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Reliability analysis of circular tunnel with consideration of the strength limit state

Seyed Hooman Ghasemi*[1] and Andrzej S. Nowak[2]

[1]*Department of Civil Engineering, Qazvin Branch, Islamic Azad University, Qazvin 1477893855, Iran*
[2]*Department of Civil Engineering, Auburn University, Auburn, AL 36849, U.S.A.*

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Abstract. Probability-based design codes have been developed to sufficiently confirm the safety level of structures. One of the most acceptable probability-based approaches is Load Resistance Factor Design (LRFD), which measures the safety level of the structures in terms of the reliability index. The main contribution of this paper is to calibrate the load and resistance factors of the design code for tunnels. The load and resistance factors are calculated using the available statistical models and probability-based procedures. The major steps include selection of representative structures, consideration of the limit state functions, calculation of reliability for the selected structures, selection of the target reliability index and calculation of load factors and resistance factors. The load and resistance models are reviewed. Statistical models of resistance (load carrying capacity) are summarized for strength limit state in bending, shear and compression. The reliability indices are calculated for several segments of a selected circular tunnel designed according to the tunnel manual report (Tunnel Manual). The novelty of this paper is the selection of the target reliability. In doing so, the uniform spectrum of reliability indices is proposed based on the probability paper. The final recommendation is proposed based on the closeness to the target reliability index.

Keywords: load and resistance factor; reliability analysis; target reliability; tunnels

1. Introduction

The contribution of this research is to calibrate the design codes for tunnels. In order to consider the uncertainties associated with load and resistance, the Load and Resistance Factor Design (LRFD) approach was introduced in 1950s. The LRFD approach is classified as a probabilistic design method which ensures the uniform safety level for structures. Basically, in the LRFD method, different load and resistance factors are multiplied by nominal values of loads and resistances. The procedure to determine the load and resistance factors is called as calibration procedure. The calibration procedure is consistent with the calibration of the AASHTO LRFD Code (2014) for the design of bridges. For each load component, two parameters are considered: bias factor, λ, which is the ratio of mean-to-nominal and, V, coefficient of variation. The statistical parameters of the major load components were based on the available literature and previous research by the authors of this paper. Recently there has been an increasing interest in the use of reliability methods and risk analysis in assessing the condition of structures (Chen and Xiao 2015). Liu *et al.* (2017) attempted to investigate the load carrying capacity of a rectangular segmental tunnel using a full-scale test. Based on their investigation (Liu *et al.* (2017)), the type of the failure has been recognized, however, the safety level of the tunnel has been undefined. Furthermore, Zhang *et al.* (2017) tried to based on the available literature and previous research by the authors of this paper. Liu *et al.* (2017) attempted to investigate the load carrying capacity of a rectangular segmental tunnel using a full-scale test. Based on their investigation (Liu *et al.* (2017)), the type of the failure has been recognized, however, the safety level of the tunnel has been undefined. Furthermore, Zhang *et al.* (2017) tried to find the failure mechanics of tunnels subjected to the seismic loads. They (Zhang *et al.* (2017)) also presented a deterministic safety factor for the considered tunnels. Yang and Li (2017) figured out the reliability level of the tunnel with consideration of the serviceability limit state functions; however, they did not propose the target level to conclude its implementation in the design code. Resistance is considered as a lognormal random variable and total load effect as a normal random variable. The reliability index, β, is calculated using closed form formula. Duncan (2000) proposed simple reliability analyses to evaluate the safety level of the geotechnical parameters. Li and Low (2010) used the reliability analysis to investigate the circular tunnel behavior under hydrostatic stress field. They used Monte Carlo simulation to illustrate the reliability-based design of tunnel support pressure. Langford and Diederichs (2013) presented a new reliability-based design method to analysis the safety level of a composite tunnel lining.

In this study, reliability analysis is performed for the considered tunnel sections and the results are presented in conclusion. For each of the considered tunnel sections, five segments were considered, the nominal load values were calculated using the computer program. For each tunnel section, and reliability indices were calculated for all of

∗Corresponding author, Assistant Professor
E-mail: Hooman.Ghasemi@auburn.edu

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them. Nominal resistance was determined using the design formula (factored load has to be less than factored resistance). The obtained spectrum of reliability indices was reviewed to prepare a background for the selection of the target reliability index, β_T (Ghasemi 2017b).

Probabilistic structural analysis is the sophisticated technique to optimize the structural cost and structural performance based on the required safety level. In order to formulate the probability structural analysis, we have to consider load and resistance uncertainties, it means, instead of using deterministic load and resistance value, it is necessary to utilize the statistical parameters of them. The design criteria in the new generation of design codes are based on reliability analysis. The important question that has to be answered is "What should be the reliability level?" If the considered reliability level is too low, cracking, excessive deflection, or severe damage will be occurred. If the given reliability level is too high, structure is going to be too expensive, with too much materials and so on. Therefore, there is a need to provide a rational justification for selection of the optimum reliability. Target reliability selection can be classified as follows

A) Methods based on the engineering judgment

1- Evaluation of the target reliability based on the previous experiences,

2- Estimation of the target reliability base on the other similar catastrophic (Hoshitani and Ishii (1986)),

3- Method based on the deterministic design method (Nagao *et al.* (2005) and Enevoldsen I. and Sørensen (1994)),

B) Methods based on the optimization

4- Method based on the figuring out the required cost to avoid the certain level of causalities. (Losada and Benedicto (2005) and Trbojevic (2009)),

5- Method based on minimization of expected total lifetime cost (Enevoldsen I. and Sørensen (1994) and Suh *et al.* (2010)),

6- Method based on benefit-cost analysis (Rackwitz and Joanni (2009)).

