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I-System: Index of Ground-Structure

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Abstract

An optimised geotechnical/geomechanical design approach includes empirical, analytical, seismic, and observational stages. Empirical and observational parts of a design are vital in initiation of the approach and in finalisation of judgements for practice and design purposes containing the derivation of ground behaviour, identification of ground hazards, determination of support systems, and characterisation of ground's mechanical properties. Engineering classifications are main part of empirical and observational stages of the design for human made structures in ground; though, they have limitations in application. I-System is a classification as well as a characterisation system for ground that is developed to cross the limitations involved with other classifications. It is comprehensively applicable for civil, mining, and oil & gas structures in ground including but not limited to abutments of bridges and dams, caverns, deep and shallow foundations, embankment and tailing dams, galleries, deep and shallow metro stations, mine stopes, open pits, shafts, slopes, trenches, tunnels, underground spaces and 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 and construction. It is first published in 2019 based on 22 years' research and verification in design and construction of underground, semi-surface, and surface works in rock and soil; however, since then further developments as well as improvements and clarifications are made. This paper provides the latest edition of I-System (as a full package) and an introduction to I-System Software.

Keywords: (I), (I)-Class, (I)-GC, blast-induced damage, characterisation, classification, Damage Indicator, GCD, GC_{ef}, Ground Conductivity Enhanced Factor, hydraulic conductivity, I-System, Index of Ground-Structure, intact rock, rock mass, soil, SRH, support system, vibration-induced damage, ViD

1. Introduction

Design approach for structures in ground includes 4 important stages as shown in Figure 1 (Bineshian et al, 2019). 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. Both parts are quite depended on ground's engineering classification and characterisation.

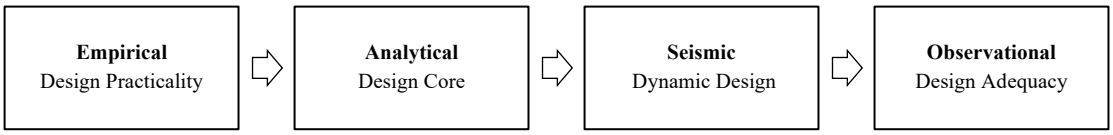
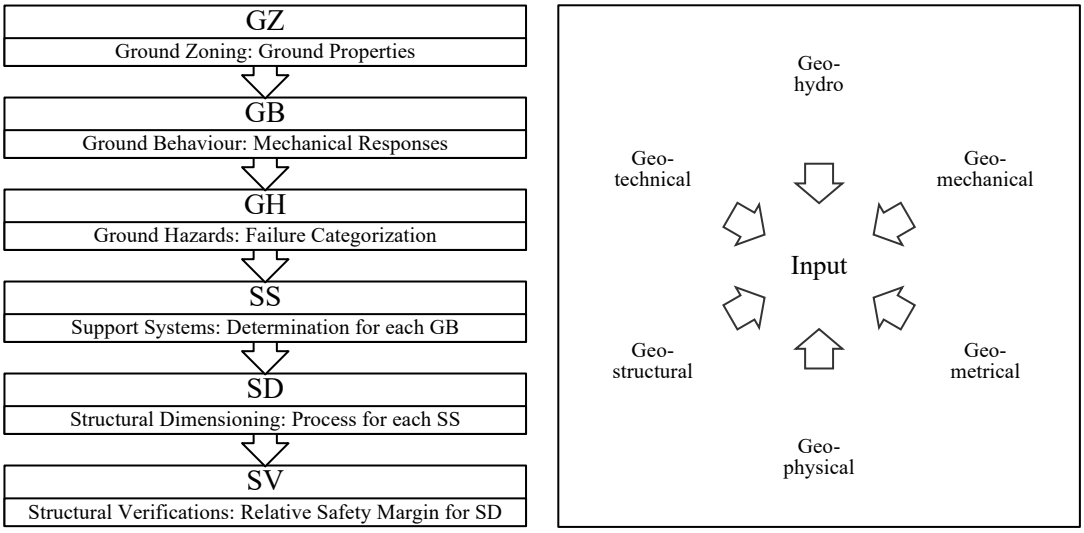


Figure 1. Design approach for structures in ground

Design procedure is presented in Figure 2 based on the design approach explained above. Figure 2a demonstrates a well-defined design procedure and Figure 2b shows the data requirements in a design setting. As a brief definition, Ground Zoning (GZ) is based on ground inherent properties that divides entire length of a tunnel to a group of limited numbers of zones or stretches with similar properties. It eases the identification of ground behaviour and related hazard/s, determination of required support system,

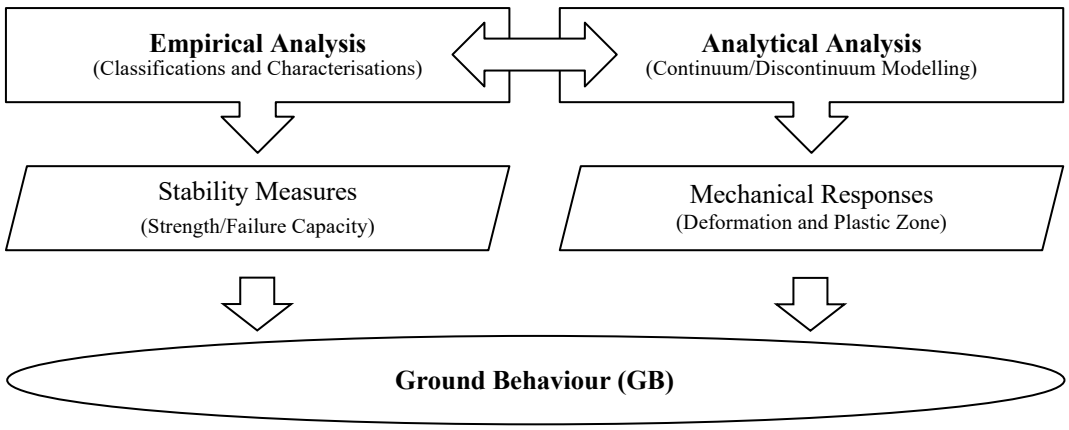
procedure of structural dimensioning, and finally verification of the required measures for each zone. GZ is the first stage in design procedure, which is conducted after completion of initial geotechnical/geomechanical investigation in initial phase of study. Empirical classification systems are the important element in identification of GZs.



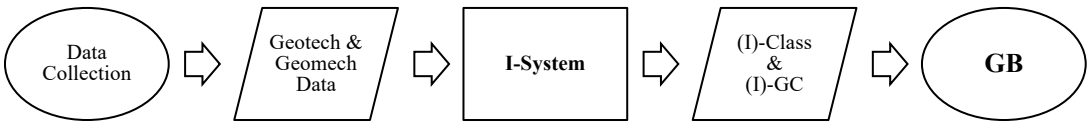
a. Design procedure diagram b. Design setting's data requirements

Figure 2. Design procedure for structures in ground

Second and third stages in a healthy design procedure are identification of the Ground Behaviour (GB) and associated Ground Hazard/s (GH) respectively. Russo and Grasso (2007) proposed an approach to identify excavation behaviour based on continuum equivalent and equilibrium models; however, in this paper, it is produced for continuum and discontinuum media by combined analytical and empirical modelling as principal concept in identification of GB (Figure 3a). As can be seen in Figure 3a, classification systems are used in empirical analysis for identification of GB. Figure 3b represents the same by a fully empirical approach using I-System (Figure 3b) as a classification and characterisation system (Bineshian, 2019a, 2019b).



a. Analytical/empirical stress analysis approach in identification of GB



b. I-System approach in determination of GB (Bineshian, 2019a, 2019b)

Figure 3. Flowcharts representing two ways to identify the GB; stress analysis and I-System

Figure 4 represents most expected Ground Hazards (GH) from the identified GB that should be considered within the design procedure (Figure 2a).

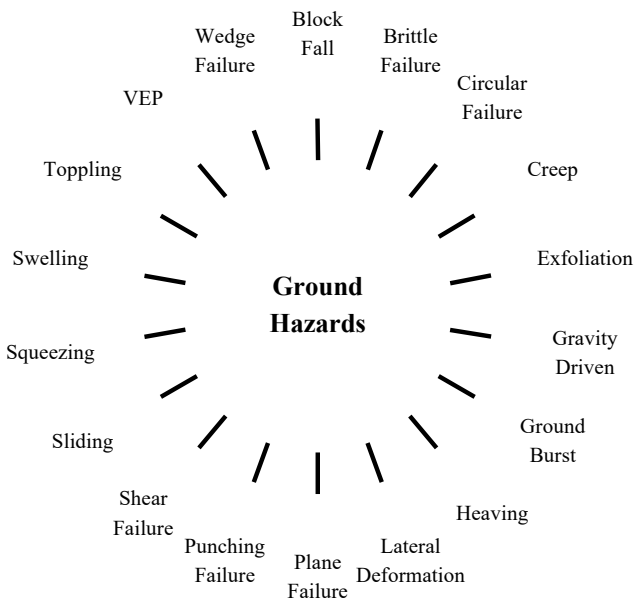


Figure 4. Ground Hazards (GH) expected from the identified GB

In the fourth stage of a design procedure (Figure 2a), Support System/s (SS) should be selected from choices of solutions required for each GZ and related GB and GH. Again, the need for a comprehensive and suitable classification system is recognised to be vital to find the best solution/s for each mechanical response and associated hazard/s.

Further to selection of suitable solution/s as SS for each GH, the measures (either primary or final SS) should be dimensioned (calculation part of design approach; fifth stage in Figure 2a) and verified (defining the relative safety margins; last stage of design approach in Figure 2a). Probabilistic Convergence-Confinement method (e.g., Carranza-Torres, 2004) can be used for Structural Dimensioning (SD). In Structural Verification (SV), Limit State Design (LSD) that known as Load and Resistance Factor Design (LRFD) method is used (McCormac, 2008). LSD itself has two procedures in design verification; Ultimate Limit State (ULS) and Serviceability Limit State (SLS). ULS includes checking against generated bending moment, axial forces, and shear forces (EN 1990:2002 E). On the other hand, SLS checks the generated crack width in the structure (e.g., crack width < 0.30 mm as per IS 456:2000). Figure 5 illustrates the SV procedure as the last stage in a design procedure (Figure 2a) required for plain or reinforced concrete structure (for primary or final SS).

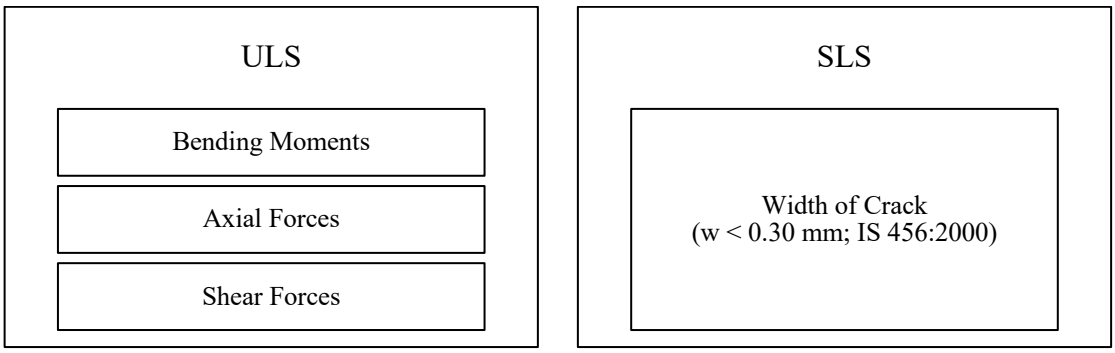


Figure 5. Structural Verification (SV) check

As per design procedure and requirement explained here, it is proved that engineering classifications are the main part of the empirical and observational design elements in a healthy design approach and design procedure shown in Figures 1 and 2 (Bineshian, 2012, Bineshian and Ghazvinian, 2012a and 2012b). Comprehensiveness and practicality of the engineering classifications are essential to make them appropriately applicable in NATM, NMT, SEM, SCL, etc.; however, 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. 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. Palmstrom and Broch (2006) stated that there is a shortcoming in most existing classifications when observed rock mass characteristics are used to estimate the conditions for design without including input of the excavation method. An excavation damage factor or similar should be applied, but none of the existing empirical or other tools in rock engineering makes use of this (Palmstrom and Broch, 2006).

I-System is developed to be used as a comprehensive classification and characterisation system for ground (Bineshian, 2019b). It is verified against varieties of ground and scrutinised in several projects through 22 years research to address and resolve the aforesaid issues involved with existing classifications (Table 1). I-System provides 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) as well as estimation for important mechanical properties of ground. Its output is optimised by analytical, numerical, and observational methods to compensate the demerits of existing classifications and strengthen its comprehensiveness.

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

Applications / **System**	**Media**		**Structure (Civil, Mining, Oil and Gas)**	
	Rock	Soil	Surface	Underground
RMR (Bieniawski, 1973)	a	n/a	c/a	a
Q (Barton et al, 1974)	a	n/a	n/a	a
I-System (Bineshian, 2019b)	a	a	a	a

a Applicable
c/a Conditionally Applicable
n/a Not Applicable

This paper is a 2021 edition of I-System in a full package, which is further developed by providing vibration-induced damage (ViD) assessment methods, pull length advisor, and systematic bolting calculator. It provides further illustrations, details, clarifications, and updates to I-System as well as introducing I-System Software as a design utility that eases the use of I-System while expected accuracy is obtained in calculation.

2. I-System: Definition

Providing a solution to engineers in their challenges with complicated ground conditions is the key perception and approach in development of this all-in-one classification and characterisation system for ground in accord with real condition to deliver design parameters and practical recommendation/s. Also, it has been in mind to provide a trusted utility for empirical part of design. In development of this system, drawbacks and limitations of other classifications (e.g., RMR and Q) are properly addressed and consequently resolved (Bineshian, 2019a, 2019b). This comprehensive classification and characterisation system for ground (rock and soil) entitled "Index of Ground-Structure" or in short form "I-System". It is conceptually different from any existing classifications due to its applicability for varieties of ground conditions and structures and its comprehensiveness in providing accurate and precise prediction of ground behaviour based on several geomechanical hazards (failure mechanisms) studied in course of development. Its range of application (Figure 6) in design and/or practice includes underground structures (caverns, deep or underground metro stations, exploration and grouting galleries, mine stopes, shafts, tunnels of any type or method, underground spaces, underground storages, wells, etc.), semi-surface structures (bridge abutments, dam abutments, deep foundations, shallow metro stations including open-cut and cut & cover, etc.), and surface structures (embankment dams, open pits, shallow foundations, slopes, tailing dams, trenches, etc.).

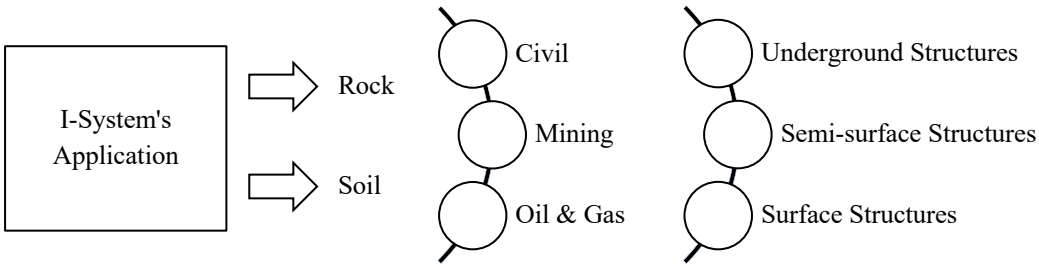
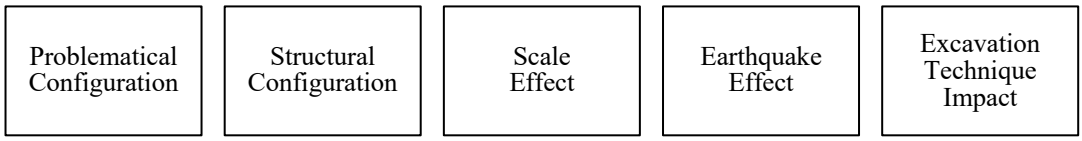


Figure 6. Range of application of I-System

It is the first ever classification, which is applicable for both rock and soil that considers ground's problematical and structural configurations, opening's scale effect, earthquake's negative effect, and excavation technique's impact (Figure 7a). Besides, it is the first ever classification that carefully provides prediction for special ground behaviour including but not limited to Squeezing, Swelling, and Heaving (SSH), Time Dependent (TD), Visco-elasto Plastic (VP), fully plastic, gravity driven (GD), and Burst Prone (BP) condition (Figure 7b).



a. First ever features covered by a classification system

b. Special ground behaviour covered by I-System

Figure 7. Most important features covered by I-System

I-System is verified in a wide varieties of challenging ground conditions to ensure that a suitable estimation is obtained in classification and characterisation. It provides recommendations on determination of primary and final SS, required ET for encountered condition, proper IT for monitoring, appropriate PT against possible failures, verified FT to predict the ground condition ahead, and practical DR that is helpful in understanding of ground behaviour, failure mechanism, and load configuration (Section 4). Moreover, it characterises the ground by deriving the mechanical properties (Section 5) that can be used as input for SD in design procedure.

