Journal of Rock Mechanics and Tunnelling Technology (JRMTT)
31 (1) 2025 pp 45-65

Available online at www.isrmtt.com

Technical Note

I-GI: I-System's Ground Investigation; An All-Inclusive Cost and Time Efficient Method

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ABSTRACT

This article aims to introduce a new ground investigation method called I-GI or in full form "I-System's Ground Investigation". I-GI is a multi-component method introduced for ground investigation, which combines six stages to derive design parameters from ground. I-GI's six-stage method includes geological desk-studies, traverse geological mapping, I-Logging, geophysical survey/s, limited conventional investigation, and finalization of data collection and concluding the I-GI. The new method features comprehensiveness in applicability in any condition and project, continuity in output data, accuracy in derived design parameters, and efficiency in terms of cost and time.

Keywords: I-System; Characterization; Classification; I-Class; I-GC, I-GI; Rock mass; Soil

1. INTRODUCTION

Design parameters, which are derived from ground to be employed in I-System's recommended design approach and design procedure (Bineshian, 2021a, 2021c) needs to be accurate. These parameters, which represents mechanical properties of ground can be derived through conventional investigation, classification and/or characterization system/s, and combination of both for an efficient outcome.

Conventional investigation derives the design parameters directly from ground through field and lab tests that are known as "geotechnical investigation/s", which are quite conservative in their approach, costly, and time consuming while it is incomprehensive and inconsistent in measurement of ground's mechanical properties (see Section 6.1 for further details).

Employment of a classification and/or characterization system is also a method to estimate the ground's mechanical properties, which may not be accurate enough when design parameters' accuracy is concerned, and structure is highly design-sensitive. In case, the classification and/or characterization system is not accurate itself; then, the estimation of design parameters from that system is not appropriate.

Combination of measurements through conventional investigation with estimation through appropriate classification and/or characterization system can lead to derivation of accurate parameters for design from ground. Enabling this target requires an appropriate classification and/or characterization system. I-System (Bineshian, 2021c) is a comprehensive and accurate hybrid system contains classification and characterization both while it employs almost 27 easily derivable important parameters of ground in its equation. An investigation based on I-System may satisfy accuracy in estimation of design parameters as well as efficiency in measurement of them. This method of investigation hereinafter called I-System's Ground Investigation and in short form as I-GI. This article aims to introduce and elaborate this method, which has been tested in India and led to accurate derivation of design parameters, optimized design, and successful construction. A detailed case history will be printed in the next issue of JRMTT as a follow up. Section 2 provides a brief description about I-System as a quick reference; however, to understand it well it is recommended to study its latest edition (Bineshian, 2021c) prior to study this article. Nomenclature section at the end provides definition for parameters/abbreviations used here.

2. I-SYSTEM

I-System or in full form "Index of Ground-Structure" is an all-in-one classification and characterization system for ground (rock and soil) in accord with real condition by inclusion of almost 27 important and determinative ground properties to deliver design parameters and practical recommendation/s for sustainable design and practice in complicated ground conditions. All drawbacks and limitations of other classifications including but not limited to RMR (Bieniawski, 1973) and Q (Barton et al., 1974) are properly addressed and consequently resolved in I-System (Bineshian, 2019a, 2019b, 2021c). It is conceptually different from any existing classifications due to its wide range of input, its applicability for varieties of ground conditions and structures, and its comprehensiveness in providing accurate and precise prediction of ground behaviour based on several geo-mechanical failure mechanisms studied during development. Its range of application (Fig. 1) in design and practice includes underground structures (caverns, deep or underground metro stations, exploration/grouting galleries, mine stopes, shafts, tunnels of any type or method, underground spaces, underground storages, wells, etc.), semi-surface structures (bridge and dam abutments, deep foundations, and shallow metro stations, e.g., open-cut, cut & cover, etc.), and surface structures (embankment dams, open pits, shallow foundations, slopes, tailing dams, trenches, etc.).

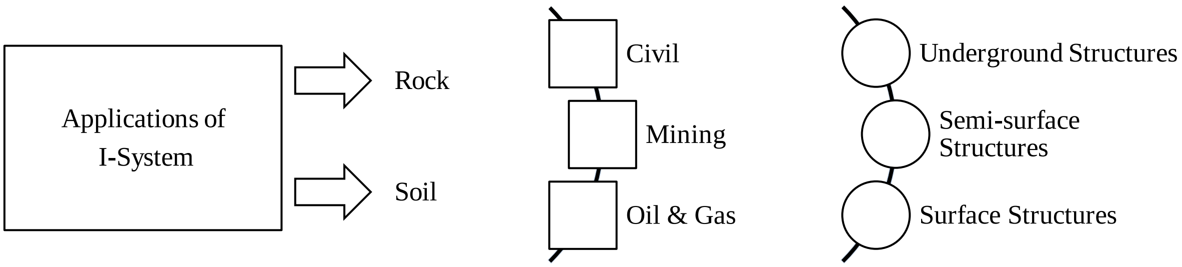
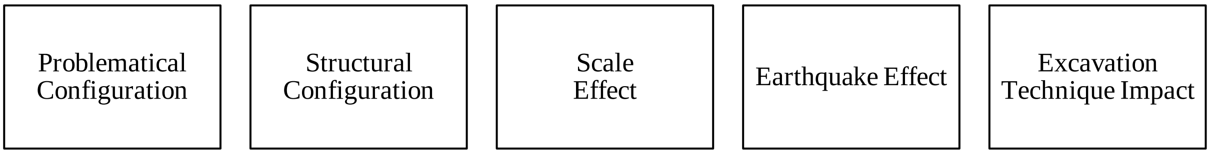


Figure 1 - Range of application of I-System

I-System is independent from RQD (Deere and Deere, 1988) and it is not a modification to any existing classifications. It is the first ever classification, which is applicable for rock and soil that considers ground's problematical and structural configurations, opening's scale effect, earthquake's negative effect, and excavation technique's impact (Fig. 2a). Besides, it is 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 (Fig. 2b).