In this paper it is intended to determine the target reliability for circular tunnels based on the engineering judgment. In doing so, first the strength limit state is defined based on the load carrying capacity for bending, shear and axial loadings. Following, in order to perform the reliability analysis, it is required to determine the load and resistance distributions. In this research load and resistance distributions are defined based on the literatures and Monte Carlo simulation for the available statistical parameters including bias factor (λ) and, coefficient of variation (V). The reliability analysis is defined to presents a philosophy to how calculate the reliability index (β). Reliability indices are calculated for the considered tunnel sections and the results are presented. It is worth mentioning that a reliability analysis approached is based on the proposed method by Ghasemi and Nowak (2017b) and the statistical parameters are given from Nowak and Collins (2013). For all tunnel segments the reliability indices are computed. As the state of the art the reliability indices spectrum are delineated on a probability plot to deliberate the best selection of the target reliability index (β_T) for the given limit state. The selection of the target reliability index is considered separately for each limit state, i.e., bending, shear and compression. The selection criteria for load and resistance factors are selected that result in reliability indices closest to the target value. The number of possible options is limited because load and resistance factors are rounded to 0.05. To confirm the validity of the recommended load and resistance factors, reliability indices were calculated and presented in conclusions. Therefore, the main contribution of this paper was to deliberate the target reliability for the given failure mode for the strength limit state function. Accordingly, the corresponded load and resistance factors for the first load combination of Tunnel Manual (2009) is determined and calibrated.

2. Methodology

Limit state function is an expression of the boundary between the safe and unsafe performance of the given structural elements. A basic form of a limit state function is

$$g = R - Q \tag{1}$$

where R is the distribution of the structural resistance, Q represents the load distribution. If $g > R - Q$, is concluded that the loads is over than the structural resistance, which causes the failure. Otherwise, the member is safe. The limit state function of a structure such as a tunnel is a condition in which the performance functionality of the structure is assured. The limit state function can be established for each given design scenario (strength, service, fatigue, or extreme events). In this study the circular structure is alienated into some segment and the limit state functions are concerned for load carrying capacity of moment, shear and axial pressure. The statistical parameters of both loads and resistance are taken from previous studies conducted by Nowak and Collins (2013). Reliability metrics are calculated in terms of the reliability index which the theory of that proposed by Nowak and Collins (2013) and extended by Ghasemi and Nowak (2017a). Based on the first given definition of the reliability index, the reliability index can be determined as follows

$$\beta = -\Phi^{-1}(P_F) \tag{2}$$

where β represents the reliability index, P_F denotes the probability failure of a system, and Φ^{-1} is the inverse of the cumulative distribution of the standard limit state function. The reliability index is related to the probability of failure of a limit state function which it distributions follows a normal phenomenon. Even so, there is no confident that the probability failure distribution of the limit state function is normally distributed. Therefore, it is required to define the reliability index for non-normally distributed limit states. Here, the authors is going to use Ghasemi-Nowak reliability index which was published in 2017 Ghasemi and Nowak (2017a). Ghasemi-Nowak reliability index is a new generation of the conventional reliability indices which can be precisely computed the reliability indices for non-normal and normal limit state functions.

$$\beta = -F_x^{-1}(P_F) \tag{3}$$

where F_x^{-1} shows the inverse function of the cumulative distribution function of the given non- normally distributed limit state functions. The simplified methods also presented by Ghasemi and Nowak (2017a) which they claimed that, under certain conditions (continuous distribution), any distribution can be formulated in terms of the sum of the Gaussian function, as follows

$$f_X(x) = \sum_{i=1}^{n} a_i \mathrm{Normal}(x, \mu_i, \sigma_i) \qquad (4)$$

where, a_i is constant coefficient, which can be positive or negative. Therefore, the probability of failure is written in the form of the series of Gaussian functions. Accordingly, a Gaussian function can be converted to the fraction of a normal distribution; then, the reliability index is defined based on the summation of the reliability indices of the normal distributions.

$$\beta = a_1\beta_1 + a_2\beta_2 + \cdots + a_i\beta_i + \cdots + a_n\beta_n \qquad (5)$$

Due to the accessibility to advanced mathematical software, such as MATLAB, the procedure to determine the reliability index is going to be more convenience in engineering applications.