It is intended that I-System to have key indices to enable an appropriate modelling of ground-structure behaviour to the full (Figure 8). It includes five indices to define the mechanical response of ground in relation to the structure. Furthermore, it has two impact factors to define the impact of Dynamic Forces (DF_i) and Excavation Technique (ET_i) on structure. Indices and impact factors in I-System (Figure 8) are based on easily derivable main properties (i.e., key geomechanical, geostructural, geohydrological, geotechnical, geophysical, and geometrical features; Figure 2b) and determinant seismic and excavation factors that affecting the ground-structure response (Figure 7a).

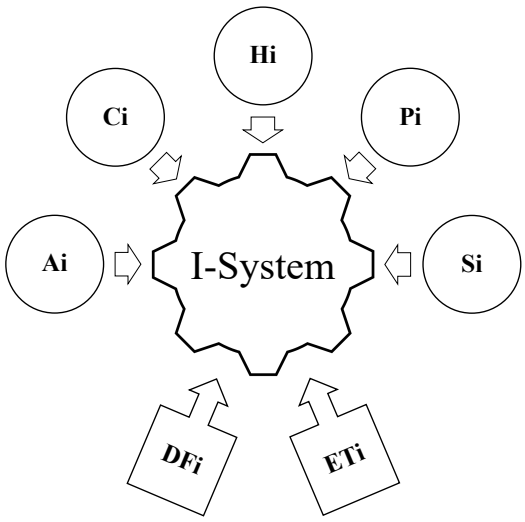


Figure 8. I-System calculation; indices and impact factors

Eq 1 represents I-System in a mathematical form entitled "(I)". Eq 2 to 8 defines the indices and the impact factors for (I) as follows:

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

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

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

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

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

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

$$DF_i = f(PGA_{SD}, ERZ, MSK) \;\&\; PGA_{SD} = f(PGA, SF, MSF) \quad (7)$$

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

where;

(I)	I-System's value
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

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 (Figure 9). Indices are defined in the Section 3. Full definition of the parameters is available in Section 10.

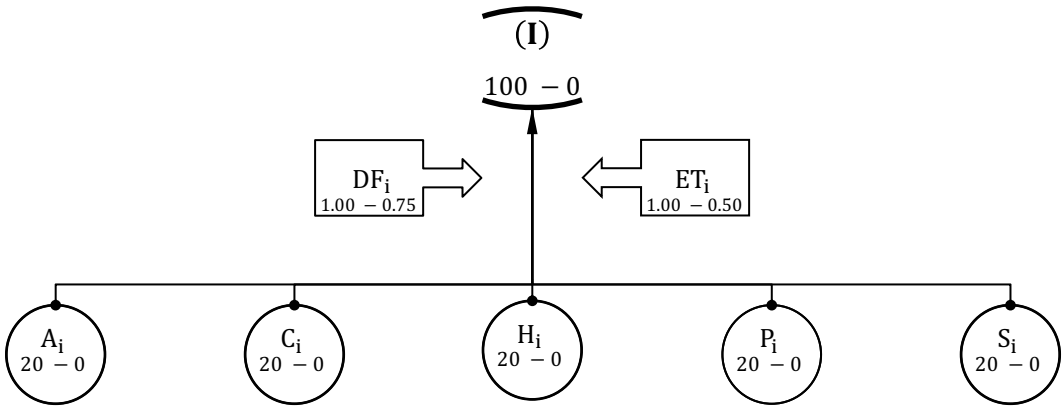


Figure 9. I-System's scoring diagram

I-System is applicable for estimation of quality of ground in relation to the structure at any scale and type. It assists with empirical and observational parts of the design approach (Figure 1). I-System is applicable in design procedure and/or in practice (Figures 2 and 3) for:

- categorizing the ground properties in relation to Ground Zoning (GZ),
- discovering Ground Behaviour (GB),
- identifying associated failure mechanism/s (Figure 4) as Ground Hazard/s (GH),
- determining the required Support System/s (SS); Section 4, and
- assisting in Structural Dimensioning and Verification (SD and SV) by characterizing the most important mechanical properties of ground (Section 5).

It is also applicable to (Tables 9 - 12 in Section 4):

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

I-System is developed to serve the above-stated purposes for underground, semi-surface, and surface structures in the field of civil, mining, and oil and gas.

3. Indices and Impact Factors

I-System (Eq 1) includes 5 indices and 2 impact factors (Figures 8 and 9) with mathematical form of Eq 2 to 8. In this section all associated parameters of each index are defined in details. Derivation of parameters from ground and their use in I-System is confusion-free; consequently, selection of the input data is certain, which makes the classification's output accurate and credible. Section 10 provides a complete list of definitions for abbreviations, parameters, and short forms used in this paper.

3.1. Armature Index

A_i is the Armature Index (Eq 1 and 2) as ground's skeleton armature, which is intended to model the most important geomechanical aspects of rock mass as a ground medium through the discontinuity properties of ground. A_i has 20 score out of 100 (Figure 9). Table 2 defines parameters of A_i.

Table 2. Armature Index (A_i): a_{dn}, a_{ds}, a_{di}, a_{da}, a_{dd}, a_{df}, a_{dp}

Discontinuity Number/s	a_{dn}	**Discontinuity Set/s**	a_{ds}	**Discontinuity Inclination**	a_{di}
0 - 9	10.00	0	10.00	[IF ($a_{dn} \geq 2.50$ & $a_{ds} \geq 4.00$) THEN↓ ELSE 0]	
10 - 14	7.50	1	9.00	n/a or Granular	0.00
15 - 19	5.00	2	7.00	0 - 10	-1.00
20 - 24	2.50	3	4.00	11 - 30	-1.50
≥ 25	0.00	≥ 4	0.00	31 - 60	-2.00
n/a or Granular	0.00	n/a or Granular	0.00	61 - 90	-2.50

Discontinuity Aperture	a_{da}	**Discontinuity Disintegration**	a_{dd}	**Discontinuity Friction**	a_{df}	**Discontinuity Persistency**	a_{dp}
n/a or Granular	1.00	n/a or Granular	1.00	n/a or Granular	1.00	n/a or Granular	1.00
Tight	1.00	Unweathered/Unaltered	1.00	High Friction - Rough/Uneven	1.00	$< 0.90 \times D^*$	1.00
Semi-Tight	0.95	Semi-Integrated	0.95	Moderate Friction - Nonsmooth	0.95	$\geq 0.90 \times D^*$	0.90
Open	0.90	Weathered/Altered	0.90	Low Friction - Smooth/Even	0.90		

*	For semi-surface and surface structure, "D" should be replaced with "B", which is the Berm's width in a slope or in a trench
a_{da}	Factor related to "Discontinuity Aperture" that is based on the most unfavourable opening of the discontinuities
a_{dd}	Factor related to "Discontinuity Disintegration" that is based on the worst weathering or alteration of surface of the discontinuity sets
a_{df}	Factor related to "Discontinuity Friction" that is based on the least friction condition of discontinuity sets
a_{di}	Score related to "Discontinuity Inclination" that is based on dip angle of the most unfavourable discontinuity set
a_{dn}	Score related to "Discontinuity Number/s" that is based on number of individual discontinuities per meter of a horizontal or vertical scanline or average of number of discontinuities per meter of horizontal and vertical scanline
a_{dp}	Factor related to "Discontinuity Persistency" that is based on the most unfavourable discontinuity set
a_{ds}	Score related to "Discontinuity Set/s" reflecting the number of sets of discontinuities
D	Diameter, width, or height (mm) of underground opening (the greater value)
Granular	A definition describing the soil; a medium, which is not considered as discontinuum
n/a	Not Applicable

It should be noted that, if "a_{dn}" and "a_{ds}" are zero, the score for "a_{di}" to be assigned as zero; it happens when the number of discontinuities is ≥ 25 and number of discontinuity sets is ≥ 4. It means that the inclination for the most unfavourable or critical discontinuity set is not easily derivable. In this case, the medium tends to be homogeneous and isotropic due to generated uniform texture – by presence of high number of discontinuities as well as discontinuity sets – that is subject to mechanical response related to continuum mechanics' principles.

Moreover, if the medium is soil mass, "n/a or Granular" to be selected for each parameter from Table 2; otherwise, for rock (intact or mass) the suitable parameter other than "n/a or Granular" to be selected.

3.2. Configuration Index

C_i is the Configuration Index (Eq 1 and 3) as ground's problematical and structural configuration that contains important problematical geostructural features of rock and/or soil. C_i has 20 score out of 100 (Figure 9). Table 3 defines parameters of C_i.

Table 3. Configuration Index (C_i): c_{pc}, c_{sc}

Problematical Configuration of Ground	c_{pc}
Homogeneous or Isotropic or Jointless or 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 - e.g., Rock Burst, Coal Burst	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
Structural Configuration of Ground	c_{sc}
Continuum Massive Rock**	20.00
Layered Rock (> 100 cm)	17.00
Layered Rock (100 - 10 cm)	15.00
Clastic Breccia/Conglomerate	13.00
Layered Rock (< 10 cm)	11.00
Foliated/Laminar/Platy Rock	9.00
Coarse Grained Skeleton Soil	7.00
Cohesive Matrix Skeleton Soil	4.00
Single Grained Skeleton Soil - Dense Texture	2.00
Single Grained Skeleton Soil - Loose Texture	0.00

* "Homogeneous or Isotropic or Jointless or Granular" represents a ground condition that it is homogenous and/or isotropic, which is jointless like intact rock or granular like soil mass. Abstractly, this option to be selected when the ground is intact rock or soil mass.

** "Continuum Massive Rock" represents a ground, which is massive medium rather than layered one; e.g., intact rock or unlayered and structurally interlocked rock mass.

c_{pc} Impacting factor related to "Problematical Configuration" of ground indicating ground's tectonic state

c_{sc} Score of "Structural Configuration" of ground (an effect of ground's texture, fabric, and structure)

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 makes ground strain rate time dependence; however, due to losing energy during static/dynamic loading cycle, its behaviour converts to fully plastic and may flows like a viscous substance.

In selection of right description for "Problematical Configuration" in Table 3, if the medium is jointless like intact rock or if it is granular like soil mass, "Homogeneous or Isotropic or Jointless or Granular" to be picked. Furthermore, to select "Structural Configuration" correctly, if ground contains unlayered and structurally interlocked rock mass rather than layered one or it contains intact rock, "Continuum Massive Rock" to be picked.

3.3. Hydro Index

H_i is the Hydro Index (Eq 1 and 4) as hydro effect on ground's mechanical behaviour and its hydro related properties. It is a function of GCD (Ground Conductivity Designation; Appendix 1, Bineshian, 2020a) or Wetness diagram (Figure 10) and softness due to presence of water (in scale of Mohs). H_i has 20 score out of 100 (Figure 9). Table 4 defines parameters of H_i.

Table 4. Hydro Index (H_i): h_{gc}, h_{gs}

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

GCD Ground Conductivity Designation (Bineshian, 2020a; Appendix 1) as a criterion to score the hydraulic conductivity of ground; it is listed in the table inside parentheses – ( ); it is not mandatory to use GCD value to derive correct value for gc from Table 4; instead, Wetness diagram (Figure 10) can be considered for the same in conjunction with Table 4.

h_{gc} Score assigned to "Ground Conductivity" that is measured using GCD or selected from Wetness diagram as criterion for hydropressure effect on ground

h_{gs} Impact factor related to "Ground Softness" that is considered as an effect of water on medium or infilling material (Mohs)

Wetness A diagram defined here to categorise the ground's water content, which is classifying the ground water condition (observational identification) in 11 ranges (Figure 10); it is listed in the table inside brackets – [ ]

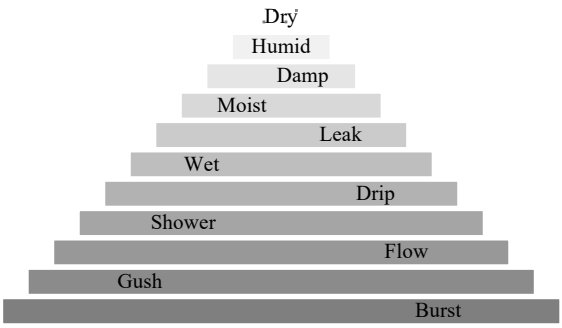


Figure 10. Wetness diagram

GCD provides a quantitative measure for "Ground Conductivity". If GCD test is not used then observational ground water condition to be considered as a criterion for scoring the "h_{gc}" using the Wetness diagram (Figure 10) in conjunction with Table 4. GCD is listed in Table 4 inside the parenthesis "( )".

Wetness diagram provides a qualitative description for "Ground Conductivity" based on observational identification for ground's hydraulic conductivity. It classifies the ground wetness into 11 ranges from dry to water burst. Wetness diagram is listed in Table 4 inside the brackets "[ ]". It is the choice of designer, engineer, or geologist to use GCD or Wetness diagram as per site condition.

3.4. Properties Index

P_i is the Properties Index (Eq 1 and 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 considered to be an important part of I-System to model essential geotechnical characteristics of ground as part of the comprehensiveness of the system in applicability for varieties of ground, which in this index, it is the soil medium. P_i has 20 score out of 100 (Figure 9). Table 5 defines parameters of P_i.

Table 5. Property Index (P_i): p_{cc}, p_{dc}, p_{ps}, p_{pm}, p_{bw}

Cohesiveness Consistency	p_{cc}	**Denseness Consistency**	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

Particles' Size	p_{ps}	**Particles' Morphology**	p_{pm}	**Body Wave Velocity** m/sec (Vp) or [Vs]	p_{bw}
n/a e.g., Rock	3.00	n/a e.g., Rock	2.00	(≥ 6000) or [≥ 3300]	1.00
Boulder	3.00	Angular	2.00	(5999 - 5000) or [3299 - 2900]	0.90
Cobble	2.50	Sub-angular	1.50	(4999 - 4500) or [2899 - 2600]	0.80
Pebble	2.00	Flat	0.75	(4499 - 4000) or [2599 - 2200]	0.70
Gravel	1.50	Rounded	0.00	(3999 - 3500) or [2199 - 2000]	0.65
Sand	1.00			(3499 - 3000) or [1999 - 1500]	0.60
Silt	0.50			(2999 - 2500) or [1499 - 1000]	0.55
Clay	0.00			(2499 - 2000) or [999 - 750]	0.50
				(1999 - 1000) or [749 - 300]	0.45
				(≤ 999) or [≤ 299]	0.40

n/a Not Applicable; it should be chosen when the ground is rock including intact rock or rock mass
p_{bw} Factor related to "Body Wave Velocity" including Vp or Vs as geophysical properties of ground that corrects P_i; Body Wave Velocity is derived either from reliable references (considering the type of materials of ground) or is measured using geophysical methods
p_{cc} Score related to "Cohesiveness Consistency" that is an important shear property of soil (cohesion)
p_{dc} Score related to "Denseness Consistency" that is an important shear property of soil (non-cohesiveness; friction)
p_{pm} Influencing parameter related to "Particles' Morphology" that is a function of shape of soil's grains/granules
p_{ps} Influencing parameter related to "Particles' Size" that is a function of size of soil's grains/granules"
Rock Intact rock or rock mass
Vp Primary Wave Velocity (m/sec); it is listed in the table inside parentheses – ( )
Vs Shear or Secondary Wave Velocity (m/sec); it is listed in the table inside brackets – [ ]

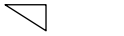
As it is stated in the footnote of Table 5, "Body Wave Velocity" can be derived from reliable references or it can be measured using geophysical surveying method/s. It is recommended to use the geophysical technique/s to derive Vp and/or Vs; however, it is not compulsory to measure "Body Wave Velocity" by conducting geophysical surveys when conduction of measurement is not feasible or practicable. Besides, it should be noted that either Vp or Vs can be used in selection of proper value for "P_{bw}" in Table 5.