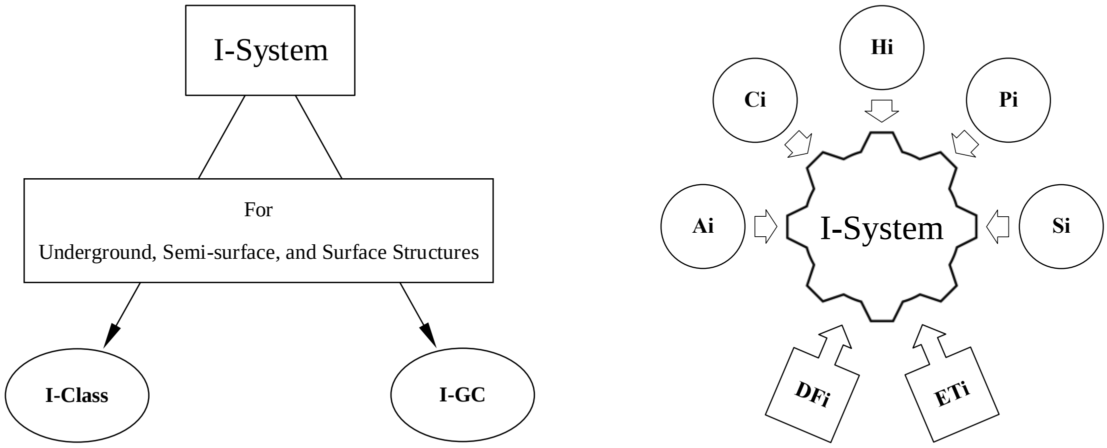
a. First ever features covered by a classification system

b. Special ground behaviour covered by I-System

Figure 2 - Most important features covered by I-System

I-System is verified in wide varieties of challenging ground conditions to ensure that a suitable estimation is obtained in classification and characterization. I-System's main output contains I-Class and I-GC (Bineshian, 2021b); see Fig. 3a. I-Class is I-System's Classification for ground that provides recommendations on determination of primary and final SS (Support System), required ET (Excavation Technique/s) for encountered condition, proper IT (Instrumentation Technique/s) for monitoring, appropriate PT (Prevention Technique/s) against possible failures, verified FT (Forecast Technique/s) to predict the ground condition ahead, and practical DR (Design Remark/s) that is helpful in understanding of ground behaviour, failure mechanism, and load configuration. The other output is I-GC, which is I-System's Ground Characterization that derives most important mechanical properties of ground including modulus of deformation (E_g), Poisson's ratio (υ_g), unconfined compressive strength (σ_{cg}), uniaxial tensile strength (σ_{tg}), cohesion (C_g), internal friction angle (ϕ_g), and ultimate bearing capacity (q_u) that can be used as input for structural dimensioning and verification 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 (Fig. 3b). 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 3b) are based on easily derivable main properties (i.e., key geomechanical, geostructural, geohydrological, geotechnical, geophysical, and geometrical features) and determinant seismic and excavation factors that affecting the ground-structure response (Fig. 2a) covered by almost 27 parameters.



a. I-System's outputs

b. I-System's engine; indices and impact factors

Figure 3 - I-System setup

Equation 1 represents I-System in a mathematical form entitled "(I)".

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

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, and

ET_i = excavation technique impact.

Unlike "Q" that ranges from 1000 to 0.001 and only applicable for rocks, I-System's value ranges meaningfully and evocatively between 100 – 0 and classifies ground-structure interaction to 10 definable 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 (Fig. 4). Definition of the parameters is available in Nomenclature section.

I-System is applicable for estimation of quality and competency of ground in relation to the structure at any scale and type irrespective of being placed underground, semi-surface, and/or surface. It assists with empirical, analytical, seismic, and observational parts of design approach (Bineshian, 2021a, 2021c) by providing most important mechanical properties of ground as output in I-GC. I-System is applicable in design procedure and/or in practice for:

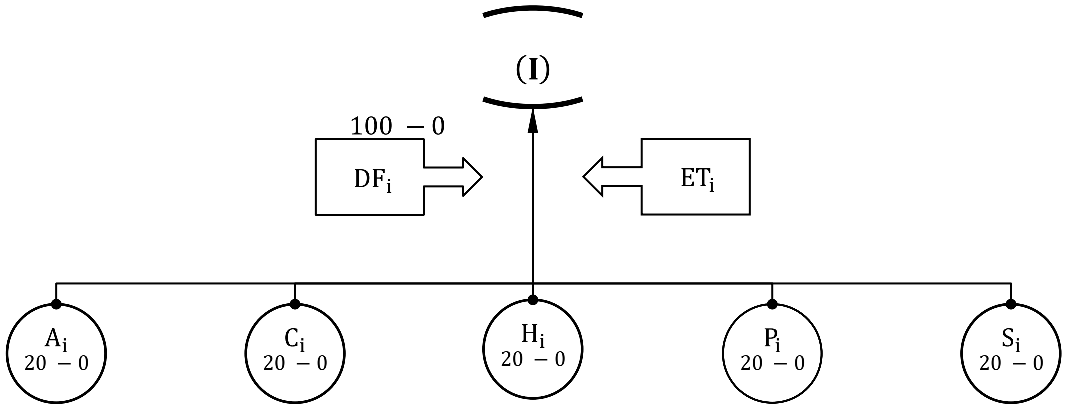


Figure 4 - I-System's scoring diagram

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

It is also applicable to (Bineshian, 2021c):
- find appropriate technique/s for excavation further to the determination of the required support system/s (ET) using I-Class,
- select suitable option for instrumentation and/or monitoring during construction (IT) using I-Class,
- implement proper technique for prevention of hazard/s (PT) using I-Class, and
- designate required technique for forecasting and/or prediction (FT) using I-Class.