2.1 Calibration procedure

Objective of calibration is to determine the load and resistance factors for tunnel design. The calibration procedure is consistent with the development of AASHTO LRFD 2014 (NCHRP Report 368). The procedure includes the following steps:

Step 1. Select representative tunnel structures

A reinforced concrete circular section will be considered. This step involves analysis of the technical drawings, dimensions, identification of structural types, materials, load components, type of soil, and so on. The computer program calculated values of load effects (bending moments and shear forces) at critical locations. The obtained designs are considered as representative for the tunnel structures covered by NCHRP 12-89 (Recommended ASHTO LRFD Tunnel Design and Construction Specifications).

For each of the considered components and cross section, the calculated load values include nominal (design) dead load, live load, earth pressure, water pressure and so on. The resistance (load carrying capacity) is calculated using the AASHTO provisions for reinforced concrete and prestressed concrete design. Load components and resistance (moment and shear) are calculated as unfactored nominal (design) values.

Step 2. Formulation of limit state functions

Limit state function is a mathematical representation of the limit between acceptable and unacceptable performance of the considered structural component. A simple example of a limit state function is

$$g = R - D - E - L = 0 \qquad (6)$$

where $R =$ resistance (load carrying capacity), $D =$ dead load, $E =$ earth pressure and $L =$ live load. If $g < 0$, it means that load is larger than load carrying capacity, which means the component fails. Otherwise, component is acceptable.

For tunnel components the limit state function can include more load components such as water pressure, horizontal and vertical earth pressure, surcharge and so on. The limit state function will be formulated for each considered design case. For a circular section, the circular structure is divided into several segments and the limit state functions will include moment, shear, and compression for all considered sections, including

(a) moment for each segment
(b) shear for each segment
(c) compression for each segment

For each case, the load components will be identified and a mathematical equation will be written similar to Eq. (1). These equations will be used in the reliability analysis.

Step 3. Nominal (design) values of load components and resistance

The nominal (design) values of load components were calculated using the commercial program. These values represent moments, shear, and compression forces due to individual load components. We will use these values in further analysis.

Nominal (design resistance) will be calculated for two cases:

For the actual tunnel design (as is) as provided by computer program.

As required by the current AASHTO Specifications, i.e., using the following formula:

R_n = (factored load) $/\varphi =$ (sum of load components multiplied by load factors specified in the current AASHTO code) /φ,

where R_n = minimum nominal resistance required by the code, and φ = resistance factor.

Step 4. Statistical parameters of load and resistance

The statistical parameters will be determined for each load component and resistance. For each load components, we will need to know the cumulative distribution function (CDF). In practice we will need at least two parameters: the mean value and standard deviation. It is convenient to actually use two non-dimensional parameters: the bias factor, λ, defined as the ratio of mean-to-nominal value and coefficient of variation, V, defined as the ratio of standard deviation and the mean. For dead load, live load and earth pressure related loads, the bias factors and coefficients of variation can be taken from previous studies (Nowak and Collins 2013).

In consideration of tunnel structures, the load components occur as a combination, or simultaneous occurrence. The probability of simultaneous occurrence of extreme load values is rather limited. To represent the actual situation, special load combination models were developed. These models take into account the fact that when considering load combination, some load components take average values. However, some of the load components can be correlated, for example a horizontal earth pressure on two sides of the tunnel can be almost the same (but opposite sign). These correlations require a special approach.

Step 5. Reliability analysis procedure

Reliability analysis procedure will be selected and adjusted for application to the considered tunnel structures. Reliability will be calculated in terms of the reliability index (Nowak and Collins (2013)). For example, for the limit state function represented by Eq. (1), the reliability index, β, is

$$\beta = \frac{(R_m - D_m - E_m - L_m)}{\sqrt{{\sigma_{R_m}}^2 + {\sigma_{D_m}}^2 + {\sigma_{E_m}}^2 + {\sigma_{L_m}}^2}} \quad (7)$$

where R_m, D_m, E_m, L_m are mean values, and σ_{R_m}, σ_{D_m}, σ_{E_m}, σ_{L_m} are standard deviations. It should be noted that reliability metrics also can be calculated in terms of the non-normal reliability index which proposed and developed by Ghasemi and Nowak (2017a and 2016).

Step 6. Calculation of reliability indices

The reliability indices will be calculated for the selected representative tunnel structures, for the considered design cases and limit states. The calculations will be performed for two sets of nominal resistance values as defined in Step 4 above. The resulting reliability indices will be treated as representative for the current design (before calibration).

The results will serve as a basis for the calibration of the code for tunnels, i.e., selection of the target reliability index and then selection of the load and resistance factors.

Step 7. Selection of the target reliability index

The results of the reliability analysis will serve as a basis for the selection of the target reliability index, β_T. This Step will involve the review of calculation results in Step 6. It is expected that there will be a wide range of β values. Selection of the target depends on several considerations. The most important are consequences of failure. This means that if failure to satisfy the limit state function (i.e., have $g < 0$) is followed by serious consequences, then β_T should be high (Ghasemi and Nowak 2017a and 2017b). For example, in the calibration of ACI 318-14 (2014), β_T for columns is 4.0, while for beams β_T is 3.5, because failure of columns is considered more serious than failure of beams. Another important consideration is the cost. If safety is cheap, we buy more of it, if it is prohibitively expensive; we accept a lower safety level. Ghasemi (2017a) proposed a new objective function to find the optimum reliability index based on the minimization of the structural cost. Yanaka *et al.* (2016) attempts to establish an optimization procedure to derive the target reliability for structures with consideration of the construction cost, failure cost, maintenance cost, structural life-cycle, inflation rate, time-dependency of the load and resistance.

