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I-System: Index of Ground-Structure

A Comprehensive Indexing System for Ground-Structure Behaviour Classification and Characterization

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Abstract

An optimised geotechnical/geomechanical design approach includes empirical, analytical, seismic, and observational stages. Empirical and observational parts of the design are very important in initiation of the approach and in finalisation of the judgements for practice and design purposes containing the derivation of the ground behaviour, identification of ground hazards, determination of support systems, and characterisation of mechanical properties of ground. Nowadays engineering classifications are main part of the empirical/observational stages of the design for human made structures in ground; though, they have limitations in application. I-System is a new classification as well as a characterisation system for ground that is developed to cross the limitations that are involved with other empirical classifications. It is smartly applicable for any type of civil/mining/oil/gas structures in ground comprehensively including but not limited to abutments of bridges/dams, caverns, deep/shallow foundations, embankment/tailing dams, galleries, deep (underground) or shallow (semi-surface) metro stations, mine stopes, open pits, shafts, slopes, trenches, tunnels (any type or method), underground spaces/storages, wells, etc. It considers easily derivable geohydrological, geomechanical, geometrical, geophysical, geostructural, geotechnical, and dynamic properties and configuration of ground in relation to the structure together with the method of excavation/construction. It is based on over 22 years' research and verification in design and construction of surface, semi-surface, and underground structures in any ground medium irrespective of being rock or soil.

Keywords: (I)-Class, (I)-GC, characterization, classification, GCD, ground, I-System, index, rock mass, soil mass, structure, support system

1. Introduction

Design approach for structures in ground includes 4 important stages (Bineshian et al., 2019) as shown in Figure 1. The design methodology should pass empirical, analytical, seismic, and observational procedures to get the optimised design badge of good for construction, while empirical and observational parts are playing very crucial role and determinative factors for this purpose. Figure 2 shows the design procedure for structures in ground and required data for the same.

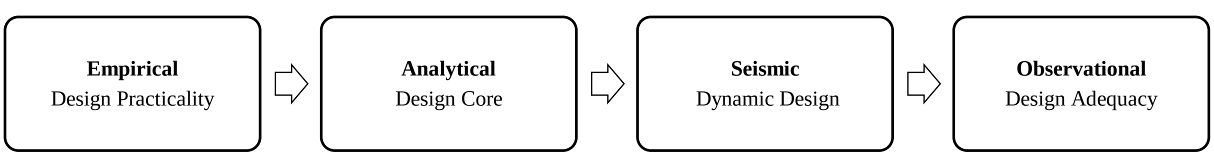
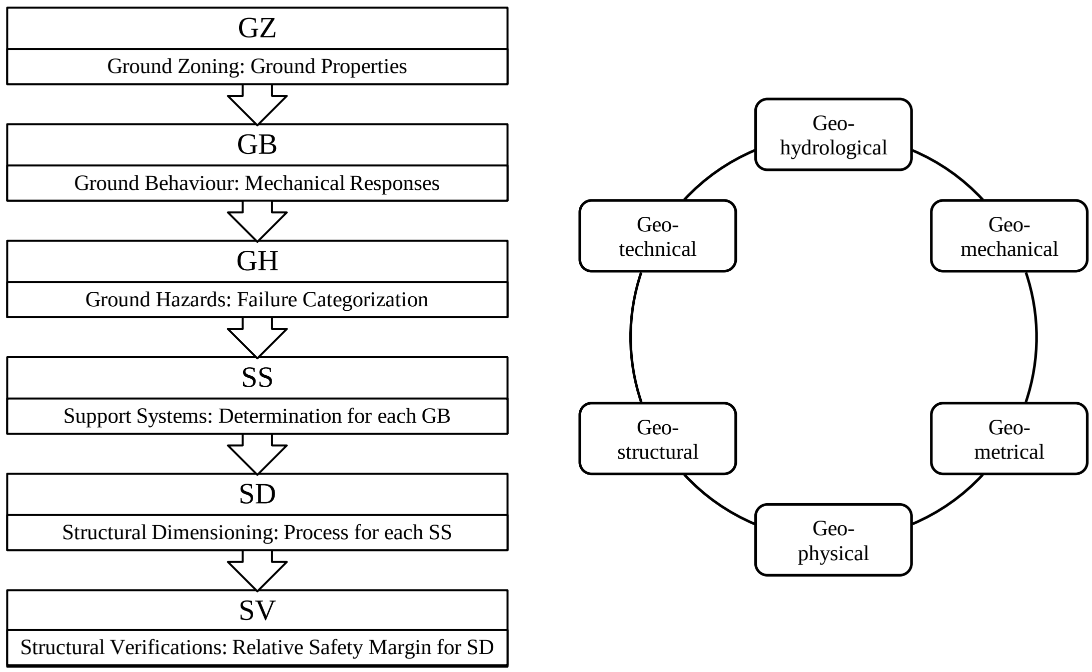


Figure 1. Design approach for structures in ground



Design Procedure Diagram Design Setting's Data Requirements

Figure 2. Design procedure for structures in ground

Engineering classifications are the main part of the empirical and observational design elements in a healthy design approach for structures in ground (Bineshian, 2012, Bineshian and Ghazvinian, 2012a and 2012b). Comprehensiveness and practicality of the engineering classifications are essential in application in NATM (New Austrian Tunnelling Method), NMT (Norwegian Method of Tunnelling), SEM (Sequential Excavation Method), SCL (Sprayed Concrete Lining Method), etc. nonetheless existing engineering classifications come with limitations in use for both rock and soil.

Limitations, inaccuracy, and imprecision involved with existing classifications make engineers uncertain in determination and dimensioning of structures specially when they encounter ground complications (Bineshian, 2014, Bineshian, 2017, Bineshian et al., 2019). RMR and Q are popular existing classifications developed by Bieniawski (1973) and Barton et al (1974) respectively (Bieniawski, 1976, Barton et al., 1974). They are only applicable for rock medium. RMR is proposed for surface and underground works but its water pressure consideration is doubtful, quantification of joint orientation is uncertain, and the effect of water on rock mass is inattentive (Bineshian et al., 2013). Q is proposed for tunnels merely, which comes with several limits in input parameters including discontinuity's aperture, orientation, persistency, size, and rock strength. Additionally, there is a shortcoming in most existing classification systems when observed rock mass characteristics are used to estimate the conditions for planning without including input of the excavation method of structure. An excavation damage factor or similar should be applied, but none of the empirical or other tools in rock engineering makes use of this (Palmstrom and Broch, 2006).

I-System or in a short form (I) as a classification and characterisation system is developed and verified based on 22 years' research in 4 continents in design and construction of mountain and metro tunnelling, dam works, road works, slope stabilizations, bridges, and mining to address and resolve the aforesaid issues with existing classifications. Table 1 demonstrates a summary for application of RMR and Q compared to the I-System.

Table 1. Application summary for popular existing engineering classifications compared to the I-System

Applications	**Media**		**Structure (Civil, Mining, Oil and Gas)**	
	Rock	Soil	Surface	Underground
RMR (Bieniawski, 1973)	✓	✗	–	✓
Q (Barton et al., 1974)	✓	✗	✗	✓
I-System (Bineshian, 2019)	✓	✓	✓	✓

✓ Applicable
– Partially Applicable
✗ Not Applicable

The I-System provides precise prediction of ground behaviour together with recommendations on required Support System/s (SS), Excavation Technique/s (ET), Instrumentation Technique/s (IT), Prevention Technique/s (PT), and Forecast Technique/s (FT) followed by Design Remark/s (DR) and estimated mechanical properties of ground. Figure 3 represents the flowchart for determination of GB (Ground Behaviour) using two approaches; Stress Analysis and the I-System.

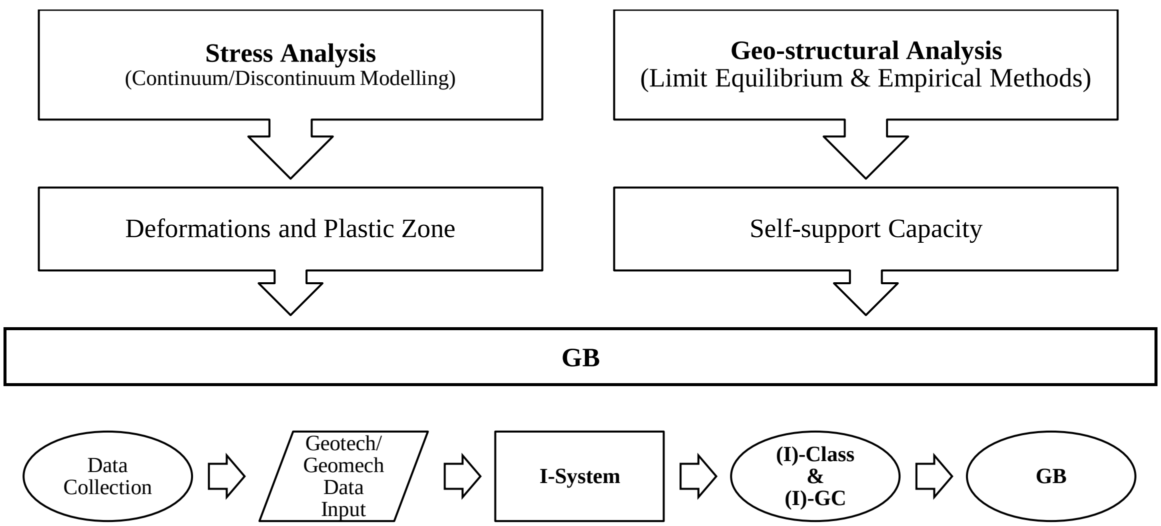


Figure 3. Flowchart representing the way to determine the GB using Stress Analysis and the I-System

Application of the I-System is verified against different types of ground and complicated challenging condition and scrutinised by several cases in over 42 projects and therefore outputs for each case is optimised in comparison to analytical, numerical, and observational methods to compensate the demerits of other classifications and strengthen its comprehensiveness. Appendix A provides a project reference in application of the I-System. In this paper definition of the I-System in details together with its applications and utilisation is provided. Appendix B represents three case histories for different conditions in which the I-System is used. Furthermore, full clarifications in derivation of parameters and comprehensive characterisation is added to this edition compared to the 2019 edition.

2. Definition and Applications of I-System

Providing a solution to engineers in their challenges with complicated ground conditions is the key perception and approach in development of this new all-in-one classification and characterisation for ground in accord with real condition and delivering design parameters and practical recommendation/s. Also, it had been in mind to provide a trusted utility for empirical part of design. In development of this system, drawbacks and limitations of other classifications including RMR and Q are properly addressed and consequently fixed (Bineshian, 2019, Bineshian, 2020).

The new system is conceptually different from any existing classifications due to its applicability for different conditions of ground and structures including but not limited to abutments of bridges/dams, caverns, deep/shallow foundations, embankment/tailing dams, galleries, deep (underground) or shallow (semi-surface) metro stations, mine stopes, open pits, shafts, slopes, trenches, tunnels (any type or method), underground spaces/storages, wells, etc. and its comprehensiveness in providing accurate and precise prediction of ground behaviour based on several geomechanical hazards (failure mechanisms) encountered in civil, mining, and oil and gas projects.

It is scrutinised and verified in different challenging ground conditions by yielding suitable estimation of ground quality, intelligent primary and final SS (Support System/s) determination, and recommendations on right ET (Excavation Technique/s) for encountered condition, proper IT (Instrumentation Technique/s) for monitoring, and appropriate PT (Prevention Technique/s) against possible failures or collapses. It also suggests verified FT (Forecast Technique/s) to predict the ground condition during excavation and provides practical DR (Design Remark/s) that is helpful in understanding of ground behaviour, failure mechanism/s, and load configuration.

Further to all of these, it also characterises the ground to derive the mechanical properties to be used in design for dimensioning of structure. It is the first ever classification, which is applicable for both rock and soil that considers problematical and structural configurations, opening's scale effect, earthquake effect, and excavation technique's impact. Moreover, it is also first ever classification that carefully provides prediction for special ground behaviour including but not limited to Squeezing/Swelling/Heaving (SSH) as a kind of Time Dependent (TD), Visco-elasto Plastic (VP), fully plastic, gravity driven (GD), and Burst Prone (BP) grounds.

The I-System is designed to have five indices, which defines the mechanical behaviour of ground in relation to the structure irrespective of type of the media being rock or soil based on easily derivable most important geohydrological, geomechanical, geometrical, geophysical, geostructural, and geotechnical parameters/properties and two influencing parameters that have impact on the structure including Dynamic Forces (DF_i) and Excavation Technique (ET_i). This comprehensive classification system is named as "Index of Ground-Structure" in the short form of (I) or I-System. Eq. 1 represents the I-System in a mathematical form. Eq. 2 to 8 defines the indices and the impact factors for (I) as follows;

$$(\mathrm{I}) = (\mathrm{A_i} + \mathrm{C_i} + \mathrm{H_i} + \mathrm{P_i} + \mathrm{S_i}) \times \mathrm{DF_i} \times \mathrm{ET_i} \quad (1)$$

$$\mathrm{A_i} = (\mathrm{a_{dn}} + \mathrm{a_{ds}} + \mathrm{a_{di}}) \times \mathrm{a_{da}} \times \mathrm{a_{dd}} \times \mathrm{a_{dp}} \times \mathrm{a_{dr}} \quad (2)$$

$$\mathrm{C_i} = \mathrm{c_{pc}} \times \mathrm{c_{sc}} \quad (3)$$

$$\mathrm{H_i} = \mathrm{h_{gc}} \times \mathrm{h_{gs}} \quad (4)$$

$$\mathrm{P_i} = \left[\mathrm{p_{cc}} + \mathrm{p_{dc}} + \left(\mathrm{p_{ps}} \times \mathrm{p_{pm}}\right)\right] \times \mathrm{p_{bw}} \;\&\; \mathrm{p_{bw}} = f(\mathrm{V_p}, \mathrm{V_s}) \quad (5)$$

$$\mathrm{S_i} = \mathrm{s_{cs}} \times \mathrm{s_{se}} \quad (6)$$

$$\mathrm{DF_i} = f(\mathrm{PGA_{SD}}, \mathrm{ERZ}, \mathrm{MSK}) \;\&\; \mathrm{PGA_{SD}} = f(\mathrm{PGA}, \mathrm{G_S}, \rho, \mathrm{d}) \quad (7)$$

$$\mathrm{ET_i} = f(\mathrm{ET}, \mathrm{PPV}) \quad (8)$$

Where,
A_i Armature Index
C_i Configuration Index
H_i Hydro Index
P_i Properties Index
S_i Strength Index
DF_i Dynamic Forces Impact
ET_i Excavation Technique Impact

Full definition of the parameters is available in Appendix C.