Furthermore, to clarify the term "Rock" in Table 5, it should be selected if the ground is intact rock or rock mass, but if the medium contains conglomerate or breccia with poor matrix that stone pieces are easily detached from the matrix, options other than "n/a" and "Rock" to be chosen.

3.5. Strength Index

S_i is the Strength Index (Eq 1 and 6) representing ground's strength behaviour under confining condition. Due to importance of this index in I-System, key parameters of both ground and structure are considered to define this index. 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 or depth of placement of structure is considered. S_i has 20 score out of 100 (Figure 9). Table 6 defines parameters of S_i.

Table 6. Strength Index (S_i): s_{cs}, s_{se}

Compressive Strength (UCS)	**s_{cs}**	**Scale Effect**	**Shape**	**s_{se}**	
≥ 200 MPa	20.00	UndS - B/H		$\sigma_v \geq \sigma_h$	$\sigma_v < \sigma_h$
199 - 150 MPa	19.00	≥ 2.50		0.80	1.00
149 - 100 MPa	18.00				
99 - 75 MPa	16.00	= 1.90 - 1.30		0.85	0.95
74 - 50 MPa	14.00				
49 - 30 MPa	12.00	= 1.20 - 0.80		0.90	0.90
29 - 20 MPa	10.00				
19 - 10 MPa	9.00	= 0.70 - 0.50		0.95	0.85
9 - 5 MPa	8.00				
4.90 - 2 MPa	7.00	≤ 0.40		1.00	0.80
1.90 - 1 MPa	6.00				
999 - 400 KPa	5.00	SurS - B/H		**s_{se}**	
399 - 200 KPa	4.00	≥ 2.50		1.00	
199 - 100 KPa	3.00				
99 - 50 KPa	2.00	= 1.90 - 1.30		0.95	
49 - 30 KPa	1.00				
≤ 29 KPa	0.00	= 1.20 - 0.80		0.90	
		= 0.70 - 0.50		0.85	
		≤ 0.40		0.80	

B/H	Underground, semi-surface, or surface structures' shape or scale factor as ratio of horizontal span to height of underground opening or ratio of width of berm to height of slope or trench
s_{cs}	Score related to "Compressive Strength" as Unconfined Compressive Strength (UCS) of ground
s_{se}	"Scale Effect" factor
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 6 a wide range of strength from below 29 KPa to over 200 MPa is considered to cover varieties of very weak soil to very strong rock. Higher range of strength is given in MPa while ranges below 1 MPa is given in KPa that makes the strength values more expressive.

Derivation of "s_{se}" for underground structure from Table 6 requires two steps:

1. Select matching shape or "Scale Effect" range based on B/H.
2. Pick the proper "s_{se}" from either $\sigma_v \geq \sigma_h$ column or $\sigma_v < \sigma_h$ column.

Derivation of "s_{se}" for surface or semi-surface structure from Table 6 is as follows:

1. Select the proper range for "Scale Effect" based on B/H.
2. Pick the proper "s_{se}" from the associated column.

3.6. Dynamic Forces Impact

DF_i is the Dynamic Forces Impact (Eq 1 and 7) on the ground-structure behaviour that represents effect of earthquake. Table 7 defines values of DF_i as a function of Scaled Design Peak Ground Acceleration (PGA_{SD}), Earthquake Risk Zone (ERZ), or Medvedev-Sponheuer-Karnik (MSK) Scale (Medvedev and Sponheuer, 1969). If PGA_{SD} is selected to be used for derivation of DF_i, it should be scaled by designer (Eq 9) that may require the ground motion time history data to produce the time-acceleration curve; consequently, scaling factor (SF) to be calculated using the PGA derived from the curve and the desired PGA; accordingly, the time-acceleration plot is scaled. This is a simple procedure that designers who performs dynamic response spectrum analysis are familiar with. Magnitude Scaling Factor (MSF) is another way for scaling the desired PGA; Eq 10 (Idriss, 1999) is an example that is derived for cohesionless soils; however, similar relationships (Idriss and Boulanger, 2008, 2010, Boulanger and Idriss, 2014) for cohesionless soils or any other reliable MSF relationships for cohesive soils may be used for derivation of MSF. When PGA_{SD} is produced, Table 7 to be used to pick the associated value of DF_i; otherwise, if use of ERZ or MSK is preferred, subsequently the earthquake zoning map for project area from reliable references to be used for determination of ERZ or MSK and then related DF_i to be picked from Table 7. ERZ is categorised in 7 classes of damage risk zones as shown in Table 7; 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 ranges between 1.00 to 0.75 (Figure 9).

$$SF = PGA_{SD} \div PGA \;\&\; PGA_{SD} = SF \times PGA \tag{9}$$

$$MSF = 6.9 \times e^{\left(\frac{-M}{4}\right)} - 0.058 \leq 1.8 \;\&\; PGA_{SD} = MSF \times PGA \tag{10}$$

where;

M	Moment Magnitude of Earthquake
MSF	Magnitude Scaling Factor
PGA	Peak Ground Acceleration (g); maximum ground acceleration during earthquake
PGA_{SD}	Scaled Design Peak Ground Acceleration (g); scaled desired PGA
SF	Scaling Factor

Table 7. Dynamic Forces Impact (DF_i)

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

DF_i	Dynamic Forces Impact
ERZ	Earthquake Risk Zone classifies seismicity to 7 grades 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 brackets – [ ]
g	g-force or peak ground acceleration due to earth's gravity (m/sec^2); 1g = 9.81 m/sec^2
MSK	Medvedev-Sponheuer-Karnik Scale (Medvedev and Sponheuer, 1969) classifies seismicity to 12 grades as I to XII; it is listed in the table inside braces – { }
PGA_{SD}	Scaled Design Peak Ground Acceleration; it is listed in the table inside parentheses – ( )

PGA_{SD}, ERZ, or MSK are the choices of designer, engineer, or geologist; their values are listed in Table 7 inside parentheses, brackets, and braces respectively.

3.7. Excavation Technique Impact

ET_i is the Excavation Technique Impact (Eq 1 and 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 ranges between 1.00 to 0.50 (Figure 9). Table 8 defines values of ET_i.

Table 8. Excavation Technique Impact (ET_i)

(ET) or **[PPV** mm/sec**]**	**ETi**
(ManDigg)	1.00
(ME/NonExBreak) or [< 2]	0.99
(ResiBlast) or [2 - 9]	0.98
(CommBlast) or [10 - 24]	0.97
(IndBlast) or [25 - 59]	0.96
(InfraBlast) or [60 - 119]	0.95
(CtldBlast) or [120 - 449]	0.90
(MineBlast) or [450 - 499]	0.80
(ProdBlast) or [500 - 599]	0.65
(UnCtldBlast) or [≥ 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 parentheses – ( )
ET_i	Excavation Technique Impact
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 (mm/sec) at the distance of 20 m from blast; listed in the table inside 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)

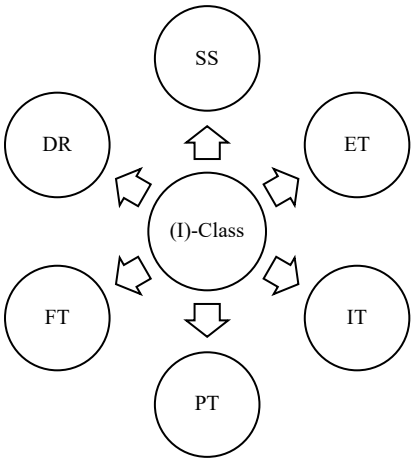
Categorization provided in Table 8 for ET and PPV is based on the research and experience of author (Bineshian, 2019a, 2019b) in design and application of engineered blasting and fragmentation techniques in various strata and several projects; however, AS 2187.2 – 1993 is taken into consideration for PPV limits for engineered blasting near important structure/s. This is for the first time that impact of excavation technique is comprehensively considered in a classification and characterisation system. I-System considers it as an impact factor influencing the total value of (I). If PPV is used as criterion for scoring the ET_i; therefore, it is recommended to measure it using seismographs; however, it can be estimated using empirical relation proposed by United States Bureau of Mines (Duvall and Fogelson, 1962), which is known as USBM PPV Predictor for estimation of blast-induced ground vibration (Appendix 2); otherwise, type of ET is the criterion to pick the proper score for ET_i from Table 8. Vibration-induced Damage (Bineshian, 2021a, 2021b; Appendix 2) assessment is necessary when blasting is used for excavation. Use of ET or PPV in Table 8 for picking the right value for ET_i, is the choice of the designer, engineer, or geologist; it can be used as per availability and condition.

In Table 8, for better differentiation, ET values are listed inside parentheses while PPV values are listed inside brackets.

4. (I)-Class

I-System's Classification entitled "(I)-Class" includes a hexad output, which is illustrated in Figure 11a. Figure 11b is a representation of table of recommendations of (I)-Class that listed below in full form:

- 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 2a).



a. (I)-Class output

(I)		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						

b. (I)-Class's table of recommendations

Figure 11. I-System's Classification output; (I)-Class

(I) ranges from 100 to 0 (Figures 9 and 11b). (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 11b). 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 9 and 10 for underground, semi-surface, and surface structures. Additionally, (I)-Class provides recommendations for special classes (Special (I)-Class) for particular types of ground behaviour/hazards (GB and GH in Figures 2a, 3, and 4) as (I)-BP, (I)-TD, and (I)-VP in Tables 11 and 12. 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, and heaving condition, 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 or dynamic loading cycle, its behaviour converts to fully plastic and may flow like a viscous substance.

Furthermore, ET column in Tables 9 and 11 for underground structures provides advice on pull length (PL), which can be estimated using the proposed method in Appendix 3. Nomenclature for all abbreviations used in this section is provided in Section 10.

Table 9. (I)-Class for Underground Structures: SS, ET, IT

(I)	(I)-Class	Recommended Measure/s		
		SS	**ET**	**IT**
100-91	**(I)-01**	Scaling	FF, ME/DnB, PL	Nil
90 - 81	**(I)-02**	Scaling, IndiB25	FF, ME/DnB, PL	Nil
80 - 71	**(I)-03**	Scaling, SpotB25	FF, ME/DnB, PL	Nil
70 - 61	**(I)-04**	Scaling, SpotB25, PatchPS50	FF, ME/DnB, PL	3DMS@400m
60 - 51	**(I)-05**	Scaling, SpotB32/SysHB25.LS, PS50, PSFS50, RDH54.L	FF, ME/DnB, PL	3DMS@200m
50 - 41	**(I)-06**	Scaling, SysB32.L.S/SysHB32.L.S, FRS100, FRFS50, RDH54.L	HnB/(FF if ≤ 45 m^2), ME/DnB, PL	3DMS@100m, StrainM@300m
40 - 31	**(I)-07**	Scaling, 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, PL	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, PL	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, PL	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, PL	3DMS@15m, StrainM@100m, PressC/LoadC@150m, MultiRodE@300m, StrainG@400m, DIC@25m

Table 9. Continued; (I)-Class for Underground Structures: PT, FT, DR

(I)	(I)-Class	Recommended Measure/s		
		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 10. (I)-Class for Semi-surface and Surface Structures: SS, ET, IT

(I)	(I)-Class	Recommended Measure/s		
		SS	ET	IT
100-91	**(I)-01**	Scaling	(PreS, DD12000^{-}), (ProdBlast, PD6000^{-})	Nil
90 - 81	**(I)-02**	Scaling, IndiB25	(PreS, DD12000^{-}), (ProdBlast, PD4000^{-})	Nil
80 - 71	**(I)-03**	Scaling, SpotB25	(PreS, DD9000^{-}), (ProdBlast, PD4000^{-})	Nil
70 - 61	**(I)-04**	Scaling, SpotB25/SpotA25, PatchHEAM/PatchWeldM, DH54.L	(PreS, DD9000^{-}), (ProdBlast, PD3000^{-})	3DMS@200m
60 - 51	**(I)-05**	Scaling, SpotB32/SpotA32, HEAM/WeldM, DH54.L	(PreS, DD6000^{-}), (ProdBlast, PD3000^{-})	3DMS@150m
50 - 41	**(I)-06**	Scaling, SysA25.L.S, FRS150, DH54.L	(PreS, DD6000^{-}), (ProdBlast, PD2000^{-})	3DMS@75m, IncM@500m
40 - 31	**(I)-07**	Scaling, 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 10. Continued; (I)-Class for Semi-surface and Surface Structures: PT, FT, DR

(I)	(I)-Class	Recommended Measure/s		
		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 11. Special (I)-Class for Underground Structures

(I)-Class	Recommended Measure/s					
	SS	**ET**	**IT**	**PT**	**FT**	**DR**
(I)-BP*	Scaling, SysDB25.L.S/ ConeB25.L.S/ YieldB25.L.S, FRS150, SRH100.L.S.X1, HEAM/CableL+ WeldM, FRFS50	HnB, ME/ DnB, PL	3DMS@25m, StrainM@100m, PressC/LoadC@ 300m, MultiRodE@ 600m	Avoid: 'ProdBlast/ UnCtldBlast, 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, PL	3DMS@10m, StrainM@100m, PressC/LoadC@ 150m, MultiRodE@ 300m, StrainG@400m, DIC@25m	Apply: 'SRH, SysLB for Minor SSH' Avoid: 'FF, DnB, rigid SS, & SysLB for Mild-Severe SSH'	TSP/ PH100. BH.L	Nonuniform deformation, 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, PL	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'

* Appendix 4 for further information.

Table 12. Special (I)-Class for Semi-surface and Surface Structures

(I)-Class	Recommended Measure/s					
	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/V PH54.L	Liquefaction prone, vibration sensitive, high passive lateral load configuration in design of retaining structure, long term consideration in time dependent behaviour

Appendix 5 illustrates some of the measures recommended in the SS and FT columns in Tables 9 and 11, including ADH, BH, BulkH, ConeB, CPS, EC, FaceB, FaceButt, FaceP, FibreD, FP, PH, PR, RDH, SysB SysDB, SysHB, SysLB, SysN, WDH, and YieldB. Definition of these measures is presented in Section 10.

Appendix 6 provides systematic bolting calculation method for bolting parameters (length and spacing) for measures proposed in the SS column in Tables 9 and 11, including ConeB, SysB, SysDB, SysLB, SysN, and YieldB. Definition of these measures is presented in Section 10.

5. (I)-GC

I-System's Ground Characterisation entitled "(I)-GC" characterizes the mechanical properties of ground (rock or soil mass) by quantifying 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). Quantified values provided as output of (I)-GC are estimations based on empirical correlations. Figure 12 is a representation of hexad output for (I)-GC.

