include the following (click on each chart to open Chart Presentation Tool):

- In-situ test (original, modified) vs depth
- Depth reduction factor (Rd) vs depth
- Overburden stress (σ_v, σ'_v) vs depth
- Relative density (Dr) vs depth
- Cyclic Resistance Ratio (CRR) vs depth
- K_σ vs depth
- Factor of safety vs depth
- Probability of liquefaction (PL) vs depth
- Maximum cyclic shear strain (γ_{max}) vs depth
- Volumetric strain vs depth
- Post-liquefaction settlement vs depth
- Post-liquefaction lateral displacement vs depth
- Post-liquefaction residual strength vs depth

Note : For "Zhang & Robertson 2004" and "Faris 2006" methods, details of calculation will be provided at each depth in a tabular format. Three columns under "Lateral Spreading Indexes" present details of the method selected in Preferences page.



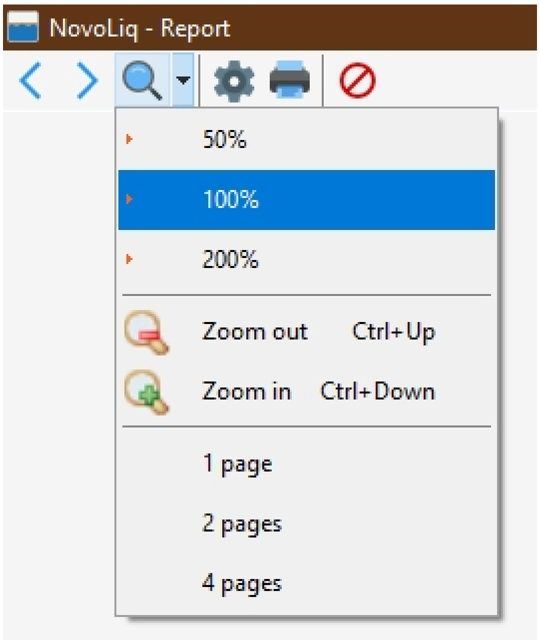
Calculation details include the following data:

Rd: depth reduction factor
Overburden Pressure: total and effective soil overburden stress. If surcharge effect is activated in analysis, these overburden stresses include ΔP due to footing loads.
Fines Content: the percentage of silt and clay at this depth (source: soil layers table)
N60: SPT blow counts (N) corrected for sampler, rod length, borehole diameter, energy
Co: correction factor = Cr.Cb.Cs.Ce for SPT
Cn: correction factor; includes depth and water level correction for SPT
$N1_{(60)}cs$: equivalent clean sand, depth corrected, fines content corrected SPT blow counts

Click on SPT Correction Details link at the bottom-right corner of page to see the detailed calculations for correction factors at each depth.

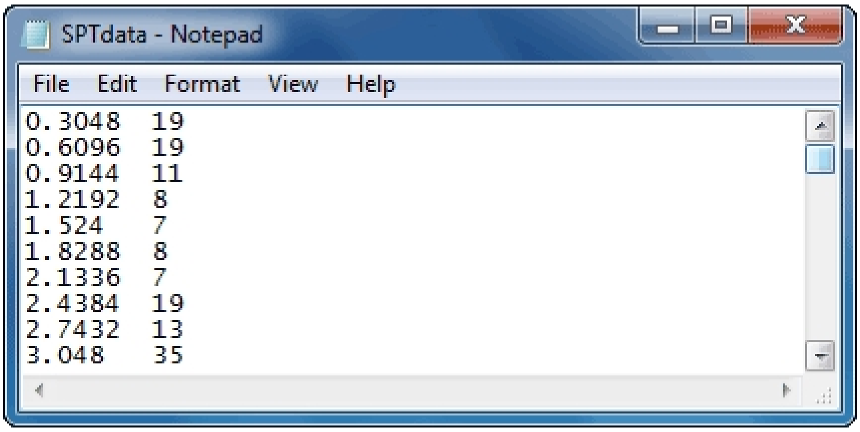
Reporting

To prepare the report, when all calculations are completed, click on File ▸ Report menu. All input data and assumptions as well as output tables and graphs will appear on the report pages. The image below describes the toolbar buttons on this page.



Import from Text Files

In case that there are large number of records for soil layers and/or SPT/BDT/Vs data, user may import such data from Text files (*.txt) using button above the tables . The Text file shall have the following format: one record per line and two numbers on each line, separated by comma or tab. The example below shows SPT data in a Text file:



In the above example, the first numbers (0.3048, 0.6096, etc) are depths and the second numbers (19, 19, etc.) are corresponding blow counts per ft (N_{60}). Text files can be easily generated using Windows **Notepad** or by exporting data from spreadsheet applications like MS **Excel** into a text file. For soil layers text file, each line consists of layer *thickness (m)* and its *unit weight (kN/m^3)* separated with comma with a general format similar to above.

Import from gINT Files

Please read the most up-to-date article from our website.

Export to Graphic Format

Please read the most up-to-date article from our website.

Preferences

This feature is used for setting NovoLIQ preferences and is accessible from toolbar and also from Tools ▸ Preferences menu. This page has three tabs:

General

In this tab user can apply constraints on some parameters used during liquefaction assessment.

0 < Dr < 100	Some correlations for relative density (Dr) yield invalid results for some SPT blow counts. If this option is selected, NovoLIQ keeps the correlated Dr between 0 and 100 to be consistent with geotechnical concept of relative density.
0.4 < Cn < 1.7	Depth (overburden stress) correction factor for SPT blow counts, is known to be valid when between 0.4 and 1.7. By selecting this option, this rule will be applied to the calculated Cn.
0 < CRR_1 < 0.8	Since most of the curves for Cyclic Resistance Ratio (CRR) are presented for CRR≤0.8, it is recommended to keep calculated CRR1 is this range. If this option is not selected, some formula may result in very large values or even negative values.
Round BDT blow counts ...	Becker Density Test results can be correlated to equivalent SPT blow counts (*see more details here*); NovoLIQ will round the equivalent SPT blow count to an integer number if this option is selected.
Ignore lateral spreading when	If selected, for "Youd 2002" and "Barlett & Youd 1992" methods only, the post-liquefaction lateral spreading will be considered ZERO when M<8 and $N1_{(60)}$>15. For more information please read page 15 of this

N1(60)>15 and M<8	reference: Liquefaction-Induced Lateral Displacement T. Leslie Youd , June 1993

In addition, on General tab you can:

- choose user interface language (when available)
- choose the input/output units system for NovoLiq user interface and reports

Analysis Methods

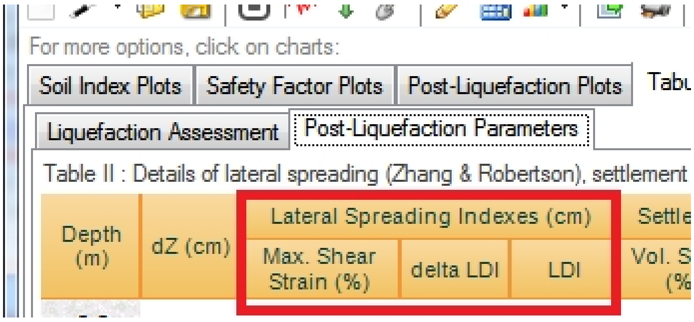
In this tab user can set the default methods for calculating the following parameters:

Magnitude Scaling Factor (MSF) : this factor is used to adjust the CRR for earthquake magnitudes other than 7.5 and could be calculated based on different methods based on user's choice (please read theory for more details).