In this study, the target reliability will be consistent with slab design in AASHTO LRFD (2014) and ACI 318 (2014).

Step 8. Calculation of load and resistance factors

Calculation of load and resistance factors is the final step in the calibration procedure. For consistency of the code, the load factors that are not tunnel-specific (e.g. dead load and live load) will be assumed the same as in Tunnel Manual (2009). For tunnel-specific load components, the preliminary values of load factor, γ, will be determined from the formula

$$\gamma = \lambda(1 + nV) \quad (8)$$

where λ is the bias factor and V is coefficient of variation of the load component. Parameter n can be taken about 1.8-2.0 for the strength limit states (NCHRP Report 368).

The number of possible values of load factors is limited because they are rounded to the nearest 0.05. Therefore, for each load component, further calculations will be carried out for three possible values of load factor: one determined from Eq. (8), rounded off to the nearest 0.05, and two other values larger and smaller by 0.05. For correlated loads, load combination factors will be considered using the approach used in previous studies. For each considered set of load factors, the required nominal resistance will be calculated from the following equation

$$R_n = \frac{(\text{factored load})}{\varphi} = \text{sum of load components multiplied by the corresponding set of load factors} \quad (9)$$

where R_n = nominal resistance corresponding to the considered set of load factors, and φ = resistance factor. Resistance factors for reinforced concrete member will be taken consistent with the AASHTO LRFD. For comparison, the reliability analysis will also be performed for φ factors higher and lower by 0.05 than AASHTO LRFD specified values.

Reliability analysis will be performed for a wide range of combinations of load factors. The final recommendation as to load and resistance factors will be based on closeness to the target reliability index.

Step 9. Final check and presentation of results

The reliability indices will be calculated for the recommended set of load and resistance factors. The calibration procedure will be documented in the Calibration Report.

3. Load models

Load Components

The load components for the considered circular tunnel include dead load (self weight), vertical earth pressure, horizontal earth pressure, water pressure (horizontal and uplift), and live load (static and dynamic). Load models are developed using the available statistical data, surveys and other observations, and engineering judgment. Load components are treated as random variables. Their variation is described by the CDF, mean value and coefficient of variation. The load components considered in this study are shown in Fig. 1. The following notation is used:

DL = self weight of structural components (cast-in-place concrete),

superimposed dead load

live load,

impact load (due to the live load),

hydrostatic pressure,

vertical earth pressure (gravity force),

horizontal earth pressure

vertical building surcharge load,

horizontal building surcharge load,

horizontal rock load (applied on the left side acting toward the right side),

horizontal rock load (applied on the right side acting toward the left side).

The basic load combination for the tunnel structures evaluated is a simultaneous occurrence of dead load, earth and water pressure, and live load. It is assumed that the economic life time for newly designed structures is 75

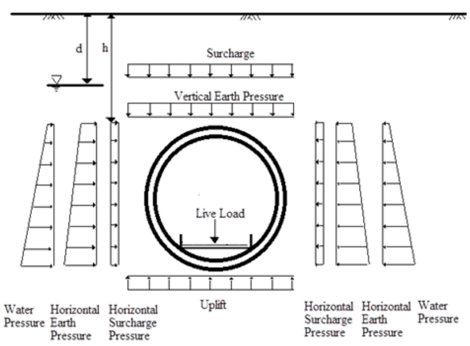

Fig. 1 Load components considered in calibration

Table 2 Statistical parameters of load components

Load Component	Bias Factor	V
Dead load	1.05	0.10
Superimposed dead load	1.03	0.08
Live load	1.25	0.18
Hydrostatic pressure	0.90	0.15
Vertical earth pressure	1.00	0.14
Horizontal earth pressure	0.95	0.15
Vertical building surcharge load	1.00	0.15
Horizontal building surcharge load	0.95	0.15
Horizontal rock load	1.00	0.12

Note: Nominal values of load components were provided by computer program. The nominal values were determined according to the Tunnel Manual (2009)

years. Therefore, the extreme values of load components are extrapolated accordingly from the available data base. The statistical parameters of all load components correspond to 75 year time period. The statistical parameters of load components are tabulated in Table 1.

4. Resistance models

The structural capacity depends on the resistance of components and connections. The component resistance, R, is determined mostly by material strength and dimensions. R is a random variable and it can be considered as a product of the following parameters (Ellingwood *et al.* 1980)

$$R = M\,F\,P\,Rn \tag{10}$$

where M = material factor representing properties such as strength, modulus of elasticity, cracking stress, and chemical composition; F = fabrication factor including geometry, dimensions, and section modulus; P = analysis factor such as approximate method of analysis, idealized stress and strain distribution model.