I-System can easily be integrated into existing work configurations for underground, semi-surface, and surface structures, requires no special tools, equipment, or machinery, and its implementation does not necessitate significant change/s to contracts. It is developed to serve above-stated purposes for structures in the field of civil, mining, and oil and gas. By instructing the use of I-System, clients can ensure the efficient and safe completion of projects. The simplicity of the system makes it practical for on-site scenarios without the need for complex support mechanisms. Application of I-System is not limited to any particular excavation technique including but not limited to manual digging, breaking of any type, drill and blast of any type, boring of any scale and type, and so forth. Output of I-System for underground works is applicable for any existing tunnelling methods; however, underground output of I-System itself is a tunnelling method called I-TM (Bineshian, 2022b, 2022c, 2024), which is short form of I-System's Tunnelling Method.

Utilization approach of I-System is based on the steps demonstrated (Fig. 5).

I-System Software is developed in 2020 (Bineshian, 2022a) to ease the use of I-System and to ensure high accuracy and precision in calculation procedure for classification as well as characterization.

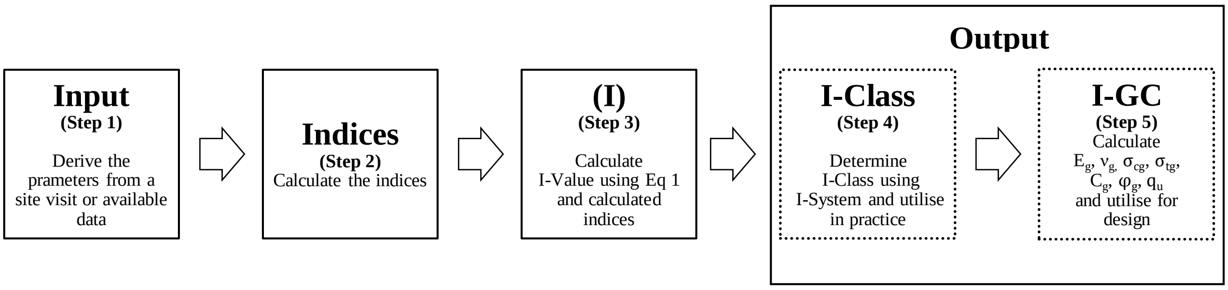


Figure 5 - Utilization diagram of I-System

I-System Software uses the same algorithm of I-System (Bineshian, 2019a, 2019b, 2020b, 2021c) and it works exactly as per the I-System's principle using the same formulations, tables, and approaches for classification as well as characterization of ground in relation to underground, semi-surface, and surface structures. I-System Software works as per following flowchart (Fig. 6):

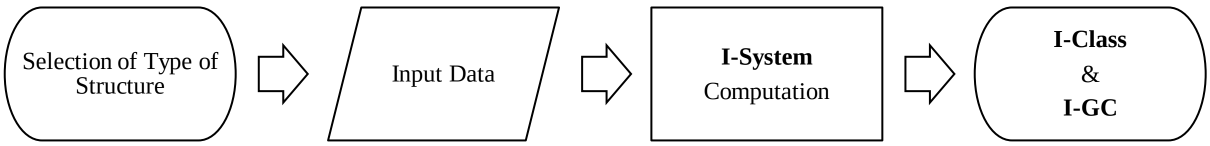


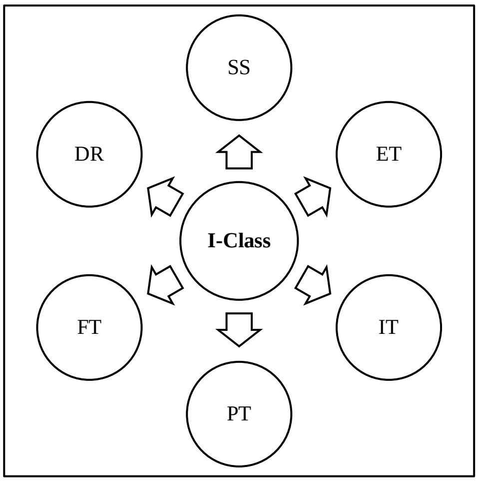
Figure 6 - Computation flowchart of I-System Software

- Type of structure includes underground, semi-surface, or surface in which the classification and characterization is going to be conducted for.
- Input data includes the same input data that considered for hand-calculation of I-System (Step 1 in Figure 5).
- Computation includes the Steps 2 and 3 in Figure 5, which is the calculation of indices and consequently (I).
- The output includes I-Class and I-GC, which is the same as Steps 4 and 5 (Fig. 5).

Besides, I-System Software provides additional output, namely, I-GC Chart that is the graphical representation of I-GC (Bineshian, 2021c). 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, 2022d). Also, other utilities included in the software that are helpful for a complete classification and characterization of ground. Summarily, output report or print of the software contains full details of input data; entered by user and processed by the software, I-Class details; computed by the software, and I-GC details and charts; calculated and plotted by the software. I-System Software is an engineering utility for classification and characterization of ground; however, it is under further development for more applications in design and practice. The software has a user-friendly interface and can deliver analyses in a short time. Minimal training is required due to the system's straightforward and confusion-free data derivation procedure from faces, making it easily adaptable for successful implementation.

3. I-CLASS

I-System's Classification entitled "I-Class" includes a hexad output, which is illustrated (Fig. 7a). 'I' ranges from 100 to 0 (Figs. 4 & 7b). 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 (Fig. 7b). Each class has 10 percent share out of 100. Recommendations for SS, ET, IT, PT, FT, and DR are provided for each class 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 as I-BP, I-TD, and I-VP (Bineshian, 2021c). Fig. 7b is a representation of table of recommendations of I-Class (Bineshian, 2021c).



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 7 - I-System's Classification output; I-Class

4. I-GC

I-System's Ground Characterization entitled "I-GC" characterizes the mechanical properties of ground (rock mass or soil mass) by quantifying most important ground's mechanical properties including modulus of deformation (E_g), Poisson's ratio (υ_g), unconfined compressive strength (σ_{cg}), uniaxial tensile strength (σ_{tg}), cohesion (C_g), internal friction angle (ϕ_g), and ultimate bearing capacity (q_u). Quantified values provided as output of I-GC are estimations based on empirical correlations (Bineshian, 2021b). Figure 8 is a representation of septet output for I-GC. This output provides most important input values required in design approach and procedure (Bineshian, 2021a, 2021c) for underground, semi-surface, and surface structures.