Stress Reduction Factor (Rd) : this factor is used for calculating the CSR calculation and may be chosen from a variety of methods.

Relative Density Method : according to Zhang & Robertson (2004) method, maximum shear strain is calculated based on relative density of soil. Relative density itself, can be estimated from SPT blow count. Correlation method used for calculating relative density can be selected by user.

Lateral Spreading Method : For "Zhang & Robertson 2004" and "Faris 2006" methods, details of calculation will be provided at each depth in a tabular format. Three columns under "Lateral Spreading Indexes" present details of the method selected in this page.



Fines Content Correction : in most liquefaction analysis methods, CRR curve is proposed for clean sand (fines content less than 5 percent). If sand contains more fines content, usually field tests should be corrected before being used for CRR calculations.

These settings will be saved and applied to the current and future analysis.

Introduction

Soil liquefaction and related ground failures are commonly associated with large earthquakes. In common usage, liquefaction refers to the loss of strength in saturated, cohesion-less soils due to the build-up of pore water pressures during dynamic loading. Sladen et al. (1985) defined liquefaction as:

> **"**Liquefaction is a phenomenon wherein a mass of soil loses a large percentage of its shear resistance, when subjected to monotonic, cyclic, or shock loading, and flows in a manner resembling a liquid until the shear stresses acting on the mass are as low as the reduced shear resistance**"**

Liquefaction Assessment

Evaluating the liquefaction resistance of soils is an important step in the engineering design of new structures and the retrofit of existing structures in earthquake-prone regions. The evaluation procedure widely used throughout the world is termed the simplified procedure. This simplified procedure was originally developed by Seed and Idriss (1971) using blow counts from the Standard Penetration Test (SPT) correlated with a parameter representing the seismic loading on the soil, called the Cyclic Stress Ratio (CSR). This parameter is compared to Cyclic Resistance Ratio (CRR) of the soil and if it exceeds CRR, the soil is likely to be liquefied. A safety factor against liquefaction is defined as ratio of CRR to CSR:

$$\textbf{Safety Factor} = \textbf{CRR / CSR} * K_\sigma * K_\alpha$$
$$\textbf{CRR} = \textbf{CRR}_{7.5(ave)} * \textbf{MSF}$$

Where:

$CRR_{7.5(ave)}$:calculated cyclic resistance ratio (average of all selected methods at a desired depth) for an earthquake with M=7.5

MSF : Magnitude Scaling Factor

K_σ : overburden stress correction factor; only applied to the following analysis methods (see details):

- Vancouver Task Force Report (2007)
- NCEER (1996)
- Cetin et al. (2004)
- Idriss & Boulanger (2004)

each of the above-mentioned methods has its own equation for calculating K_σ

K_α : ground slope correction (is considered 1.0 in NovoLIQ)

Note: NovoLIQ uses an upper limit of 3.0 when calculating Factor of Safety.

Note: This theory manual is just an introduction to methods implemented in NovoLIQ and does not encompass all the technical knowledge and comments needed for soil liquefaction assessment. Therefore this document shall not be used as a reference for learning how to assess liquefaction potential. Please refer to the related books and other references for more details.

Note: Recently there has been technical discussions (by Dr Boulanger and Dr Idriss, 2010) about the accuracy and reliability of Cetin et al (2004) method. Therefore it is recommended that this method is used with cautious and full understanding of its risks. To obtain the full report please contact us.

Cyclic Stress Ratio (CSR)

The Cyclic Stress Ratio (CSR), is given by Seed and Idriss (1971) formula (also known as 'Simplified' approach):

$$CSR_{7.5} = 0.65\left(\frac{\sigma_v}{\sigma_v'}\right)\left(\frac{a_{max}}{g}\right)(r_d)$$

Where:

$CSR_{7.5}$: the cyclic stress ratio with reference to earthquake magnitude of 7.5

σ_v : total overburden pressure at the depth considered

σ_v' : effective overburden pressure at the same depth

a_{max} : maximum horizontal acceleration at the ground surface

g : acceleration due to earth's gravity

r_d : stress reduction factor (more)

Stress Reduction Factor (rd)

NovoLIQ covers the following methods for calculating r_d:

NCEER 1997

$r_d = 1.0 - 0.00765\ Z$	for $z \le 9.15$ m
$r_d = 1.174 - 0.0267\ Z$	for $9.15\ m < z \le 23$ m
$r_d = 0.744 - 0.008\ Z$	for $23\ m < z \le 30$ m
$r_d = 0.50$	for $z > 30$ m

Thomas F. Blake (FugroWest Inc., Ventura, California)

$$r_d = \frac{(1.000 - 0.4113 z^{0.5} + 0.04052 z + 0.001753 z^{1.5})}{(1.000 + 0.4177 z^{0.5} + 0.05729 z - 0.006205 z^{1.5} + 0.001210 z^{2})}$$

Idriss 1999 and Golesorkhi 1989

$$r_d = \exp\left[\alpha(z) + \beta(z) \cdot M\right]$$

$$\alpha(z) = -1.012 - 1.126 \sin\left(\frac{z}{11.73} + 5.133\right)$$

$$\beta(z) = 0.106 + 0.118 \sin\left(\frac{z}{11.28} + 5.142\right)$$

Kayen et al. 1992

$r_d = 1 - 0.012\ Z$

Note: for Idriss and Boulanger 2014 method, r_d from 'Idriss 1999 and Golesorkhi 1989' is used.

Magnitude Scaling Factor (MSF)

Since the CSR and $CRR_{7.5}$ are provided for earthquake magnitude of 7.5, a Magnitude Scaling Factor should be multiplied at $CRR_{7.5}$ to adjust its value for the target earthquake magnitudes. NovoLiq covers the following MSF methods:

Tokimatsu & Seed (1987)	2.5-0.2M
Idriss (NCEER 1997)	(7.5 / M) ^ 2.56
Idriss & Boulanger (2008)	$MSF = 6.9\ e^{(-M/4)} - 0.058 < 1.8$
Idriss & Boulanger (2014)	$MSF = 1+(MSF_{max} - 1)\{8.64\ e^{(-M/4)} - 1.325\}$ $MSF_{max} = 1.09 + (N1\_60cs/31.5)^2 < 2.2$

other methods (source : NCEER 1997 report):

Magnitude, M (1)	Seed and Idriss (1982) (2)	Idriss (3)	Ambraseys (1988) (4)	o (1996) (5)	Arang (6)	Andrus and Stokoe (in press) (7)	Youd and Noble (this report) P_L<20% (8)	P_L<32% (9)	P_L<50% (10)
5.5	1.43	2.20	2.86	3.00	2.20	2.8	2.86	3.42	4.44
6.0	1.32	1.76	2.20	2.00	1.65	2.1	1.93	2.35	2.92
6.5	1.19	1.44	1.69	1.60	1.40	1.6	1.34	1.66	1.99
7.0	1.08	1.19	1.30	1.25	1.10	1.25	1.00	1.20	1.39
7.5	1.00	1.00	1.00	1.00	1.00	1.00			1.00
8.0	0.94	0.84	0.67	0.75	0.85	0.8?			0.73?
8.5	0.89	0.72	0.44			0.65 ?			0.56?