The variation of resistance has been modeled by tests, simulations, observations of existing structures and by engineering judgment. The statistical parameters are developed for reinforced concrete slabs and beams (Nowak and Rakoczy (2012)). Bias factors and coefficients of

Table 2 Statistical parameters of resistance based on the Nowak and Rakoczy (2012) for moment and shear carrying capacity and Monte Carlo simulation for axial load carrying capacity

Statistical Parameters of resistance*	Bias Factor	V
Flexure	1.140	0.080
Minimum practical shear reinforcement (2#3 bars)	1.26-1.19	0.15-1.35
Shear, average shear reinforcement	1.225-1.19	0.135-0.125
Axial compressive load**	1.22-1.15	0.14-0.11

*fc’ = 20.7-41.4 MPa (3000-6000 psi)
**Statistical parameters of the compression were determined using the procedure in Nowak and Rakoczy (2012)

variation are determined for material factor, M, fabrication factor, F, and analysis factor, P. Factors M and F are combined. The parameters of R are calculated as follows

$$\lambda_R = (\lambda_{FM})(\lambda_P) \tag{11}$$

where λ_R = bias factor of R; λ_{FM} = bias factor of FM; and λ_P = bias factor of P, and

$$V_R = \sqrt{V_{FM}^2 + V_P^2} \tag{12}$$

where V_R = coefficient of variation of R; V_{FM} = coefficient of variation of FM; and V_P = coefficient of variation of P.

Validity of the procedure was checked by comparison of parameters (material properties and dimensions), and analytical models, and it was concluded that the results are applicable to tunnel structures.

Statistical data on material and dimensions used in previous report (NCHRP Report 368) was based on the available literature. Recently it was observed that the quality of materials such as reinforcing steel and concrete has improved over the years. Therefore the material database has been updated, and so updated parameters were used (Nowak and Rakoczy (2012), Celik *et al.* (2012), and Campana (2014) as shown in Table 2.

The other required statistical parameters of loads and resistance are taken from previous studies conducted by Ghasemi and Nowak (2017b).

5. Reliability analysis

Limit states are the boundaries between safety and failure. Structures can fail in many ways, or modes of failure, by cracking, corrosion, excessive deformations, exceeding carrying capacity for shear or bending moment, local or overall buckling, and so on. Some members fail in a brittle manner, some are more ductile. In the traditional approach, each mode of failure is considered separately. There are two types of limit states. Ultimate limit states (ULS) are mostly related to the bending capacity, shear capacity and stability. Serviceability limit states (SLS) are related to gradual deterioration, user’s comfort or maintenance costs (Ghasemi and Nowak 2017b). A traditional notion of the safety limit is associated with the ultimate limit states. For example, a beam fails if the moment due to loads exceeds the moment carrying capacity. Let R represent the resistance (moment carrying capacity) and Q represent the load effect (total moment applied to the considered beam). Then the corresponding limit state function, g, can be written, (see Nowak and Collins (2013)).

The reliability index, β, is defined as a function of P_F. This paper used Nowak and Collins (2013) formula to compute the reliability index, which is shown in Eq. (1).

There are various procedures available for calculation of the reliability index, β. These procedures vary with regard to accuracy, required input data and computing costs.

The simplest case involves a linear limit state function (Eq. (1)). If both R and Q are independent (in the statistical sense), normal random variables, then the reliability index is

$$\beta = \frac{m_R - m_Q}{\sqrt{{\sigma_R}^2 + {\sigma_Q}^2}} \tag{13}$$

where m_R = mean of R, m_Q = mean of Q, σ_R = standard deviation of R and σ_Q = standard deviation of Q. If R is normally distributed and Q is lognormal random variables, then β The formula for reliability index can be expressed in terms of the given data (R_n, λ_R, V_R, m_Q, σ_Q) and parameter k.

$$\beta = \frac{m_R - m_Q}{\sqrt{{\sigma_R}^2 + {\sigma_Q}^2}} \tag{14}$$

where V_R = coefficient of variation of R, σ_Q = standard deviation of Q, and k is a constant variable which can be taken as 2 for initial guess (See Nowak and Collins (2013)). A different formula is needed for larger coefficients of variation.

Eq. (14) requires the knowledge of only two parameters for each random variable, the mean and standard deviation (or coefficient of variation). Therefore, the formulas belong to the second moment methods.

6. Reliability indices for tunnels

The code calibration is based on calculations performed for a selected set of structures. The selection was based on structural type, dimensions (radius = 11 ft. [3.35 meter]) and cover depth (depth to crown ranged between 54 to 71 ft. [16.45 to 21.64 meter]).

The basic design requirement according to the Tunnel Manual (2009) is given by formula in Eq. (1). The reliability indices are calculated for reinforced concrete slabs and the limit states (moment, shear, and compression) described by the representative load components and resistance.

