Proc. of the 8th International Symposium on Geotechnical Safety and Risk (ISGSR)
Edited by Jinsong Huang, D.V. Griffiths, Shui-Hua Jiang, Anna Giacomini and Richard Kelly
 Published by Research Publishing, Singapore.
doi: 10.3850/978-981-18-5182-7_06-006-cd

ISGSR 2022

Stability Design for Spalling Behavior in Deep Hard Rock Tunnel under Uncertainty Using Inverse-Reliability Strategy

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Abstract: The spalling behavior is considered as a representative failure mode involved in the hard rock surrounding the deep tunnel, which has a strong influence on the resulting safety of tunnelling operations. Since the stability design for such a type of the deep hard rock tunnel is a significant aspect of geotechnical community dominated heavily by the inherent uncertainty, it is desirable to employ the reliability methods (via the reliability index or probability of failure) to produce meaningful results in a logical and realistic fashion. With the tremendous development of those reliability methods, the current design standards have an increasing tendency to guarantee stability of geotechnical structures by prescribing a target reliability index. This manifests that the reliability level of a deep hard rock tunnel is pre-defined as a target to be fulfilled. In this scenario, an inverse-reliability strategy is proposed to solve the stability problem of the deep hard rock tunnel. The basic idea behind this strategy is to, when knowing the target reliability index, how to back-calculate the design variable involved in the process of stability analysis to ensure the acceptable level of the pre-set reliability. In conformity with this strategy, an inverse first-order reliability method (IFORM) is developed and its solution procedure is also summarized. By using a typical example of the deep hard rock tunnel, the computational accuracy and efficiency are both verified in identifying the design variable pertinent to the spalling behavior. On this basis, its associated stability design is implemented, considering various levels of the target reliability index in the analysis process. By dint of the presented IFORM, the design variable relevant to the spalling behavior can be adjusted conveniently, thus providing effective guidelines which are found to be in accordance with the practical situations for the stability design of the deep hard rock tunnel.

Keywords: Deep tunnel; Hard rock; Spalling; Stability design; Inverse-reliability; Target reliability index.

1 Introduction

Tunnelling in the hard rock presents one special challenge, especially as the depth is increased, to the geotechnical researchers and practitioners, since the deformation process of the hard rock under a high-stress condition is dominated by a typical stress-induced brittle failure of the surrounding rock, called the spalling (or slabbing) behavior (Fairhurst and Cook 1966; Martin et al. 2003; Martin and Christiansson 2009). Such behavior usually occurs on the tunnel sidewalls at a certain distance in the form of rock slab-strip running parallel with the advancing tunnel face, which results, to a great extent, in a complete collapse and has a strong impact on the long-term stability of the deep hard rock tunnel (associated with some unconventional failure phenomena, like the V-shaped notch and the strain rockburst) (Hoek et al. 1995; Hoek and Brown 2019). As a consequence, the so-called spalling behavior pertaining to deep underground excavations in the hard rock poses a serious threat to the safety of tunnelling operations (e.g. when installing the support structures).

In order to investigate the mechanism of the sidewall spalling in the deep hard rock surrounding the advancing tunnel, and then provide informative guidelines to prevent the spalling-induced failure events, a number of studies on this topic have been reported in the literature and the reader may refer, among many others, to those analyzed experimentally (e.g. He et al. 2010; Jiang et al. 2017; Wu et al. 2020) and numerically (e.g. Cai 2008; Hou et al, 2013). It is worth stressing that the spalling behavior and the resulting failure phenomena may actually be considered to constitute an evaluation of the extremely serious stability risk for deep underground excavations in the hard rock (Read 2004). In this sense, the assessment of stability (or safety including strength and serviceability) for the deep hard rock tunnel in practice entails a large extent of many extraneous uncertainties. However, the existing studies mentioned above, often classified as the deterministic method to explore the rock spalling behavior, cannot explicitly reflect those uncertainties involved in the deep hard rock tunnel. It is therefore desirable to adopt a reliability-based method within a probabilistic framework to take the uncertainties into account in a more logical and realistic manner. In general, the reliability-based method with the reliability index (or the probability of failure) should be regarded as a useful supplement to the conventional deterministic method.