Please note for clay-like material, MSF recommended by Idriss and Boulanger 2014 is used:
$MSF = 1.12\ e^{(-M/4)} + 0.828 < 1.13$

Structure Loading Effect

When a structure applies load on a footing, total and effective stress increases in soil mass. NovoLiq can update σ_v and σ_v based on stress increase (ΔP) due to stress below the footing. This overburden stress update will not be applied for calculating $N_{1(60)}$ which is dependent on overburden stress, too. All other parameters which are function of overburden stress will be raised by ΔP; for example Cyclic Stress Ratio will be calculated as below:

$$CSR_{7.5} = 0.65 \left(\frac{\sigma_v + \Delta P}{\sigma_v' + \Delta P} \right) \left(\frac{a_{max}}{g} \right) (r_d)$$

Where:
σ_v : total overburden pressure at the depth considered
σ_v' : effective overburden pressure at the same depth

Stress increase is calculated based on 2:1 slope method: Δ**P=B.L.P / {(B+Z).(L+Z)}**

Where:
B: Foundation width
L: Foundation Length
P: Stress below the foundation (load / length^2)

Probability of Liquefaction

The following method is implemented in NovoLiq for estimating the probability of soil liquefaction which is recommended in NCEER Workshop Report:

Youd and Noble, 2001

They used a logistic analysis to analyze case history data from sites where effects of liquefaction were or were not reported following past earthquakes. This analysis yielded the following probabilistic equation:

Logit (PL) = ln(PL/(1-PL)) = -7.633 + 2.256 Mw - 0.258 $N1_{(60)cs}$ + 3.095 ln(CRR)

Where PL is the probability that liquefaction occurred, 1 - PL is the probability that liquefaction did not occur, and $N1_{(60)cs}$ is the corrected blow count, including the correction for fines content. Youd and Noble recommend direct application of this equation to calculate the CRR for a given probability of liquefaction occurrence. In lieu of direct application, Youd and Noble define MSF for use with the simplified procedure. These MSF were developed by rotating the simplified base curve to near tangency with the probabilistic curves for PL of 50%, 32%, and 20% and various earthquake magnitudes. These MSF are defined as the ratio of the ordinate of the rotated base curve at the point of near tangency to the ordinate of the unrotated simplified base curve at the same $N1_{(60)cs}$. Because the rotated simplified base curves lie entirely below the given probability curve, CRR calculated with these MSF are characterized by smaller probability of liquefaction occurrence than the associated probabilistic curves.

Thus the MSF listed in this table, are denoted by PL<50%, PL<32%, and PL<20%, respectively. Because the derived MSF are less than 1.0, Youd and Noble do not recommend use of MSF for PL<32% and PL<20% for earthquakes with magnitudes greater than 7.0; Equations for defining the Youd and Noble MSF are listed below:
Probability, PL < 20% MSF = 103.81/M4.53 For M < 7
Probability, PL < 32% MSF = 103.74/M4.33 For M < 7

Probability, PL < 50% MSF = 104.21/M4.81 For M < 7.75

Cetin et al, 2004

A complete explanation of this method is resented in the following paper:

[Standard Penetration Test-Based Probabilistic and Deterministic Assessment of Seismic Soil Liquefaction Potential](#)
K. Onder Cetin, M.ASCE; Raymond B. Seed, M.ASCE; Armen Der Kiureghian, M.ASCE; Kohji Tokimatsu; Leslie F. Harder Jr., M.ASCE; Robert E. Kayen, M.ASCE ; and Robert E. S. Moss, M.ASCE

Note: Recently there has been technical discussions (by Dr Boulanger and Dr Idriss, 2010) about the accuracy and reliability of Cetin et al (2004) method. Therefore it is recommended that this method is used with cautious and full understanding of its risks. To obtain the full report please contact us.

Cyclic Resistance Ratio

NovoLiq supports a variety of field tests for evaluation of CRR at each depth. For each test type, a comprehensive explanation of the related theory and formulae are presented at the following articles:

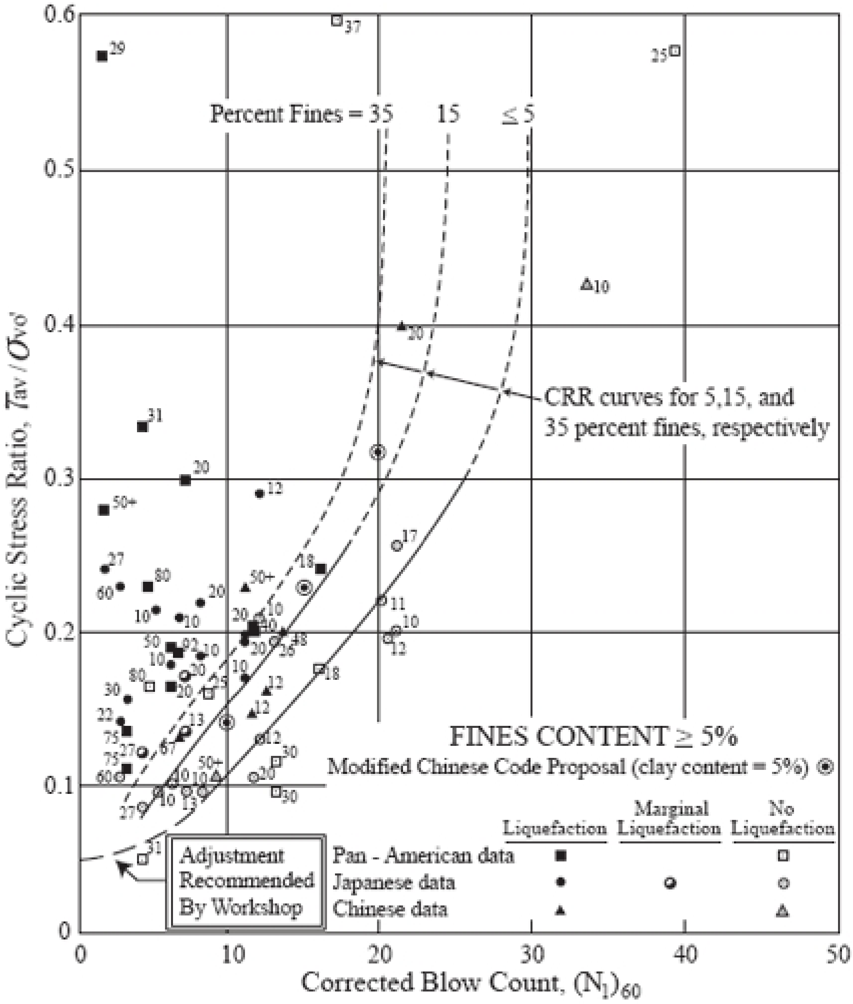
- CRR methods based on Standard Penetration Test (SPT)
- CRR methods based on Becker Density Test (BDT)
- CRR methods based on Shear Wave Velocity (Vs)