For the selected structures, moments, shears, and compression are calculated due to applied load. Nominal (design) values can be calculated using the current Tunnel Manual (2009) the mean maximum 75 year values of loads are obtained using the statistical parameters presented in Table 1. Resistance is calculated in terms of the moment carrying capacity, shear capacity, and axial load carrying capacity. For each case, the minimum required resistance, Rmin, is calculated as the minimum R which satisfies the design manual. For given loads, Q_i, the minimum required resistance, Rmin, according to design manual can be calculated as follows, (see Nowak and Collins 2013).

Table 3 Load factors specified in Tunnel Manual (2009)

	Load Factor	
Loads	Min	Max
Dead	1.25	0.90
Other dead	1.50	0.65
Earth Pressure	1.35	0.90
Surcharge	1.50	075
Live	1.75	1.75
Water Pressure	1.75	1.00

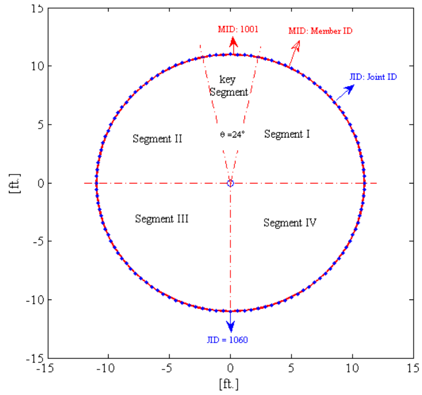

Fig. 2 Considered segments for tunnel's cross section

$$\text{Rmin} = \left(\sum \gamma_i Q_i\right)/\varphi \tag{15}$$

where γ_i are load factors. The load factors specified in the Tunnel Manual (2009) are listed in Table 3.

In Tunnel Manual (2009) resistance factors for moment is considered $\varphi = 0.90$ for shear recommends $\varphi = 0.85$ and for compression represented $\varphi = 0.75$, for concrete structure. The reliability indices are calculated for moment and shear. For each considered case, given are: mean total load, m_Q, standard deviation of total load, σ_Q, nominal (design) value of resistance, R_n, and the reliability index, β. Bias factor for resistance for various cases are listed Table 2.

Regarding the design criteria, in this study the strength limit state (Ultimate Limit State) of the circular concrete tunnel was investigated. Ultimate limit states (ULS) are mostly related to the bending capacity, shear capacity and stability of the structure. For circular tunnels, the tunnels were divided into several segments, and the load carrying capacity of the concrete structures were calculated based on the pervious and proposed load combinations. Also, the type of the soil was depends on the considered station of the tunnels, which tabulate in the following table.

In order to compute the reliability indices, the tunnels are divided into five segments (see Fig. 2). It is assumed that each segment is designed to resist the maximum moment, shear, and axial load within the considered segment.

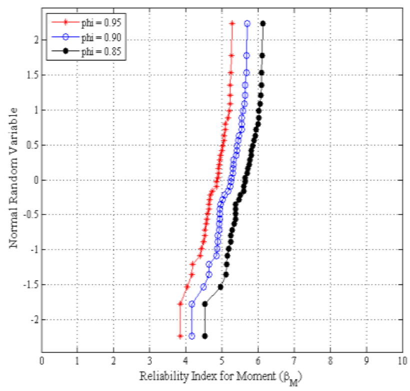

Fig. 3 The reliability indices for moment and different values of resistance factor, using the Tunnel Manual (2009) load factors

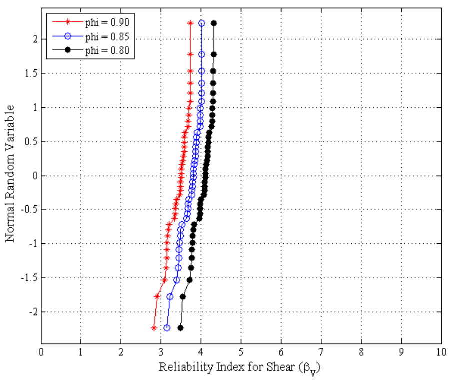

Fig. 4 The reliability indices for shear and different values of resistance factor, using the Tunnel Manual (2009) load factors

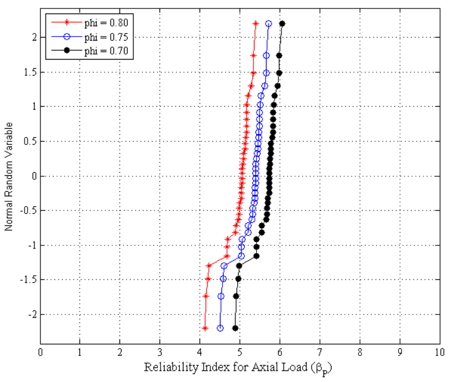

Fig. 5 The reliability indices for compression and different values of resistance factor, using the Tunnel Manual (2009) load factors

The nominal resistance is determined using the factored loads, with load factors from the Tunnel Manual (2009). Then, using the statistical parameters of load and resistance, the reliability indices were calculated for all the cross sections. For each case, the calculations were performed for three values of resistance factor: which the middle value was taken from Tunnel Manual (2009), and two other values larger than smaller by 0.05 (see Tables 3-5).