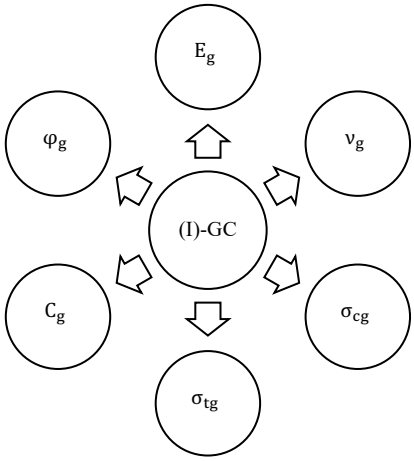


Figure 12. I-System's Ground Characterisation; (I)-GC

(I)-GC's output (Figure 12) provides most important input values required in design approach and procedure (Figures 1 and 2a) for underground, semi-surface, and surface structures. The mathematical form of (I)-GC's hexad output is presented in Eq 11 to 16 (Bineshian, 2019b), whereas the graphical form is presented in Figure 13. These empirical equations are developed and examined by author for several cases (Bineshian, 2019b); however, their accuracy may improve by study on further cases.

$$E_g = e^{0.05\times(I)}-1 \tag{11}$$

$$\nu_g = 0.5 - 0.004 \times (I) \tag{12}$$

$$\sigma_{cg} = 0.007 \times \sigma_c \times e^{0.05\times(I)} \tag{13}$$

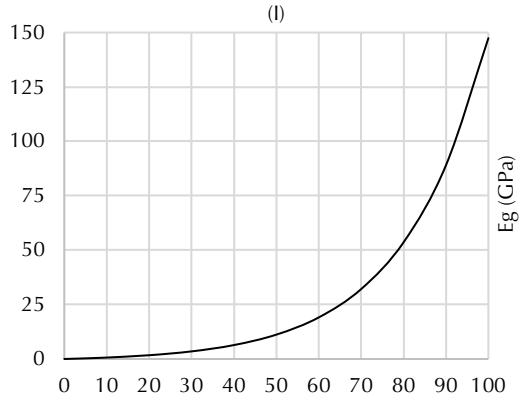
$$\sigma_{tg} = -\sigma_{cg} \times e^{(0.04\times(I)-4)} \tag{14}$$

$$C_g = 0.002 \times \sigma_{cg} \times e^{0.05\times(I)} \tag{15}$$

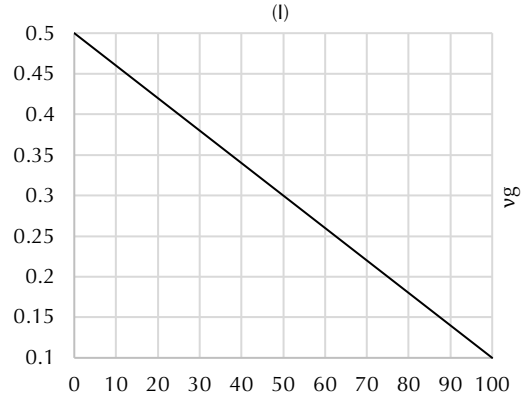
$$\varphi_g = 15 + 0.55 \times (I) \tag{16}$$

where;

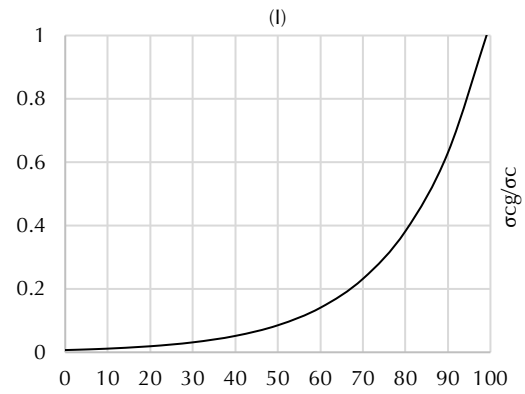
(I)	I-System's Value
E_g	Modulus of Deformation of ground – rock-/soil-mass (GPa)
ν_g	Poisson's Ratio of ground
σ_c	Unconfined Compressive Strength of intact rock or soil (MPa)
σ_{cg}	Unconfined Compressive Strength of ground – rock-/soil-mass (MPa)
σ_{tg}	Uniaxial Tensile Strength of ground – rock-/soil-mass (MPa)
C_g	Cohesion of ground (KPa)
φ_g	Internal Friction Angle of ground (degrees)



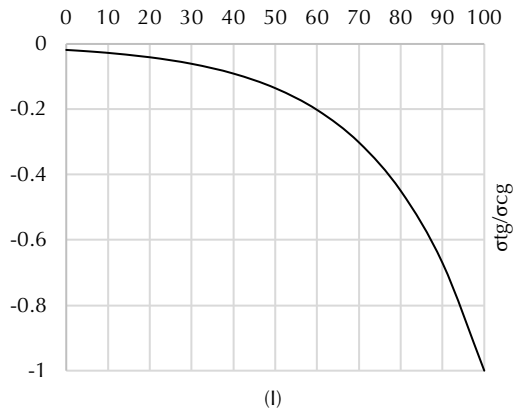
a. (I) vs Modulus of Deformation



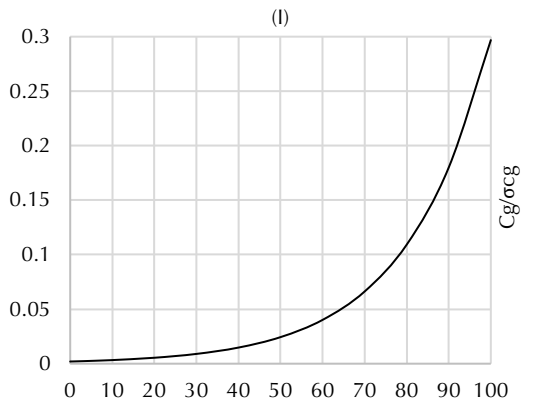
b. (I) vs Poisson's Ratio



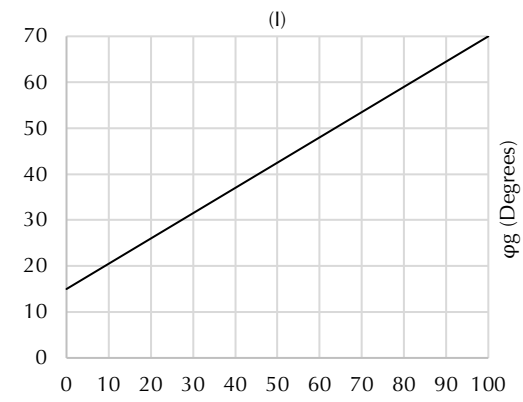
c. (I) vs Unconfined Compressive Strength



d. (I) vs Uniaxial Tensile Strength



e. (I) vs Cohesion



f. (I) vs Internal Friction Angle

Figure 13. (I)-GC Chart

6. Utilisation Guideline

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

- Stage 1. Derivation of input parameters from a site visit or reference data. Figure 2b demonstrates the data group, which is used in I-System as input.
- Stage 2. Calculation of indices; A_i, C_i, H_i, P_i, S_i, DF_i, and ET_i using the derived data in Stage 1, Eq 2 – 8, and Tables 2 – 8.
- Stage 3. Calculation of (I) using Eq 1 and calculated indices in Stage 2.
- Stage 4. Determination of (I)-Class using the calculated (I) value in Stage 3 and Tables 9 – 12. Recommendations for SS, ET, IT, PT, FT, and DR provided in Tables 9 – 12 are applicable in practice.
- Stage 5. Calculation of (I)-GC; E_g, ν_g, σ_{cg}, σ_{tg}, C_g, and φ_g using Eq 11 to 16 or Figure 13, which is applicable for design.

Figure 14 summarises the utilisation approach explained above in a simple diagram.

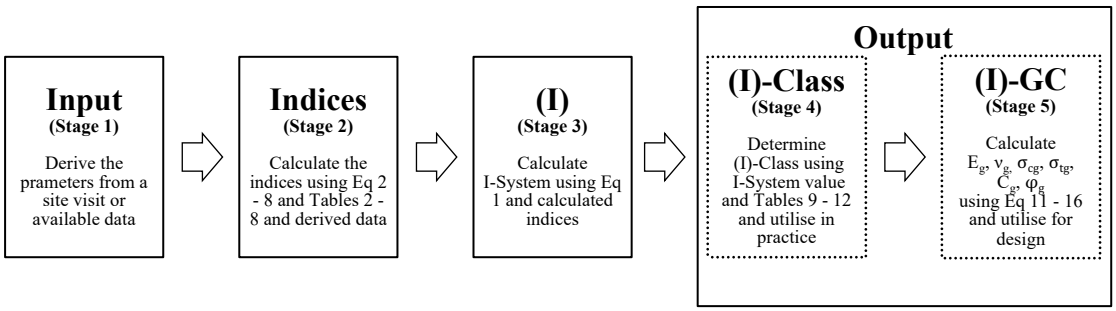


Figure 14. Utilisation diagram of I-System

An example of I-System calculation for a tunnel is provided in Appendix 7; input parameters for calculation of (I) in Figure 24a, (I)-Class as output of classification in Figure 24b, (I)-GC as characterisation output in Figure 24c, and (I)-GC Charts in Figure 24d. Below, a summary of (I)-Class for the same example is provided as a guide for decoding the recommendations' script:

(I) = 25 ⟹ (I)-08 ⟹ Table 9 ⟹ Derive recommendations for (I)-08 as follows:

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, PL

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'

Tunnel's largest dimension in a cross section (diameter, width, or height) for above example is 8000 mm; therefore, D = 8000 mm.

Section 10 provides a comprehensive nomenclature that is necessary to be used for decoding of the output of I-System's classification. I-System's classification output, namely, (I)-Class that is provided in Tables 9 – 12, should be decoded using Section 10. Accordingly, above output-example is decoded (using Section 10) and interpreted in details as follows:

- **SS** – Support System to be applied:

  - **PR100.300.L.X1** or **FP76.250.L.X1** or **FP32.200.L.X1**
    (Piperoofing 100 mm dia, 300 mm spacing, L = 0.7D to L = D then L = 5600 to 8000 mm in one row) or
    (Forepoling 76 mm dia, 250 mm spacing, L = 0.7D to L = D then L = 5600 to 8000 mm in one row) or
    (Forepoling 32 mm dia, 200 mm spacing, L = 0.7D to L = D then L = 5600 to 8000 mm in one row).
    Specified length (L) for the piperoofing or forepoling is a function of D (Diameter, width, or height (mm) of underground opening, the greater value), which can be derived from the empirical equation (L = 0.7D to L = D) proposed in Section 10 and Appendix 5. The length between 5600 to 8000 mm to be selected as per condition.

  - **SysLB32.L.S**
    (Systematic Long Bolting 32 mm dia, L = 0.7D or $L = D \times \frac{100-(I)}{100}$ then L = 5600 to 6000 mm, S = 0.3L = 1700 to 1800 mm).
    Specified length (L) and spacing (S) for systematic long bolting as a function of D (Diameter, width, or height (mm) of underground opening, the greater value) can be derived from empirical equations (L = 0.7D and S = 0.3L) proposed in Section 10 and Appendix 5 or using proposed equations in Appendix 6 ($L = D \times \frac{100-(I)}{100}$ and S = 0.3L) as a function of D and (I). The length between 5600 to 6000 mm to be selected as per condition.

  - **LG32.25.180.1000**$^{-}$ or **RigidR150UC23.1000**$^{-}$
    (Lattice Girder with 32 mm dia rebar at intrados and two 25 mm dia rebars at extrados with 180 mm spacing between the intrados and extrados and spacing between the LGs below 1000 mm) or
    (Rigid Rib made with Universal Column as per Australian Standard of 150UC23 and spacing of below 1000 mm).

  - **FRS225** or **FRC225**
    (Fibre Reinforced Shotcrete with 225 mm thickness) or
    (Fibre Reinforced Concrete with 225 mm thickness).

  - **FaceButt.L**
    (Face Buttress with L = 0.25D = 2000 mm if D ≥ 6000 mm).
    Specified length (L) for buttress as a function of D (Diameter, width, or height (mm) of underground opening, the greater value) can be derived from empirical equation (L ≥ 0.25D) proposed in Section 10 and Appendix 5.

  - **FRFS200**
    (Fibre Reinforced Face Sealing with 200 mm thickness).

  - **RDH54.L+CF**
    (Radial Drainage Holes 54 mm dia, L ≤ D ≅ 8000 mm + Collar Filtration).
    Specified length (L) for radial drainage holes as a function of D (Diameter, width, or height (mm) of underground opening, the greater value) can be derived from empirical equation proposed in Section 10 and Appendix 5 (L ≤ D).

- **ET** – Excavation Technique/s to be implemented:
    - **PSE-ME/NonExBreak, PL**
      (Partial Sequential Excavation using Mechanised Excavation or Non-Explosives Breaking with Pull Length as $PL = 0.5D\frac{(I)}{100}$ then PL = 1000 mm).
      Specified pull length (PL) for advance at face as a function of D (Diameter, width, or height (mm) of underground opening, the greater value) and (I) can be derived from empirical equation ($PL = 0.5D\frac{(I)}{100}$) proposed in Appendix 3.
- **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).
    - **SingleRodE@400m**
      (Single-Rod Extensometer at every 400 m).
- **PT** – Prevention Technique/s to be considered:
    - Apply **PR/FP** (Piperoofing or Forepoling).
    - Maintain **Buttress**.
    - Avoid '**FF** (Full Face Excavation) and **DnB** (Drill and Blast)'.
- **FT** – Forecast Technique/s to be utilised:
    - **TSP/PH54.EC.L**
      (Tunnel Seismic Prediction) or
      (Probe Hole 54 mm dia using Exploratory Coring with L = 3D = 24000 mm).
      Specified length (L) for probe hole using exploratory coring as a function of D (Diameter, width, or height (mm) of underground opening, the greater value) can be derived from empirical equation (L = 3D) proposed in Section 10.
- **DR –** Design Remark/s to be taken into consideration:
    - Passive load configuration, and
    - Sensitive to 'scale, unsupported span, and stand-up time'.

Example provided here in this section is analysed with I-System Software (it is introduced in Section 7 and output of the same is presented in Appendix 7). Further case studies are available in reference number 8 for application of I-System for underground, semi-surface, and surface structures.

Notably, two methods are used for calculation of the length of the Systematic Long Bolting (SysLB), which illustrated in Appendix 5 and fully explained in Appendix 6. It is the choice of designer, engineer, or geologist to select the method that is more compatible with site condition; however, it is recommended to take the greater value between the calculated ones (using illustrations in Appendix 5 or proposed equation in Appendix 6). Same logic is applicable for other calculations for the proposed measures.

7. I-System Software

A software for I-System is developed in 2020 named "I-System Software" aimed to ease the use of I-System and to ensure high accuracy and precision in calculation procedure for classification as well as characterisation is obtained.

I-System Software uses the same algorithm of I-System (Bineshian, 2019a, 2019b, 2020c) originally published and it works exactly as per the I-System principle using the same formulations, tables, and approaches for classification as well as characterisation of ground in relation to underground, semi-surface, and surface structures.

I-System Software works as per following flowchart (Figure 15):

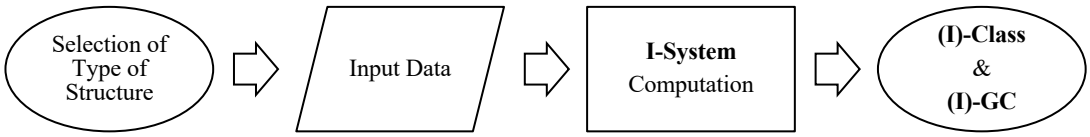


Figure 15. Computation flowchart of I-System Software

- Type of structure includes underground, semi-surface, or surface in which the classification and characterisation is going to be conducted for.
- Input data includes the same input data that considered for hand-calculation of I-System (Stage 1 of Section 6). Appendix 7 (Figure 24a) represents a print of the input of the software.
- Computation includes the Stages 2 and 3 of Section 6, which is the calculation of indices and consequently (I).
- The output includes (I)-Class and (I)-GC, which is the same as Stages 4 and 5 of Section 6. Appendix 7 (Figures 24b and 24c) represent print of the output of the I-System Software.

