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Reliability Analysis of Seismic Bearing Capacity of Bridge Foundation on Slope: A Case Study on Simaltar Khola Bridge

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Abstract

This research studies about the co-relation of reliability index and factor of safety with respect to ground seismicity, ground slope and depth of foundation. Simaltar Khola Bridge is considered for the study purpose. It uses Taylor's series approximation to evaluate the reliability, varying different parameters like horizontal ground acceleration, ground slope, depth of foundation, coefficient of variance. The sensitivity analysis is carried out by adjusting each parameter by 30% above and below the original (normal) value by 10% in increment and decrement order, while leaving the other parameters constant. The finding of this research determines that ultimate seismic bearing capacity is 580.754 KN/m^2, factor of safety is 2.927, and reliability index is 4.418 for horizontal ground acceleration 0.34g; all of them lies within the acceptable range. Factor of safety is most sensitive to horizontal ground acceleration, and also sensitive to other factor like ground slope and foundation depth than reliability index. Reliability index is most sensitive to coefficient of variance of soil internal frictional angle.

Keywords

Reliability index, Factor of Safety, Seismic Bearing Capacity, Shallow foundation, Sensitivity Analysis

1. Introduction

Estimation of ultimate bearing capacity is the important factor to decide the safe foundation design. Ultimate Bearing Capacity means intensity of loading at the base or the foundation which would cause shear failure of the soil support (BIS:6403, 1981)[1].The deterministic method and the probabilistic approach are the two main design approaches in geotechnical engineering. The deterministic approach involves determining the permissible bearing capacity using well-known formulae and charts. It is well known that the input parameters for geotechnical computations are related to uncertainty. To accommodate for the uncertainty, the ultimate bearing capacity is usually given a single factor of safety value. There is no way to make a mathematical estimate of risk because the factor of safety estimated in this approach is primarily based on experience and judgment. This traditional deterministic technique may be insufficient or overestimated, resulting in unreliable or cost-ineffective construction. A reliability analysis is thus essential for a reliable and cost-effective design.

Due to the regional heterogeneity of soil and load qualities, limited site exploration, limited calculation models and uncertainties in soil parameters, foundation behavior predictions cannot be determined with certainty. The uncertainties that enter the formulation of a geotechnical problem can be defined and evaluated using reliability-based studies. If a deterministic model for the analysis of a geotechnical problem already exists, a probabilistic analysis model can be quickly created using today's techniques. The fact that measuring uncertainty is difficult is not a good justification to avoid defining them or determining their significance in design. All this facts create the necessity of probabilistic/ reliability analysis in geotechnical solution. Reliability analysis incorporates the uncertainty and variability of soil properties. In reliability analysis, all possible random variables that represent the uncertainty and variability of soil properties are considered and assessed in terms of the reliability index, which is the shortest distance from random variables to the failure region. The main purpose of the research is to study the reliability of estimated seismic bearing capacity for shallow foundation on slope. The main study question is how the several independent parameters used to measure ultimate bearing capacity are related to the factor of safety and reliability index.

2. Literature Review

General equation of ultimate bearing capacity, proposed by (Terzaghi, 1943)[2], has been modified by (Meyerhof, 1951),(Hansen, 1970)[3] and (Vesic, 1973)[4] to address the problem of various shape, depth of foundation and inclined loads on foundations. Theoretical method to predict the ultimate bearing capacity of a shallow foundation positioned on the slope's face or near the top edge was proposed by (Meyerhof, 1951)[5]. Later on, (Hansen, 1970)[3] provided equation for the ultimate bearing capacity of a continuous foundation at the slope's edge with slope factors. Limit analysis was utilized by (Richards et al., 1993)[6] to derive formulas for seismic bearing capacity factors that are directly connected to their static counterparts. They noted that the decrease in foundation capacity is due to both seismic degradation of soil strength and lateral inertial forces transferred by shear to the foundation through the structure and any surcharge using a coulomb-type mechanism with inertial forces in the soil and on the footing.(Budhu & Al-Karni, 1993)[7] concluded the bearing capacity coefficients are greatly affected by horizontal accelerations, as well as soil cohesiveness and vertical accelerations. The designer can evaluate the seismic bearing capacity coefficients from the static ones using the limit equilibrium solution given in this paper. To obtain Seismic bearing capacity of shallow strip footings,(Choudhury & Subba Rao, 2005)[8] used the Limit equilibrium method of analysis with composite failure surface to obtain pseudo-static seismic bearing capacity factors N_{cd}, N_{qd}, and $N_{\gamma d}$. Both horizontal and vertical seismic acceleration coefficients have been found to severely reduce ultimate bearing capacity. (Saran & Rangwala, 2011)[9] developed an analysis for getting the seismic bearing capacity considering the rupture surface. The analysis has been done considering the three different cases separately, assuming that the principle of superposition holds well, (i) considering the weight of soil only (ii) considering the only surcharge and (iii) considering cohesive forces only.

(Lumb, 1974)[10] compiled a list of variations in some basic soil properties that influence bearing capacity. Inherent variability, measurement error, and transformation uncertainty are the sources to cause uncertainties in soil property estimates (Phoon & Kulhawy, 1999)[11]. (Duncan, 2000)[12] described methods for estimating soil parameter standard deviations. (Alawneh et al., 2006)[13] suggested coefficient of variation range for soil parameters based on the findings of several studies.