The I-System's value ranges between 100 – 0 and classifies the ground-structure interaction to 10 classes as (I)-01 to (I)-10 from best to worst class. The indices of A_i, C_i, H_i, P_i, and S_i have 20 per cent share out of a total score of 100. DF_i and ET_i are factors ranging between 1 – 0.75 and 1 – 0.50 respectively, which impact the summation of indices (see Figure 4 as the I-System's scoring diagram). Indices are defined comprehensively in the Section 3.

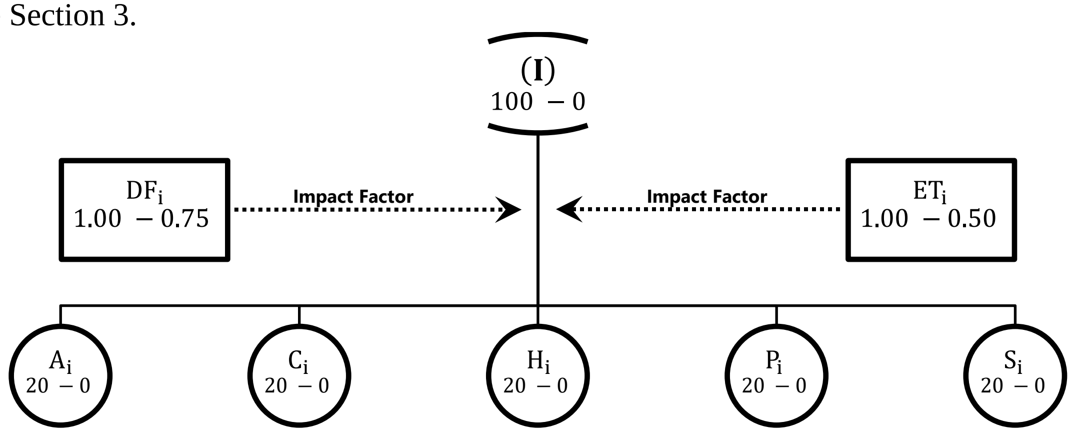


Figure 4. I-System's scoring diagram

The I-System is applicable for estimation of quality of both rock and soil in relation to the structure at any scale and type. It can be considered as empirical and observational parts of the design approach (Figure 1). The I-System is applicable in design procedure and/or in practice (see Figures 2 and 3) for:

- categorizing the ground properties in relation to the Ground Zoning (GZ),
- discovering the Ground Behaviour (GB),
- identifying associated failure mechanism/s with the discovered GB as the Ground Hazard/s (GH),
- determining the required Support System/s (SS), and
- assisting in Structural Dimensioning and Verification (SD and SV) by characterizing the most important mechanical properties of ground.

It is also applicable (see Tables 10 -13) to:

- find the appropriate technique/s for excavation further to the determination of the required support system/s (ET),
- select the suitable choice for instrumentation/monitoring during construction (IT),
- implement the right technique for prevention of hazard/s (PT), and
- designate the required technique for forecasting/prediction (FT).

The I-System is applicable to serve the above-stated purposes for surface, semi-surface, and underground structures in the field of civil, mining (quarry/coal/open-pits/other), and oil and gas exploration/drilling works. Range of application of the I-System includes but it is not limited to the use in design and/or practice for:

- Surface Structures:
    - Embankment Dams,
    - Open Pits,
    - Shallow Foundations,
    - Slopes,
    - Tailing Dams,
    - Trenches, etc.

- Semi-Surface Structures:
    - Bridge Abutments,
    - Dam Abutments,
    - Deep Foundations,
    - Shallow Metro Stations (Open-Cut/Cut&Cover), etc.

- Underground Structures:
    - Caverns,
    - Deep Metro Stations (underground),
    - Galleries (exploration/grouting galleries),
    - Mine Stopes,
    - Shafts,
    - Tunnels (comprising of any type or method),
    - Underground Spaces,
    - Underground Storages,
    - Wells, etc.

3. I-System's Indices

The I-System equation includes 5 indices and 2 impact factors with mathematical form of Eq. 2 to 8. In this section all associated parameters of each index is defined in details while Appendix C provides an easy reference for the nomenclature. Derivation of parameters from ground and their use in the I-System is easy and confusion-free that makes the classification accurate in selection of the input data for a credible output.

3.1. Armature Index

A_i is the Armature Index (Eq. 2) as ground's skeleton armature, which is designed to model most important geomechanical aspects of rock mass media through the discontinuity properties of the ground. A_i has 20 score out of 100. Table 2 defines parameters of A_i.

Table 2. Armature Index (A_i): $\mathbf{a}_{dn}$, $\mathbf{a}_{ds}$, and $\mathbf{a}_{di}$, $\mathbf{a}_{da}$, $\mathbf{a}_{dd}$, $\mathbf{a}_{df}$, and $\mathbf{a}_{dp}$

dn	$\mathbf{a}_{dn}$	ds	$\mathbf{a}_{ds}$	di	$\mathbf{a}_{di}$ [IF ($\mathbf{a}_{dn} \geq 2.50$ & $\mathbf{a}_{ds} \geq 4.00$) THEN↓ ELSE 0]
0 - 9	10.00	0	10.00	N/A || Jointless	0.00
10 - 14	7.50	1	9.00	0 - 10	-1.00
15 - 19	5.00	2	7.00	11 - 30	-1.50
20 - 24	2.50	3	4.00	31 - 60	-2.00
≥ 25	0.00	≥ 4	0.00	61 - 90	-2.50
N/A || Jointless	0.00	N/A || Jointless	0.00		

da	$\mathbf{a}_{da}$	dd	$\mathbf{a}_{dd}$	df	$\mathbf{a}_{df}$	dp	$\mathbf{a}_{dp}$
N/A || Jointless	1.00	N/A || Jointless	1.00	N/A || Jointless	1.00	N/A || Jointless	1.00
Tight	1.00	Unweathered/Unaltered	1.00	High Friction - Rough/Uneven	1.00	< 0.90 × D	1.00
Semi-Tight	0.95	Semi-Integrated	0.95	Moderate Friction - Nonsmooth	0.95	≥ 0.90 × D	0.90
Open	0.90	Weathered/Altered	0.90	Low Friction - Smooth/Even	0.90		

$\mathbf{a}_{da}$ Factor related to da influencing A_i
$\mathbf{a}_{dd}$ Factor related to dd influencing A_i
$\mathbf{a}_{df}$ Factor related to df influencing A_i
$\mathbf{a}_{di}$ Score related to di as an effect on A_i
$\mathbf{a}_{dn}$ Score related to dn of A_i
$\mathbf{a}_{dp}$ Factor related to dp influencing A_i
$\mathbf{a}_{ds}$ Score related to ds of A_i
da Discontinuity Aperture based on the opening of the discontinuities
dd Discontinuity Disintegration based on weathering or alteration of surface of the discontinuities
df Discontinuity Friction based on the friction condition of the discontinuities
di Discontinuity Inclination based on the dip angle of the most unfavourable discontinuity
dn Discontinuity Number/s based on number of individual discontinuities per m of a horizontal or vertical scanline or average
dp Discontinuity Persistency
ds Discontinuity Set/s reflecting the number/s of set/s of the discontinuities
Jointless A definition for soil that doesn't have any discontinuities. It reflects the state that the medium doesn't have a countable joint.
N/A Not Applicable
|| Or

If $\mathbf{a}_{dn}$ and $\mathbf{a}_{ds}$ are zero, the score for $\mathbf{a}_{di}$ to be assigned as zero; it happens when the number of discontinuities is ≥ 25 and number of discontinuity sets is ≥ 4 that inclination for the discontinuities are not easily derivable. In this case the medium tends to be a homogeneous and isotropic due to generated uniform texture with continuum mechanics' principles.

If the medium is soil mass, "N/A || Jointless" to be selected for each parameter from the Table 2; otherwise, for rock mass the suitable parameter other than "N/A || Jointless" to be selected.

3.2. Configuration Index

C_i is the Configuration Index (Eq. 3) as ground's problematical and structural configuration that covers important problematical geostructural features of rock and/or soil. C_i has 20 score out of 100. Table 3 defines parameters of C_i.

Table 3. Configuration Index (C_i): $\mathbf{c_{pc}}$ and $\mathbf{c_{sc}}$

pc	$\mathbf{c_{pc}}$
Homogeneous || Isotropic || Jointless || Granular*	1.00
Fractured - Slightly	0.95
Faulted - Brittle Single	0.90
Folded - Anticline/Syncline	0.85
Folded - Dome/Basin	0.80
Fractured - Moderately	0.75
Faulted - Graben/Horst	0.70
Folded - Complex/Plunging	0.65
Fractured - Highly	0.60
Faulted - Brittle/Ductile Multiple	0.55
Differed - Unconformities	0.50
BP - High Stress Zone; High Overburden	0.45
Tectonised - Complex of Geostructures	0.40
Sheared - High Shear Stresses - e.g. Mylonite	0.35
TD - Flaky/Micaceous/Cleated - Coals, Mudstone, Phyllite, Schist, Shale, Slate, Young Sandstones	0.30
VP - Incremental-Sudden Large Shear Movement, Cyclic Mobility-Flow Liquefaction, Limited-Continuous Debris Discharge - Flowing/Overrunning	0.25

sc	$\mathbf{c_{sc}}$
Massive || Grainless Continuum**	20.00
Layered (> 100 cm)	17.00
Layered (100 - 10 cm)	15.00
Clastic Breccia/Conglomerate	13.00
Layered (< 10 cm)	11.00
Foliated/Laminar/Platy	9.00
Coarse Grained Skeleton	7.00
Cohesive Matrix Skeleton	4.00
Single Grained Skeleton - Dense Texture	2.00
Single Grained Skeleton - Loose Texture	0.00

$\mathbf{c_{pc}}$ Impacting factor related to pc indicating ground's tectonic state on C_i
$\mathbf{c_{sc}}$ Score related to sc as an effect of ground's texture, fabric, and structure on C_i
pc Problematical Configuration
sc Structural Configuration
BP Burst Prone - Ground Condition with Rock Burst or Coal Burst Behaviour
TD Time Dependent - Ground Condition with Time Dependent Shearing Behaviour such as Squeezing/Swelling/Heaving Behaviour, or even Creep
VP Visco-elasto-Plastic - Ground condition as visco-elasto-plastic to fully plastic behaviour that contains elastic component/s together with viscous component/s, which gives the ground strain rate dependence on time; however, due to losing energy during static/dynamic loading cycle, its behaviour converts to fully plastic and may flows like a viscous substance.
|| Or
* Homogeneous || Isotropic || Jointless || Granular represents a ground condition, which is homogenous or isotropic like intact rock and soil mass or jointless or granular like soil mass.
** Massive || Grainless Continuum represents a ground condition, which is massive rock mass rather than layered rock or grainless like intact rock or rock mass.

3.3. Hydro Index

H_i is the Hydro Index (Eq. 4) as ground hydro effect on mechanical behaviour and hydro related properties, which is a function of GCD – Ground Conductivity Designation – (Bineshian, 2017) or Wetness condition and softness due to presence of water in scale of Mohs. H_i has 20 score out of 100. Table 4 defines parameters of H_i.