The main contribution of this paper was to deliberate the target reliability for the given failure mode which was

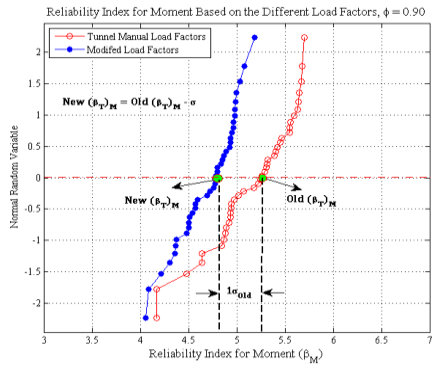

Fig. 6 Graphical approach for selection of the target reliability index using Ghasemi-Nowak (2016)

Table 4 Proposed target reliability

Failure Mode	β_T
Moment	4.75
Shear	3.50
Compression	5.00

Table 5 Proposed new load factors

Load Combination for Strength Limit I	Max	Min
live load	1.75	
impact load	1.75	
hydrostatic pressure	1.00	
self-weight dead load	1.25	0.90
superimposed dead load	1.50	0.65
vertical earth pressure	1.35	0.75
horizontal earth pressure	1.35	0.75
vertical building surcharge load	1.35	0.75
horizontal building surcharge load	1.35	0.75
horizontal rock load	1.35	0.75

summarized in Table 4. Accordingly, the corresponded load and resistance factors were proposed in Table 5.

Fig. 6 shows the graphical approach to how to select the target reliability index using Ghasemi-Nowak approach (2016).

Based on the proposed lifecycle consideration theory by Ghasemi (2017a), the new target reliability index is selected for 150 years lifetime. Briefly, the new target reliability is selected one standard deviation from the average target reliability. Based on the review of the obtained reliability indices, the target reliability indices can be selected. Since the considered tunnel sections perform adequately, it can be concluded that the acceptable range of Target Reliability, β_T, can be ranged between 4 to 6. Therefore, based on the obtained result, the proposed target reliability indices are as listed in Table 4.

As can be seen in Figs. 3-5, by decreasing the resistance factor, the reliability indices are increased. To obtain a more uniform spectrum of reliability indices, some adjustment of load factors were considered. The recommended set of load factors is shown in Table 5.

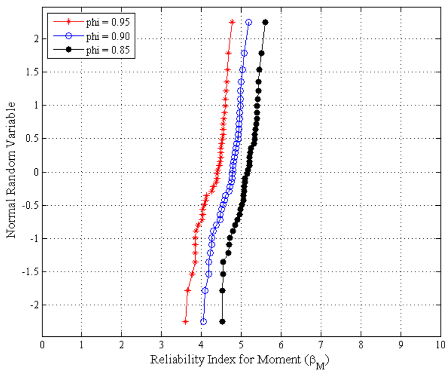

Fig. 7 The reliability indices for moment and different values of resistance factor, using the proposed load factors

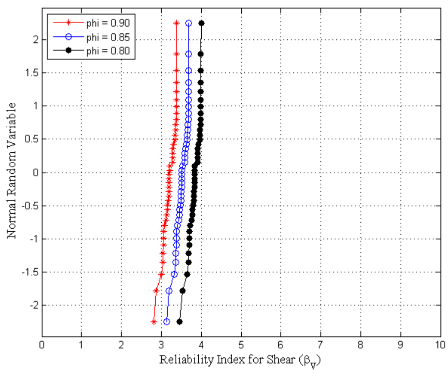

Fig. 8 The reliability indices for shear and different values of resistance factor, using the proposed load factors

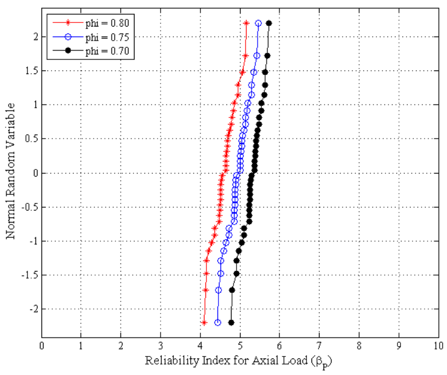

Fig. 9 The reliability indices for compression and different values of resistance factor, using the proposed load factors

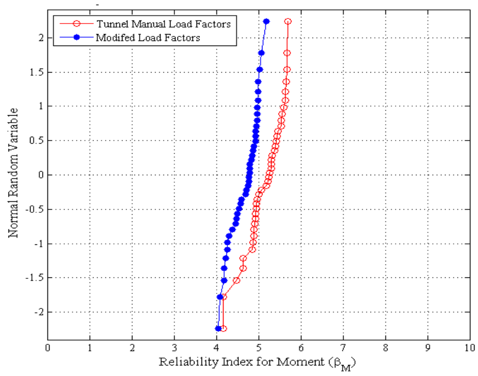

Fig. 10 Comparison between the load factors in Tunnel Manual (2009) and new modified load factors (moment carrying capacity)