As of this date, the concepts and principles of the reliability-based method on tunnels and other structures relevant to underground excavations have been progressively developed, and this development have given an impetus to designing such structures for evaluating the stability. In particular, the current design standards in geotechnical engineering have an increasing tendency to ensure the stability by pre-defining a target reliability index, implying that the reliability level is decided first as a target to be fulfilled. Specifically, let an unknown parameter be a design variable, one wishes to find a certain value of this design variable such that the reliability index becomes a target value in estimating the stability. That is, when the target reliability index is known, an attempt is made to seek one effective route to back-calculate the design variable during the process of stability analysis in order to ensure the desirable level of the pre-designated reliability. Such an issue can be referred to as the "inverse-reliability" problem compared with the widely recognized "forward-reliability" problem aiming to compute the reliability index (or the probability of failure) when knowing statistical knowledge on the random variables. Notice that to cope with the "inverse-reliability" problem, one could of course employ the trial-and-error scheme in an iterative way based on the conventional "forward-reliability" analysis: the unknown design variable is selected to fall within a certain range until the reliability index calculated corresponds exactly to the required target value. Nevertheless, it should be stressed that in most environments, this type of trial-and-error schemes is quite tedious because of the tremendous computational cost, and more importantly, some numerical difficulties usually occur in conducting the repetitive "forward-reliability" analysis (Der Kiureghian et al. 1994; Li and Foschi 1998).

Considering the potential inadequacies of this treatment, an "inverse-reliability" strategy is established as a direct and transparent way of identifying the unknown design variable when the target reliability is pre-specified. Note that the analysis pertinent to the "inverse-reliability" has its origin in an early work of Birger (1970), who dealt with an inverse measure of the cumulative distribution functions with respect to the stochastic variables. Up to now, investigations performed over the past five decades on its applications have merited extensive studies for structural engineering designs (e.g. Balu and Rao 2012; Fontaine et al. 2013). However, partly because of unfamiliarity and technical language barriers, the research on the "inverse-reliability" has not attracted much attention on geotechnical applications. From authors' knowledge, only sporadic work recently appears on the application to geotechnics, say, the cantilever sheet pile walls (Babu and Basha 2008), the strip footing and the earth slope (Ji et al. 2019), as well as the shallow tunnel face (Ji et al. 2021). Also, the author and co-worker suggested, in a form of Abstract, using the concept of "inverse-reliability" as a potential way of solving tunnelling problems in rock engineering (Li and Li 2016), but did not extend this subject to real-world applications in detail. This is what has inspired the current study.

In this context, we here explore an initial application of the "inverse-reliability" strategy to handling stability design of the deep hard rock tunnel involving the spalling behavior. As a first step in this direction, an inverse first-order reliability method (IFORM) is introduced and its corresponding solution procedure is outlined. Then the present work is carried out with a typical example of the deep hard rock tunnel connected with the spalling behavior, where the computational accuracy and efficiency of the IFORM itself are both validated in determining the design variable; on this basis, the stability design is further implemented, in view of different levels of the target reliability index in the analysis process.

2 Basic Concepts of "Inverse-Reliability" Strategy

2.1 Presentation of IFORM

As elucidated earlier, the emphasis for the "inverse-reliability" strategy is mainly placed on the issue on how to reasonably identify the unknown design variable, provided a given target reliability is reached. According to such a strategy, we here give an outline of the IFORM; for more detailed exposition, please refer to Der Kiureghian et al. (1994), and Li and Foschi (1998).

First, given a target reliability index β_t, the analysis process of determining an unknown design variable ω is formulated as

$$\text{Provided } \beta_t\text{, Find: } \omega\text{, Suject to: } \min(\mathbf{U}^T\mathbf{U}) = \beta_t^2 \text{ and } G(\mathbf{U}, \omega) = g(\mathbf{X}, \omega) = 0 \tag{1}$$

where $\mathbf{U} = (u_1, u_2, \ldots, u_i, \ldots, u_n)^T$ is a vector of the standard normal variables acquired from a one-to-one mapping $\mathbf{U} = \mathbf{U}(\mathbf{X})$, and $\mathbf{X} = (x_1, x_2, \ldots, x_i, \ldots, x_n)^T$ is a vector consisting of multiple n basic random variables. $g(\mathbf{X}, \omega)$ and $G(\mathbf{U}, \omega)$ denote the performance functions in the original space and the standard normal space, respectively, and $G(\mathbf{U}, \omega)$ is considered to be the transformation of $g(\mathbf{X}, \omega)$ from the original space to the standard normal space.