It is quite useful to estimate the design parameters on the basis of I-System; although, such values should be scrutinised prior to use for final design. The mathematical form of I-GC's septet output is presented in Eq. 2 to 8 (Bineshian, 2021c). Equations 9 and 10 are derivations from Eq. 8. These empirical equations are developed and examined by author for several cases (Bineshian, 2019b); however, their accuracy in estimation may improve by study on further cases.

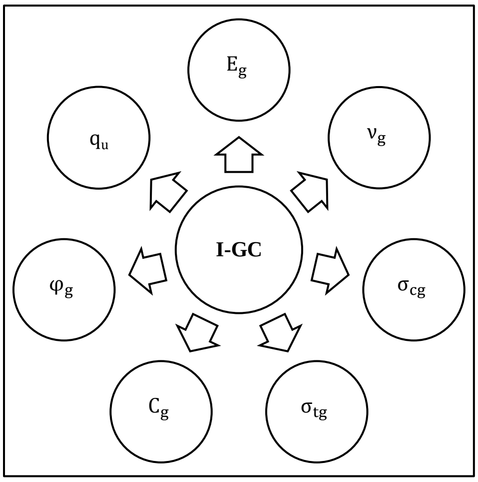


Figure 8 - I-System's ground characterization; I-GC

$$E_g = e^{0.05(I)}-1 \tag{2}$$

$$\nu_g = 0.5 - 0.004(I) \tag{3}$$

$$\sigma_{cg} = 0.007\sigma_c e^{0.05(I)} \tag{4}$$

$$\sigma_{tg} = -\sigma_{cg} e^{(0.04(I)-4)} \tag{5}$$

$$C_g = 0.002\sigma_{cg} e^{0.05(I)} \tag{6}$$

$$\varphi_g = 15 + 0.55(I) \tag{7}$$

$$q_u = 1.65(I)^2 \tag{8}$$

$$q_{nu} = 1.65(I)^2 - \gamma_g d_f \tag{9}$$

$$q_{ns} = \frac{1.65(I)^2-\gamma_g d_f}{f_s} \tag{10}$$

where

'I' = I-system's value ranging between 0 and 100,
E_g = modulus of deformation of ground - rock/soil mass (GPa),
υ_g = Poisson's ratio,
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),
q_u = ultimate bearing capacity (kPa),
q_{nu} = net ultimate bearing capacity (kPa),
q_{ns} = net safe bearing capacity (kPa),

γ_g = unit weight of ground, and
d_f = depth of foundation (mm), with f_s or $f(S)$ almost equates 3 and S stands for settlement (mm).

While Eq. 2 to 10 are applicable for (I) ranging between 0 to 100, Upadhye (2023) proposed new correlations for E_g, C_g and ϕ_g, as a function of (I) for I-Value between 20 and 40 in a specific case of ground (Upadhye et al, 2023, Upadhye et al, 2024). Lakhani (2023) in similar research (Upadhye et al., 2023, Upadhye et al., 2024) also proposed new correlations for υ_g, σ_{cg} and σ_{tg} as a function of (I) for I-Value between 20 and 40 in a project.

5. I-LOGGING

I-Logging refers to a procedure in which assists in deriving the ground parameters needed for calculation of indices and impact factors required for calculation of I-Value. I-Logging contains a straightforward face mapping to collect geohydrological, geo-mechanical, geometrical, geophysical, geo-structural, and geotechnical data as input to I-System to enable calculation of indices and impact factors. I-Logging includes 7 groups of parameters to be derived from ground (Fig. 9):

1. Armature Index's Parameters: It contains 7 input parameters to be derived from ground including discontinuity number/s, set/s, inclination, aperture, disintegration, friction, and persistency.
2. Configuration Index's Parameters: It contains 2 input parameters to be derived from ground including problematical and structural configuration.
3. Hydro Index's Parameters: It contains 2 input parameters to be derived from ground including ground conductivity (GCD-Value or Wetness) and softness in terms of Mohs.
4. Properties Index's Parameters: It contains 5 input parameters to be derived from ground including cohesiveness and denseness consistency, particles' size and morphology, and body wave velocity in terms of V_p or V_s.
5. Strength Index's Parameters: It contains 4 input parameters to be derived from ground including compressive strength of ground, scale effect input including B/H of structure and relativity of σ_v compared to σ_h, and structure's shape.
6. Dynamic Forces Impact: It contains 1 input parameter to be derived from ground including PGA_{SD} (usually derived by designer) or ERZ or MSK.
7. Excavation Technique Impact: It contains 1 input parameter to be derived from ground including excavation technique or PPV value.

Following contains practical notes for a confusion-free I-Logging in form of clarification provided to geologists, engineers, and designers who enquired during employment of I-System since release of 2021 edition:

1. *Mixed Geology:* Since, I-System in its Armature Index and Configuration Index almost covers all features of ground, mixed geology is already considered specially when the right choice is

picked for Configuration Index from the associated table. In the meantime, it should be noted that in a face or area subject to indexing by I-System, when it contains mixed condition, the governing portion is determinative.