SPT-Based CRR

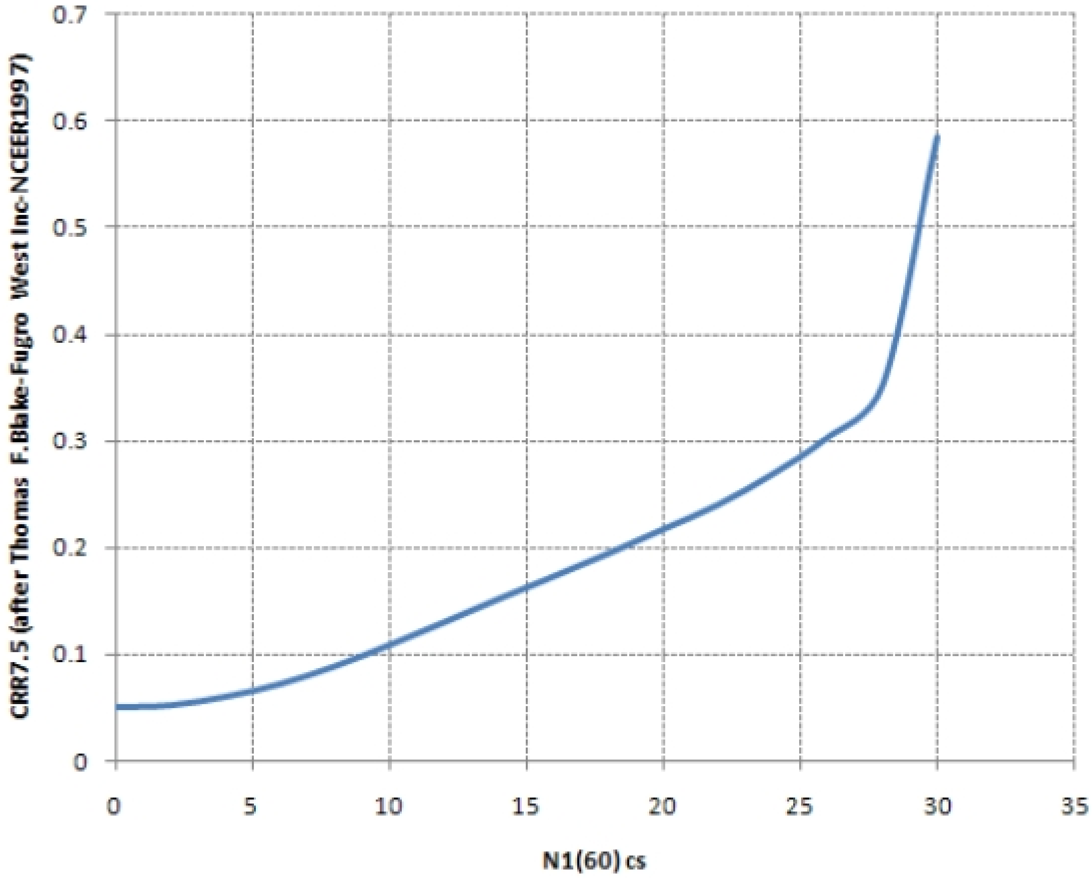
All $CRR_{7.5}$ calculation methods utilized in NovoLiq are described below:

NCEER (1997) and Vancouver Task Force Report (2007)

These two methods are very similar expect that in "Vancouver Task Force Report (2007)" a K_σ parameter is multiplied in $CRR_{7.5}$. In these methodologies, $CRR_{7.5}$ is a function of depth corrected SPT blow counts $N1_{(60)}$ for clean sand (fines content less than 5 percent). For sands containing more fines content, more corrections will be applied on $N1_{(60)}$. The $CRR_{7.5}$ curve proposed by these methodologies based on $N1_{(60)}$ is shown below:



In NovoLiq, the equation proposed by Thomas F. Blake (Fugro West Inc., Ventura, California) recommended by NCEER Workshop (1997) for clean sand curve, as shown below is used. This equation is valid for $N1_{(60)cs} \leq 30$



Proposed CRR7.5 curve for clean sand (after Thomas F. Blake - NCEER Workshop)

The K_σ factor is calculated from the following formula:

$$K_\sigma = (\sigma'_{vo} / P_a)^{f-1}$$

Where P_a is atmospheric pressure in the chosen units and f depends on relative density (Dr) and given by:

f = 1 - 0.005 * Dr   for 40% < Dr < 80%

Dr ≤ 80% can be estimated using Dr = 100 * S(N1$_{(60)}$/46)

Boulanger and Idriss (2004)

The following equation is proposed by Boulanger and Idriss (2004) for clean sand:

$$CRR_{\sigma=1,\alpha=0} = \exp\left\{\frac{(N_1)_{60}}{14.1} + \left(\frac{(N_1)_{60}}{126}\right)^2 - \left(\frac{(N_1)_{60}}{23.6}\right)^3 + \left(\frac{(N_1)_{60}}{25.4}\right)^4 - 2.8\right\}$$

Japanese Bridge Code

This methodology is based on SPT blow counts and particle size distribution of sand.

$$0.05mm < D_{50} < 0.6mm \longrightarrow CRR_1 = 0.0882\sqrt{\frac{N_{1(60)}}{\sigma'_v + 0.7}} + 0.255\log\frac{0.35}{D_{50}} + R_3$$

$$0.6mm < D_{50} < 2mm \longrightarrow CRR_1 = 0.0882\sqrt{\frac{N_{1(60)}}{\sigma'_v + 0.7}} - 0.05$$

$$F_c < 40\% \Rightarrow R_3 = 0$$

$$F_c \geq 40\% \Rightarrow R_3 = 0.004F_c - 0.16$$

Where:
D_{50} : particle size corresponding to 50 percent passing
F_c : percent fines content passing sieve #200 (clay and silt)

Cetin et al, 2004

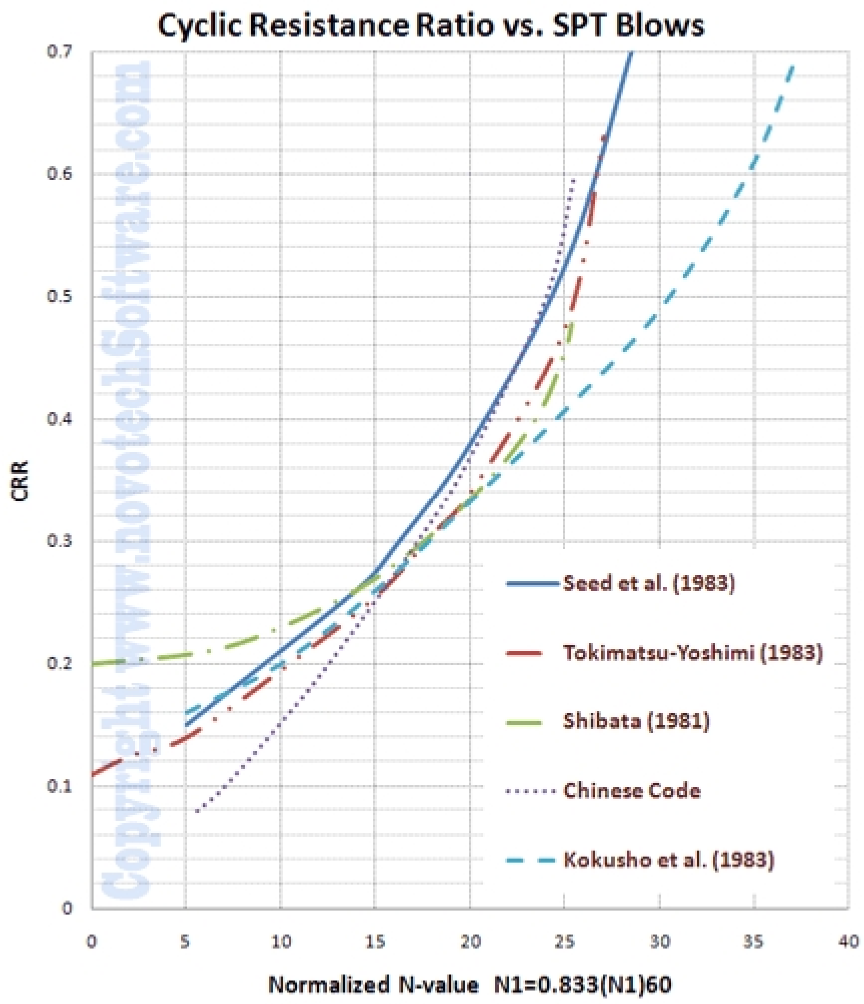
A complete explanation of this method is presented in the following paper:

> Standard Penetration Test-Based Probabilistic and Deterministic Assessment of Seismic Soil Liquefaction Potential
> K. Onder Cetin, M.ASCE; Raymond B. Seed, M.ASCE; Armen Der Kiureghian, M.ASCE; Kohji Tokimatsu; Leslie F. Harder Jr., M.ASCE; Robert E. Kayen, M.ASCE ; and Robert E. S. Moss, M.ASCE

Note: Recently there has been technical discussions (by Dr Boulanger and Dr Idriss, 2010) about the accuracy and reliability of Cetin et al (2004) method. Therefore it is recommended that this method is used with caution and full understanding of its risks. For further details please see Appendix A of this document.

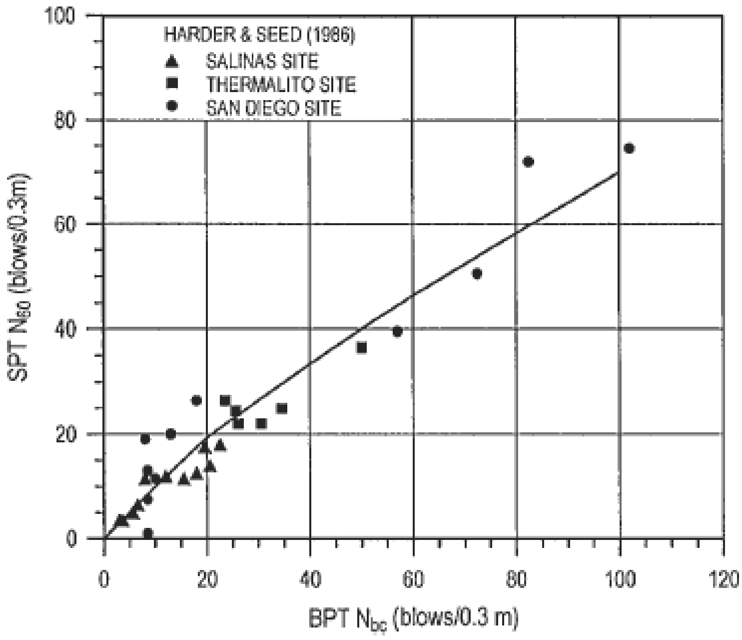
Other Methods

Some other CRR1 curves proposed by geoscientists are also implemented in NovoLIQ. These curves are shown in the following graph; Horizontal axis is normalized corrected SPT blow counts ($N1=0.833N1_{(60)}$).

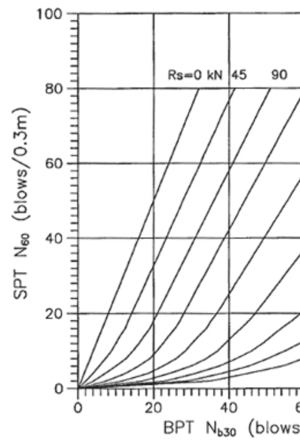


BDT-Based CRR

The approach for liquefaction assessment based on Becker Density Test (BDT) is essentially assessing the potential using equivalent SPT blow counts (N_{60}). Two following methods are covered in NovoLiq for corre blows to SPT blows:



Harder & Seed (1986)



Alex Sy & Campanella
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When BDT blow counts are converted to equivalent SPT blow counts (N_{60}), the procedures for Standard Penet
be applied to field test data.

Note: it is assumed that user has already corrected BPT blow counts for 'bounce chamber pressure'.
program NovoBPT can be used for Becker penetration test processing and correlations.

Vs-Based CRR

The $CRR_{7.5}$ based on V_S is calculated based on the following methodology (source: NCEER Workshop 1997 report):

Recommended Method by NCEER, 1997

Robertson et al. (1992) proposed a stress-based liquefaction assessment procedure using field performance data from sites in the Imperial Valley, California. These investigators normalized V_S by:

$$V_{S1} = V_S(P_a/\sigma'_{vo})^{0.25}$$

where P_a is a reference stress of 100 kPa, approximately atmospheric pressure, and σ'_{vo} is effective overburden pressure in kPa. **Robertson et al., 1992** suggested the liquefaction resistance bound (CRR curve) for magnitude 7.5 earthquakes, plotted in the following figure along with several sites where liquefaction did or did not occur. Subsequent liquefaction resistance boundaries proposed by **Kayen et al., 1992** and **Lodge, 1994** for magnitude 7 earthquake are also shown.