Knowing the analysis process summarized in Problem (1), we now have the possibility to develop the equations used to calculate the vector $\mathbf{U}$ (at the design point in the standard normal space) and the target reliability index β_t. This can be, respectively, expressed by Eqs. (2) and (3) given as follows:

$$\mathbf{U}=\left\{\left[\left(\nabla_{\mathbf{U}}G^{\mathrm{T}}(\mathbf{U},\omega)\right)\mathbf{U}\right]\Big/\left[\nabla_{\mathbf{U}}G^{\mathrm{T}}(\mathbf{U},\omega)\cdot\nabla_{\mathbf{U}}G(\mathbf{U},\omega)\right]\right\}\nabla_{\mathbf{U}}G(\mathbf{U},\omega) \tag{2}$$

$$\beta_{\mathrm{t}}=-\left[\left(\nabla_{\mathbf{U}}G^{\mathrm{T}}(\mathbf{U},\omega)\right)\mathbf{U}\right]\Big/\left[\nabla_{\mathbf{U}}G^{\mathrm{T}}(\mathbf{U},\omega)\cdot\nabla_{\mathbf{U}}G(\mathbf{U},\omega)\right]^{\frac{1}{2}} \tag{3}$$

where $\nabla_{\mathbf{U}}G=\left(\partial G/\partial u_1,\partial G/\partial u_2,\mathrm{L}\ ,\partial G/\partial u_i,\mathrm{L}\ ,\partial G/\partial u_n\right)$, which signifies the gradient of G in regard to $\mathbf{U}$.

From Eqs. (2) and (3), we obtain the following relationship between $\mathbf{U}$ and β_{t}:

$$\mathbf{U}=-\beta_{\mathrm{t}}\left[\nabla_{\mathbf{U}}G(\mathbf{U},\omega)\right]\Big/\left[\nabla_{\mathbf{U}}G^{\mathrm{T}}(\mathbf{U},\omega)\cdot\nabla_{\mathbf{U}}G(\mathbf{U},\omega)\right]^{\frac{1}{2}} \tag{4}$$

Combining this result with $G(\mathbf{U},\omega)=g(\mathbf{X},\omega)=0$ in Problem (1), we then expand the performance function $G(\mathbf{U},\omega)$ in the standard normal space into a Taylor series around ω_0 (an initial value assumed in seeking the desirable ω)and then disregard the higher order terms, namely, truncate it with the first-order term, a linear approximation of $G(\mathbf{U},\omega)$ at ω_0 is hence found to be

$$G(\mathbf{U},\omega)\approx G(\mathbf{U},\omega_0)+\frac{\partial G(\mathbf{U},\omega)}{\partial\omega}\Big|_{\omega_0}(\omega-\omega_0)=0 \tag{5}$$

Eq. (5) can further be rearranged to obtain the design variable ω, whose representation is written in the following form:

$$\omega=\omega_0-G(\mathbf{U},\omega_0)\Big/\frac{\partial G(\mathbf{U},\omega)}{\partial\omega}\Big|_{\omega_0} \tag{6}$$

Notice that to find a solution to an acceptable ω, a special iterative scheme based on Eqs. (4) and (6) is necessary. This issue will be addressed in a subsequent subsection.

2.2 Solution procedure for IFORM

For the solution procedure corresponding to the IFORM, it can be done in virtue of the following steps:

(a) Specify an initial pair (ω_0, $\mathbf{U_0}$), in which $\mathbf{U_0}$ usually takes the mean values;

(b) Calculate the gradient $\nabla_{\mathbf{U}_0}G$ and $\partial G(\mathbf{U},\omega)/\partial\omega\big|_{\omega_0}$, respectively;

(c) Attain a new vector $\mathbf{U}$ according to Eq. (4);

(d) Obtain a new ω_0 value by means of Eq. (6);

(e) Substitute the obtained ω_0 into Eq. (4) to acquire an upgrade of $\mathbf{U}$ via successive iterations until the difference between the pairs (ω, $\mathbf{U}$) with respect to the previous iteration lies within a small pre-defined tolerance ε (varying from $10^{-4}\sim10^{-3}$) of the current one.