(I)-Class's output (Section 4) includes hexad of SS, ET, IT, PT, FT, and DR that are applicable in practice. The same is the output of the software for (I)-Class shown in Appendix 7 (Figure 24b). (I)-GC's output (Section 5) includes hexad of E_g, ν_g, σ_{cg}, σ_{tg}, C_g, and φ_g in form of values and chart that are applicable in design as input. Appendix 7 (Figure 24c) shows the same as output of the software for (I)-GC. Besides, I-System Software provides additional output, namely, (I)-GC Chart that is the graphical representation of (I)-GC (Appendix 7; Figure 24d).

Additionally, the software provides GCD calculator that can be used for measurements of ground hydraulic conductivity that is used as input in the software for H_i (Hydro Index) or it may be used individually in practice and/or in design for grouting/injection assessment (Bineshian, 2020a). Also, other utilities included in the software that are helpful for a complete classification and characterisation of ground. Summarily, output report or print of the software (Appendix 7) contains full details of input data (Figure 24a); entered by user and processed by the software), (I)-Class details (Figure 24b); computed by the software), and (I)-GC details and charts (Figures 24c and 24d); calculated and plotted by the software). Appendix 7 at the end of this paper provides output of the software for the case, which is solved and decoded in Section 6. I-System Software is an engineering utility for classification and characterisation of ground; however, it is under further development for more applications in design and practice.

8. Conclusions

I-System is developed to compensate demerits of existing engineering classifications including their limitations, drawbacks, impreciseness, and inaccuracy. It is applicable for rock and soil with acceptable precision and accuracy with simplicity in use and certainty in its approach for derivation of input parameters besides clarity and trust in the output data.

It is developed in challenging projects in varieties of ground and verified for perfectness. There is no limitation/s in its application for any type of underground, semi-surface, and surface structures in rock and soil. It comes with a simple equation containing essential parameters, which can be derived from doubtless input tables, reliable references, or test results. It is based on certain key indices, which defines mechanical behaviour of surrounding ground of structure considering impact of dynamic forces as well as excavation technique impact.

I-System contains two main parts; (I)-Class as classification system and (I)-GC as characterization system.

(I)-Class classifies the ground to 10 classes from the best to the worst, which contains a hexad output as recommendations that is required in practice for execution including; Support System, Excavation Technique/s, Instrumentation Technique/s, Prevention Technique/s, Forecast Technique/s, and Design Remark/s.

(I)-GC provides a hexad output, which is required for design as input including; E_g, ν_g, σ_{cg}, σ_{tg}, C_g, and φ_g.

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

9. Future Research Recommendations

Author recommends following additional researches for further development and improvement of I-System:

- Scrutinization of indices including their parameters as well as their scorings for a better modelling of each index of ground.
- Investigation on impact factors and their influence on total value of I-System to obtain better accuracy – if possible – in effect of influencing parameters on (I).
- Study on impact of important factors of shape, scale, in-situ stresses, and/or overburden, which are already considered in Strength Index to develop – if possible – a more effective method in consideration of these factors.
- Adding more recommendation/s on required SS, ET, IT, PT, FT, and DR as output of (I)-Class.
- Work on (I)-GC and their output in characterisation of mechanical aspects of ground for already proposed properties and more parameters by collecting further data in a comprehensive range and varieties of ground for obtaining best fit to derive more accurate correlations.

10. Nomenclature

(I)	I-System's value
(I)-Class	I-System's Ground Classification, which provides recommendations on SS, ET, IT, PT, FT, and DR that are applicable in practice as well as design for structures in ground
(I)-GC	I-System's Ground Characterisation, which provides hexad of E_g, ν_g, σ_{cg}, σ_{tg}, C_g, and φ_g that are applicable in design as input parameters for design of structures in ground
3DM	3D Monitoring - using Bi-Reflex Target
3DMS	3D Monitoring Station
a_{da}	Factor related to "Discontinuity Aperture" that is based on the most unfavourable opening of the discontinuities; a parameter of A_i
a_{dd}	Factor related to "Discontinuity Disintegration" that is based on the worst weathering or alteration of surface of the discontinuity sets; a parameter of A_i
a_{df}	Factor related to "Discontinuity Friction" that is based on the least friction condition of discontinuity sets; a parameter of A_i
ADH	Axial Drainage Hole/s - NX hole/s (w/- or w/o casing), parallel to axis of tunnel, perpendicular to face; L ≤ 1.5D, S as per site condition
a_{di}	Score related to "Discontinuity Inclination" that is based on the dip angle of the most critical/unfavourable discontinuity set; a parameter of A_i
a_{dn}	Score related to "Discontinuity Number/s" that is based on number of individual discontinuities per meter of a horizontal or vertical scanline or average of number of discontinuities per meter of horizontal and vertical scanline; a parameter of A_i
a_{dp}	Factor related to "Discontinuity Persistency" that is based on the most unfavourable discontinuity set; a parameter of A_i
a_{ds}	Score related to "Discontinuity Set/s" reflecting the number of sets of discontinuities; a parameter of A_i
A_i	Armature Index
B	Width of a berm in a slope or trench or width or horizontal span of an underground space
B/H	Underground, semi-surface, or surface structures' shape or scale factor as ratio of horizontal span to height of underground opening or ratio of width of berm to height of slope or trench
BH	Blind Hole - triangular patterned probing parallel to axis of underground space using blind hole/s; L = 2D and 100+ mm diameter
BP	Burst Prone – highly stressed ground condition with rock burst or coal burst behaviour
BRT	Bi-Reflex Target - 3, 5, or 7 targets installed in a 3DMS based on severity of convergency
BulkH	Bulk Head - shotcrete/concrete plug at whole section of excavation at face to prevent the ground from flowing; L ≤ 0.15D
C	Convergency (mm)
c/a	Conditionally Applicable
c_1	Site constant in USBM PPV Predictor
c_2	Site constant in USBM PPV Predictor
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 (MPa)
C_i	Configuration Index
CommBlast	Commercial Blasting (engineered blast near commercial area)
ConeB	Cone Bolts - oriented/radial cone bolts; L = 0.5D, S = 0.3L

Continuum Massive Rock	A massive medium rather than layered one; e.g., intact rock or unlayered and structurally interlocked rock mass
c_{pc}	Impacting factor related to "Problematical Configuration" of ground indicating ground's tectonic state; a parameter of C_i
CPD_{max}	Maximum charge per delay (kg)
CPS	Crown Periphery Spiling - SN umbrella at 5-30 deg; L = 0.7D
c_{sc}	Score of "Structural Configuration" of ground (an effect of ground's texture, fabric, and structure); a parameter of C_i
CtldBlast	Controlled Blasting (an ordinary engineered blast for civil works)
CYSS	Conventional Yield Support System - a conventional system of yield measures used in tunnelling under SSH condition; it includes TH or H sliding ribs, LSC, and/or LCN
d	Depth of placement of the structure
D	Diameter, width, or height (mm) of underground opening (the greater value)
DD	Drilling Depth (mm)
DF_i	Dynamic Forces Impact
DH	Drainage Hole/s - upward NX hole/s (w/- or w/o casing); L = 1.5H, S as per site condition
Di	Damage Indicator (%); Bineshian (2021a, 2021b)
Di-Class	Classification of ViD based on Di
DIC	Digital Image Correlation (Bineshian et al, 2021a, 2021b)
Dist	The distance between the blasting location and concerned structure (m)
DL	Drilling Length of blastholes (mm)
DnB	Drill and Blast - controlled blast using a designed drilling pattern
DR	Design Remark/s
DWall	Diaphragm Wall
EC	Exploratory Coring - single NX hole parallel to axis of tunnel; L = 3D
E_g	Deformation Modulus of ground - rock mass or soil mass's deformation modulus (GPa)
ElFootR	Elephant Foot Rib – a stiff/rigid rib applicable when vertical load above crown is high
EN	European Standard – Eurocode of practice
ERT	Electrical Resistivity Tomography - a non-destructive geophysical method for ground characterisation
ERZ	Earthquake Risk Zone classifies seismicity to EH (Extremely High), VH (Very High), H (High), M (Moderate), L (Low), VL (Very Low), EL (Extremely Low)
ET	Excavation Technique/s
ET_i	Excavation Technique Impact
FaceB	Face Bolting – Fibreglass Dowel/s or SDA bolts drilled parallel to axis to support against face pressure/thrust, perpendicular to face; L = D, S ≤ 0.3L
FaceButt	Face Buttress - keeping part of face in place as a buttress to absorb face pressure or thrust as part of face stabilization; L ≥ 0.25D (Only if D ≥ 6 m)
FaceP	Face Plug - shotcrete at face to plug outlet of debris discharge; L ≤ 0.05D
f_b	Frequency of blast-induced vibration (Hz)
FF	Full Face excavation
FibreD	Fibreglass Dowel/s - used as FaceB; L = D, S ≤ 0.3L
FP	Fore Poling - umbrella using perforated/blind SDA; L = D
FRC	Fibre Reinforced Concrete
Freezing	A pre-excavation solidification for underground, semi-surface, and surface openings
FRFS	Fibre Reinforced Face Sealing

FRS	Fibre Reinforced Shotcrete
FT	Forecast Technique/s
g	g-force or peak ground acceleration due to earth's gravity (m/sec^2); 1g = 9.81 m/sec^2
GB	Ground Behaviour based on mechanical response of ground
GCD	Ground Conductivity Designation (Bineshian, 2020a)
GCD_e	Existing GCD; post-blast measured GCD
GCD_p	Pre-existing GCD; pre-blast measured GCD
GC_{ef}	Ground Conductivity Enhanced Factor (Bineshian, 2021a, 2021b)
GD	Gravity Driven - flowing ground with fully plastic behaviour
GH	Ground Hazards based on failure categorisation
Rock	Intact rock or rock mass
Granular	Soil mass (conglomerate and breccia is excluded from this category)
GRC	Ground Reaction Curve
GZ	Ground Zoning based on ground properties
H	Height of a slope, trench, opening, or buttress
HCF	Half Cast Factor (%)
HEAM	High Energy Absorption Mesh - mesh over shotcrete; protective mesh against dynamic or impact loads
h_{gc}	Score assigned to "Ground Conductivity" that is measured using GCD or selected from Wetness diagram as criterion for hydropressure effect on ground; a parameter of H_i
h_{gs}	Impact factor related to "Ground Softness" that is considered as an effect of water on medium/infilling material (Mohs); a parameter of H_i
H_i	Hydro Index
HnB	Heading and Benching - an excavation method to control the scale effect on stability
I-System	Index of Ground-Structure; a comprehensive classification and characterisation system for ground including both rock and soil media (Bineshian, 2019a, 2019b, 2020c)
IncM	Inclinometer/s
IndBlast	Industrial Blasting (engineered blast near industrial area)
IndiB	Individual Bolting - oriented and in very limited number
InfraBlast	Infrastructures Blasting (engineered blast for demolishing infrastructures)
IS	Indian Standard - code of practice
IT	Instrumentation Technique/s
JetG	Jet Grouting - applicable in construction of underground, semi-surface, and surface metro station
Jointless	A definition describing an important feature of intact rock; a medium that does not have any countable joint set
L	Length of ADH, BH, ConeB, CPS, DH, EC, FaceB, FaceButt, FaceP, FP, PH, PR, RDH, SRH, SysA, SysB, SysDB, SysHB, SysLB, SysN, VPH, WDH, WH, and YieldB (mm)
LCN	Longitudinal Compression Niche; applicable in YSS for tunnelling under SSH condition (Bineshian, 2020b)
L_{ch}	Length of contour or periphery blasthole (m)
LG	Lattice Girder
L_{hc}	Length of half-cast or half barrel (m)
L_i	Length of water injected portion (packed length) of drilled hole (m) or length of casing hole (m) or length of installed perforated SDA (m) in the GCD test procedure
LoadC	Load Cell/s
LRFD	Load and Resistance Factor Design method

LSC	Longitudinal or Liner Stress Controller - rubber/spring/soft-timber/rolled-MSP; it is a member of CYSS for tunnelling under SSH condition (Bineshian, 2020b)
LSD	Limit State Design method
M	Earthquake Magnitude
ManDigg	Manual Digging (small scale excavation without use of explosives or NonExBreak)
MASW	Multichannel Analysis of Surface Waves - a non-destructive geophysical method for characterisation of ground
McNally	A system for rock burst treatment in tunnelling using TBM
ME	Mechanised Excavation (Medium- to large-scale excavation using TBM, Roadheader, Excavator, or Hammer without use of explosives or NonExBreak)
MicroP	Micro Piles - distribute concentrated load to a wider footing area under elephant ribs
MineBlast	Mining Blasting (controlled blast as per mining standards)
MSF	Magnitude Scaling Factor
MSK	Medvedev-Sponheuer-Karnik Scale classifies seismicity as I to XII
MSP	Mild Steel Plate
MultiRodE	Multiple Rod Extensometer - measuring points @ 2, 4, and 6 m recommended
n/a	Not Applicable
NATM	New Austrian Tunnelling Method; it minimises SS needs based on utilisation of ground capacity in load bearing and activation of load configuration by application of active SS. NATM is applicable for comprehensive range of ground conditions. SCL and SEM are following the same philosophy of NATM.
NMT	Norwegian Method of Tunnelling; it is a method in tunnelling using Q for ground classification and cross-hole seismic tomography for further characterisation. NMT is not providing a new philosophy in tunnelling.
NonExBreak	Non-Explosive Breaking (ground fragmentation using expansive materials)
NX	Hole with 54.7 mm diameter
OB	Over Break or over cut or over excavation
OC	Open Cut
PatchHEAM	Patch High Energy Absorption Mesh (protection against dynamic/impact loads) – used in slope protections against rock falls and/or tunnelling under burst prone condition
PatchPS	Patch Plain Shotcrete
PatchWeldM	Patch Weld Mesh - applicable as protective mesh in underground, semi-surface, and surface openings to prevent spot rock falls
p_{bw}	Factor related to "Body Wave Velocity" including Vp or Vs as geophysical properties of ground that corrects P_i; Body Wave Velocity is derived either from reliable references (considering the type of materials of ground) or is measured using geophysical methods
p_{cc}	Score related to "Cohesiveness Consistency" that is an important shear property of soil (cohesion); a parameter of P_i
PCC	Plain Cement Concrete
PD	Pull Depth
p_{dc}	Score related to "Denseness Consistency" that is an important shear property of soil (non-cohesiveness; friction); a parameter of P_i
PGA	Peak Ground Acceleration (g)
PGA_{SD}	Scaled Design Peak Ground Acceleration (g); desired scaled PGA
PH	Probe Hole - probing using blind hole drilling with 100+ mm diameter or exploratory coring using NX hole/s; L = 2D for BH and L = 3D for EC
P_i	Properties Index
PL	Pull Length (mm) - advance length

P_m	Peak head (MPa) during injection period of T_i in GCD test procedure; it is the measured water pressure before the first drop in peak is observed.
PostG/I	Post-excavation Grouting/Injection - consolidation/solidification
p_{pm}	Influencing parameter related to "Particles' Morphology" that is a function of shape of soil's grains/granules; a parameter of P_i
p_{ps}	Influencing parameter related to "Particles' Size" that is a function of size of soil's grains/granules"; a parameter of P_i
PPV	Peak Particle Velocity (mm/sec)
PR	Pipe Roofing - perforated/blind pipe (w/- or w/o grouting); L = D
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
ProdBlast	Production Blasting (controlled blast for rock production in large scale)
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 to prevent hazards/disintegration
PT	Prevention Technique/s
PU-2C	Polyurethane with two components
Q	Rock mass classification for tunnel supports (Barton et al, 1974)
Q_w	Water intake rate (lit/min) in GCD test procedure
RCC	Reinforced Cement Concrete (Conventional)
RDH	Radial Drainage Hole/s - NX radial holes (w/- or w/o casing); L ≤ D, S as per site condition
ResiBlast	Residential Blasting (engineered blast near residential area)
RigidR	Rigid Ribs – steel ribs made from H profile (heavy beam) or any equivalent profile/s used for manufacturing rigid ribs to absorb entire dead/passive load from the ground
RingC	Ring Closure or invert closure
RMR	Rock Mass Rating (Bieniawski, 1973)
RSS	Rigid Support System
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 ≤ 0.3L
SCL	Sprayed Concrete Lining; it is a tunnelling method using shotcrete (sprayed concrete) as a primary liner as a member of SS for interaction with ground load configuration. SCL is almost the same as NATM with higher emphasis on shotcreting as primary SS.
s_{cs}	Score related to "Compressive Strength" as Uniaxial Compressive Strength of ground; a parameter of S_i
SD	Structural Dimensioning for each SS
SDA	Self-Drilling Anchor
SecP	Secant Piling or equivalent driven or bored piles including friction or end bearing piles
SEM	Sequential Excavation Method; it is not a tunnelling method; instead, it is an excavation method based on NATM principles for optimisation of load configuration.