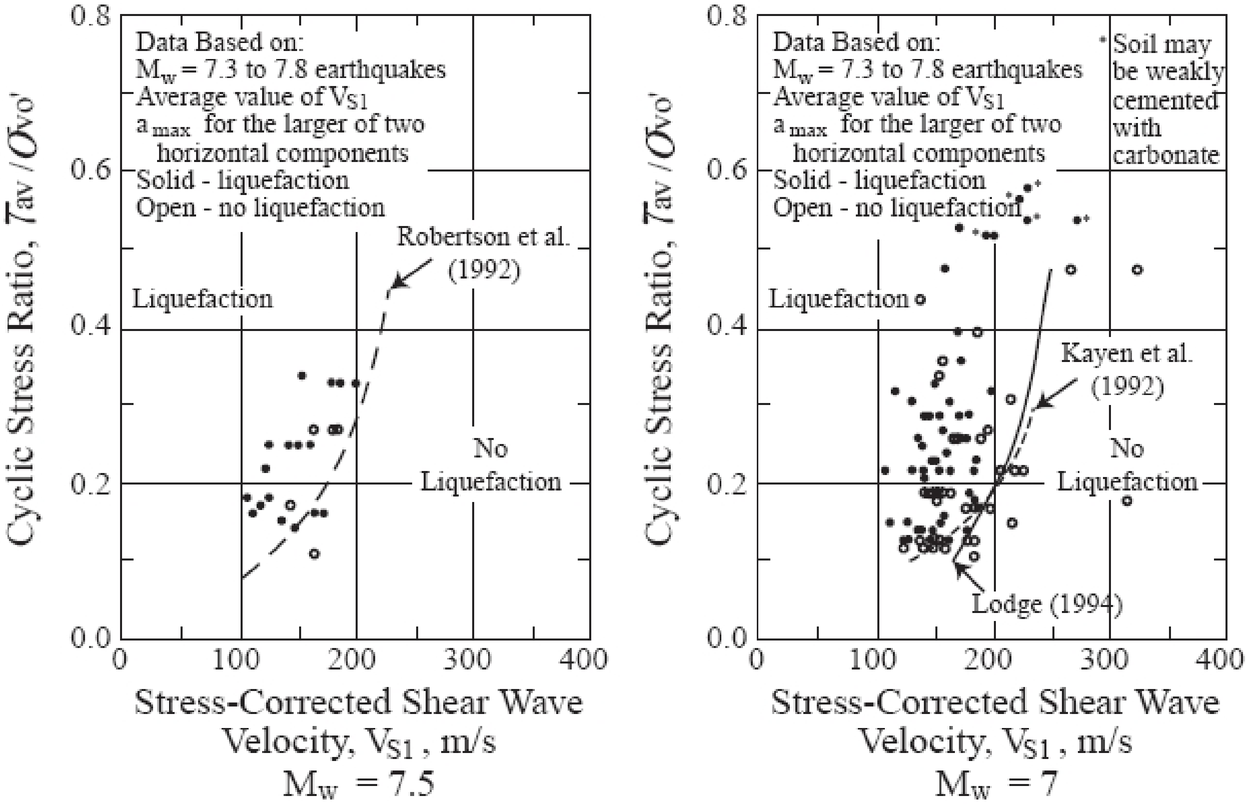


Figure 1 : Proposed cyclic stress ratio based on shear wave velocity.

The relationship proposed by **Lodge (1994)** provides a conservative lower boundary for liquefaction case histories with V_{S1} less than about 200 m/s. The relationship by **Robertson et al. (1992)** is the least conservative of the three. Professor **Ricardo Dobry** suggested a relationship between cyclic resistance ratio and V_{S1} for constant average cyclic shear strain; This formula supports a CRR bound passing through the origin and provides a rational approach for extrapolating beyond the limits of the available field performance data, at least for lower values of V_{S1} ($V_{S1} \le 125$ m/s).

For higher values of V_{S1} , **Andrus and Stokoe** reason that the CRR bound should become asymptotic to some limiting V_{S1} value. This limit is caused by the tendency of dense granular soils to exhibit dilative behavior at large strains. Thus, equation is modified to:

$$\boldsymbol{\tau_{av}/\sigma'_{vo} = CRR = a(V_{S1}/100)^2 + b/(V_{S1c} - V_{S1}) - b/V_{S1c}}$$

where V_{S1c} is the critical value of V_{S1} which separates contractive and dilative behavior, and a and b are curve fitting parameters. Using the relationship between V_{S1} and CRR expressed by this equation , **Andrus and Stokoe** drew curves to separate data from sites where liquefaction effects were and were not observed. Best fit values for the constants a and b were 0.03 and 0.9, respectively, for magnitude 7.5 earthquakes. **Andrus and Stokoe** also determined the following best-fit values for V_{S1c} :

V_{S1c} = 220 m/s for sands and gravels with fines contents less than **5 %**
V_{S1c} = 210 m/s for sands and gravels with fines contents of about **20 %**
V_{S1c} = 200 m/s for sands and gravels with fines contents greater than **35 %**

Figure 2 presents CRR boundaries recommended by **Andrus and Stokoe** for magnitude 7.5 earthquakes and un-cemented Holocene-age soils with various fines contents. Although these boundaries pass through the origin, natural alluvial sandy soils with shallow water tables rarely have corrected shear wave velocities less than 100 m/s, even near ground surface. For a V_{S1} of 100 m/s and a magnitude 7.5 earthquake, the calculated CRR is 0.03

This minimal CRR value is generally consistent with intercept CRR values for the CPT and SPT procedures.

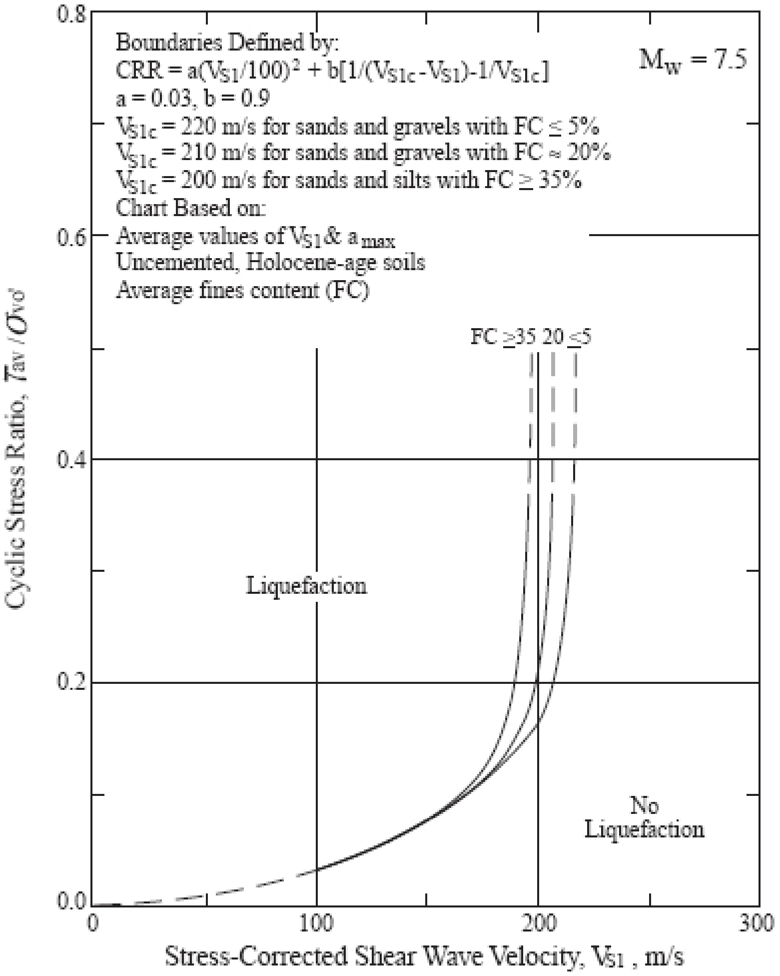


Figure 2 : Proposed cyclic stress ratio curves for different fines content (FC).

Post-Liquefaction

Lateral Displacements

The following method of estimating the post-liquefaction lateral displacements is incorporated into NovoLiq:

Zhang, Robertson and Brachman, 2004

This method is essentially based on estimating maximum cyclic shear strain of each layer during and after liquefaction which is estimated from safety factor against soil liquefaction (FS) and relative density of soil (Dr), when Dr itself can be correlated from SPT or equivalent SPT blow counts.