3 Illustrative Example of Deep Hard Rock Tunnel Involving Spalling Behavior

3.1 Background

For the purpose of justifying the developed IFORM within the framework of the "inverse-reliability" strategy, it is timely to conduct now the stability design related to the spalling behavior involved in the hard rock surrounding the deep tunnel under the condition of uncertainty. As noted earlier, we here focus on an initial application of the IFORM for deep underground excavations in the hard rock. To do so, a representative example in relatively simplified tunnelling conditions is intended to serve an illustrative purpose. This example is selected from the early and influential work by Sun and co-workers (e.g. Sun and Zhang 1985; Sun and Huang 1988), who pioneered in development of the concept of "slab-rent structure" in rock mass (e.g., the slab-strip deformation and failure caused by slab-rending of surrounding rock).

It is noteworthy that because of the formulas derivations for addressing the spalling behavior have been specifically described in the afore-mentioned literature, we here provide the associated expression directly to place emphasis on the subsequent demonstration of the proposed IFORM. In this example, a typical arch-strip model was constructed to clarify a phenomenon of the slab-strip failure caused by the surrounding hard rock spalling found to appear on the tunnel sidewalls. Based on such a mechanical model analyzed deterministically, one limit state function $g(\mathbf{X})=0$ accounting for the uncertainty can then be built, when the critical stress σ_{cr} acting on the slab-strip layer by layer exhibited near the surface of the tunnel sidewalls touches a limiting value, called the prescribed maximum allowable stress $\sigma_{\max}$. This yields the relation

$$g(\mathbf{X})=g(l,E,q)=\sigma_{\mathrm{cr}}-\sigma_{\max}=\frac{1}{S}\left(\frac{4\pi^2EI}{l^2}-\frac{1}{2}ql\sin\alpha\right)-\sigma_{\max}=0 \tag{7}$$

where $g(\mathbf{X})$ is the performance function and $\mathbf{X}$ is a random vector involving the mechanical and geometrical parameters. Notice that l, E, and q are, respectively, the height, the Young's modulus and the dead weight of the slab-strip. It is worthwhile pointing out that I and S are the moment of inertia and the area of the cross-section of the slab-strip, which are, respectively, computed by $I=bt^3/12$ and $S=bt$, in which b and t are, respectively, the unit width (i.e. $b=1.0$ m) and the thickness of a single slab-strip. In addition, α is an intersection angle for the orientation of the slab-strip with respect to the horizontal direction. Apparently, since we consider the slab-strip failure taking place on the tunnel sidewalls, it is understood that the orientation of the slab-strip and the horizontal direction form a right angle (namely, α is taken as 90°).

In our stability design for this example under uncertainty with the aid of the IFORM, the random variables and the design variable should be first provided. For those parameters mentioned above, the height l, the Young's modulus E, and the dead weight q of the slab-strip are commonly varied within a relatively wide range in realistic geological environments. Therefore, such three parameters l, E and q are regarded as the random variables, whose mean values are, respectively, 7.2 m, 40 GPa and 3.7×10^{-4} GN/m, as well as standard deviations are, respectively, 0.576 m, 4.8 GPa, 5.55×10^{-4} GN/m based on several precedents of engineering projects. In passing, it is mentioned that to demonstrate the "inverse-reliability" strategy in a form which can be understood as readily as possible, the scope of our stability design under uncertainty will be limited to a discussion of the IFORM under the assumption that those random variables are of statistical independence with normal distributions. Note further that the thickness t of a single slab-strip is intimately related to a deformation pattern during the spalling process, which plays an important role in managing the reinforcement (or remedial options) of the hard rock characterized by the slab-trips layer by layer. Consequently, the thickness t stands for the design decision to be made could be specified as the design variable in the subsequent inverse-reliability analysis by dint of the current IFORM to guarantee the stability of deep underground excavations.

3.2 Examination of results

Let us now investigate the computational accuracy and efficiency of the IFORM itself in this subsection. Before proceeding, the prescribed maximum allowable stress σ_{max}, as a limiting value in Eq. (7) should be determined. Frequently, it may be chosen in light of the deep tunnel's properties based on in situ observations and the associated design guidelines. Here σ_{max} is assigned a value of 40 MPa to illustrate the following analysis.