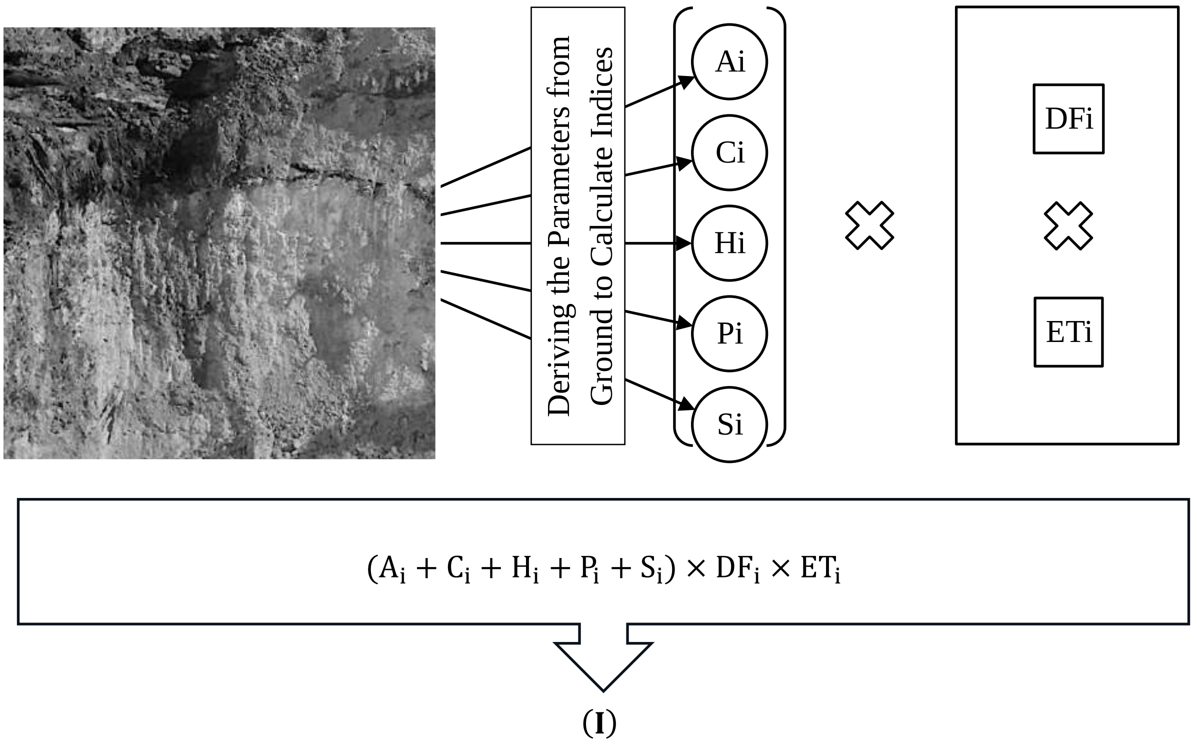


Figure 9 - I-Logging Chart

2. *Different I-Value at a Face:* Sometimes after I-Logging the value may vary for different locations of face due to scale of underground space and variable geology in a single face, which represents various ground condition (e.g., logged I-Value for left hand side is different from right hand side of tunnel face or the I-Value for upper part of slope is different from lower part). In this scenario/s lower I-Value should be considered as governing index of ground-structure for the subject face.
3. In wetness diagram, ground wetness is categorized in 10 categories including dry, humid, damp, moist, leak, wet, drip, shower, flow, gush, and burst (Bineshian, 2021c).

6. I-SYSTEM'S GROUND INVESTIGATION (I-GI)

6.1 I-GI Concept

A thorough investigation, often referred to as site characterization and/or geotechnical/ geo-mechanical investigation should be conducted for a project to understand the ground's features, properties, and condition (Bineshian, 2023). I-GI, an I-System-based method, offers a practical yet comprehensive investigation. In contrast, conventional investigation during the pre-design's study phase primarily includes vertical boreholes with defined spacing along the structure's alignment (e.g., tunnel), coring, sampling, bore-logging, and the conduction of field (in-situ) and/or laboratory phase primarily includes vertical boreholes with defined spacing along the structure's alignment (e.g., tunnel), coring, sampling, bore-logging, and the conduction of field (in-situ) and/or laboratory tests to measure physical and mechanical properties. These tests assist in deriving the geotechnical/ geo-mechanical parameters needed for design input. However, these practices are quite costly and

time-consuming, which often makes clients hesitant to invest significant resources in conventional investigation. Additionally, there are shortcomings in conventional investigation that provide clients with sufficient reasons to consider skipping them during the pre-design phase, including;

- inapplicability in inaccessible area,
- time consuming procedures at the beginning of the project/s,
- costly drilling techniques require significant investment prior to commencement of design and construction,
- spot data featuring discontinuity in range and inconsistency in the defined stretches between the boreholes that may be inappropriate for entire stretch/alignment if strata is frequently varying,
- unreachable depth of structure for conventional drilling from surface,
- inaccuracy due to single measurement at a point, and uncertainties in prediction of ground's geological features, and
- inability in prediction of ground geological setting including problematical and structural configurations.

Also, the conventional investigation is missing ground classification, ground zoning concept in design procedure (Bineshian, 2021a, 2021c), and utilization of modern geophysical survey techniques to provide continuous information of subsurface and rather providing discrete point information at drilling locations only. The concept of an I-System's recommended Ground Investigation (I-GI) for pre-design phase is to overcome above-stated shortfalls associated with conventional investigations. I-GI is based on four main assumptions;

1. offering comprehensiveness in applicability in all terrains and conditions where conventional investigation is inapplicable due to high overburden, unfavourable topography, and/or unreachable terrains for machineries,
2. providing continuity to the output data and prediction of the engineering parameters,
3. improving accuracy of output of study compared to conventional investigation by employing modern techniques/methods and making investigation time- and cost-efficient.

Considering the advantages involved with I-GI's concept, it will assist in selection of right alignment and/or optimisation of existing rout/alignment for tunnelling projects as well; if, it is implemented appropriately. Implementing a well-planned I-GI requires a procedure as elaborated in Section 6.2.

6.2 I-GI Procedure

I-GI as an I-System recommended ground investigation method includes six stages demonstrated below. For ease of explanation, a tunnel alignment is assumed as the case subject to I-GI, which is illustrated through these six stages. I-GI is complete when all the six stages executed.

Stage i - Geological Desk-Studies: This stage involves gathering information about the area, focusing on the local geological information for the project zone, including structural geology, engineering geology, tectonics, groundwater conditions, and earthquake/seismic risk zones (including but not limited to extracting information useful for estimation of A_i, C_i, H_i, P_i, S_i, and DF_i of I-System from references). Additionally, this stage assesses field conditions to determine the applicability of traverse geological mapping, conducting I-Logging, applying geophysical surveys, and executing conventional investigations. The outcomes of these assessments are crucial for decision-making in Stages ii to v. The output of this stage serves as an input for Stage ii and should be scrutinized in Stage ii as well.