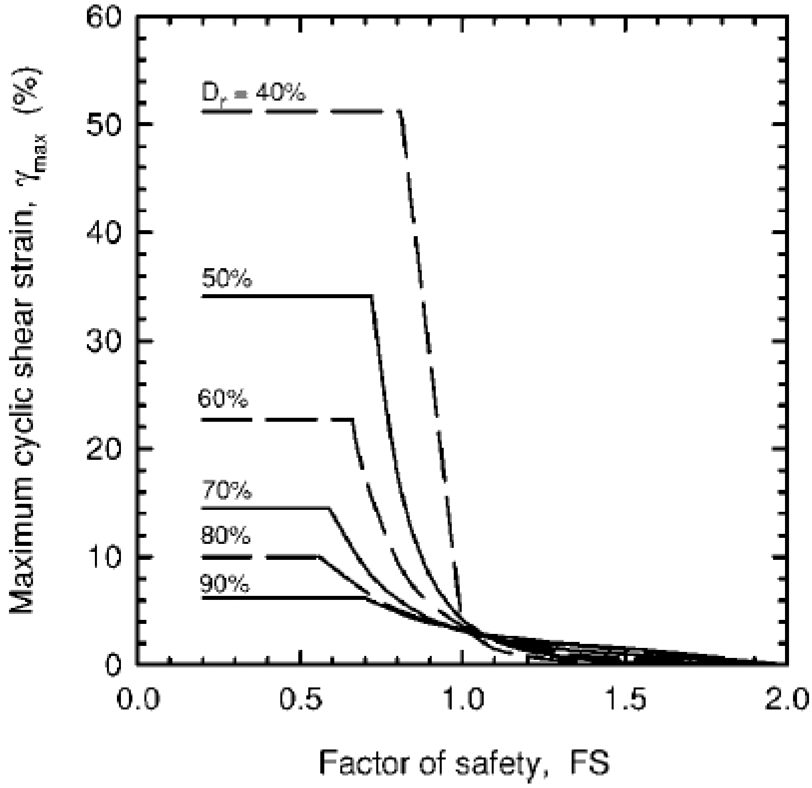


Figure 1 : maximum cyclic shear strain for post liquefaction lateral displacement proposed by Zhang, Robertson and Brachman, 2004.

Then, the Lateral Displacement Index (LDI) is calculated from the following equation:

$$\mathrm{LDI} = \int_0^{Z_{max}} \gamma_{max} dz$$

Where γ_{max} is the maximum shear strain in each layer induced by cyclic load, and dz is depth interval at each test. Based on the topography of the site (**Gently Sloped** / **Free Face)** the lateral displacement is then estimated from LDI. The complete procedure proposed by the authors, is available in the following paper from our website:

Estimating Liquefaction-Induced Lateral Displacements Using the Standard Penetration Test or Cone Penetration Test
G. Zhang; P. K. Robertson; and R. W. I. Brachmann

Faris, 2006

This method is similar to Zhang and Robertson method; but instead a Displacement Potential Index (DPI) is calculated based on Cyclic Stress Ratio (CSR) and $N1(60)_{cs}$:

$$\mathrm{DPI} = \int_0^{Z_{max}} \gamma_{max} dz$$

Where γ_{max} is the maximum shear strain in each layer induced by cyclic load, and dz is depth interval at each test. Based on the topography of the site (**Gently Sloped** / **Free Face)** the lateral displacement is then estimated from DPI. The procedure is available for download from our website:

Guidelines on Foundation Loading and Deformation Due to Liquefaction Induced Lateral Spreading

DOT (February 2011)

Note: Please note that for both Faris 2006 and Zhang 2004 methods, you can choose to ignore lateral spread when factor of safety is greater than a certain number. For more information please read this article.

Youd 2002

The following equations are used for estimation of lateral displacements:

Gently Sloped:

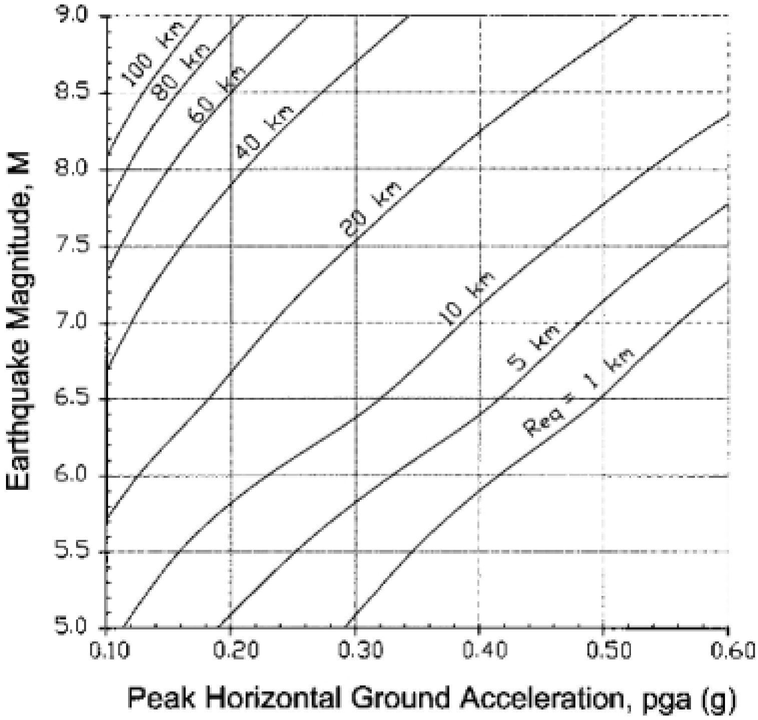
$$\log D_H = -16.213 + 1.532M - 1.406 \log R^* - 0.012R + 0.338 \log S + 0.540 \log T_{15} + 3.413 \log(100 - F_{15}) - 0.795 \log(D50_{15} + 0.1 \text{ mm})$$

Free Face:

$$\log D_H = -16.713 + 1.532M - 1.406 \log R^* - 0.012R + 0.592 \log W + 0.540 \log T_{15} + 3.413 \log(100 - F_{15}) - 0.795 \log(D50_{15} + 0.1 \text{ mm})$$

Where D_H is the estimated lateral ground displacement in meters; M is the moment magnitude of the earthquake, R* is the nearest horizontal or map distance from the site to the seismic energy source in kilometers, T15 is the cumulative thickness of saturated granular layers with corrected blow counts N1(60) less than 15, in meters, F_{15} is the average fines content for granular materials included within T_{15} in percent, $D50_{15}$ is the average mean grain size for granular materials within T_{15} in millimeters, S is the ground slope in percent, and W is the free-face ratio defined as the height of the free face divided by the distance from the base of the free face to the point in question in percent. It is recommended that R be estimated from the following graph based on PGA and M:

$$R^* = R + 10^{(0.89M-5.64)}$$



The complete paper can be downloaded at:

[Revised Multilinear Regression Equations for Prediction of Lateral Spread Displacement]
T. Leslie Youd, Corbett M. Hansen, Steven F. Bartlett

Hamada et al 1986

Hamada compiled lateral spread and borehole data from Niigata and Noshiro, Japan and developed the following preliminary empirical equation for estimating lateral spread displacement:

$$D = 0.75H^{1/2}\theta^{1/3}$$

D is predicted lateral displacement, H is the thickness of the liquefied layer and θ is ground slope.