Table 4. Hydro Index (H_i): $\mathbf{h_{gc}}$ and $\mathbf{h_{gs}}$

gc (GCD) or [Wetness]	$\mathbf{h_{gc}}$	gs Mohs	$\mathbf{h_{gs}}$
(≤ 0.99) || [Dry]	20.00	≥ 7	1.00
(1 - 1.99) || [Humid]	19.00	6	0.60
(2 - 2.99) || [Damp]	18.00	5	0.50
(3 - 4.99) || [Moist]	16.00	4	0.40
(5 - 6.99) || [Leak]	15.00	3	0.30
(7 - 9.99) || [Wet]	13.00	2	0.20
(10 - 14) || [Drip]	11.00	1	0.10
(15 - 24) || [Shower]	9.00	Moulded by Light Finger Pressure	0.05
(25 - 49) || [Flow]	6.00	Exuded between Fingers	0.00
(50 -99) || [Gush]	3.00		
(≥ 100) || [Burst]	0.00		

gc Ground Conductivity
GCD The Ground Conductivity Designation as a criterion to score the hydraulic conductivity of ground (it is explained in details in this section; it is listed in the table inside the parentheses – ())
gs Ground Softness as effect of hydrosoftness on medium/infilling material based on Mohs Scale
$\mathbf{h_{gc}}$ Score assigned to gc using GCD or Wetness diagram as criterion for hydropressure effect on ground as main part of H_i
$\mathbf{h_{gs}}$ Impact factor related to gs on H_i
Wetness A diagram defined here to classify the ground's water content, which is classifying the ground water condition (observational identification) in 11 ranges (see Figure 5); it is listed in the table inside the brackets – []
|| Or

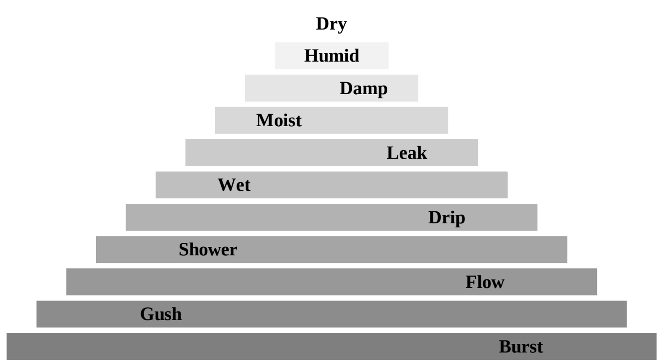


Figure 5. Wetness diagram

GCD is an empirical equation based on a simple single stage water injection test for examination of the ground's hydraulic conductivity. It is essentially based on water-intake measurement that is pumped thorough a drilled hole (NX preferred) at any direction/angle before and after grouting/injection. GCD is developed by author in 2013 - based on Lugeon concept and over 18 years practical verification - as a quick examination technique in practice. It is further examined in 2015 in USBRL project and the results were published by the author for the first time in 2017 (Bineshian, 2017) and later on in 2019 (Bineshian et al. 2019, Bineshian, 2019, Choudhary et al. 2019). GCD test is an easy and quick practice that provides an appropriate economic estimate for hydraulic conductivity to examine the solidification for further consolidation, water ingress reduction, or sealing. Eq. 9 represents dimensionless empirical form for GCD. Figure 6 presents schematics for the GCD test setup. Table 5 shows the classification for ground hydraulic conductivity and ground solidification quality.

$$\mathrm{GCD} = \mathrm{Q_w}/(\mathrm{P_m} + \mathrm{L_i}) \tag{9}$$

In which,

GCD Ground Conductivity Designation (dimensionless)
Q_w Water flow rate (lit/min)
P_m Maximum water pressure during injection (MPa)
L_i Length of water injected portion (packed length) of hole or perforated SDA in m

It is recommended to repeat the test for 3 times and make an average for a better precision in GCD estimation. It is also preferred to conduct the test on a necked hole except otherwise the hole is not sustained and SDA or casing is used. If during the water injection, pressure is not obtained, or it is lesser than 0.20 MPa, then the ground hydraulic conductivity would be considered as VH, which means that the quality of grouting or injection executed at the location of the hole is classified as VP. In this case the section must be further grouted/injected by proper consolidation material/s and configuration to improve the ground solidification quality.

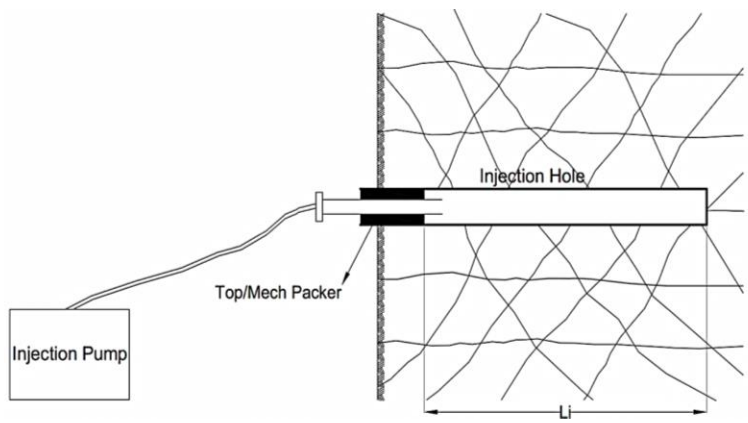


Figure 6. GCD setup (Bineshian, 2017, 2019)

Table 5. Ground Conductivity Designation

GCD	Ground Hydraulic Conductivity	Ground Solidification
> 100	VH - Very High	VP - Very Poor
100 - 50	H - High	P - Poor
50 - 15	M^+ - Medium	F - Fair
15 - 5	M^- - Moderate	G - Good
5 - 1	L - Low	VG - Very Good
< 1	VL - Very Low	E - Excellent

If in any case the GCD measurement is not used then observational ground water condition to be considered as a criterion for scoring the $\mathbf{h}_{gc}$ using the Wetness diagram (Figure 5) in conjunction with Table 4. Wetness diagram is based on observational identification. It classifies the ground Wetness into 11 ranges as shown in Figure 5 that used in Table 4.

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3.4. Properties Index

P_i is the Properties Index (Eq. 5) as ground shear properties by way of a definition as a function of texture, fabric, shape, and size of soil materials together with body wave velocity. P_i is designed to be an important part, which is going to model the important geotechnical characteristics of soil media as part of the I-System's comprehensiveness in applicability. P_i has 20 score out of 100. Table 6 defines parameters of P_i.

Table 6. Property Index (P_i): $\mathbf{p_{cc}}$, $\mathbf{p_{dc}}$, $\mathbf{p_{ps}}$, $\mathbf{p_{pm}}$, and $\mathbf{p_{bw}}$

cc	$\mathbf{p_{cc}}$	dc	$\mathbf{p_{dc}}$
Indurated	8.00	Never Indented by Thumbnail	6.00
Large Size Particles	6.50	Indented Hardly by Thumbnail	5.00
Picked Difficult	5.00	Indented by Thumbnail	4.00
Picked Easily	3.50	Indented by Thumb	3.00
Shovelled Difficult	2.00	Moulded by Strong Finger Pressure	2.00
Shovelled Easily	0.50	Moulded by Light Finger Pressure	1.00
Foot Imprint Easily	0.00	Exuded between Fingers when Squeezed in Hand	0.00

ps	$\mathbf{p_{ps}}$	pm	$\mathbf{p_{pm}}$
N/A e.g. Grainless	3.00	N/A e.g. Grainless	2.00
Boulder	3.00	Angular	2.00
Cobble	2.50	Sub-angular	1.50
Pebble	2.00	Flat	0.75
Gravel	1.50	Rounded	0.00
Sand	1.00		
Silt	0.50		
Clay	0.00		

bw (Vp) or [Vs] m/sec	$\mathbf{p_{bw}}$
(≥ 6000) || [≥ 3300]	1.00
(5999 - 5000) || [3299 - 2900]	0.90
(4999 - 4500) || [2899 - 2600]	0.80
(4499 - 4000) || [2599 - 2200]	0.70
(3999 - 3500) || [2199 - 2000]	0.65
(3499 - 3000) || [1999 - 1500]	0.60
(2999 - 2500) || [1499 - 1000]	0.55
(2499 - 2000) || [999 - 750]	0.50
(1999 - 1000) || [749 - 300]	0.45
(≤ 999) || [≤ 299]	0.40

bw	Body Wave Velocity
cc	Cohesiveness Consistency as shear properties of soil (Cohesion)
dc	Denseness Consistency as shear properties of soil (Non-cohesiveness; Friction)
Grainless	Intact rock or rock mass, which unlike the soil is not granular.
$\mathbf{p_{bw}}$	Factor related to bw including Vp or Vs as Geophysical properties of ground, which corrects P_i; it is derived either from available references considering the type of materials of ground or to be measured using Tunnel Seismic Prediction (TSP).
$\mathbf{p_{cc}}$	Score related to cc of P_i
$\mathbf{p_{dc}}$	Score related to dc of P_i
pm	Particles' Morphology as a function of shape of soil's grains/granules
$\mathbf{p_{pm}}$	Influencing parameter related to pm on P_i
$\mathbf{p_{ps}}$	Influencing parameter related to ps on P_i
ps	Particles' Size as a function of size of soil's grains/granules
Vp	Primary Wave Velocity in m/sec; it is listed in the table inside the parentheses – ()
Vs	Shear/Secondary Wave Velocity in m/sec; it is listed in the table inside the brackets – []
||	Or

If the medium is rock (intact or mass), the "Grainless" category to be picked from Table 6.

3.5. Strength Index

S_i is the Strength Index (Eq. 6) as ground strength behaviour under confining condition. It is an important index in classification of ground-structure using the I-System; so, important influencing parameters of both ground and structure are considered to define the index irrespective of type of medium (rock or soil). In definition of S_i, unconfined compressive strength of ground, scale effect, shape factor of the structure, and stress ratio between vertical and horizontal virgin stresses at the location/depth of the placement of the structure is carefully considered. S_i has 20 score out of 100. Table 7 defines parameters of S_i.

Table 7. Strength Index (S_i): $\mathbf{s_{cs}}$ and $\mathbf{s_{se}}$

cs - UCS	$\mathbf{s_{cs}}$
≥ 200 MPa	20.00
199 - 150 MPa	19.00
149 - 100 MPa	18.00
99 - 75 MPa	16.00
74 - 50 MPa	14.00
49 - 30 MPa	12.00
29 - 20 MPa	10.00
19 - 10 MPa	9.00
9 - 5 MPa	8.00
4.90 - 2 MPa	7.00
1.90 - 1 MPa	6.00
999 - 400 KPa	5.00
399 - 200 KPa	4.00
199 - 100 KPa	3.00
99 - 50 KPa	2.00
49 - 30 KPa	1.00
≤ 29 KPa	0.00

se		$\mathbf{s_{se}}$	
UndS - D/H		$\sigma_v \geq \sigma_h$	$\sigma_v < \sigma_h$
≥ 2.50		0.80	1.00
= 1.90 - 1.30		0.85	0.95
= 1.20 - 0.80		0.90	0.90
= 0.70 - 0.50		0.95	0.85
≤ 0.40		1.00	0.80
SurS - B/H			$\mathbf{s_{se}}$
≥ 2.50			1.00
= 1.90 - 1.30			0.95
= 1.20 - 0.80			0.90
= 0.70 - 0.50			0.85
≤ 0.40			0.80

B/H	Surface and Semi-surface Structures' (SurS) shape or scale factor as ratio of width of berm of slope or trench to height of slope or trench
cs	Compressive Strength considering the Uniaxial Compressive Strength of the ground
D/H	Underground Structures' (UndS) shape or scale factor as ratio of width or horizontal span of underground opening to height of opening
$\mathbf{s_{cs}}$	Score related to cs of S_i
se	Scale Effect
$\mathbf{s_{se}}$	Scale effect factor related to se on S_i
SurS	Surface or Semi-surface Structure
UCS	Unconfined Compressive Strength
UndS	Underground Structure
σ_h	Horizontal Stresses at the location or at the depth of the placement of the structure
σ_v	Vertical Stresses at the location or at the depth of the placement of the structure

In Table 7 a wide range of strength is considered from below 29 KPa to over 200 MPa to cover varieties of very weak soil to very strong rock. The higher range of strength is given in MPa and the range below 1 MPa is given in KPa to make the values more meaningful.

The right option of shape and scale factor to be picked from Table 7 as per the structure's features for calculation of S_i for surface, semi-surface, or underground structures. It also can be picked visually as per the schematical shapes given in Table 7. In a same way, considering the relationship between horizontal and vertical virgin stresses, the right score to be picked from Table 7.

3.6. Dynamic Forces Impact

DF_i is the Dynamic Forces Impact (Eq. 7) on the ground-structure behaviour that represents the earthquake influence as a function of;

- Scaled Design Peak Ground Acceleration (PGA_{SD}) or
- Earthquake Risk Zone (ERZ) or
- Medvedev-Sponheuer-Karnik Scale for earthquake (MSK).

In case of utilisation of $PGA_{SD} = f(PGA, G_S, \rho, d)$ by designer, Eq. 10 and 11 to be used as follows;

$$PGA_{SD} = MSF \times PGA_D \tag{10}$$

$$MSF = 6.9 \times \exp[-M/4] - 0.058 \tag{11}$$

Where,
MSF Magnitude Scaling Factor ≤ 1.8
M Earthquake Magnitude
PGA_D Design Peak Ground Acceleration
G_S Shear modulus
ρ Unit mass of ground
d Depth of placement of the structure.

It is recommended PGA_{SD} to be calculated then Table 8 to be used for the associated value within the 7 ranges of PGA_{SD} for picking up the correct DF_i; however, if use of ERZ or MSK is preferred, the earthquake zoning to be used from references, which is available for the project area and then Table 8 to be utilised for the associated DF_i. ERZ is categorised in 7 classes of damage risk zones as shown in Table 8; EH (MSK XI-XII), VH (MSK IX-X), H (MSK VII-VIII), M (MSK V-VI), L (MSK IV), VL (MSK III), and EL (MSK I-II). DF_i has a range of 1.00 to 0.75. Table 8 defines parameters of DF_i.