SF	Scaling Factor
SFL	Structural Final Liner
S_i	Strength Index
SingleRodE	Single Rod Extensometer - measuring point @ 3 m recommended
SLS	Serviceability Limit State design check - a LSD method
SN	Store Norfors - a rigid system of bolts using steel rebars
SolP	Soldier Piling or equivalent driven or bored piles
SPL	Structural Primary Liner
SpotA	Spot Anchoring
SpotB	Spot Bolting - oriented with limited number
SRH	Stress Release Holes - long radial naked holes; 100 - 300 mm diameter; L = D (Bineshian, 2020b)
SRT	Seismic Refraction Tomography - a non-destructive geophysical method
SS	Support System
s_{se}	"Scale Effect" factor; a parameter of S_i
SSH	Squeezing/Swelling/Heaving (Bineshian, 2020b)
SSH-Class	Classification for SSH ground based on severity of convergency (Bineshian, 2020b)
StrainG	Strain Gauge/s
StrainM	Strain Meter
SurS	Surface Structure including surface and semi-surface structure/s and mine/s in general comprising of but not limited to bridge and dam abutments, cut & cover, deep and shallow foundations, embankment and tailing dams, open cuts, open pits, shallow metro stations (cut & cover or open cut), slopes, surface power house openings, trenches
SV	Structural Verification based on the definition of relative safety margin for SD
Swellex	An expandable rock bolting system from Atlas Copco
SysA	Systematic Anchoring - anchors perpendicular to face of slope; L = 0.5H, S = 0.3L
SysB	Systematic Bolting - radial direction; L = 0.5D, S = 0.3L
SysDB	Systematic Dynamic Bolts - oriented/radial dynamic bolts; a system of ductile bolting, which is applicable for tunnelling under stressed condition like burst prone and/or SSH ground (Bineshian, 2020b); L = 0.5D, S = 0.3L
SysHB	Systematic Horn Bolting – a system of bolts oriented towards the direction of advancement at tunnel, which is used to prevent over-breaks and rock falls from crown in tunnelling with unfavourable orientation of discontinuities; to be used only above SPL of tunnel (crown) at 30 - 45 deg; L = 0.7D, S $\leq$ 0.3L
SysLB	Systematic Long Bolting - radial long bolts; L = 0.7D, S = 0.3L
SysN	Systematic Nailing - radial bolts/anchors; L = D = H, S = 0.3L
t	Time period or duration of vibration in a blast (sec)
TanP	Tangent Piling or equivalent driven or bored piles including friction or end bearing piles
TBM	Tunnel Boring Machine
TD	Time Dependent - ground condition with time dependent shearing behaviour such as squeezing/swelling/heaving condition, or even creep
TH	Toussaint-Heintzmann - steel profile used in fabrication of yield/sliding ribs
T_i	Injection period (minutes) taken for injection of V_w quantity of water in GCD test procedure; it is the period of time from initial raise in pressure till the first drop in peak.
TSP	Tunnel Seismic Prediction
UB	Under Break or under cut or under excavation
UC	Universal Column as per Australian Standard (i.e., 150UC23 and 200UC46)

UCS	Unconfined Compressive Strength
ULS	Ultimate Limit State design check - a LSD method
UnCtldBlast	Un-Controlled Blasting (Non-engineered blast)
UndS	Underground Structure/s including underground shallow and deep structures, openings, and mines comprising of but not limited to caverns, deep metro stations, galleries, stopes, shafts, tunnels, underground power houses, stations, storages, wells
USBM	The United States Bureau of Mines
ViD	Vibration-induced Damage or blast-induced damage (Bineshian, 2021a, 2021b)
Vp	Primary Wave Velocity (m/sec)
VP	Visco-elasto-Plastic - ground condition as visco-elasto- to fully plastic behaviour; ground contains elastic component/s together with viscous component/s that causes strain rate dependence on time; however, due to losing energy during static or dynamic loading cycle, its behaviour converts to fully plastic and may flow like viscous substance.
VPH	Vertical Probe Hole - vertical NX blind/coring exploration hole/s; L = 0.5H
Vs	Shear/Secondary Wave Velocity (m/sec)
V_w	Injected quantity of water (lit) during injection period of T_i in GCD test procedure; it is measured from the moment that the pressure is started rising till the first drop in peak is observed.
w	Width of crack in concrete (mm); as per IS 456:2000 permissible crack width in the SLS design check for SV must be as: w < 0.30 mm
WDH	Wing Drainage Holes - NX wing shape (w/- or w/o casing) at 30 - 45 deg applicable in underground openings to drain water from sides and ahead of face to reduce the pore hydrostatic pressure; L ≤ 2D, S as per site condition
WeldM	Weld Mesh - conventional weld mesh used over shotcrete in ground burst condition or used as reinforcement for shotcrete
Wetness	A diagram defined here to clarify the ground's water content, which is classifying the ground water condition (observational identification) in 11 ranges
WH	Weep Holes - upward angled NX weeps (w/- or w/o casing); L = H, S as per 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 ductile bolts for stressed condition including burst prone and/or SSH ground (Bineshian, 2020b); L = 0.5D, S = 0.3L
YieldFRC	Yield Fibre Reinforced Concrete - FRC with embedded LSC and/or LCN, which is applicable for tunnelling under SSH condition (Bineshian, 2020b)
YieldFRS	Yield Fibre Reinforced Shotcrete - FRS with embedded LSC and/or LCN, which is applicable for tunnelling under SSH condition (Bineshian, 2020b)
YieldR	Yield Ribs - sliding ribs using TH or H yield/sliding steel profile; it is an important member of CYSS for tunnelling under SSH condition (Bineshian, 2020b)
YSS	Yield Support System - a system of yield measures, which is used for tunnelling under SSH condition; it includes CYSS and/or SRH System (Bineshian, 2020b)
ν_g	Poisson's Ratio of ground
σ_c	Unconfined Compressive Strength of intact rock or soil (MPa)
σ_{cg}	Unconfined Compressive Strength of ground - rock mass or soil mass (MPa)
σ_h	Horizontal Stresses (MPa) at the location or depth of placement of structure (d)
σ_{tg}	Uniaxial Tensile Strength of ground - rock mass or soil mass (MPa)
σ_v	Vertical Stresses (MPa) at the location or depth of placement of structure (d)
φ_g	Internal Friction Angle of ground (degrees)

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Appendix 1: GCD

Ground Conductivity Designation (GCD) is a test method based on a simple single stage water injection procedure for examination of the ground's hydraulic conductivity (Bineshian, 2020a). The output of GCD guides engineers and/or geologists to have a pre- and/or post-grouting/injection assessment on ground quality in terms of permeability, solidification, consolidation, water ingress reduction, or sealing quality.

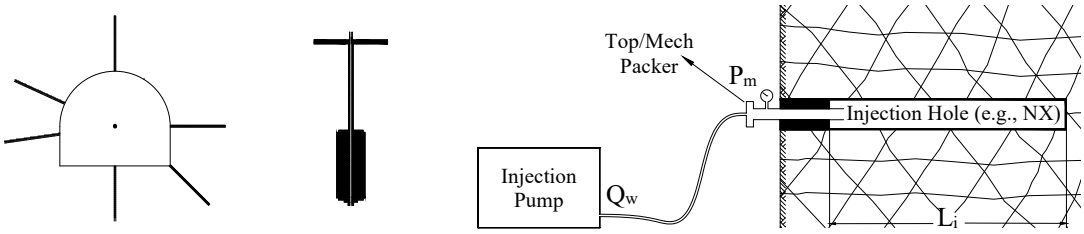
Eq 17 represents dimensionless empirical form of GCD. Eq 18 represents water intake rate in lit/min, which is used in Eq 17. Figure 16 demonstrates schematics for the GCD test setup. Table 13 provides classification for ground hydraulic conductivity as well as ground solidification quality.

$$GCD = Q_w/(P_m + L_i) \tag{17}$$

$$Q_w = \frac{V_w}{T_i} \tag{18}$$

where;

GCD	Ground Conductivity Designation (dimensionless)
L_i	Length of water injected portion (packed length) of hole or perforated SDA (m)
P_m	Peak head (MPa) during injection period of T_i; measured pressure before the first drop in peak
Q_w	Water intake rate (lit/min); to be calculated using Eq 18
T_i	Injection period of time (min) taken to inject V_w quantity of water; it is the period of time from initial raise in pressure till the first drop in peak is observed.
V_w	Injected quantity of water (lit) during injection period of T_i; it is measured from the time that pressure is started to raise till the first drop in peak pressure is observed.



a. Drilling orientation b. Top-Mech Packer c. GCD configuration during the test

Figure 16. GCD setup (Bineshian, 2020a)

Table 13. Ground Conductivity Designation (Bineshian, 2020a)

Ground Hydraulic Conductivity	GCD	Ground Solidification Quality
Very High - VH	> 100	VP - Very Poor
High - H	100 - 51	P - Poor
Medium - M^+	50 - 16	F - Fair
Moderate - M^-	15 - 6	G - Good
Low - L	5 - 1	VG - Very Good
Very Low - VL	< 1	E - Excellent

A proper conduction of GCD test method includes procedures as follows:

1. Select the location in which ground conductivity to be measured.

2. Drill a single naked hole in any direction or orientation in the chosen location including horizontal, vertical, or inclined at face, wall/s, crown, or invert (Figure 16a). Drilling can be conducted using a rotary-percussion or rotary drilling system; however, rotary drilling system is preferred.

3. Stabilise the drilled hole using casing; however, naked hole for GCD test is preferred. If hole is not sustained, casing can be applied or SDA can be used.

4. Flush the naked hole using clear water to remove fine debris and cuttings. If casing hole or SDA is used, the same flushing procedure to be applied.

5. Pack the collar of the naked drilled hole using a top/mechanical packer (Figure 16b). Packing must be conducted in a proper way that the collar is completely sealed and no leakage of water is observed. If casing or SDA is used, a proper packing inside casing or on the outlet of SDA is necessary to be conducted. The space between casing and ground and/or between the SDA and ground should be completely sealed only at collar using cement mortar or PU-2C or any method/material that may be applicable. It is important to note that only a short portion (maximum 300 mm length) at collar of the hole to be sealed.

6. Set up a suitable water pump and connections for injection of water to the hole (Figure 16c). The water pump should have the capacity in providing enough pressure and be equipped with pressure gauge. Use of grouting pump unit in GCD test procedure is highly recommended.

7. Inject water to the hole and measure the V_w in T_i period of time.

8. Calculate Q_w and consequently GCD.

9. Find the proper range of GCD in Table 13 based on the calculated value.

10. Classify the Ground Hydraulic Conductivity and Ground Solidification Quality using Table 13 for further judgment and use in design and/or practice.

GCD ranges from below 1 to above 100 (Table 13) that classifies ground's hydraulic conductivity into 6 categories; very low (VL), low (L), moderate (M^-), medium (M^+), high (H), and very high (VH). It also classifies solidification quality into 6 categories as excellent (E), very good (VG), good (G), fair (F), poor (P), and very poor (VP).

Conduction of GCD test does not contain complicated procedure; however, there are some important notes that needs to be considered in measurements as follows:

- It is recommended to repeat the test for 3 times and then making an average of values to obtain a better precision and accuracy in GCD estimation.

- 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 quality of grouting or injection executed at the location of the hole is classified as VP (Table 13). In this case the section should be further grouted/injected by a proper consolidation material/s and/or with a better configuration to obtain the targeted GCD value that designated in particular design.

- If the pressure is rapidly raised and exceeded 1 MPa, then the ground hydraulic conductivity would be considered as VL, which means that quality of grouting or injection executed at the location of the hole is classified as E (Table 13).

Appendix 2: ViD

Vibration-induced Damage (ViD) or in other words blast-induced damage includes deterioration of ground, further development of plastic zone beyond the excavation line, aggravation of overbreak, and damage to vicinity structure/s induced by vibration (Bineshian, 2021a). Peak Particle Velocity (PPV) is a suitable vibration parameter that is used to assess the ViD that is measured, calculated, or predicted using seismographs, mathematical formulas, or empirical equations respectively. In absence of measurement or calculation, empirical equations are developed. One of the first and most credible empirical PPV predictor (Eq 19) is proposed by USBM (Duvall and Fogelson, 1962).

$$PPV = c_1 \left(\frac{Dist}{CPD_{max}^{0.5}}\right)^{c_2} \tag{19}$$

where;
c_1 Site constant; determined by regression analysis on (Dist, PPV) or empirical values to be used
c_2 Site constant; determined by regression analysis on (Dist, PPV) or empirical values to be used
CPD_{max} Maximum charge per delay (kg)
Dist The distance between the blasting location and concerned structure or transducer (m)
PPV Peak Particle Velocity (mm/sec)

"Dist" to be assumed as 20 m when Eq 19 is used for derivation of ET_i value from Table 8 (Section 3.7). c_1 and c_2 can be derived from regression analysis; however, use of empirical values for site constants (e.g., Table 14) assists in prediction of PPV.

Table 14. Site constants for USBM PPV Predictor (Eq 19); constants from Dyno Nobel (2010)

Ground Strength	Confinement Condition of Blast	Site Constants	
		c_1	c_2
Hard	Free Face	500	-1.6
Average	Free Face	1140	-1.6
Hard-Average	Heavily Confined	5000	-1.6

Considering that I-System includes the ETi in its equation as a dependent variable on PPV, the same is used to define an indicator for ViD as a function of the same, which is expressed in a percentage (Bineshian, 2021b). Mathematical form of this indicator is defined in Eq 20 and the classification for ViD is shown in Table 15 (Bineshian, 2021b).

$$Di = (1- ETi)\times 100 \tag{20}$$

where;
Di Damage Indicator (%); indicator for ViD to the structure in ground
ETi Excavation Technique's Impact factor; part of I-System (Bineshian, 2019a, 2019b, 2020c)

Table 15. Damage Indicator's classification (Bineshian, 2021a, 2021b)

ET	PPV (mm/sec)*	ETi	Di Range (%)	Di-Class	ViD
ManDigg	-	1.00	0	D_i-01	Nil
ME/NonExBreak	< 2	0.99	0.1 - 1	D_i-02	Unscathed
ResiBlast	2 - 9	0.98	1.1 - 2	D_i-03	Unnoticeable
CommBlast	10 - 24	0.97	2.1 - 3	D_i-04	Negligible
IndBlast	25 - 59	0.96	3.1 - 4	D_i-05	Minor
InfraBlast	60 - 119	0.95	4.1 - 5	D_i-06	Mild
CtldBlast	120 - 449	0.90	5.1 - 10	D_i-07	Moderate
MineBlast	450 - 499	0.80	10.1 - 20	D_i-08	Major
ProdBlast	500 - 599	0.65	20.1 - 35	D_i-09	Destructive
UnCtldBlast	≥ 600	0.50	35.1 – 50 & 50^+	D_i-10	Catastrophic

* @ Dist = 20 m

Another method to assess the ViD is the Ground Conductivity Enhanced Factor (GC_{ef}), which is developed by author (Bineshian, 2021a, 2021b) using GCD (Bineshian, 2020a; Appendix 1). Post-blast enhanced conductivity can be a criterion for assessment of ViD to the surrounding ground of tunnel by taking the pre-blast conductivity as a reference value. Eq 21 and Table 16 provide ViD assessment based on GC_{ef} (Bineshian, 2021b).