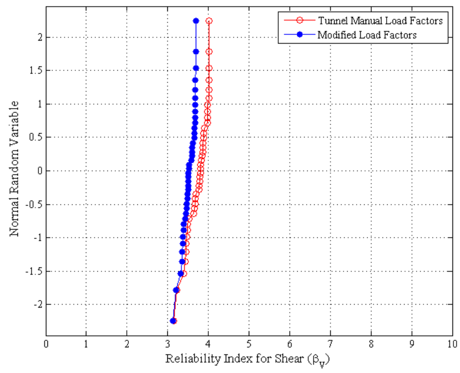

Fig. 11 Comparison between the load factors in Tunnel Manual (2009) and new modified load factors (shear carrying capacity)

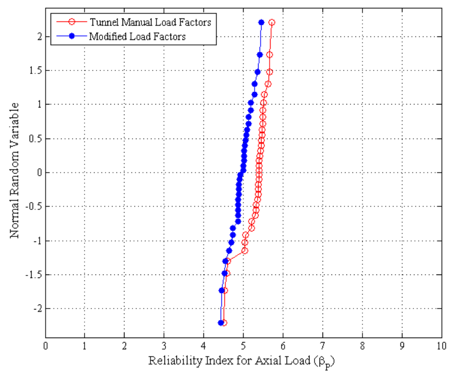

Fig. 12 Comparison between the load factors in Tunnel Manual (2009) and new modified load factors (axial load carrying capacity)

Figs. 7-9 depict the reliability indices for moment, shear and compression based on the recommended load factors.

A comparison of the reliability indices obtained for the design using the load and resistance factors specified in the Tunnel Manual (2009) and the proposed load factors is shown in Figs. 10-12 for moment, shear and compression, respectively.

By comparison between variation of the reliability indices based on the Tunnel Manual (2009) load factors and proposed load factors, using the new load factors represents noticeably more constant reliability indices.

As the limitation of this study it should b noted that in this study the considered limit state function refers to the strength limit state of the tunnel lining with consideration of the several linear elastic failure modes (moment, shear, axial), which is related to the first load combination of the tunnel manual. However, in order to investigate the other load combination which may lead to the different type of the failure the other limit state functions such as the serviceability, fatigue, or even the extreme events should be considered. In addition, the present study, determine the target reliability based on the comparison technique.

Table 6 Selected target reliability indices

	φ	β_T
Moment	0.90	4.75
Shear	0.85	3.50
Compression	0.75	5.00

Table 7 Average target reliability of the tunnels resulting from Tunnel Manual (2009) load factors and proposed load factors

Failure mode of the Strength Limit State I	φ	β	
		Old	Proposed
Moment	0.85	5.59	5.11
	0.90	5.17	4.69
	0.95	4.78	4.29
Shear	0.80	4.05	3.85
	0.85	3.75	3.52
	0.90	3.45	3.22
Compression	0.70	5.66	5.31
	0.75	5.31	4.95
	0.80	4.97	4.60

However, the optimization approaches is the new sophisticated method to determine the target reliability (Ghasemi 2014). The major factors that effect of the selection of the optimized target reliability are consequences of failure, lifetime of the system, and costs. Therefore, it is necessary to consider the various components of costs to develop an optimization procedure for calculation of the target reliability that corresponds to the minimum total expected cost. This research area is expected to grow in the future in response to the demand for more economical structures.

7. Conclusions

This researched was planned to determine the required safety level for the tunnels. In doing so, the probability based design approach was considered. In this study, the target reliability index was proposed based on the consistency of the obtained reliability indices. For all tunnel segments the reliability indices are computed. The reliability indices spectrum was delineated on a probability plot to deliberate the best selection for the target reliability index, β_T. As the result the optimum target reliability indices were proposed. The proposed reliability indices were utilized to determine the load and resistance factor of tunnels. The novelty of this paper stems from the selection of the target reliability, where the uniform spectrum of reliability indices was proposed using probability paper.

Target reliability indices and corresponding φ factors are listed in Table 6.

The major proposed change is adjustment of the load factors. The recommended load factors are as follows (for each load components two load factors are provided, one for maximum value and the other for minimum value):

Dead load	1.25/0.90
Horizontal rock pressure	1.35/0.75
Superimposed dead load	1.50/0.65
Horizontal earth pressure	1.35/0.75
Vertical earth pressure	1.35/0.75
Horizontal surcharge pressure	1.35/0.75
Vertical surcharge pressure	1.35/0.75
Live load and dynamic load	1.75/0.00
Water pressure	1.00/0.00

Reliability indices were calculated using these proposed load factors and φ factors from the Tunnel Manual (2009). For comparison, the average values of φ were also calculated for the load factors from the Tunnel Manual (2009). In addition, the calculation were also performed for φ+0.05 and φ–0.05. The results are shown in Table 7.

Reliability indices were calculated using these proposed load factors and φ factors from the Tunnel Manual (2009). For comparison, the average values of φ were also calculated for the load factors from the Tunnel Manual (2009). In addition, the calculation were also performed for φ+0.05 and φ–0.05. The results are shown in Table 7.

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