Table 8. Dynamic Forces Impact (DF_i)

(PGA_{SD}) or [ERZ] or {MSK}	**DFi**
(< 0.05g) || [EL] || {I-II}	1.00
(0.06g - 0.10g) || [VL] || {III}	0.99
(0.11g - 0.15g) || [L] || {IV}	0.97
(0.16g - 0.25g) || [M] || {V-VI}	0.94
(0.26g - 0.35g) || [H] || {VII-VIII}	0.90
(0.36g - 0.50g) || [VH] || {IX-X}	0.85
(> 0.50g) || [EH] || {XI-XII}	0.75

ERZ Earthquake Risk Zone classifies seismicity as EH (Extremely High), VH (Very High), H (High), M (Moderate), L (Low), VL (Very Low), and EL (Extremely Low); it is listed in the table inside the brackets – []
g g-force or peak ground acceleration due to earth's gravity in m/sec^2 (1g = 9.81 m/sec^2)
MSK Medvedev-Sponheuer-Karnik Scale classifies seismicity as I to XII; it is listed in the table inside the braces – {}
PGA_{SD} Scaled Design Peak Ground Acceleration; it is listed in the table inside the parentheses – ()
|| Or

Picking the right value for DF_i based on PGA_{SD}, ERZ, or MSK is the choice of designer/engineer/geologist.

3.7. Excavation Technique Impact

ET_i is the Excavation Technique Impact (Eq. 8) on the ground-structure behaviour representing vibration impacts on structure during the excavation, which is designed to be a function of Excavation Technique (ET) or Peak Particle Velocity (PPV). ET_i has a range of 1.00 to 0.50. Table 9 defines parameters of ET_i.

Table 9. Excavation Technique Impact (ET_i)

(ET) or [PPV mm/sec]	**ETi**
(ManDigg)	1.00
(ME/NonExBreak) || [< 2]	0.99
(ResiBlast) || [2 - 9]	0.98
(CommBlast) || [10 - 24]	0.97
(IndBlast) || [25 - 59]	0.96
(InfraBlast) || [60 - 119]	0.95
(CtldBlast) || [120 - 449]	0.90
(MineBlast) || [450 - 499]	0.80
(ProdBlast) || [500 - 599]	0.65
(UnCtldBlast) || [≥ 600]	0.50

CommBlast	Commercial Blasting (Engineered blasting near commercial area)
CtldBlast	Controlled Blasting (An ordinary engineered blasting for civil works)
ET	Excavation Technique; it is listed in the table inside the parentheses – ()
IndBlast	Industrial Blasting (Engineered blasting near industrial area)
InfraBlast	Infrastructures Blasting (Engineered blasting for demolishing the infrastructures)
ManDigg	Manual Digging (Small scale excavation without use of explosives or NonExBreak)
ME	Mechanised Excavation (Medium-large scale excavation without use of explosives or NonExBreak)
MineBlast	Mining Blasting (Controlled blasting with underground/surface mining standards)
NonExBreak	Non-Explosive Breaking (Ground fragmentation using expansive materials)
PPV	Peak Particle Velocity in mm/sec; it is listed in the table inside the brackets – []
ProdBlast	Production Blasting (Controlled blasting for rock production in large scale)
ResiBlast	Residential Blasting (Engineered blasting near residential area)
UnCtldBlast	Un-Controlled Blasting (Non-engineered blasting)
||	Or

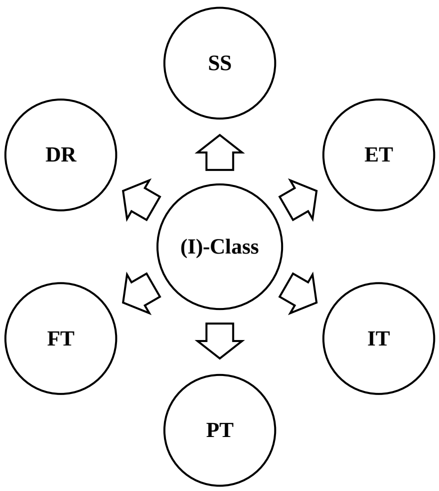
Categorization provided in Table 9 for ET and PPV is based on the research and experience of author (Bineshian, 2019) in application of engineered blasting and fragmentation techniques in different strata for different projects. It is empirical and safely applicable for any type structures in ground. It is for the first time that impact of excavation technique is comprehensively considered in a classification and characterisation system. The I-System considers it as an impact factor influencing the total value of (I).

If PPV is going to be used as criterion for scoring the ET_i, then it is recommended it to be measured using blasting vibration measurers; otherwise, type of ET is the criterion to pick the proper score for ET_i. Use of ET or PPV in Table 9 for picking the right value for ET_i, is the choice of the designer/engineer/geologist; it can be used as per availability.

4. (I)-Class

The I-System's Classification is called in short form "(I)-Class". Figure 7 is an illustration for output of (I)-Class, which represents 6 outputs as follows:

- Support System/s (SS)
- Excavation Technique/s (ET)
- Instrumentation/monitoring Technique/s (IT)
- Prevention Technique/s (PT)
- Forecast Technique/s (FT)
- Design Remark/s (DR) to help in structural dimensioning and verification (SD and SV in Figure 2).



I-System		Recommended Measure/s					
Range	**(I)-Class**	**SS**	**ET**	**IT**	**PT**	**FT**	**DR**
100-91	(I)-01						
90-81	(I)-02						
80-71	(I)-03						
70-61	(I)-04						
60-51	(I)-05						
50-41	(I)-06						
40-31	(I)-07						
30-21	(I)-08						
20-11	(I)-09						
10-0	(I)-10						

Figure 7. I-System's Classification output; (I)-Class

The I-System ranges from 100 to 0 (Figure 4). (I)-Class classifies the ground into 10 classes as per the value of (I) from (I)-01 as the best to (I)-10 as the worst ground (Figure 7). Each class has 10 percent share out of 100. Recommendations for SS, ET, IT, PT, FT, and DR are provided for each class in Tables 10 and 11 for underground, semi-surface, and surface structures. (I)-Class also provides recommendations for special classes for particular types of ground behaviour/hazards (GB and GH in Figure 2) as (I)-BP, (I)-TD, and (I)-VP in Table 12 and 13. Definition for BP, TD, and VP is recalled here;

BP Burst Prone - Ground Condition with Rock Burst or Coal Burst Behaviour

TD Time Dependent - Ground Condition with Time Dependent Shearing Behaviour such as Squeezing/Swelling/Heaving Behaviour, or even Creep

VP Visco-elasto-Plastic - Ground condition as visco-elasto-plastic to fully plastic behaviour that contains elastic and viscous component/s, which causes strain rate dependence on time; however, due to losing energy during static/dynamic loading cycle, its behaviour converts to fully plastic and may flows like a viscous substance.

Nomenclature for all abbreviations used in this section is provided in Appendix C.

Table 10. I-System Classes for Underground Structures: SS, ET, and IT

(I)		Recommended Measures		
%	**Class**	**SS**	**ET**	**IT**
100-91	**(I)-01**	Scng	FF-ME/DnB, $PL4200^-$	Nil
90 - 81	**(I)-02**	Scng, IndiB25	FF-ME/DnB, $PL4000^-$	Nil
80 - 71	**(I)-03**	Scng, SpotB25	FF-ME/DnB, $PL3800^-$	Nil
70 - 61	**(I)-04**	Scng, SpotB25, PatchPS50	FF-ME/DnB, $PL3600^-$	3DMS@400m
60 - 51	**(I)-05**	Scng, SpotB32/SysHB25.LS, PS50, PSFS50, RDH54.L	FF-ME/DnB, $PL3300^-$	3DMS@200m
50 - 41	**(I)-06**	Scng, SysB32.L.S/SysHB32.L.S, FRS100, FRFS50, RDH54.L	HnB/(FF if ≤ 45 m^2)-ME/DnB, $PL3000^-$	3DMS@100m, StrainM@300m
40 - 31	**(I)-07**	Scng, CPS32.L.S/FP32.250.L.X1, SysB32.L.S/SysHB32.L.S, LG25.20.150.1000-, FRS200, FRFS150, RDH54.L	HnB/(FF if ≤ 35 m^2)-ME/NonExBreak/DnB, $PL2000^-$	3DMS@75m, StrainM@250m, PressC/LoadC@300m
30 - 21	**(I)-08**	FP32.200.L.X1/FP76.250.L.X1/PR100.300.L.X1, SysLB32.L.S, LG32.25.180.1000-/RigidR150UC23.1000-, FRS225/FRC225, FaceButt.L, FRFS200, RDH54.L+CF	PSE-ME/NonExBreak, $PL1000^-$	3DMS@50m, StrainM@200m, PressC/LoadC@250m, SingleRodE@400m
20 - 11	**(I)-09**	PR100.250.L.X1/FP76.200.L.X1/FP32.200.L.X2, FaceB25.L.S/FaceP300-, FaceButt.L, PreG/I, RigidR150UC23.750-+RingC, SysN32.L.S, FRS225/FRC225, FRFS200, RDH54.L+CF	PSD-ME, $PL750^-$	3DMS@25m, StrainM@150m, PressC/LoadC@200m, MultiRodE@400m, StrainG@500m
10 - 0	**(I)-10**	PR100.200.L.X1/FP76.200.L.X2, PreG/I, PostG/I, FaceB32.L.S/FaceP300-, FaceButt.L, RigidR200UC46.500-+RingC, SysN32.L.S, FRS250/FRC250, FRFS225, (RDH54.L, WDH54.L)+CF	PSD-ME, $PL500^-$	3DMS@15m, StrainM@100m, PressC/LoadC@150m, MultiRodE@300m, StrainG@400m, DIC@25m

Table 10. Continued; I-System Classes for Underground Structures: PT, FT, and DR

(I)		Recommended Measures		
%	**Class**	**PT**	**FT**	**DR**
100-91	**(I)-01**	Avoid: UnCtldBlast	TSP/PH100.BH.L	Active load configuration, SPL and/or SFL not required
90 - 81	**(I)-02**	Avoid: UnCtldBlast	TSP/PH100.BH.L	Active load configuration, SPL and/or SFL not required
80 - 71	**(I)-03**	Avoid: UnCtldBlast	TSP/PH100.BH.L	Active load configuration, SPL and/or SFL not required
70 - 61	**(I)-04**	Avoid: ProdBlast/UnCtldBlast	TSP/PH100.BH.L	Active load configuration, SFL not required
60 - 51	**(I)-05**	Avoid: ProdBlast/UnCtldBlast	TSP/PH100.BH.L/PH54. EC.L	Load configuration to be maintained as active, SFL not required
50 - 41	**(I)-06**	Avoid: ProdBlast/UnCtldBlast	TSP/PH100.BH.L/PH54. EC.L	Load configuration to be maintained as active
40 - 31	**(I)-07**	Apply CPS, Avoid: MineBlast/ProdBlast/UnCtldBlast	TSP/PH100.BH.L/PH54. EC.L	Critical load bearing capacity
30 - 21	**(I)-08**	Apply FP/PR, Maintain Buttress, Avoid: FF & DnB	TSP/PH54.EC.L	Passive load configuration, sensitive to scale, unsupported span, & stand-up time
20 - 11	**(I)-09**	Apply PreG/I & PR/FP, Maintain Buttress, Avoid: FF, NonExBreak/DnB, & Ductile SS	TSP/PH54.EC.L	Passive load configuration, sensitive to scale, unsupported span, & stand-up time
10 - 0	**(I)-10**	Apply PreG/I & PR, Maintain Buttress, Avoid: FF, NonExBreak/DnB, & Ductile SS	TSP/PH54.EC.L	Passive load configuration, sensitive to scale, unsupported span, & stand-up time

Table 11. I-System Classes for Semi-surface and Surface Structures: SS, ET, and IT

(I)		**Recommended Measures**		
%	**Class**	**SS**	**ET**	**IT**
100-91	**(I)-01**	Scng	(PreS, DD12000^{-}), (ProdBlast, PD6000^{-})	Nil
90 - 81	**(I)-02**	Scng, IndiB25	(PreS, DD12000^{-}), (ProdBlast, PD4000^{-})	Nil
80 - 71	**(I)-03**	Scng, SpotB25	(PreS, DD9000^{-}), (ProdBlast, PD4000^{-})	Nil
70 - 61	**(I)-04**	Scng, SpotB25/SpotA25, PatchHEAM/PatchWeldM, DH54.L	(PreS, DD9000^{-}), (ProdBlast, PD3000^{-})	3DMS@200m
60 - 51	**(I)-05**	Scng, SpotB32/SpotA32, HEAM/WeldM, DH54.L	(PreS, DD6000^{-}), (ProdBlast, PD3000^{-})	3DMS@150m
50 - 41	**(I)-06**	Scng, SysA25.L.S, FRS150, DH54.L	(PreS, DD6000^{-}), (ProdBlast, PD2000^{-})	3DMS@75m, IncM@500m
40 - 31	**(I)-07**	Scng, SysA32.L.S, FRS250, PostG/I, DH54.L	ME/NonExBreak	3DMS@25m, IncM@400m
30 - 21	**(I)-08**	RWall-SolP/FRS300/FRC300, SysN32.L.S, WH54.L+CF	PSE-ME	3DMS@10m, IncM@300m
20 - 11	**(I)-09**	DWall-TanP/FRS350/FRC350, SysN32.L.S, WH54.L+CF	PSE/OC-ME	3DMS@10m, IncM@200m, DIC
10 - 0	**(I)-10**	DWall-SecP/FRS400/FRC400, SysN32.L.S, WH54.L+CF	PSE/OC-ME	3DMS@10m, IncM@150m, DIC

Table 11. Continued; I-System Classes for Semi-surface and Surface Structures: PT, FT, and DR