Stage ii - Traverse Geological Mapping: This is a geological survey on ground surface. It should be conducted along the alignment from one portal to another by a team comprise of geologist/s and surveyor/s. The purpose is to identify geological features of discontinuities (consisting of deriving data required for calculation of A_i and P_i of I-System from ground), tectonic state and problematical and structural configuration (including deriving data required for calculation of C_i of I-System from ground), and ground water condition/s (such as deriving data required for calculation of H_i of I-System from ground). This stage further goes into details of ground compared to Stage i and should scrutinise output of desk-studies conducted in Stage i. Stage ii's output contains a tentative longitudinal geological profile as well as preliminary Data Collection (DC).

Stage iii - I-Logging: It should be conducted as per instructions provided at Section 5 using preliminary DC obtained at Stage ii. It is recommended to do the I-Logging during traverse geological mapping at Stage ii. A_i, C_i, H_i, P_i, S_i, and DF_i were calculated in Stage ii; in Stage iii, ET_i must be estimated/assumed as well. Output of the I-Logging includes tentative longitudinal I-System profile (I-Profile) along the whole alignment (e.g., calculation of I-Value at every 25 m stretch of the alignment and then preparation of I-Profile along the whole alignment). Using these outputs followings to be prepared:

- Ground Zoning (GZ; Bineshian 2021a, 2021c) along the alignment, which is a congregating of stretches with similar mechanical properties and ground class as function of I-System's output (I-Class and I-GC)
- Identification of Ground Behaviour (GB) for each Ground Zone (GZ)
- Diagnosis of associated Ground Hazards (GH) for each identified GB in each GZ

Stage iv- Geophysical Survey/s: Prior to any further investigation to collect required input for design, it is needed to conduct comprehensive geophysical surveys to ensure a thorough understanding of ground properties and conditions as an important part of I-GI. Engineering geophysics developments in the recent decades have improved the reliability and accuracy of geophysical survey results. Nowadays, the geophysical surveys can be carried out in a complex geology and at high slope areas as well with quality results. The results from these survey/s must be integrated into I-GI model to prepare for a realistic and practical design in the study phase, to refine the design for an optimised output in construction phase, and to perform a safe construction by avoiding surprises aiming to mitigate risks associated with ground condition during the execution phase.

Geophysical surveys should employ suitable resistivity, electromagnetic and/or seismic techniques, tailored to the depth of the tunnel, to accurately predict zones of water content, problematic and structural configurations of ground, and to derive essential engineering parameters for the design.

- Resistivity techniques including electrical (e.g., Electrical Resistivity Tomography/Imaging (ERT/ERI) applicable up to maximum depth of 300 m based on existing technologies; engineering geophysicists recommend dipole-dipole protocol at close electrode spacing to achieve better accuracy in data acquisition) and electromagnetic techniques (e.g., Transient Electro-Magnetics (TEM), airborne/heliborne Electro Magnetic (EM), and/or Time Domain Electro Magnetic (TDEM) survey applicable for depth greater than 300 m and up to maximum 1000 m based on existing technologies) are quite suitable for identification of water bearing zones and problematical/structural configuration of ground including but not limited to faults and shear zones.
- Seismic techniques including Seismic Refraction Technique (SRT; applicable for shallow depth up to 70 m based on existing technologies, which assists in characterization of ground properties and identification of zones with potential anomalies; e.g., faults and/or shear zones; engineering geophysicists recommend close geophone spacing to achieve better accuracy in data acquisition) and Multichannel Analysis of Surface Waves (MASW; applicable for shallow depth up to 40 m in active mode and deeper up to 100 m in passive mode based on existing technologies) assists in understanding mechanical properties of ground. Engineering geophysicists recommend employing combining results of SRT and MASW for determining engineering properties of ground, which yields reasonable accuracy.
- Seismic reflection techniques also help to characterize ground properties for much deeper depth up to 2000 m based on existing technologies; however, geophysicists recommend application of this technique for deep exploration in plain area rather than hilly zones.

The suitable geophysical technique (considering further development and advances in geophysics, newer technics/methods with higher depth of reach, accuracy, and precision may be introduced later that can be a choice in this stage as well) should be selected based on the overburden's depth and output of Stages i and ii. Output of Stages i and ii may be utilized as a tentative reference data in geophysical survey/s in I-GI. Output of this stage contains a longitudinal geophysical profile of seismic and/or resistivity survey/s, which assists in characterization of ground properties. This should be used for scrutinization of output of Stage ii and a conclusion to be made using output of Stage iii.

Stage v - Limited Conventional Investigation: It is a conventional method of investigation for geotechnical/geomechanical purposes, which comes with a range of shortfalls and difficulties in application (Section 6.1). After identification of most problematical parts/stretches along the alignment using output of Stages i-iii, very limited number of boreholes with required sampling and tests (field or lab tests) to be conducted IF POSSIBLE/REQUIRED; otherwise, if terrain is not favourable for conduction of this stage, practically it can be skipped. If Stage v is accomplished, output of Stages ii to iv can be further scrutinised using spot data obtained from Stage v during limited conventional investigation.

Stage vi - Finalisation of Data Collection and Concluding I-GI: Outputs from Stages ii through iv, and v (when available), should be conclusively synthesized to provide the necessary inputs for design. This synthesis marks the culmination of the I-GI process, setting the stage for transitioning into an optimised and realistic design post-study phase. The outputs of these stages are critical in the I-System-based design procedure (I-DP; Bineshian, 2021a, 2021c), enabling a well-informed start to the design phase. Moreover, the outputs not only guide the initial design but also offer substantial benefits during the construction phase. They facilitate design optimization and provide predictive insights to prevent unforeseen issues, thereby enabling proactive management of construction challenges. This strategic use of I-GI output helps in navigating through problematic zones effectively and utilising I-Class's recommendations as outlined by Bineshian (2021c) and briefed in Section 3. Additionally, the I-GI output serves a dual purpose by further enhancing the scrutiny of I-GC output, as referenced in Bineshian (2021b, 2021c) and Section 4. This scrutiny is instrumental in refining the design and optimizing it further during the construction phase. The integration of I-GI outputs throughout these stages not only ensures a robust design framework but also reinforces the adaptability and effectiveness of the construction process and underscoring the critical role of comprehensive ground investigation in infrastructure projects.