Reconsolidation Settlement

Post-liquefaction settlements occur during and after earthquake shaking. For level ground conditions the amount can be computed from the volumetric re-consolidation strains induced as the excess pore water pressures dissipate. Based on field experience during past earthquakes, the amount of volumetric strain depends on penetration resistance and the CSR applied by the design earthquake. Curves proposed by Ishihara and Yoshimine (1992) are shown in Figure 1 and indicate that volumetric re-consolidation strains can range between about 4.5% for very loose sand to 1% for very dense sands. These curves are recommended for estimating post-liquefaction settlements.

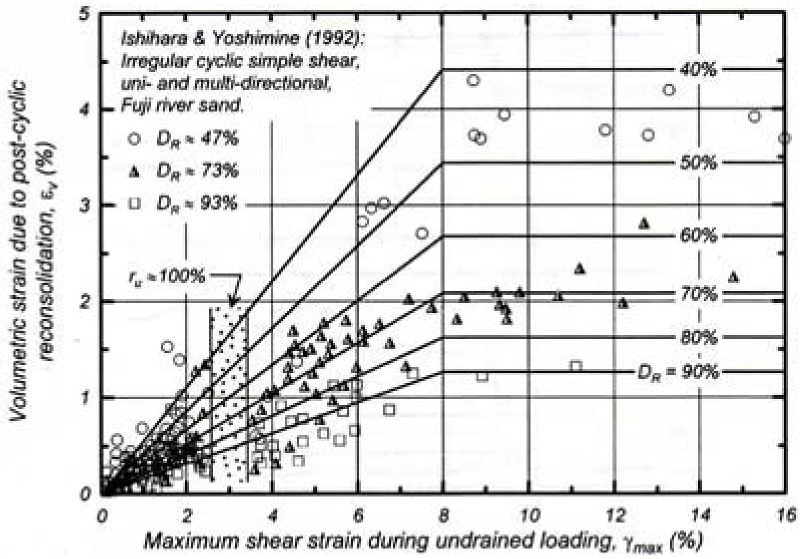


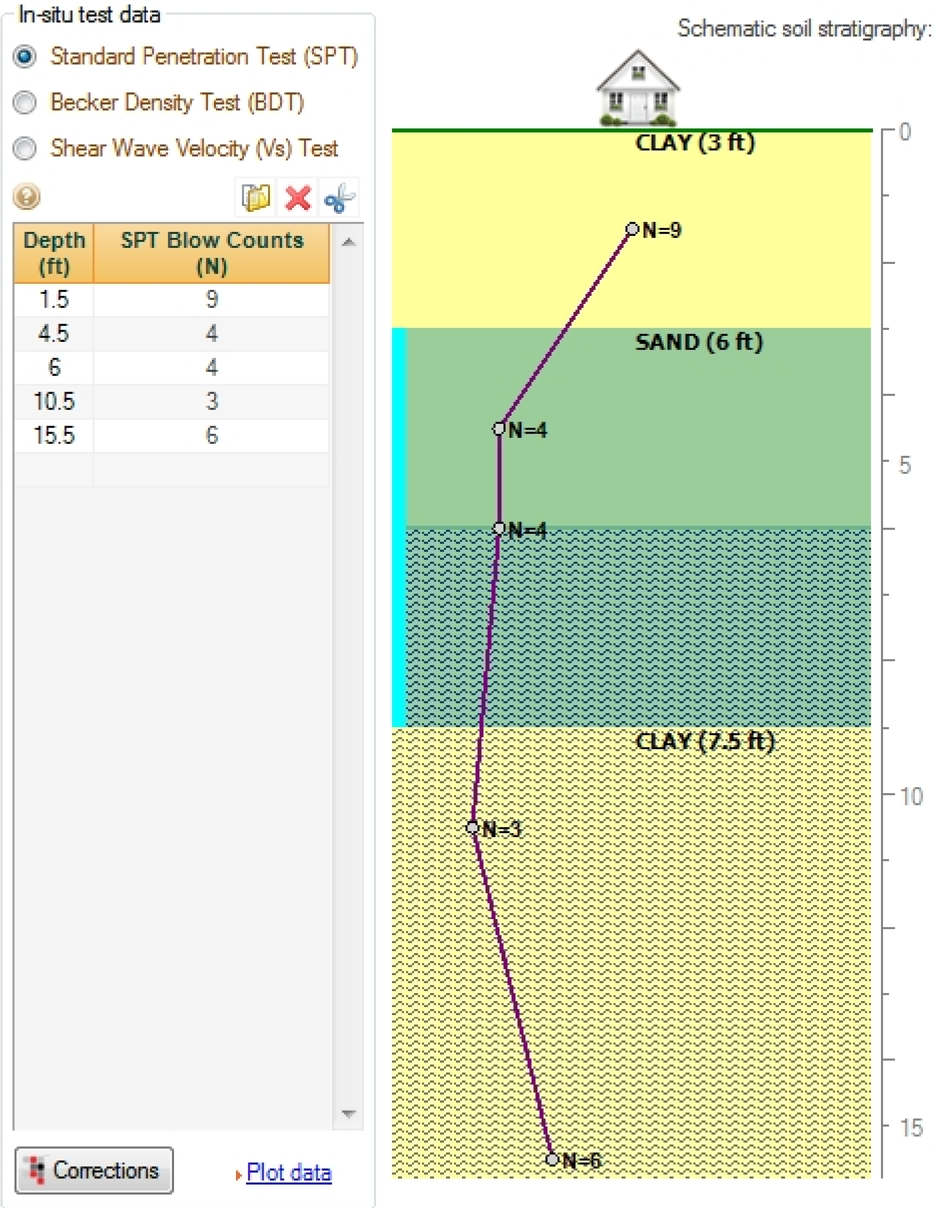
Figure 1 : Recommended relationships for volumetric re-consolidation strains as a function of maximum shear strain and relative density (Ishihara & Yoshimine 1992)

How depth interval is calculated?

NovoLIQ calculates depth interval dz during calculation of post-liquefaction displacements. In general $dz = z_b - z_t$ where z_t and z_b are the depth to the top and bottom of the depth interval, between the test depth and the previous / next test depths. The following explains how dz is calculated for each case:

1. If a test is above the water level, dz = 0.
2. In general, the depth interval for tests within the same layer is calculated by calculating the average depth between the depths of two subsequent tests. For example for N=3 at z=10.5 ft, z_b= (10.5+15.5)/2=13 ft. However, z_t for this test is the top of this layer which is 9 ft.
3. If the test is the first test in a layer, z_t is equal to top of the layer. For example for N=9 at z=1.5 ft, z_t would be zero. For N=3 at 10.5 ft, z_t is 9 ft.
4. If the test is the last test in a layer, z_b is equal to bottom of the layer. For example for N=6 at z=15.5 ft, z_b would be 16 ft.
5. If water level is present within a layer, z_t for tests within that layer will depend on depth of water level. For example for N=4 at z=6 ft, z_t=6 ft and z_b=9 ft.
6. For first test below the ground water level, Z_t will be water level.
7. If a test depth is exactly on the interface between to layers (e.g. N=4 at 6 ft), then the test is considered to be the first test in the lower layer.
8. If there is no field test in a layer, no dz will be considered for that layer (remember dz is calculated at each test depth).

Note: dz, Z_t and Z_b are presented on the 'Post-Liquefaction Parameters' tab in the output tables.



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