(I)		Recommended Measures		
%	**Class**	**PT**	**FT**	**DR**
100-91	**(I)-01**	Avoid: UnCtldBlast	VPH54.L	Permanent stable condition, SPL and/or SFL not required
90 - 81	**(I)-02**	Avoid: UnCtldBlast	VPH54.L	Check against plain failure criteria, SPL and/or SFL not required
80 - 71	**(I)-03**	Avoid: UnCtldBlast	VPH54.L	Check against plain/wedge failure criteria, SPL and/or SFL not required
70 - 61	**(I)-04**	Avoid: ProdBlast/UnCtldBlast	VPH54.L	Check against plain/wedge failure & rock fall criteria, SPL and/or SFL not required
60 - 51	**(I)-05**	Protect Crest with FRS to Prevent Increment in Pore Water Pressure, Avoid: ProdBlast/UnCtldBlast, & Bulk Removal of Toe	ERT/VPH54.L	Check against plain/wedge/toppling failure & rock fall criteria, SFL not required
50 - 41	**(I)-06**	Cover Slope Crest with WPM & FRS at a Width Equal to Height to Help Prevention of Tension Crack Generation, Avoid: ProdBlast/UnCtldBlast, Surcharge at Crest, & Toe Lightening	ERT/VPH54.L	Check against plain/wedge/toppling failure & rock fall criteria
40 - 31	**(I)-07**	Cover Slope Crest with WPM & FRS at a Width Equal to Height to Help Prevention of Tension Crack Generation, Avoid: ProdBlast/UnCtldBlast, Sharp/Tall Slope, Short Berm, Surcharge at Crest, & Toe Lightening	ERT/SRT/VPH54.L	Check against plain/wedge/toppling failure & rock fall criteria
30 - 21	**(I)-08**	Cover Slope Crest with WPM & FRS at a Width Equal to Height to Help Prevention of Tension Crack Generation, Avoid: NonExBreak/DnB, Sharp/Tall Slope, Short Berm, & Surcharge at Crest	MASW/SRT/ERT/VPH54.L	Check against circular failure criteria
20 - 11	**(I)-09**	Avoid: NonExBreak/DnB, Unretained Wall/s, & Surcharge at Crest	MASW/SRT/VPH54.L	Check against circular failure criteria
10 - 0	**(I)-10**	Avoid: NonExBreak/DnB, Unretained Wall/s, & Surcharge at Crest	MASW/SRT/VPH54.L	Check against circular failure criteria

Table 12. I-System Special Classes for Underground Structures

(I)	Recommended Measures					
Class	**SS**	**ET**	**IT**	**PT**	**FT**	**DR**
(I)-BP	Scng, SysDB25.L.S/ConeB25.L.S/YieldB25.L.S, FRS150, HEAM/CableL+WeldM, FRFS50	HnB-ME/DnB, PL2700^{-}	3DMS@25m, StrainM@100m, PressC/LoadC@300m, MultiRodE@600m	Avoid: ProdBlast/UnCtld Blast, Rigid SS, & Naked Faces	TSP/PH100.BH.L	Bursting initiation time and depth of plastic zone around periphery to be measured
(I)-TD	Mild-Severe SSH: YieldR1000+RingC, SRH100.L.S.X2, YieldFRS200/YieldFRC200, LSC, SysDB25.L.S || Minor SSH: RigidR200UC46.1000-+RingC, FRS200/FRC200+SRH100.L.S.X1+SysLB32.L.S	HnB-ME, PL1000^{-}	3DMS@10m, StrainM@100m, PressC/LoadC@150m, MultiRodE@300m, StrainG@400m, DIC@25m	Apply SRH, Apply SysLB for Minor SSH, Avoid: FF, DnB, Rigid SS, & SysLB for Mild-Severe SSH	TSP/PH100.BH.L	Nonuniform deformation, dawdled load relaxation, scale sensitive
(I)-VP	BulkH300+, FaceP300-, PR100.150.L.X1, PreI/JetG/PreF, PostG/I, RigidR200UC46.500-+RingC, FRS300/FRC300, FRFS275, (RDH54.L, WDH54.L, ADH54.L)+CF	PSD-ME, PL500^{-}	3DMS@10m, StrainM@100m, PressC/LoadC@150m, MultiRodE@400m, StrainG@400m, DIC@25m	Apply PreG/I & PR, Maintain Buttress, Strictly Avoid: FF, NonExBreak/DnB, Ductile SS, & Build-up of Hydrostatic Pressure/Thrust at Face	TSP/PH54.EC.L	Passive load configuration, sensitive to scale, unsupported span, & stand-up time

Table 13. I-System Special Classes for Semi-surface and Surface Structures

(I)	Recommended Measures					
Class	**SS**	**ET**	**IT**	**PT**	**FT**	**DR**
(I)-VP	JetG/PreG/I/PreF, DWall-SecP/TanP, WH54.L+CF	PSE/OC-ME	3DMS@10m, DIC	Apply PreG/I/Freezing, Strictly Avoid: NonExBreak/DnB, Unretained Wall/s, & Surcharge at Crest	MASW/VPH54.L	Liquefaction prone, vibration sensitive, high passive lateral load configuration in design of retaining structure, long term consideration in time dependent behaviour

5. (I)-GC

The I-System's Ground Characterization is named in short form as (I)-GC. It characterizes the mechanical properties of ground (rock/soil mass) and quantifies most important ground properties including Modulus of Deformation (E_g), Poisson's Ratio (ν_g), Unconfined Compressive Strength (σ_{cg}), Uniaxial Tensile Strength (σ_{tg}), Cohesion (φ_g), and Internal Friction Angle (φ_g). Figure 8 represents the output for (I)-GC.

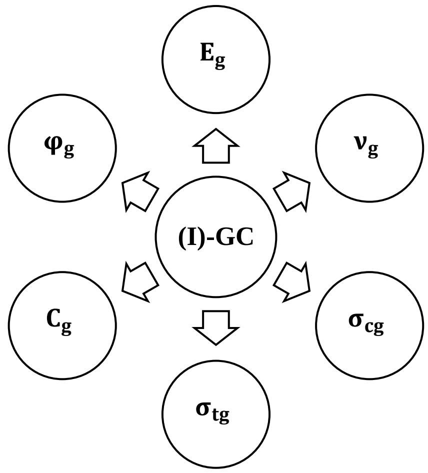


Figure 8. I-System's Ground Characterization; (I)-GC

(I)-GC provides most important design input values, which are applicable in design approach/procedure (Figures 1 and 2) for structures in ground including underground, semi-surface, and surface. The mathematical form of the (I)-GC equations is presented here using Eq. 12 to 17 and the graphical form is presented in Figures 9 – 14. These empirical equations are developed and examined in recent years by author for several practical cases.

$$E_g = e^{0.05\times(I)}\text{-}1 \tag{12}$$

$$\nu_g = 0.5 - 0.004 \times (I) \tag{13}$$

$$\sigma_{cg} = 0.007 \times \sigma_c \times e^{0.05\times(I)} \tag{14}$$

$$\sigma_{tg} = -\sigma_{cg} \times e^{(0.04\times(I)-4)} \tag{15}$$

$$C_g = 0.002 \times \sigma_{cg} \times e^{0.05\times(I)} \tag{16}$$

$$\varphi_g = 15 + 0.55 \times (I) \tag{17}$$

Where,

(I) Index of Ground – Structure or I-System's Value
E_g Modulus of Deformation of Ground – Rock/Soil Mass in GPa
ν_g Poisson's Ratio of Ground
σ_{cg} Unconfined Compressive Strength of Ground – Rock/Soil Mass in MPa
σ_{tg} Uniaxial Tensile Strength of ground – Rock/Soil Mass in MPa
C_g Cohesion of Ground in KPa
φ_g Internal Friction Angle of Ground in Degrees