$$GC_{ef} = \frac{GCD_e}{GCD_p} \tag{21}$$

where;
GCD Ground Conductivity Designation (Bineshian, 2020a)
GCD_e Existing GCD; post-blast measured GCD
GCD_p Pre-existing GCD; pre-blast measured GCD
GC_{ef} Ground Conductivity Enhanced Factor

Table 16. Assessment of ViD using GC_{ef} (Bineshian, 2021a, 2021b)

GC_{ef} Range	ViD
$GC_{ef} = 1.00$	Nil
$1.00 < GC_{ef} \leq 1.01$	Unscathed
$1.01 < GC_{ef} \leq 1.05$	Unnoticeable
$1.05 < GC_{ef} \leq 1.10$	Negligible
$1.10 < GC_{ef} \leq 1.20$	Minor
$1.20 < GC_{ef} \leq 1.50$	Mild
$1.50 < GC_{ef} \leq 2.00$	Moderate
$2.00 < GC_{ef} \leq 5.00$	Major
$5.00 < GC_{ef} \leq 15.0$	Destructive
$GC_{ef} > 15.0$	Catastrophic

HCF (McKown, 1986) is a handy (Eq 22) but inaccurate method for assessment of ViD due to considering only the length of half-barrels for assessment. Likewise, the ViD classifications proposed by researchers based on HCF are not in details. Author to make this handy assessment more detailed, proposed a classification for ViD based on HCF (Table 17) with more details in categorisation of damage (Bineshian, 2021a, 2021b) that is matched with ViD classification presented in Tables 15 and 16.

$$HCF = \frac{\sum L_{hc}}{\sum L_{ch}} \times 100 \tag{22}$$

where;
HCF Half-Cast Factor (%)
L_{ch} Length of contour hole (m)
L_{hc} Length of half-cast (m)

Table 17. ViD assessment based on HCF (Bineshian, 2021a, 2021b)

HCF Ranges	ViD
$HCF = 100$	Nil
$90.0 \leq HCF < 100$	Unscathed
$80.0 \leq HCF < 90.0$	Unnoticeable
$60.0 \leq HCF < 80.0$	Negligible
$40.0 \leq HCF < 60.0$	Minor
$20.0 \leq HCF < 40.0$	Mild
$10.0 \leq HCF < 20.0$	Moderate
$5.00 \leq HCF < 10.0$	Major
$2.50 \leq HCF < 5.00$	Destructive
$0 \leq HCF < 2.50$	Catastrophic

Use of Di, GCef, or HCF is the choice of designer, engineer, or geologist.

Appendix 3: Pull Length Advisor

Implementation of suitable length for pull is crucial for stability of opening in tunnelling specially under challenging condition. I-System in its earlier edition (e.g., 2019, 2020) proposed values for pull length (PL) to be considered for each (I)-Class during excavation in underground spaces; however, in this edition an equation (Eq 23) is proposed (Bineshian, 2021b) – based on the best fit on empirical data – for calculation of PL as a function of D and (I) values, which provides a better advice for safe PL based on tunnel dimension and ground's quality or condition. The "PL" recommendation that is reflected in (I)-Class in Tables 9 and 11 for underground structures should be calculated using Eq 23. The calculated value for PL should be further assessed by engineer as per site condition for the safe and efficient advance at face. When drill and blast technique (DnB) is used for excavation, Eq 24 provides an estimate for the drilling length (DL) for an optimised engineered blasting with a reasonable blasting efficiency.

$$\mathrm{PL} = 0.5\mathrm{D}\frac{(\mathrm{I})}{100} \tag{23}$$

$$\mathrm{DL} = 1.1\mathrm{PL} \tag{24}$$

where;
(I) I-System's value
D Diameter, width, or height (mm) of underground opening (the greater value)
DL Drilling Length (mm) when DnB is used for excavation
PL Pull Length (mm) as an advice for advance in tunnel using DnB or ME

Figure 17 is a graphical representation of Eq 23. Calculated PL from Eq 23 or derived from Figure 17 can be further reviewed by the engineer at site based on the actual condition of ground and structure.

An example as a guide is also shown in Figure 17 for a tunnel with D = 8,000 mm and (I) = 75; the PL for DnB technique for tunnel's face advance is derived from Figure 17 and DL is calculated using Eq 24:

PL = 3000 mm

DL = 3300 mm

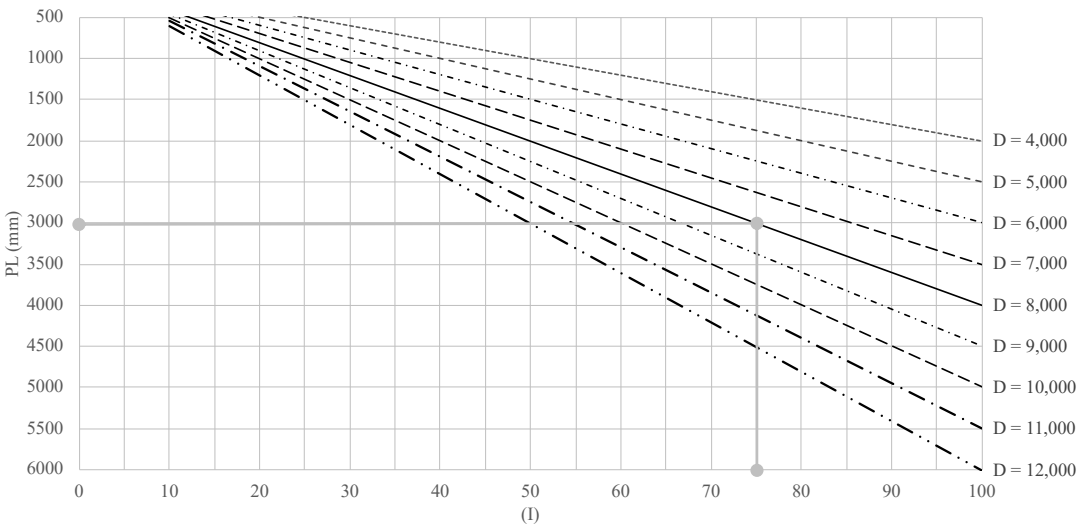


Figure 17. PL graph; derivation of PL as a function of D and (I) for tunnels (Bineshian, 2021b)

Appendix 4: SRH

SSH (squeezing, swelling, and heaving) behaviour is a complicated non-uniform time-dependent mechanical response of ductile ground to excavation; however, it is different in load configuration compared to creep as a typical time dependent behaviour. It is a post-excavation procedure of yield stress development that generates plastic zone around the opening, however; because of stimulation caused by micro-scale sliding failure of existing non-uniformly distributed weak planes, shear stresses further magnified that initiates non-uniform deformation toward free space in a plastification process. Convergence is occurred when excavated space is the only existing free space. Severity of SSH condition depends on ground properties and induced stresses (Bineshian, 2020b). An empirical identification criterion for distinguishing SSH from Non-SSH as well as a classification for severity of SSH is presented in Table 18.

Table 18. Identification criterion and classification for SSH condition (Bineshian, 2020b)

Convergency (mm)	SSH-Class
$C \leq \frac{0.5D}{100}$	Non-SSH
$\frac{0.5D}{100} < C \leq \frac{2D}{100}$	Minor
$\frac{2D}{100} < C \leq \frac{4D}{100}$	Mild
$C > \frac{4D}{100}$	Severe

C Convergency (mm)
D Diameter, width, or height (mm) of underground opening (the greater value)

Support system used for SSH ground includes Rigid Support System (RSS), and Yield/Ductile Support System (YSS). RSS is a stiff system of measures to resist against induced deformation due to SSH behaviour by absorbing entire accumulative SSH stresses. RSS is applicable for passive load configuration in gravity driven and shallow depth overburden with less arch effect; it is not recommended to be applied for tunnelling in SSH ground. YSS is designed to accommodate deformations that is induced to periphery of tunnel in SSH ground by controlled yielding to prevent/terminate accumulation of load. Application of YSS in its conventional form (CYSS) includes reaming (Figure 18a), LCN (Figure 18b), LSC (Figure 18c), YieldR (Figures 18d and 18e), YieldB, convergency measurements, and instrumentation.

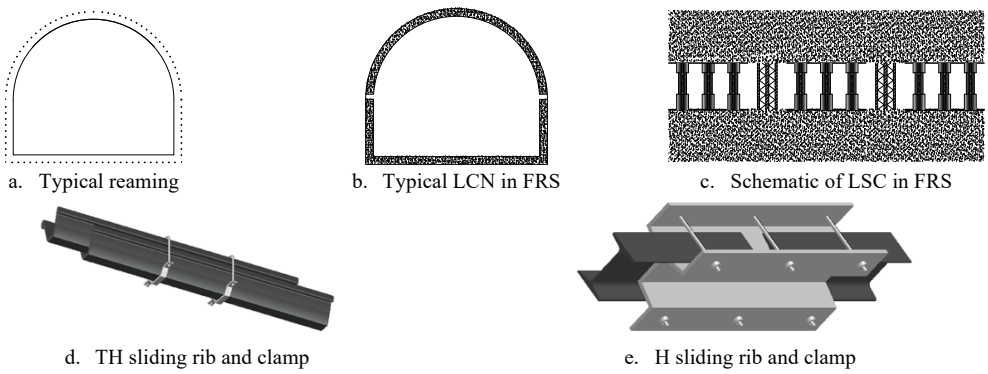


Figure 18. CYSS elements (Bineshian, 2020b)

Application of CYSS is a cost- and time-inefficient system, which includes several sequences as well as delay and hindrance in the tunnelling procedures. Consequently, SRH (Stress Release Hole/s) is developed for tunnelling under SSH condition (Bineshian, 2020b) to eliminate the hazards and challenges involved with tunnelling under SSH condition as well as lessening the hindrance and cost caused by application

of CYSS without compromise in safety. Key concept behind SRH is to divert the SSH stresses towards the uniformly distributed free spaces created by SRHs; therefore, non-uniform deformation caused by SSH behaviour is induced to the SRHs instead of their occurrence on periphery (Figure 19). Thus, further accumulation of SSH stresses also will be controlled and finally terminated. Table 19 offers requirements for application of SRH System for treatment of each class of SSH condition in tunnelling as well as requirements for CYSS. SRH System releases/terminates incremental non-uniform time-dependent shear stresses around the periphery, prevents/minimises convergency, eliminates repair or rework of primary SS, saves in cost and time and reduces hindrance compared to CYSS, and also improves efficiency of advancement (Bineshian, 2020b).

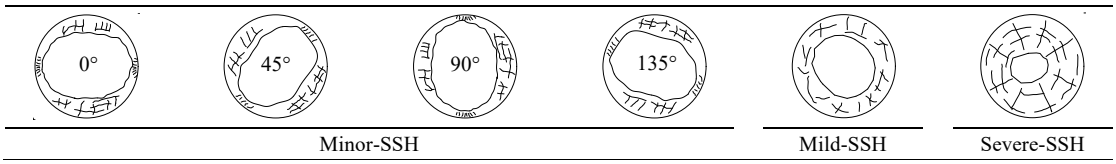


Figure 19. Illustration of observed patterns of induced deformation inside SRH (Bineshian, 2020b)

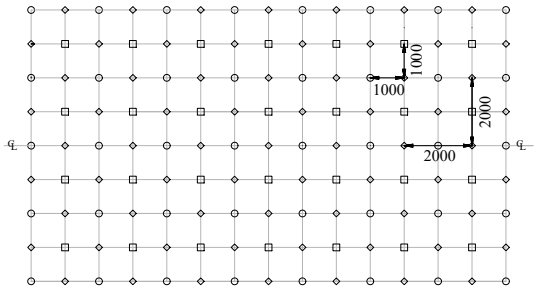
Table 19. Guideline for requirements in application of SRH and/or CYSS (Bineshian, 2020b)

Main Required Resources	**SSH-Class**					
	Minor*		Mild*		Severe*	
	CYSS	SRH	CYSS	SRH	CYSS	SRH
Reaming	n/a	n/a	a	n/a	a	a
YieldR^	a	n/a	a	n/a	a	a
LG (If TH or H profile is not used)	a	n/a	n/a	c/a	n/a	c/a
RingC<	n/a	n/a	a	n/a	a	c/a
FRS	a	a	a	a	a	a
LCN>	a	n/a	a	n/a	a	a
LSC and laxation of clamps>	a	n/a	a	n/a	a	n/a
YieldB using SysDB (L = 0.5D)	n/a	n/a	a	n/a	a	a
YieldB using SN, SDA, Swellex (L = 0.5D)	a	n/a	n/a	a	n/a	n/a
Drilling of 100 - 300 mm holes for SRH (L = 1D)	n/a	a	n/a	a	n/a	a
3DM or Chord Convergency Meter@	a	a	a	a	a	a
DIC# @ 25 m	n/a	n/a	a	a	n/a	n/a
Strain Meter @ 100 m	a	n/a	a	n/a	a	a
Pressure Cell or Load Cell @ 150 m	a	n/a	a	n/a	a	a
Single-/Multi-Rod Extensometer @ 300 m	n/a	n/a	a	n/a	a	a
Strain Gauge @ 400 m	n/a	n/a	n/a	n/a	a	a

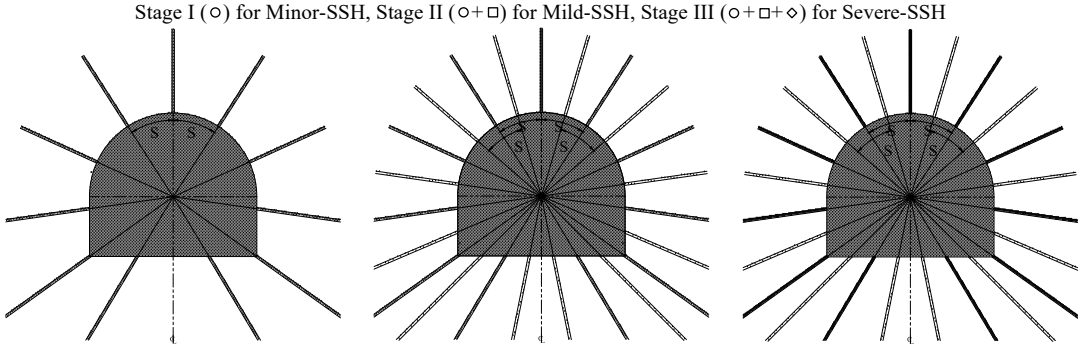
* Table 18.
^ TH or H profile capable of sliding; Figures 18d and 18e.
< Ring Closure or Invert Closure; It is recommended to be applied to prevent heaving; however, its applicability depends on observations, SSH-Class, and (I)-Class to be decided by Engineer at site.
> Figure17b; skilled team for installation and deformation control is required.
\# Bineshian et al (2021a, 2021b)
@ Spacing between the measuring stations (Table 20)
a Applicable
c/a Conditionally Applicable; applicable for (I)-07; not applicable for (I)-05 and (I)-06
D Diameter, width, or height (mm) of underground opening (the greater value)
L Length (mm)
n/a Not Applicable

SRH System is applied in a systematic pattern of large diameter drilled – using ordinary rotary percussion drilling system – holes (100 - 300 mm) in an individual system as shown in Figure 20 or combined with other measures (Table 19) depending on the severity of convergency. Continues monitoring of stresses is required when CYSS (e.g., sliding ribs and LSC) is applied, further to several periodical sequences of measurements and clamps laxation, which is time-consuming procedure that hinders the advancement. Contrastingly, SRH replaces all these sequences of CYSS with a simple systematic inexpensive drilling of holes. SRH works in a continuous no-

maintenance manner until it ends the accumulation of shear stresses and convergency. It is individually applicable for Minor to Mild-SSH condition with (I)-05 to (I)-07 without needs of CYSS. Moreover, it is applicable for Severe-SSH in combination with some elements of CYSS (Table 19). When LG is applied in combination with SRH in ground with (I)-07, it prevents occurrence of large deformation at periphery while SRH System absorbs the deformation beyond the periphery (Bineshian, 2020b).