We begin by carrying out reliability calculations in a conventional manner, that is, calculate the reliability index in the framework of "forward-reliability". As such, the thickness t of a single slab-strip, regarded as a known parameter, is assumed to be varied as follows: 0.15 m, 0.18 m, 0.21 m, 0.24 m and 0.27 m. By using Eq. (7), the corresponding reliability index β_f (and the design point (x_l, x_E, x_q)) for each t value can thus be obtained (see Table1). In the sequel, we perform the analysis of "inverse-reliability" with the help of the developed IFORM. During the analysis process, the reliability index β_f computed within the framework of "forward-reliability" is now considered to be the target reliability index β_t pre-set in the context of "inverse-reliability" (viz., let $\beta_t = \beta_f$). Notice also that the thickness t of a single slab-strip then becomes an unknown design variable to be solved. In line with the IFORM's solution procedure depicted in subsection 2.2, the thickness t of a single slab-strip can be obtained when satisfying the pre-designated target reliability index β_t.

Table 1. Implementation of IFORM in context of "inverse-reliability"

Thickness t of slab-strip (m)	Forward reliability analysis		Inverse-reliability analysis ($\beta_t = \beta_f$)			
	Reliability index β_f	Design point in original space (x_l (m), x_E (GPa), x_q (10^{-4}GN/m))	Design point in original space (x_l (m), x_E (GPa), x_q (10^{-4}GN/m))	Design point in standard normal space (u_l, u_E, u_q)	Desirable thickness t of slab-strip to be obtained	No. of iterations
0.15	0.732661	(7.533616, 37.897743, 3.754114)	(7.533622, 37.897802, 3.754115)	(0.579204, -0.437958, 0.097505)	0.149999992307	4
0.18	2.602797	(8.247156, 31.184264, 3.872286)	(8.247289, 31.185443, 3.872343)	(1.818209, -1.836366, 0.310529)	0.179999953198	5
0.21	4.063773	(8.584124, 24.381659,3.916751)	(8.586416, 24.396780, 3.917707)	(2.406973, -3.250671, 0.392265)	0.209996712239	5
0.24	5.138037	(8.626564, 18.463322,3.903214)	(8.628346, 18.472035, 3.903931)	(2.479768, -4.484993, 0.367444)	0.239998781632	6
0.27	5.898057	(8.509713, 13.917181,3.865922)	(8.513635, 13.931585, 3.867392)	(2.280617, -5.430920, 0.301608)	0.269993801304	6

As revealed in tabular form as in Table 1, for the computational accuracy, the desirable t value (corresponding to each pre-specified β_t value) attained in the "inverse-reliability" analysis is very close and almost identical to the assumed t value (as one known parameter) involved in the "forward reliability" analysis. Also, the same is true of the design point values. For the computational efficiency, Table 1 lists the total number of iterations required in performing the analysis of "inverse-reliability" to calculate the desirable t for each pre-set β_t. Evidently, the presented IFORM can be economical to achieve reasonable accuracy through only 4~6 iterations.

Further, it should be emphasized that choosing an initial value of the design variable is the first step needed in the solution procedure, as delineated in subsection 2.2. To wit, a t value of the thickness of a single slab-strip is necessary to initiate the iteration during the solution process. Note that in Table 1, the initial value of the design variable t is designated as 0.1 to obtain the its desirable value and the corresponding design point for each target reliability index β_t in performing the "inverse-reliability" analysis. To examine the influence of an initial t value on the final results, we assume it to be varied as 0.01, 0.1, 0.5, 1 and 2. Let us take the desirable $t \approx 0.18$ at the target reliability index $\beta_t \approx 2.6028$ shown in Table 1 as an example to illustrate the implementation. Table 2 displays the final results with varying the initial t values in the iteration process. As seen from this table, the IFORM can successfully converge and yield the desirable value of $t \approx 0.18$, albeit those initial t values vary from 0.01 to 2. This indicates that when employing the IFORM, the selection of an initial t value does not impact the final acceptable t value, whereas it affects the required number of iterations, but not pronouncedly (only 5~7 iterations are needed, as seen in Table 2).

Table 2. Calculation of design variable with different initial values during iteration process

Initial value of desirable thickness t of slab-strip	Sequence of desirable thickness t (design variable) to be obtained						
	1	2	3	4	5	6	7
0.01	0.022367	0.053890	0.132603	0.167396	0.179481969512	0.179959975811	0.179999594614
0.1	0.149268	0.178656	0.179733	0.179997	0.179999953198	—	—
0.5	0.268396	0.192416	0.180166	0.179987	0.179999931670	—	—
1	0.508711	0.283110	0.196857	0.180385	0.179978056747	0.179999857727	—
2	1.004230	0.515988	0.286552	0.197832	0.180445566326	0.179976022194	0.179999838380