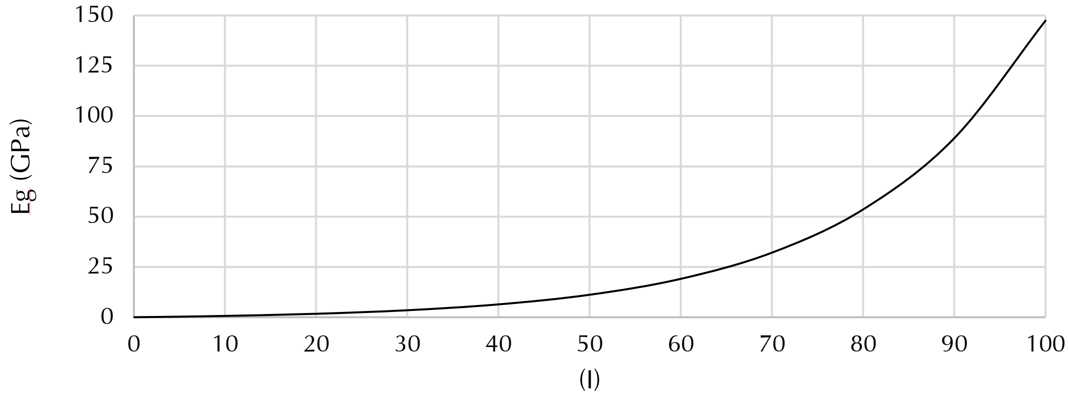


Figure 9. (I)-GC; (I) vs Modulus of Deformation

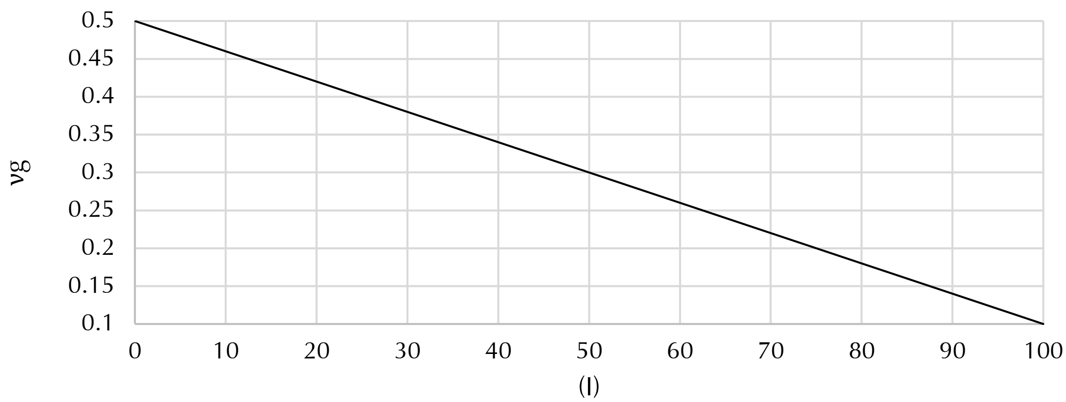


Figure 10. (I)-GC; (I) vs Poisson's Ratio

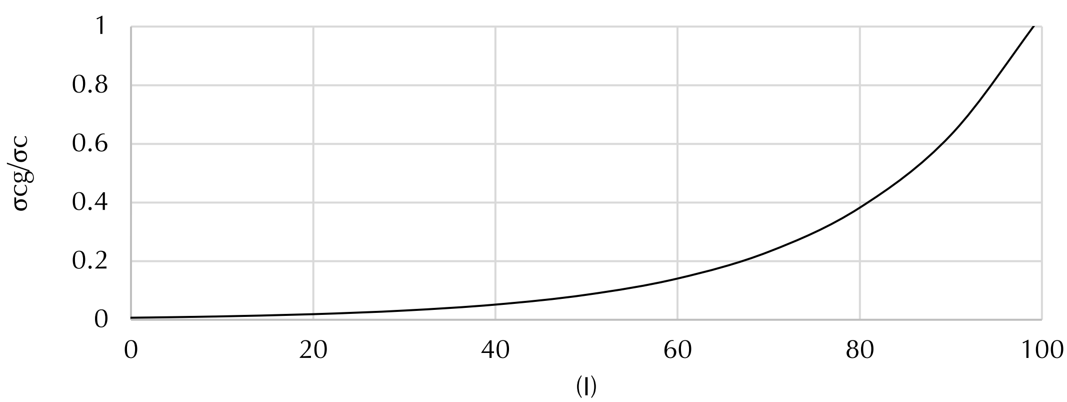


Figure 11. (I)-GC; (I) vs Unconfined Compressive Strength

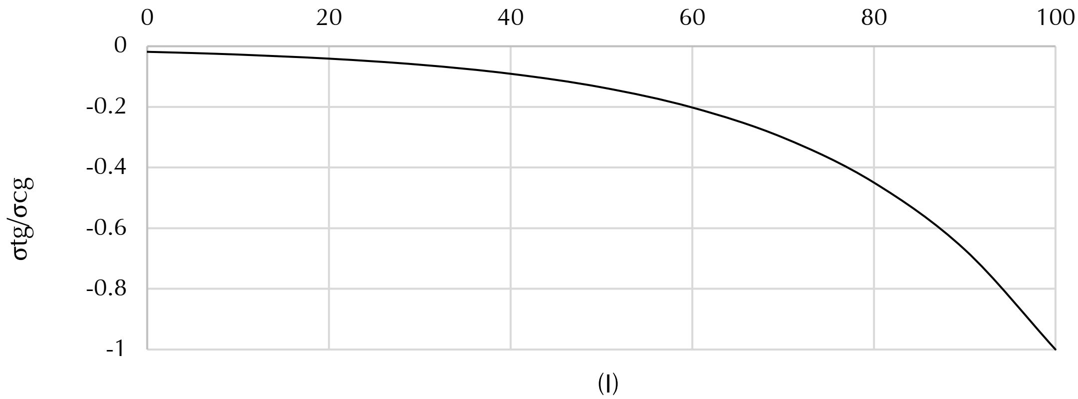


Figure 12. (I)-GC; (I) vs Uniaxial Tensile Strength

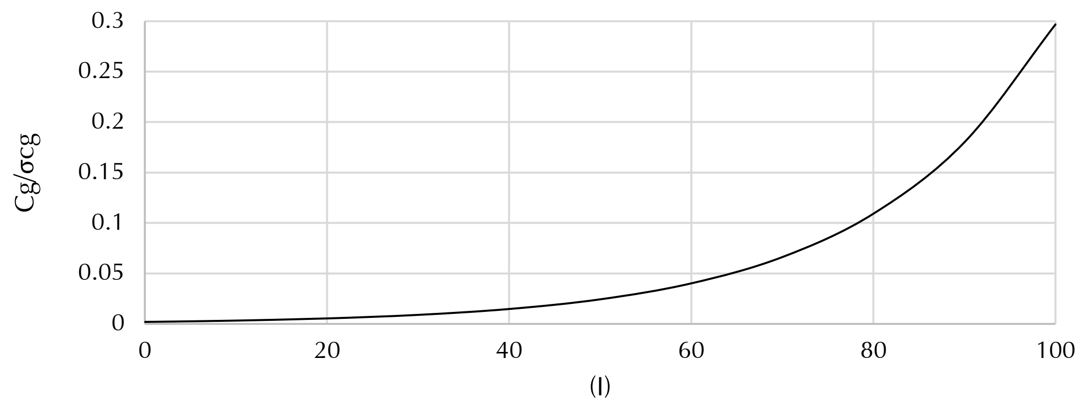


Figure 13. (I)-GC; (I) vs Cohesion

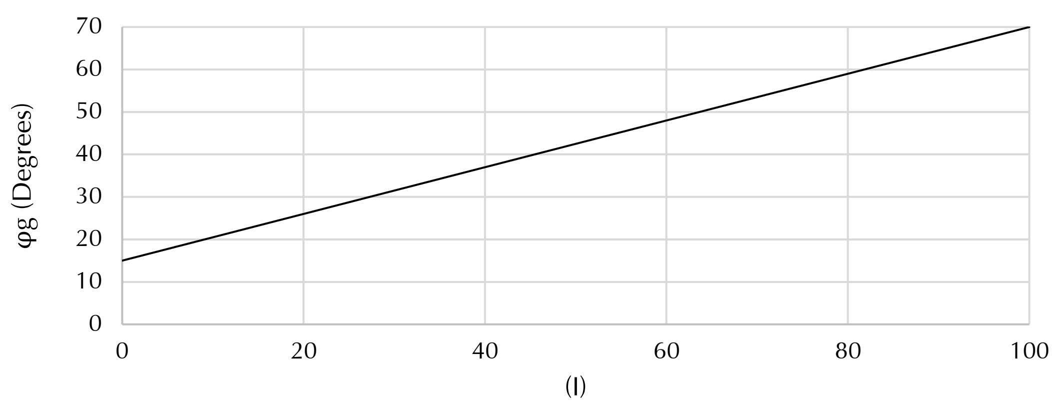


Figure 14. (I)-GC; (I) vs Internal Friction Angle

6. Utilisation Guideline

Utilisation of the I-System is an approach based on the following steps:

- Stage 1. Derivation of the Input: Derive the parameters from a site visit or available data in the references.

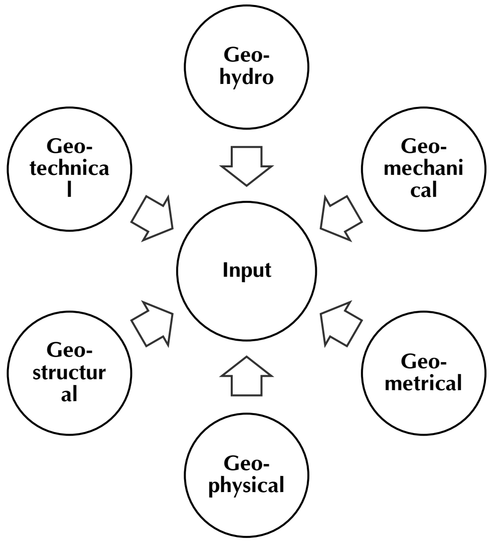


Figure 15. Input Data for the I-System

- Stage 2. Calculation of the Indices: Calculate A_i, C_i, H_i, P_i, S_i, DF_i, and ET_i using the derived data in Stage 1 and Eq. 2 – 8 and Tables 2 – 9.
- Stage 3. Calculation of the I-System: Calculate the I-System using Eq.1 and calculated indices in Stage 2.
- Stage 4. Determination of the (I)-Class: Determine the (I)-Class using the calculated I-System value in Stage 3 and Tables 10 – 13. Utilise the recommendations for SS, ET, IT, PT, FT, and DR provided in Tables 10 – 13 in practice.
- Stage 5. Calculation of the (I)-GC: Calculate the values of E_g, ν_g, σ_{cg}, σ_{tg}, C_g, and φ_g using Eq. 12 to 17 or Figures 9 – 14 and utilise them in design.

Figure 16 summarises the utilisation approach explained above in a simple diagram.

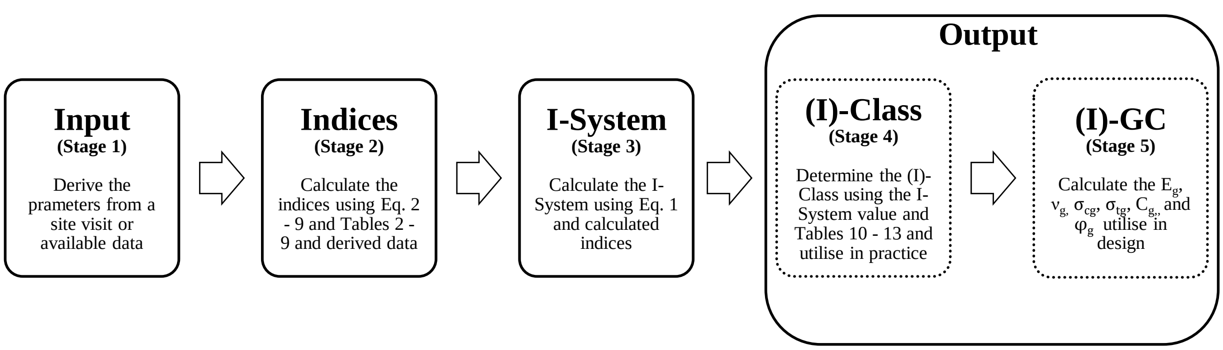


Figure 16. Utilisation diagram of the I-System

7. Conclusions

The I-System is developed to compensate demerits of existing engineering classifications including their limitations, drawbacks, impreciseness, and inaccuracy.

It is applicable for all types of geomaterials with acceptable precision and accuracy provided by simplicity and certainty in its approach for derivation of input parameters and clarity and trust in output data.

It is developed in challenging projects in varieties of ground fields and verified for perfectness. There is no limitation/s in its application for any type of surface, semi-surface, and underground structures in rock and soil.

It comes with a simple equation containing important parameters, which can be derived from doubtless input tables, references, or test results. It is based on certain essential indices, which defines mechanical behaviour of surrounding ground of structure considering impact of dynamic forces as well as excavation technique impact. The I-System contains two main parts; the (I)-Class and the (I)-GC.

The (I)-Class is the I-System's Classification, which classifies the ground to 10 classes from the best to the worst ground irrespective of being rock or soil. The (I)-Class provides 6 outputs including recommendations for required in practice as Support System, Excavation Technique/s, Instrumentation Technique/s, Prevention Technique/s, Forecast Technique/s, and Design Remark/s.

The (I)-GC is the I-System's Ground Characterisation, which provides 6 valuable outputs required in design of structures in ground. The outputs of the (I)-GC include Modulus of Deformation, Poisson's Ratio, Unconfined Compressive Strength, Uniaxial Tensile Strength, Cohesion, and Internal Friction Angle.

It practically takes into consideration most important mechanical aspects of ground for an appropriate optimised design. It has the capacity to be a credible comprehensive classification as well as characterisation system to be utilised in practice and design intelligently for all ground related structures.

8. Acknowledgement

While this research was funded by the author entirely, during 22 years of development course of the I-System, author has worked in/with several firms in projects directly/indirectly.

I thank all of them for sharing their pearls of wisdom with me during the course of this research. Their name is briefly included here but not limited to: SAB, Ziggurat, Mahab, GM, Perlite, University of Western Australia, Geodata, LnT, Amberg, KRCL, and NR.

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Appendix A: Project References

The I-System has been developed in several cases for a course of 22 years. It is scrutinised, and examined directly/indirectly in several projects in different countries as listed below and its applicability with accepted engineering accuracy and precision is verified. Following list represents the same:

- Railway projects - tunnels, slopes, and bridge abutments:
    - USBRL project comprising of
        - Tunnels T1 – T13 with over 45 km length,
        - Tunnel T41 Wider Section,
        - T12P2 Portal,
        - Kauri Road, and
        - Chenab Bridge Left Abutment.

- Metro projects - tunnels and stations:
    - Ahmedabad
    - Bangaloru
    - Chennai
    - Delhi
    - Lucknow
    - Mumbai
    - Pune
    - Tehran

- Road projects - tunnels, trenches, and slopes:
    - Diftah-Shis
    - Eqlid
    - Jammu Ring
    - Kaikoura
    - Mumbai Coastal
    - Penjween
    - Resalat Hwy
    - Tohid
    - WestConnex

- Urban projects - canal and trenches:
    - Arabian Canal in Persian Gulf

- Subordinate tunnels - small size and micro tunnels:
    - Shahmirzad
    - Shiraz
    - Torrington

- Hydropower/dam projects - slope stabilizations, dam foundation, bridge foundations, dam abutments, caverns, shafts, and tunnels:
    - Aassi
    - Balaroud
    - Broadlands
    - Galehroud
    - Kahir
    - Karuma
    - Kheirabad
    - Seidoun
    - Seimareh
    - Snowy Mountains
    - Sonateh

- Mining projects - stopes, adits, drifts, wells, shafts, and pits:
    - Kalgoorlie Super Pit
    - Kolomdar
    - Pashkalat
    - Tazareh

Appendix B: Case Histories

For clarification on the method of application of the I-System and as evidence for the comprehensiveness of applicability of the same, three cases of most recent applications of the system are provided here. The applied cases provided here includes the use of the I-System for rock mountain tunnelling by NATM in Section 5.1, soil tunnelling by NATM in Section 5.2, and surface excavations in Section 5.3. The client of the projects considered here is Northern Railway and engineer in charge is KRCL.

A.1. Underground Rock Works
Tunnel T05 is one of the most challenging NATM tunnels in USBRL Project in North India. It is a 6 km twin tube tunnel in young Himalayas terrain in dolomite rock formation, which pass through several hazardous zones. On 2019/05/11 an incident was reported at T05's main tunnel at chainage CH46598. The I-System were utilised to assess the condition of the face and to provide a solution to cross the zone. Based on Section 6 following steps were taken:

- **Input** data were simply derived from the site visit observations and from the collected available data of the client (all derived input data are presented in Table 14).
- **Indices** were calculated using Tables 2 – 9 to score the input parameters. Eq. 2 – 9 were used for the calculation of indices.
- **I-System** value was calculated using calculated indices (Table 14) and Eq. 1 (Figure 17).
- **(I)-Class** was determined using Tables 10 -13. Figure 17 provides determined (I)-Class for this case.
- **(I)-GC** calculations were done using Eq. 12 -17.
- **Output** of the I-System was derived from Tables 10 – 13, which was given as recommendation/solution to cross the challenging zone (Figure 17). Another output is the (I)-GC calculation results, which provides design input.

Table 14. Input Data: Utilisation of the I-System for T05 CH46598 in rock.