Stage I (○) for Minor-SSH, Stage II (○+□) for Mild-SSH, Stage III (○+□+◇) for Severe-SSH



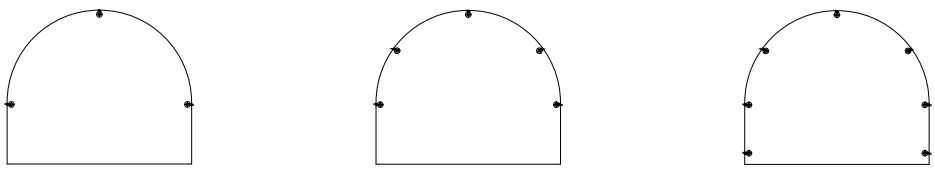
Stage I for Minor-SSH Stage II for Mild-SSH Stage III for Severe-SSH

Figure 20. SRH drilling pattern – plan and cross section views; L = D, S = 2000 mm (Bineshian, 2020b)

3DM measures for tunnelling under SSH condition is provided in Table 20. Each 3DMS may contain 3, 5, or 7 BRTs depending on the SSH-Class (Figure 21) and the size of the underground space. It is not recommended to place the final liner before termination of convergency and earlier than ending of proposed minimum period of monitoring.

Table 20. 3DM; guideline for application in tunnelling under SSH condition (Bineshian, 2020b)

SSH-Class	Number of BRTs at each 3DMS	Frequency of Reading	Minimum period of monitoring (month)	Spacing of 3DMS (m)
Non-SSH	Measures proposed at (I)-Class in I-System (Tables 9 – 12 in Section 4) is applicable; (I)-01 to (I)-10			
Minor	3	Once a fortnight	6	15
Mild	5	Once a week	9	10
Severe	7	Twice a week	12	5

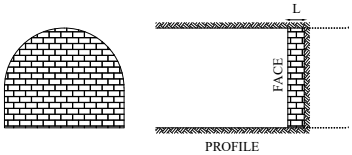


Minor SSH-Class Mild SSH-Class Severe SSH-Class

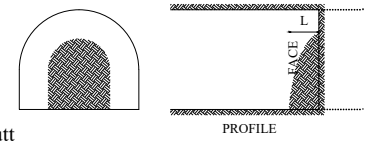
Figure 21. 3DM; illustration of configuration of 3DMS based on SSH-Class (Bineshian, 2020b)

Similarly, SRH System is applicable for tunnelling in burst prone (BP) condition; however, if TBM is used application of McNally et al (2002) support system with HEAM/WeldM is an alternative choice. Use of SRH System to control the plastic zone around the tunnel in BP load configuration is recommended with use of CtldBlast (PPV ≤ 449 mm/sec), SysDB, FRS, and HEAM or WeldM (Bineshian, 2020b).

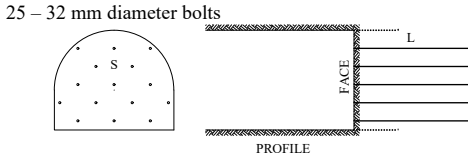
Appendix 5: Schematic Illustrations of SS



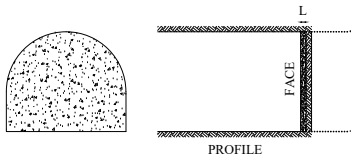
a. BulkH
L ≤ 0.15D



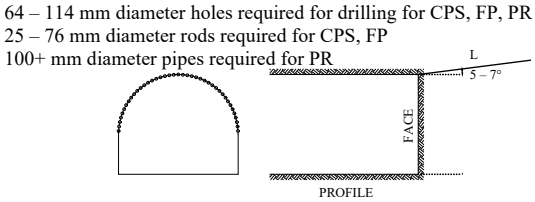
b. FaceButt
L ≥ 0.25D



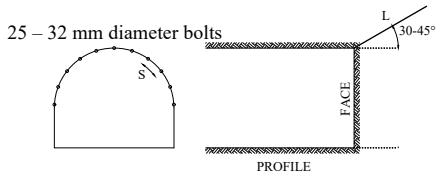
c. FaceB, FibreD
L = D and S ≤ 0.3L



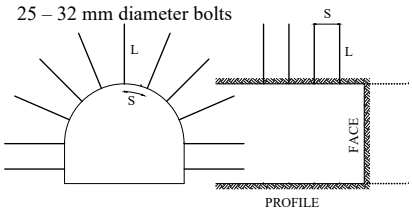
d. FaceP
L ≤ 0.05D



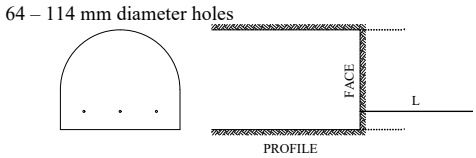
e. CPS, FP, PR
L = 0.7D to L = D



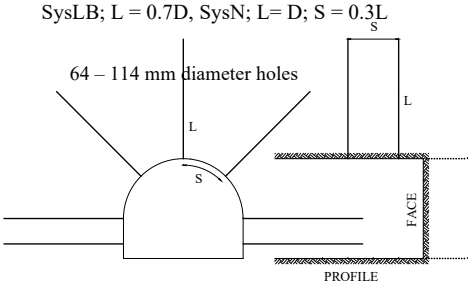
f. SysHB
L = 0.7D; S ≤ 0.3L



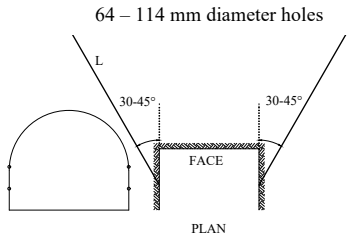
g. ConeB, SysB, SysDB, YieldB; L = 0.5D
SysLB; L = 0.7D, SysN; L= D; S = 0.3L



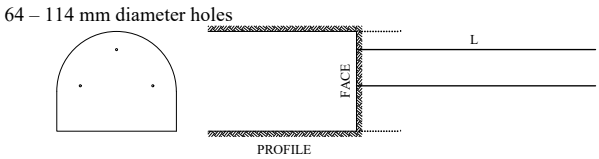
h. ADH
L ≤ 1.5D



i. RDH
L ≤ D



j. WDH
L ≤ 2D



k. BH, EC, PH
L = 2D to L = 3D

Figure 22. Schematical illustration of some SS elements proposed in (I)-Class; Sections 4 and 10

Appendix 6: Systematic Bolting Calculator

Estimation of the length of bolting system (Section 10) is summarised here in Table 21, which is proposed for (I) ≤ 50 (Tables 9 and 11) to provide an initial estimation for length and spacing of bolts as variables dependent on D; however, due to having only one independent variable without considering the ground quality, it gives less precision and accuracy in estimation of bolt parameters when ground condition varies.

Table 21. Estimation of the length of systematic bolting proposed in I-System for underground works

Bolting Parameters	**Systematic Bolting***					
	ConeB	SysB	SysDB	YieldB	SysLB	SysN
L	0.5D				0.7D	D
S	0.3L					

* Using 25-32 mm diameter steel-bar/-pole including (e.g., SDA, SN, etc.)
D Diameter, width, or height (mm) of underground opening (the greater value)
L Length of ConeB, SysB, SysDB, SysLB, SysN, YieldB (mm)
S Spacing of bolts along the both axis and transverse direction (mm)

Author proposed Eq 25 and 26 for calculation of length and spacing of aforementioned bolting systems as a function of D and (I). Eq 25 is valid for (I) ≤ 50. Systematic bolting for (I) > 50 is not recommended in I-System; instead, spot and/or individual bolting is recommended (if required). Neither to be conservative nor incautious, a comparison of output of Table 21 and Eq 25 and 26 may help to decide on bolting system's parameters.

$$L = D \times \frac{100-(I)}{100} \tag{25}$$

$$S = 0.3L \tag{26}$$

where;
(I) I-System's value
D Diameter, width, or height (mm) of underground opening (the greater value)
L Length of ConeB, SysB, SysDB, SysLB, SysN, YieldB (mm) for 25-32 mm diameter bolts
S Spacing of bolts along the both axis and transverse direction (mm)

Figure 23 provides a graph based on Eq 25 for L when D and (I) are known. An example is also shown in Figure 23 for a tunnel with D = 10,000 mm and (I) = 30; the length of the bolting system is derived as L = 7000 mm.

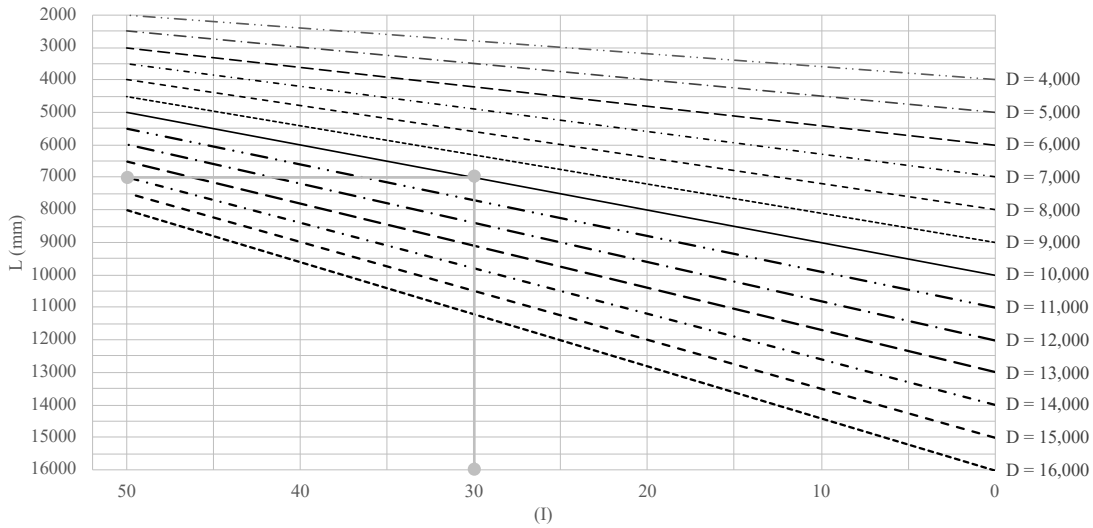


Figure 23. L graph; derivation of length of bolting systems (25-32 mm diameter ConeB, SysB, SysDB, SysLB, SysN, YieldB) as a function of D and (I) for underground spaces

Appendix 7: I-System Software – Input and Output

(I) = (Ai + Ci + Hi + Pi + Si) × DFi × ETi — Bineshian (2019)

Calculation Sheet: CH46598	Location: JK
Project: USBRL-T05	Type of Structure: Underground
Country: IN	Date: 2021/03/11

Ai - ARMATURE INDEX: 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 x D

Ci - CONFIGURATION INDEX: 5.25

pc Problematical Configuration	Sheared - High Shear Stresses - e.g. Mylonite
sc Structural Configuration	Layered (100 - 10 cm)

Hi - HYDRO INDEX: 6.50

gc Ground Conductivity (GCD) || [Wetness]	(7 - 9.99) || [Wet]
gs Ground Softness - Mohs	5

Pi - PROPERTIES INDEX: 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 - STRENGTH INDEX: 8.10

cs UCS	19 - 10 MPa
se Scale Effect	D/H = 1.20 - 0.80 & σv ≥ σh

DFi - DYNAMIC FORCES IMPACT: 0.85

(PGASD) || [ERZ] || {MSK}	(0.36g - 0.50g) || [VH] || {IX-X}

ETi - EXCAVATION TECHNIQUE IMPACT: 0.99

(ET) || [PPV mm/sec]	(ME/NonExBreak) || [< 2]

Figure 24a. I-System Software's output; Input

I-System - Index of Ground-Structure Bineshian (2019)

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 24b. I-System Software's output; (I)-Class Output

I-System - Index of Ground-Structure Bineshian (2019)

(I)-GC; I-System's Ground Characterization

(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} = -0.012 MPa

Cohesion

C_g = 1.706 KPa

Internal Friction Angle

φ_g = 28.750°

(I)-GC characterizes the ground based on (I); however, it is recommended to scrutinise it by deriving the mechanical properties of ground by standardised in-situ testing methods.

Figure 24c. I-System Software's output; (I)-GC Output

I-System - Index of Ground-Structure Bineshian (2019)

(I)-GC Chart

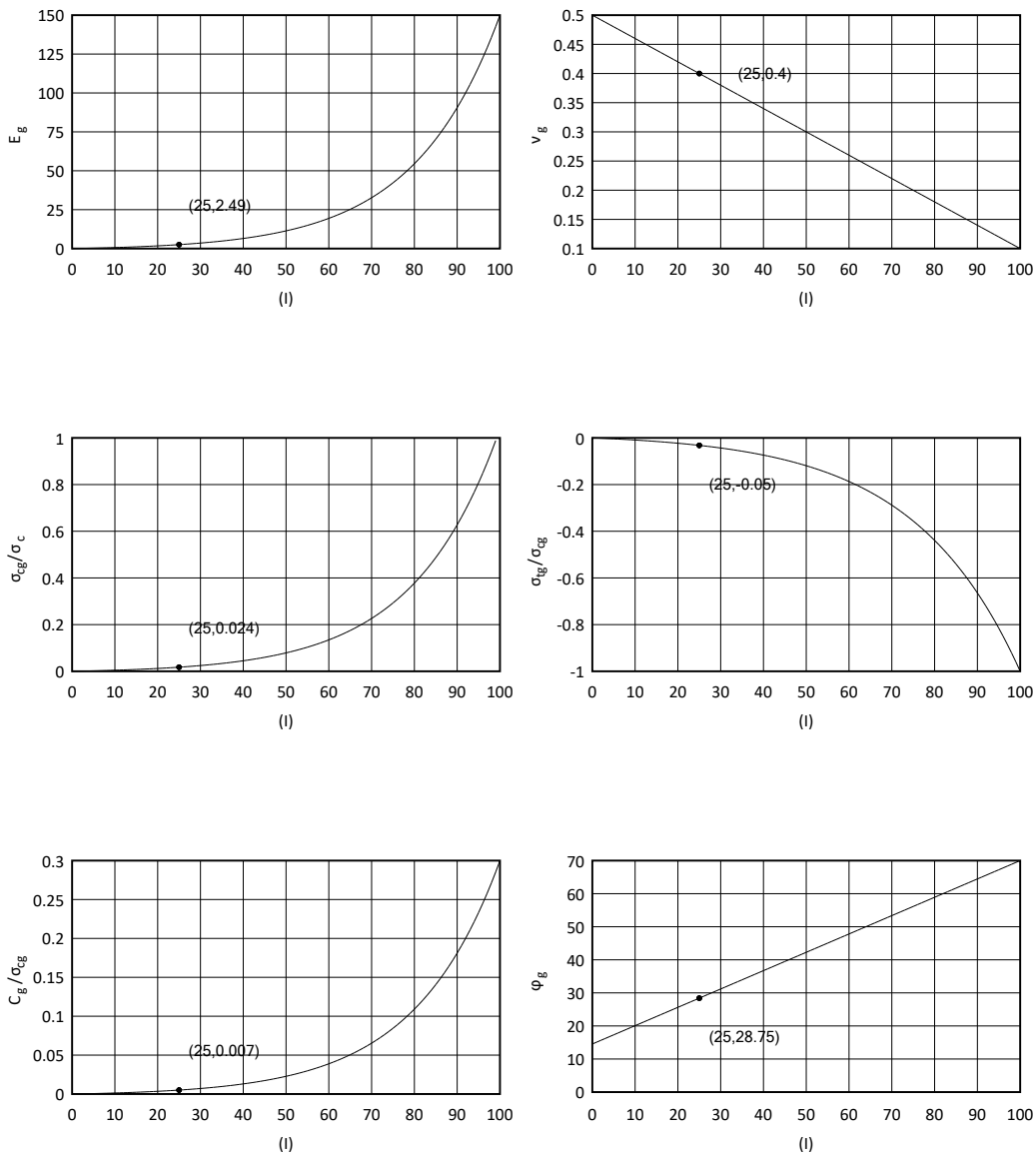


Figure 24d. I-System Software's output; (I)-GC Chart Output