3.3 Stability design in context of "inverse-reliability"

After verifying the computational accuracy and efficiency of the IFORM, we now apply such a tool to addressing the issue on the stability design for this typical example formulated as Eq. (7) in context of the "inverse-reliability". As analyzed earlier, the final acceptable thickness t value of the design variable is connected with the pre-defined target reliability index β_t. Also, it is notable that the maximum allowable stress σ_{max}, viewed as a limiting value in Eq. (7) has a significant influence on the identification of the desirable t value. Hence the process of stability design involves evaluating the design variable t for varying σ_{max} to achieve the prescribed level of β_t. By doing so, the calculations are accomplished in sequence at the pre-set level of β_t, viz., the target reliability index is varied from 1.2 to 6.0: β_t = 1,2, 2.0, 2.8, 3.6, 4.4, 5.2 and 6.0. The obtained results are then translated into a design chart, where the vertical t is plotted against the horizontal σ_{max}, as illustrated diagrammatically in Figure 1.

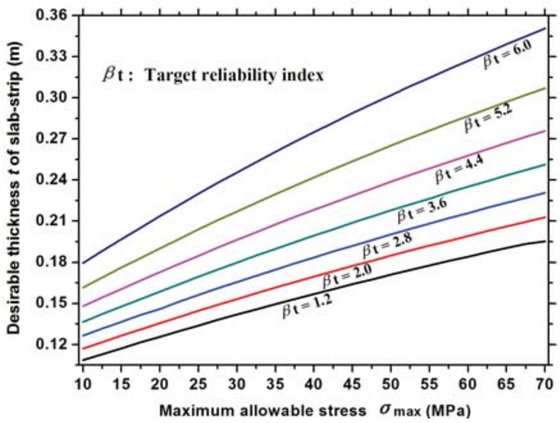

Figure 1. Stability design chart for t in reference to σ_{max} with varying β_t

Typical features observed in this figure are as follows:

(1) For a single curve with any prescribed β_t, it is clear that the desirable t increases gradually with increasing the limiting value of σ_{max}. The reason is that at a certain reliability level of β_t, a large σ_{max} means a more demanding performance requirement than a small one in evaluating the tunnel stability. This suggests the improvement in the performance requirement in response to the spalling behavior of this tunnel example. For this purpose, the desirable thickness t of a single slab-strip corresponding to, for instance, a required length of the rockbolts or cables involved in reinforcement has to be increased.

(2) If the limiting value of σ_{max} touches the same value for any reliability level of β_t, then the desirable t is on the increase once β_t gets larger. This is because the increase of pre-defined β_t will make the reliability level required for the tunnel stability has a tendency to increase. In this case, it is necessary to make an improvement in the safety requirement of this tunnel example. Therefore, when the limiting value of σ_{max} is invariable, the desirable t becomes definitely larger to avoid failure resulting from the spalling behavior.

(3) If the desirable t reaches a certain given value at all reliability level of β_t, then the limiting value of σ_{max} appearing in this figure tends to increase with the decrease of β_t. This result is ascribed to the fact that a diminishing β_t indicates the degraded performance requirement in the tunnel stability. Correspondingly, it is understood that when the desirable t remains unchanged, σ_{max} showing increasing trend will undoubtedly accelerate the formation and propagation of the spalling behavior until the failure occurs for this tunnel example.

4 Conclusions

To cope with the stability design for the spalling behavior characterized in deep hard rock tunnel under uncertainty, a practical IFORM in the context of the "inverse-reliability" was developed to fulfill this task. Distinguished from the previous work done with the traditional "forward-reliability", the present study conducted with the "inverse-reliability" aims to solve the problem of acquiring, in a direct and transparent fashion, the unknown design variable in the case where the pre-designated reliability is achieved.

As an initial step to propose the IFORM in deep underground excavations, its calculated results in accuracy and efficiency are both validated by virtue of a representative example of the deep hard rock tunnel. On this basis, the current IFORM's application within a framework of the "inverse-reliability" to the deep tunnel stability design involving the spalling behavior in the hard rock is further demonstrated with the aid of the obtained design chart. Such a type of this chart is considered helpful in the sense that it enables the designer to make informed decisions in the face of uncertainty concerning what the design variable could be at the target reliability index.

Acknowledgments

The research on which this paper is based is supported in part by the National Natural Science Foundation of China under Grants No. 51874354 and 52074350. The support is gratefully acknowledged.

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