(I) = (Ai + Ci + Hi + Pi + Si) × DFi × ETi	
Ai	**2.77**
dn Discontinuity Number/s - per m	≥ 25
ds Discontinuity Set/s	3
di Discontinuity Inclination - °	31 - 60
da Discontinuity Aperture	Open
dd Discontinuity Disintegration	Semi-Integrated
df Discontinuity Friction	Low Friction - Smooth/Even
dp Discontinuity Persistency	≥ 0.90 × D
Ci	**5.25**
pc Problematical Configuration	Sheared - High Shear Stresses - e.g. Mylonite
sc Structural Configuration	Layered (100 - 10 cm)
Hi	**6.50**
gc Ground Conductivity	(7 - 9.99) || [Wet]
gs Ground Softness - Mohs	5
Pi	**6.60**
cc Cohesiveness Consistency	Picked Easily
dc Denseness Consistency	Never Indented by Thumbnail
ps Particle Size	Sand
pm Particle Morphology	Sub-angular
bw Body Wave Velocity - m/sec (Vp) || [Vs]	(3499 - 3000) || [1999 - 1500]
Si	**8.10**
cs UCS	19 - 10 MPa
se Scale Effect	D/H = 1.20 - 0.80 & $\sigma v \geq \sigma h$
DFi	**0.85**
(PGASD) || [ERZ] || {MSK}	(0.36g - 0.50g) || [VH] || {IX-X}
ETi	**0.99**
(ET) || [PPV mm/sec]	(ME/NonExBreak) || [< 2]

I-System = 25%
↓
(I)-Class = (I)-08
↓
RECOMMENDED MEASURE/S

SS - Support System
FP32.200.L.X1/FP76.250.L.X1/PR100.300.L.X1, SysLB32.L.S, LG32.25.180.1000-/RigidR150UC23.1000-, FRS225/FRC225, FaceButt.L, FRFS200, RDH54.L+CF
ET - Excavation Technique/s
PSE-ME/NonExBreak, PL1000-
IT - Instrumentation Technique/s
3DMS@50m, StrainM@200m, PressC/LoadC@250m, SingleRodE@400m
PT - Prevention Technique/s
Apply FP/PR, Maintain Buttress, Avoid: FF & DnB
FT - Forecast Technique/s
TSP/PH54.EC.L
Design Remark/s
Passive load configuration, sensitive to scale, unsupported span, & stand-up time

Figure 17. Output Data: Utilisation of the I-System for T05 CH46598 in rock

Following explanation further clarifies Figure 17 using Appendix C;

SS – Support System to be applied:

- **PR100.300.L.X1** (One row of Piperoofing with 100 mm dia, 300 mm spacing, and specified Length) or **FP76.250.L.X1** (One row of Forepoling with 76 mm dia, 250 mm spacing, and specified Length) or **FP32.200.L.X1** (One rows of Forepoling with 32 mm dia, 200 mm spacing, and specified Length),
- **SysLB32.L.S** (Systematic Long Bolting with 32 mm dia and specified Length and Spacing),
- **LG32.25.180.1000**$^{-}$ (Lattice Girder with 32 mm dia rebar at intrados and two 25 mm dia at extrados with 180 mm spacing between the intrados and extrados and spacing between the LGs below 1000 mm) or **RigidR150UC23.1000**$^{-}$ (Rigid Rib made with Universal Column as per Australian Standard of 150UC23 and spacing of below 1000 mm),
- **FRS225** (Fibre Reinforced Shotcrete with 225 mm thickness) or **FRC225** (Fibre Reinforced Concrete with 225 mm thickness),
- **FaceButt.L** (Face Buttress with specified Length),
- **FRFS200** (Fibre Reinforced Face Sealing with 200 mm thickness), and
- **RDH54.L+CF** (Radial Drainage Holes with 54 mm dia + Collar Filtration).

ET – Excavation Technique/s to be implemented:

- **PSE-ME/NonExBreak, 1000**$^{-}$ (Mechanised Excavation using Partial Sequential Excavation or Non-Explosives Breaking with Pull Length below 1000 mm).

IT – Instrumentation Technique/s to be used:

- **3DMS@50m** (3D Monitoring Station at every 50 m),
- **StrainM@200m** (Strain Meter at every 200 m),
- **PressC/LoadC@250m** (Pressure Cell or Load Cell at every 250 m), and
- **SingleRodE@400m** (Single-Rod Extensometer at every 400 m).

PT – Prevention Technique/s to be considered:

- Apply **PR/FP** (Piperoofing or Forepoling),
- Maintain **Buttress**, and
- Avoid **FF** (Full Face Excavation), **DnB** (Drill and Blast).

FT – Forecast Technique/s to be utilised:

- **TSP/PH54.EC.L** (Tunnel Seismic Prediction or Probe Hole and Exploratory Coring with 54 mm dia and specified Length)

DR – Design Remark/s to be taken into consideration:

- Passive load configuration, and
- Sensitive to scale, unsupported span, and stand-up time.

Above-mentioned recommendations from the I-System were advised for the problematic zone at T05 and tunnel was crossed the section successfully without any safety or construction issues.

Nomenclature used in Figure 17 is provided in Appendix C.

Further to the classification output, the ground was characterised using (I)-GC equations (Eq. 12 – 17) to derive the mechanical properties, which were used in design:

(I) = 25
Selected UCS range is 19 - 10 MPa.
Specified σ_c Value = 10 MPa
Modulus of Deformation E_g = 2.490 GPa
Poisson's Ratio ν_g = 0.400
Unconfined Compressive Strength σ_{cg} = 0.244 MPa
Uniaxial Tensile Strength σ_{tg} = -0.104 MPa
Cohesion C_g = 15.539 KPa
Internal Friction Angle φ_g = 32.050 °

A.2. Underground Soil Works

Tunnel T02 is another challenging NATM tunnel in USBRL Project in North India with a length of almost 5.6 km twin tube in young Himalayas terrain, which for some stretches of the length it passed through soil formation. Work were stopped due to a gravity driven failure on 2018/09/23 till 2018/11/03 at CH37488.

The I-System were utilised and condition were assessed. Same approach as discussed in the Section 5.1 were followed to calculate the I-System; in this case for soil NATM tunnelling. Table 15 and Figure 18 provides the input and output of the I-System for the case respectively. To avoid repetition of the approach, explanation on the utilisation stages are skipped here. Nomenclature used in Figure 18 is provided in Appendix C.

Table 15. Input Data: Utilisation of the I-System for T02 CH37488 in soil.

(I) = (Ai + Ci + Hi + Pi + Si) × DFi × ETi	
Ai	0.00
dn Discontinuity Number/s - per m	N/A ‖ Jointless
ds Discontinuity Set/s	N/A ‖ Jointless
di Discontinuity Inclination - °	N/A ‖ Jointless
da Discontinuity Aperture	N/A ‖ Jointless
dd Discontinuity Disintegration	N/A ‖ Jointless
df Discontinuity Friction	N/A ‖ Jointless
dp Discontinuity Persistency	N/A ‖ Jointless
Ci	4.00
pc Problematical Configuration	Homogeneous ‖ Isotropic ‖ Jointless ‖ Granular
sc Structural Configuration	Cohesive Matrix Skeleton
Hi	2.40
gc Ground Conductivity	(25 - 49) ‖ [Flow]
gs Ground Softness - Mohs	4
Pi	8.13
cc Cohesiveness Consistency	Picked Easily
dc Denseness Consistency	Never Indented by Thumbnail
ps Particle Size	Gravel
pm Particle Morphology	Angular
bw Body Wave Velocity - m/sec (Vp) ‖ [Vs]	(3999 - 3500) ‖ [2199 - 2000]
Si	7.20
cs UCS	9 - 5 MPa
se Scale Effect	D/H = 1.20 - 0.80 & $\sigma v \geq \sigma h$
DFi	0.85
(PGASD) ‖ [ERZ] ‖ {MSK}	(0.36g - 0.50g) ‖ [VH] ‖ {IX-X}
ETi	0.90
(ET) ‖ [PPV mm/sec]	(CtldBlast) ‖ [120 - 449]

I-System = 17% ⇣ **(I)-Class = (I)-09** ⇣ RECOMMENDED MEASURE/S
SS - Support System PR100.250.L.X1/FP76.200.L.X1/FP32.200.L.X2, FaceB25.L.S/FaceP300-, FaceButt.L, PreG/I, RigidR150UC23.750-+RingC, SysN32.L.S, FRS225/FRC225, FRFS200, RDH54.L+CF **ET - Excavation Technique/s** PSD-ME, PL750- **IT - Instrumentation Technique/s** 3DMS@25m, StrainM@150m, PressC/LoadC@200m, MultiRodE@400m, StrainG@500m **PT - Prevention Technique/s** Apply PreG/I & PR/FP, Maintain Buttress, Avoid: FF, NonExBreak/DnB, & Ductile SS **FT - Forecast Technique/s** TSP/PH54.EC.L **Design Remark/s** Passive load configuration, sensitive to scale, unsupported span, & stand-up time

Figure 18. Output Data: Utilisation of the I-System for T02 CH37488 in soil

Proposed remedy for T02 in the above-said problematic zone is as follows (see Figure 18):

SS – Support System to be applied:
- **PR100.250.L.X1** (One row of Piperoofing with 100 mm dia, 250 mm spacing, and specified Length) or **FP76.200.L.X1** (One row of Forepoling with 76 mm dia, 200 mm spacing, and specified Length) or **FP32.200.L.X2** (Two rows of Forepoling with 32 mm dia, 200 mm spacing, and specified Length),
- **FaceB25.L.S** (Face Bolting with 25 mm dia and specified Length and Spacing) or **FaceP300-** (Face Plug with thickness below 300 mm),
- **FaceButt.L** (Face Buttress with specified Length),
- **PreG/I** (Pre-Excavation Grouting/Injection),
- **RigidR150UC23.750$^-$** (Rigid Rib made with Universal Column as per Australian Standard of 150UC23 and spacing of below 750 mm) + **RingC** (Ring Closure),
- **SysN32.L.S** (Systematic Soil Nailing with 32 mm dia and specified Length and Spacing),
- **FRS225** (Fibre Reinforced Shotcrete with 225 mm thickness) or **FRC225** (Fibre Reinforced Concrete with 225 mm thickness),
- **FRFS200** (Fibre Reinforced Face Sealing with 200 mm thickness), and
- **RDH54.L+CF** (Radial Drainage Holes with 54 mm dia + Collar Filtration).

ET – Excavation Technique/s to be implemented:
- **PSD-ME, PL750$^-$** (Mechanised Excavation using Partial Sequential Digging with Pull Length below 750 mm)

IT – Instrumentation Technique/s to be used:
- **3DMS@25m** (3D Monitoring Station at every 25 m),
- **StrainM@150m** (Strain Meter at every 150 m),
- **PressC/LoadC@200m** (Pressure Cell or Load Cell at every 200 m),
- **MultiRodE@400m** (Multi-Rod Extensometer at every 400 m), and
- **StrainG@500m** (Strain Gauge at every 500 m).

PT – Prevention Technique/s to be considered:
- Apply **PreG/I** (Pre-Excavation Grouting/Injection) and **PR/FP** (Piperoofing or Forepoling),
- Maintain Buttress, and
- Avoid **FF** (Full Face Excavation), **NonExBreak/DnB** (Non-Explosives Breaking or Drill and Blast), and **Ductile SS** (Support System).

FT – Forecast Technique/s to be utilised:
- **TSP/PH54.EC.L** (Tunnel Seismic Prediction or Probe Hole and Exploratory Coring with 54 mm dia and specified Length).

DR – Design Remark/s to be taken into consideration:
- Passive load configuration, and
- Sensitive to scale, unsupported span, and stand-up time.

Works at T02 were restored by application of the above-mentioned recommendations using the I-System; no further instabilities occurred due to application of the abovesaid remedy during the course of crossing the challenging zone.

For design purpose the (I)-GC equations (Eq. 12 – 17) were used for characterisation of the ground to derive the mechanical properties as follows;

(I) = 17
Selected UCS range is 9 - 5 MPa.
Specified σ_c Value = 5 MPa
Modulus of Deformation E_g = 1.340 GPa
Poisson's Ratio ν_g = 0.432
Unconfined Compressive Strength σ_{cg} = 0.082 MPa
Uniaxial Tensile Strength σ_{tg} = -0.003 MPa
Cohesion C_g = 0.383 KPa
Internal Friction Angle φ_g = 24.350 °

A.3. Surface Rock and Soil Works

Portal works of Tunnel T13 (the longest tunnel in USBRL Project in North India with 9 km length in young Himalayas terrain) is considered here as a real example of application of the I-System for surface structures in rock and soil. Entire slope of the T13 portal is placed in a formation with the mix of sandstone fragments in soil matrix.

The I-System is utilised for design purpose for the slope of the outlet portal of the T13 tunnel. Same approach as explained in Section 4 is applied for the case. Proposed remedy for the slope of the T13's portal is as follows (see Table 16 and Figure 19):

SS – Support System to be applied:
- **Scng (**Scaling),
- **SysA25.L.S** (Systematic Anchoring with 25 mm dia and specified Length and Spacing),
- FRS150 (Fibre Reinforced Shotcrete with 150 mm thickness), and
- **DH54.L** (Drainage Holes with 54 mm dia and specified Length).

ET – Excavation Technique/s to be implemented:
- **(PreS, DD6000⁻)** Presplitting with Drilling Depth of below 6000 mm, and
- **(ProdBlast, PD2000⁻)** Production Blasting with Pull Depth below 2000 mm.

IT – Instrumentation Technique/s to be used:
- **3DMS@75m** (3D Monitoring Station at every 75 m), and
- **IncM@500m** (Inclinometer at every 500 m).

PT – Prevention Technique/s to be considered:
- Cover Slope Crest with **WPM** (Waterproofing Membrane) and **FRS** (Fibre Reinforced Shotcrete) at a with equal to height to help prevention of tension crack generation, and
- Avoid **ProdBlast/UnCtldBlast** (Production Blasting or Un-controlled Blasting), application of Surcharge at Crest, and Toe Lightening.

FT – Forecast Technique/s to be utilised:
- **ERT/VPH54.L** (Electric Resistivity Tomography or Vertical Probe Holes with 54 mm dia and specified Length).

DR – Design Remark/s to be taken into consideration:
- Check against plain/wedge/toppling failure and rock fall criteria.

Above-mentioned recommendations for the slope of the T13's portal using the I-System is under application at the time of write up of the paper.

Table 16 and Figure 19 represents the input and output details of the I-System calculation procedure respectively.

Table 16. Input Data: Utilisation of the I-System for T13 Portal in Rock and soil.