There are some conditions/exemptions as follows that requires to be checked prior to implementation of I-GI:

1. IF Stage ii and/or iii is not applicable (e.g., inaccessibility in urban area, which alignment is covered by buildings and/or road/s, etc.); THEN, Stage iv to be implemented after Stage i.

2. IF Stage v is not applicable (e.g., inaccessibility in difficult terrains, high overburden, and/or densely covered area by trees and/or thick topsoils, etc.); THEN, Stage vi to be implemented after Stage iv.

In addition to the proposed geophysical techniques in Stage iv, following techniques are quite helpful for data acquisition in Stage v from boreholes:

- P-S Suspension Logging: It assists in determining compression wave velocities (V_p) and formation shear velocities (V_s) of ground. Mechanical properties of ground including shear and bulk modulus, Poisson's ratio, and compressibility can be derived through this technique using measured V_p and V_s.
- Gamma Logging: It is wireline logging that can be used to characterize ground properties with good accuracy.

Figure 10 demonstrates a summary of I-GI as ground investigation recommended by I-System in a flowchart. Flowchart demonstrated in Fig. 10 is a general procedure for I-GI, which requires above-stated conditions to be considered for the case subject to ground investigation. Most accurate data are achieved when all six stages of I-GI are conducted carefully as explained in this section.

Author has employed I-GI in study phase for tunnels T33 (formerly known as T01) and T43 (formerly known as T14) in USBRL project in the state of J&K in India (Amberg, 2020, 2022, Bineshian, 2022e, 2024). Stage iv was skipped by the client for both cases due to time limitation. Outcome was satisfactory without encountering any geological surprises due to well-conducted I-GI. Conduction of traverse geological mapping and I-Logging led to preparation of an accurate longitudinal geological profile and derivation of mechanical properties, which employed in design. Geophysical survey using TSP (Choudhary and Bineshian, 2022) has been employed for scrutinization of obtained data. During construction, comparison of I-GI output with encountered data was also made. Accuracy of I-GI for T01 measured as at least 97%; the same for T14 measured as 95%, which is quite satisfactory in engineering practices. Mechanical parameters derived from ground for both tunnels were used in design with successful outcome. Construction of T14 is successfully completed and it is already commissioned. T33's excavation is completed, and it is in final stage of placement of final liner as well as electrical and mechanical facilities and ballast-less track. T33's I-System-based Design and its successful completion as a case history as a follow up will be printed in the next issue of JRMTT.

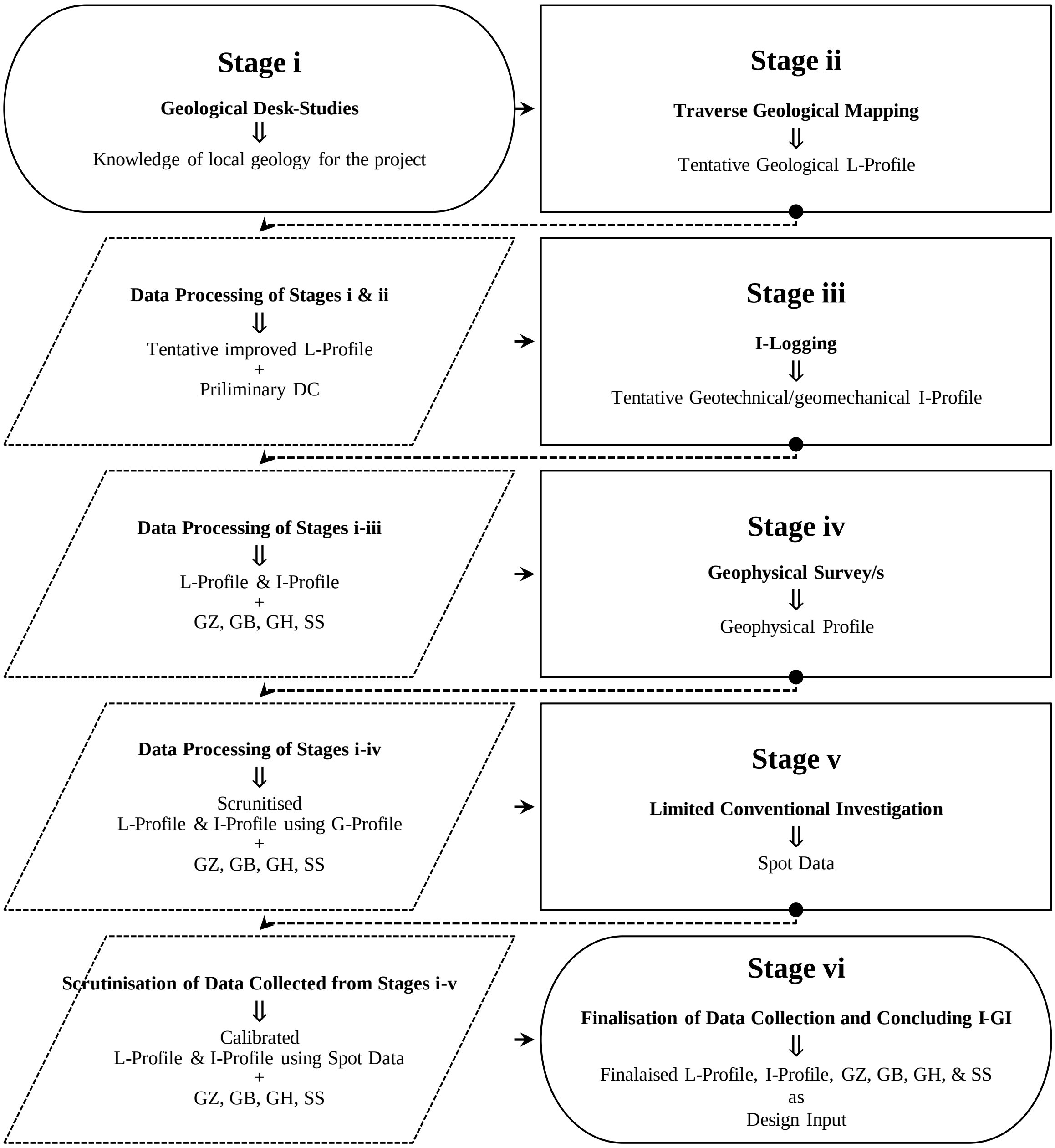


Figure 10 - I-System's recommended ground investigation; I-GI procedure

7. CONCLUSIONS

I-System is a hybrid classification and characterization system with I-GI as its ground investigation method, which developed to enhance comprehensiveness in applicability. I-GI is applicable across all terrains and conditions where conventional methods fall short, such as areas with high overburden, challenging topography, or terrains inaccessible to machineries. It aims to provide continuous data output and precise prediction of engineering parameters, enhance the accuracy of study outputs compared to conventional investigations by employing modern techniques, and ensure time and cost efficiency in investigations.

I-GI is structured into six stages including; geological desk studies, traverse geological mapping, I-Logging, geophysical surveys, limited conventional investigation, and the finalization of data collection for conclusion on conducted I-GI. This article outlines the scope and methodology of I-GI; however, a comprehensive case history as a follow up will be printed in the next issue of JRMTT.

Acknowledgment

I would like to extend my gratitude to Dr S Rana and Mr S L Kapil for their comments and remarks on review of the article. Their valuable inputs have greatly benefited the outcome.

Nomenclature

(I)	I-System's value; also called I-value
A_i	Armature index
AI	Artificial intelligence
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
BP	Burst prone – highly stressed ground condition with rock burst or coal burst behaviour
C_g	cohesion of ground (MPa)
C_i	Configuration Index
d_f	Depth of foundation (mm)
DC	Data collection; input data for I-System as well as design procedure defined in I-System
DF_i	Dynamic forces impact
DR	Design remark/s
E_g	Deformation modulus of ground - rock mass or soil mass's deformation modulus (GPa)
EM	Electro-Magnetic – a group of non-destructive geophysical methods including TEM, airborne TM, etc. based on electromagnetic properties of ground
ERI	Electrical Resistivity Imaging - a non-destructive geophysical method based on electrical resistivity using DC current; also known as ERT (Electrical Resistivity Tomography)
ERT	Electrical Resistivity Tomography - a non-destructive geophysical method based on electrical resistivity using DC current; also known as ERI (Electrical Resistivity Imaging)
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
f_s	Factor of Safety
FT	Forecast Technique/s
G-Profile	A longitudinal geophysical (seismic and/or resistivity) profile along alignment of tunnel containing seismic and/or resistivity data; it is an important element of I-GI.

Gamma Logging	A wireline logging that can be used to characterise ground's mechanical properties
GB	Ground Behaviour based on mechanical response of ground
GCD	Ground Conductivity Designation (dimensionless)
GD	Gravity Driven - flowing ground with fully plastic behaviour
GH	Ground Hazards based on failure categorisation
GZ	Ground Zoning based on ground properties
H_i	Hydro Index
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 Characterization, which provides septet of E_g, ν_g, σ_{cg}, σ_{tg}, C_g, φ_g, and q_u that are applicable in design as input parameters for design of structures in ground
I-GI	I-System's Ground Investigation
I-Logging	Derivation of ground parameters to calculate I-Value conducted by a geologist, engineer, and/or a designer
I-Profile	A longitudinal geotechnical/geomechanical profile along alignment of tunnel containing I-Value along the alignment; usually obtained during traverse on the surface of ground along the alignment as important element of I-GI.
I-System	Index of Ground-Structure; a comprehensive classification and characterization system for ground including both rock and soil media (Bineshian, 2019a, 2019b, 2020b, 2021c)
I-TM	I-System's Tunnelling Method
IT	Instrumentation technique/s
L-Profile	A longitudinal geological profile along alignment of tunnel including local geological data; L-Profile is an important element of I-GI.
MASW	Multichannel analysis of surface waves - a non-destructive geophysical method for characterization of ground
MSK	Medvedev-Sponheuer-Karnik Scale classifies seismicity as I to XII (Medvedev and Sponheuer, 1969)
P-S Suspension Logging	A geophysical technique employed in determining V_p and V_s of ground used in characterization of ground's mechanical properties
PGA	Peak ground acceleration (g)
PGA_{SD}	Scaled design peak ground acceleration (g); desired scaled PGA
P_i	Properties index
PPV	Peak particle velocity (mm/sec)
PT	Prevention technique/s
Q	Rock mass classification for tunnel supports (Barton et al, 1974)
q_{ns}	Net safe bearing capacity (kPa)
q_{nu}	Net ultimate bearing capacity (kPa)
q_u	Ultimate bearing capacity (kPa)
RMR	Rock Mass Rating (Bieniawski, 1973)
RQD	Rock quality designation by D U Deere in 1964 (Deere and Deere, 1988)
S	Settlement (mm)

SD	Structural dimensioning for each SS
S_i	Strength index
SRT	Seismic refraction tomography - a non-destructive geophysical method based on seismic refraction
SS	Support system
SSH	Squeezing/swelling/heaving (Bineshian, 2020a)
SV	Structural verification based on the definition of relative safety margin for SD
TD	Time dependent - ground condition with time dependent shearing behaviour such as squeezing/swelling/heaving condition, or even creep
TDEM	Time Domain Electro Magnetic - a geophysical survey technique in deep ground exploration employed in
TEM	Transient electro-magnetic – a non-destructive geophysical method based on electromagnetic resistivity
TSP	Tunnel seismic prediction (Choudhary and Bineshian, 2022)
V_p	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.
V_s	Shear/secondary wave velocity (m/s)
γ_g	Unit weight of ground
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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