(I) = (Ai + Ci + Hi + Pi + Si) × DFi × ETi	
Ai	5.48
dn Discontinuity Number/s - per m	15 - 19
ds Discontinuity Set/s	3
di Discontinuity Inclination - °	11 - 30
da Discontinuity Aperture	Semi-Tight
dd Discontinuity Disintegration	Weathered/Altered
df Discontinuity Friction	Moderate Friction - Nonsmooth
dp Discontinuity Persistency	≥ 0.90 × D
Ci	9.00
pc Problematical Configuration	Fractured - Highly
sc Structural Configuration	Layered (100 - 10 cm)
Hi	12.00
gc Ground Conductivity	(≤ 0.99) || [Dry]
gs Ground Softness - Mohs	6
Pi	16.00
cc Cohesiveness Consistency	Indurated
dc Denseness Consistency	Never Indented by Thumbnail
ps Particle Size	N/A (e.g. Grainless)
pm Particle Morphology	N/A (e.g. Grainless)
bw Body Wave Velocity - m/sec (Vp) || [Vs]	(4999 - 4500) || [2899 - 2600]
Si	12.60
cs UCS	74 - 50 MPa
se Scale Effect	B/H = 1.20 - 0.80
DFi	0.85
(PGASD) || [ERZ] || {MSK}	(0.36g - 0.50g) || [VH] || {IX-X}
ETi	0.99
(ET) || [PPV mm/sec]	(ME/NonExBreak) || [< 2]

I-System = 46%
⇣
(I)-Class = (I)-06
⇣
RECOMMENDED MEASURE/S

SS - Support System
Scng, SysA25.L.S, FRS150, DH54.L
ET - Excavation Technique/s
(PreS, DD6000-), (ProdBlast, PD2000-)
IT - Instrumentation Technique/s
3DMS@75m, IncM@500m
PT - Prevention Technique/s
Cover Slope Crest with WPM & FRS at a Width Equal to Height to Help Prevention of Tension Crack Generation, Avoid: ProdBlast/UnCtldBlast, Surcharge at Crest, & Toe Lightening
FT - Forecast Technique/s
ERT/VPH54.L
Design Remark/s
Check against plain/wedge/toppling failure & rock fall criteria

Figure 19. Output Data: Utilisation of the I-System for T13 Portal in Rock and soil

The (I)-GC equations (Eq. 12 – 17) were used for characterisation of the ground for design purpose;

(I) = 46
Selected UCS range is 74 - 50 MPa.
Specified σ_c Value = 50 MPa
Modulus of Deformation E_g = 8.974 GPa
Poisson's Ratio ν_g = 0.316
Unconfined Compressive Strength σ_{cg} = 3.491 MPa
Uniaxial Tensile Strength σ_{tg} = -0.403 MPa
Cohesion C_g = 69.639 KPa
Internal Friction Angle φ_g = 40.300 °

Appendix C: Nomenclature

(I)	Index of Ground – Structure or I-System
(I)-Class	I-System's Class
(I)-GC	I-System's Ground Characterization
3DM	3D Monitoring - Using Bi-Reflex Target Markers
3DMS	3D Monitoring Station
ADH	Axial Drainage Hole/s - NX Size Drainage Hole/s (with/without casing) with the Orientation Parallel to the Axis of Underground Opening and Perpendicular to Face with L $\leq$ 3/2D and Spacing Determined based on Ground Water Condition
B	Width of Berm of a Slope/Trench
BH	Blind Hole - Triangular Patterned Probing Parallel to Axis of Underground Space Using Blind Hole/s with L = 2D and 100+ mm Dia
BP	Burst Prone - Ground Condition with Rock Burst or Coal Burst Behaviour
BulkH	Bulk Head - Shotcrete/Concrete Plug at Whole Section of Excavation at Face to Prevent the Ground to Flow
CableL	Cable Lacing - Applicable for Controlling Rock Burst in Deep Underground Spaces
CF	Collar Filtration - Filtration of Drainage Holes' Outlet to Stop Debris/Fines Discharge
C_g	Cohesion of ground in MPa
ConeB	Cone Bolts - Oriented/Radial Cone Bolts with L = 1/2D
CPS	Crown Periphery Spiling - SN Umbrella at 5-30 deg with L = 2/3D
D	Width or Horizontal Span of Underground Opening
DD	Drilling Depth
DH	Drainage Hole/s - Upward Angled NX Size Hole/s (with/without casing) with L = 3/2H and Spacing Determined based on Ground Water Condition
DIC	Digital Image Correlation
DnB	Drill and Blast - Controlled/Smooth
DR	Design Remark/s
DWall	Diaphragm Wall
EC	Exploratory Coring - Single Hole Coring Parallel to Axis of Underground Space Using NX Size Hole/s with L = 3D
E_g	Modulus of Deformation of ground - Rock Mass or Soil Mass's Deformation Modulus in GPa
ElFootR	Elephant Foot Rib - Applicable in Case of High Vertical/Passive/Dead Load above Crown of Tunnel as a Very Stiff/Rigid Support System
ERT	Electrical Resistivity Tomography - A non-destructive geophysical method for characterization of ground
ET	Excavation Technique/s
FaceB	Face Bolting - Fibreglass/SDA Bolts Parallel to Axis and Perpendicular to Face with L = 1D
FaceButt	Face Buttress - Keeping Part of Face in Place with a Nose Length Equal to L = 1/4D (Only if D $\geq$ 6 m) as a Buttress to Absorb Face Pressure and Thrust as Part of Face Stabilization
FaceP	Face Plug - Application of 300 mm Shotcrete at Face to Plug the Outlet of the Debris Discharge
FibreD	Fibreglass Dowel/s
FF	Full Face Excavation
FP	Fore Poling - Umbrella using Perforated/Blind SDA with L = 1D
FRC	Fibre Reinforced Concrete

Freezing	Solidification Technique for Underground and Surface Openings Prior Excavation
FRFS	Fibre Reinforced Face Sealing
FRS	Fibre Reinforced Shotcrete
FT	Forecast Technique/s
GD	Gravity Driven - Flowing Ground Class with Fully Plastic Behaviour
H	Height of a Slope/Trench/Opening/Buttress
HEAM	High Energy Absorption Mesh - Protective Mesh against Dynamic Loads or Mesh Over Shotcrete
HnB	Top Heading and Benching
IncM	Inclinometer/s
IndiB	Individual Bolting - Oriented and in Very Limited Number
IT	Instrumentation Technique/s
JetG	Jet Grouting -Application in Underground or Surface Metro Station Construction
L	Length of ADH, ConeB, CPS, DH, FaceB, FaceButt, FP, BH, EC, PR, RDH, SRH, SysA, SysB, SysDB, SysHB, SysLB, SysN, VPH, WDH, WH, and YieldB
LG	Lattice Girder
LoadC	Load Cell/s
LSC	Longitudinal Stress Controller - Rubber/Spring
MASW	Multichannel Analysis of Surface Waves - A non-destructive geophysical method for characterization of ground
ME	Mechanised Excavation - TBM/Roadheader/Excavator/Hammer
MicroP	Micro Piles - Applicable for Elephant Rigid Ribs to Distribute the Concentrated Load to a Wider Footing Area
MultiRodE	Multiple Rod Extensometer - Measuring Points @ 2, 4, and 6 m Recommended
NX	Hole with 54.7 mm diameter
OC	Open Cut
PatchHEAM	Patch High Energy Absorption Mesh (Protective Mesh against Dynamic Loads)
PatchPS	Patch Plain Shotcrete
PatchWeldM	Patch Weld Mesh - Applicable as Protective Mesh in Surface/Underground Openings to Prevent Spot Rock Falls
PCC	Plain Cement Concrete
PD	Pull Depth
PH	Probe Hole - Probing Using Blind Hole Drilling with 100+ mm Dia or Exploratory Coring Using NX Size Hole/s
PL	Pull Length - Advance Length
PostG/I	Post-excavation Grouting/Injection - Consolidation/Solidification
PPV	Peak Particle Velocity
PR	Pipe Roofing - With/Without Grouting/Injection using Perforated/Blind Pipe with L = 1D
PreF	Pre-Excavation Freezing of Face or Excavation Line/Periphery
PreG/I	Pre-excavation Grouting/Injection - Cement/Mineral/Chemical-base
PreS	Pre-excavation Splitting
PressC	Pressure Cell/s
ProbH	Probe Hole/s - Blind hole/s or Coring to Predict Ground Ahead of Current Face in Underground Openings

PS	Plain Shotcrete
PSD	Partial-Sequential Digging - Small Scale Partial Digging in Several Sequences e.g. Small Pilots, Considering Stand-up Time and Maximum Unsupported Span
PSE	Partial-Sequential Excavation - Small Scale Partial Excavation larger than Digging Scale in Several Sequences e.g. Pilot and Enlargement, Considering Stand-up Time and Maximum Unsupported Span
PSFS	Plane Shotcrete Face Sealing - Application of 50 mm Plain Shotcrete at Face for Hazards and Disintegration Prevention
PT	Prevention Technique/s
RCC	Reinforced Cement Concrete (Conventional)
RDH	Radial Drainage Hole/s - NX Size Radial/Axial Holes (with/without casing) with L $\leq$ 1D and Spacing Determined based on Ground Water Condition
RigidR	Rigid Ribs - H Section Heavy Beams
RingC	Ring Closure
RWall	Retaining Wall including Cladding Wall and any other types
S	Spacing related to ConeB, CPS, FaceB, SRH, SysA, SysB, SysDB, SysHB, SysLB, SysN, or YieldB; S = 1/3L
Scng	Scaling - Removal of Loose Fragments/Blocks
SDA	Self-Drilling Anchor
SecP	Secant Piling
SFL	Structural Final Liner
SingleRodE	Single Rod Extensometer - Measuring Point @ 3 m Recommended
SolP	Soldier Piling
SPL	Structural Primary Liner
SpotA	Spot Anchoring
SpotB	Spot Bolting - Oriented with Limited Number
SRH	Stress Release Holes - Long Radial Necked Holes at Minimum 100 mm Dia with L = 1D (Invented and developed by the author in 2015 at USBRL Project; Client: Northern Railway, Engineer in Charge: Konkan Railway Corporation Limited)
SRT	Seismic Refraction Tomography - A non-destructive geophysical method for characterization of ground
SS	Support System
SSH	Squeezing/Swelling/Heaving
StrainG	Strain Gauge/s
StrainM	Strain Meter
SurS	Surface Structure - It includes Surface and Semi-surface Structure/s and/or Mine/s in general comprising of but not limited to Bridge and Dam Abutments, Cut and Covers, Deep and Shallow Foundations, Embankment and Tailing Dams, Open Cuts, Open Pits, Shallow Metro Stations (Cut and Cover or Open Cut), Slopes, Surface Power House Openings, and Trenches
SysA	Systematic Anchoring - Perpendicular Anchors to the Face of Slope with L = 1/2H
SysB	Systematic Bolting - Radial Direction with L = 1/2D
SysDB	Systematic Dynamic Bolts - Oriented/Radial Dynamic Bolts with L = 1/2D
SysHB	Systematic Horn Bolting - Only above SPL at 30 - 45 deg with L = 2/3D
SysLB	Systematic Long Bolting - Radial Long Rock Bolts with L = 2/3D
SysN	Systematic Nailing - Radial Bolts/Anchors with L = 1D = 1H

TanP	Tangent Piling
TD	Time Dependent - Ground Condition with Time Dependent Shearing Behaviour such as Squeezing/Swelling/Heaving Behaviour, or even Creep
TSP	Tunnel Seismic Prediction
UC	Universal Column as per Australian Standard (i.e. 150UC23 and 200UC46)
UndS	Underground Structure/s - It includes Underground Shallow and Deep Structures/Openings/Mines comprising of but not limited to Caverns, Deep Metro Stations, Galleries, Mine Stopes, Shafts, Tunnels, Underground Power Houses, Stations, and Storages, and Wells
VP	Visco-elasto-Plastic - Ground condition as visco-elasto-plastic to fully plastic behaviour that contains elastic component/s together with viscous component/s, which gives the ground strain rate dependence on time; however, due to losing energy during static/dynamic loading cycle, its behaviour converts to fully plastic and may flows like a viscous substance
VPH	Vertical Probe Hole - Blind/Coring Exploration Using Vertical NX Size Hole/s Drilling with L = 1/2H
WeldM	Weld Mesh - Conventional Weld Mesh used in Reinforcement of Shotcrete or as Mesh Over Shotcrete in Rock Burst Condition
WDH	Wing Drainage Holes - NX Size Wing Shape with Umbrella Patterned Holes (with/without casing) at 30 - 45 deg applicable in Underground Openings to Drain the Water from sides and ahead of Face to Reduce the Pore Hydrostatic Pressure with $L \leq 2D$ and Spacing Determined based on Ground Water Condition
WH	Weep Holes - Upward Angled NX Size Weeps (with/without casing) with L = 1H and Spacing Determined based on Ground Water Condition
WPM	Waterproofing Membrane - An Elastic/Flexible Impermeable Geotextile or Fibre Reinforced Geomembrane or Composite to be used for Sealing
X1	One Row
X2	Two Rows
YieldB	Yielding Bolts - Oriented/Radial Yield Bolts with L = 1/2D
YieldFRC	Yield Fibre Reinforced Concrete - Cast Fibre Reinforced Concrete with Embedded LSC
YieldFRS	Yield Fibre Reinforced Shotcrete - Cast Fibre Reinforced Shotcrete with Embedded LSC
YieldR	Yield Ribs - Sliding Ribs using T-H Profile or any Profile Capable of Sliding Function
ν_g	Poisson's Ratio of ground
ρ	Unit Mass of Ground
σ_c	Unconfined Compressive Strength of intact rock or soil - Intact UCS in MPa
σ_{cg}	Unconfined Compressive Strength of ground - Rock Mass or Soil Mass in MPa
σ_h	Horizontal Stresses at the location or at the depth of the placement of the structure
σ_{tg}	Uniaxial Tensile Strength of ground - Rock Mass or Soil Mass in MPa
σ_v	Vertical Stresses at the location or at the depth of the placement of the structure
φ_g	Internal Friction Angle of ground in degrees