Index proposed by (Hasofer & Lind, 1974)[14] is a widely used reliability indicator that measures the shortest distance in units of directional standard deviations between the mean value point of the random variables and the limit state surface. (Cherubini, 2000) [15] proposed probabilistic approaches to examine the reliability of shallow foundation bearing capacity of shallow foundation. Rather of using traditional design methodologies, (Alawneh et al., 2006)[13] provides a reliable alternative for shallow foundation design and analysis. (Alhajami, 2013)[16] proposing a resistance factor for LRFD method that would yield a reliability index of 4 which means a lower probability of failure and a safer overall structure. (Acharya & Acharya, 2019)[17] used the Mathcad computer program to offer the Reliability Based Design method for assessing the bearing capacity of shallow foundations. ("(BS EN 1990:2002)," 2005)[?] defined an alternative measure of reliability which is related to Pf by:

$$Pf = -\Phi(-\beta) \tag{1}$$

Where β is reliability index and Φ is the cumulative distribution function of the standardized Normal distribution. For this research, the general formula established by Terzaghi and modified by Mayerhoff, Hasen, and Vesic, as well as slope factors and seismic factors proposed by Hasen and Rangwala et al, are used to estimate seismic bearing capacity on slope. Taylor's series approximation as suggested by Alwaneh et all is used to calculate mean and standard deviation of ultimate bearing capacity for reliability analysis. Range for coefficient of variance proposed by several researchers are taken as references to characterize the independent soil properties.

3. Materials and methodology

3.1 Study Area

Bridge Foundation of Simaltal Khola River Bridge at Simaltar Chitwan along Narayanghat-Muglin Highway was taken for the case study. The bridge site of the Simaltal Khola at chainage 24+250 at Kabilas along the Narayanghat-Mugling Road lies in Chitwan District, Narayani Zone, Bagmati Province. Geologically the location falls on the rocks of the Nourpul Formation, Lesser Himalaya. New bridge has been proposed upstream from existing bridge over Simaltal Khola.

3.2 Methodology

To achieve the study's goal, independent soil parameters associated with uncertainty must first be identified, which was done by reviewing the literature. To characterize the independent properties of foundation soil, data collection work was carried out.

3.2.1 Data collection

Technical data and facts about the foundation soil were gathered through a field visit as part of an ongoing project, sampling, and a literature review. Primary and secondary data were collected during data collection. For primary data, direct shear test was used to determine shear strength parameters in the laboratory and in-situ test, i.e. field density test, was carried out on the foundation's base using the sand replacement method. Angle of Internal Friction and soil unit weight were taken as primary data. Secondary data from secondary sources such as related literature and project reports Foundation depth, length, breadth, ground slope, ground acceleration were taken as secondary data. The damping effect of peak ground acceleration with the distance from epicenter of Gorkha Nepal Earthquake was reported by (Sharma et al., 2018)[18]. At the soil site (KATNP, at kantipath) and the rock site (KTP, at Tribhvan University), the main shock's peak ground accelerations (PGA) in horizontal direction are 164 cm/sec^2 and 241 cm/sec^2, respectively. According to geotechnical report, The Bridge over the Simaltal Khola falls in the seismic moderate hazard area (Seismic zone 3) of the Nepal Himalaya. But for study maximum pga 0.36, has been taken to penalize the capacity of soil.

After data collection, input parameters were characterized as listed in table 1.

3.2.2 Calculation and Analysis

Final expression to estimate seismic bearing capacity on slope is modified from (Terzaghi 1943)'s equation can be presented as:

$$q_u = qN_qS_qSF_qg_{q\Psi} + 0.5\gamma BN_\gamma S_\gamma SF_\gamma g_{\gamma\Psi} \quad (2)$$

where bearing capacity factors N_q, N_γ shape factors S_q, S_γ proposed by (Meyerhof, 1951), (Hansen, 1970) and (Vesic, 1973) are

$$N_q = e^{\pi \tan\phi} \tan^2(\pi/4 + \phi/2) \quad (3)$$

$$N_\gamma = 2(N^q + 1)\tan(\phi) \quad (4)$$

$$S_q = 1 + 0.2B/L \quad (5)$$

$$S_\gamma = 1 - 0.4B/L \quad (6)$$

$SF_q$and SF_γ are seismic factors proposed by (Rangwala, H. M., Saran, S. and Mukerjee, S., 2011) , can be expressed as:

$$SF_q = e^{-a_qA_h} \quad (7)$$

$$SF_\gamma = e^{-6.994 tan\lambda} \quad (8)$$

$$a_q = 5(\tan\phi)^{0.44} \quad (9)$$

$$\tan\lambda = \frac{A_h}{1 - A_v} \quad (10)$$

Here, A_h and A_v represent horizontal and vertical ground acceleration respectively. Where $g_{q\psi}$ and $g_{\gamma\psi}$ are slope factors provided by Hasen (1970) as

$$g_{q\psi} = g_{\gamma\psi} = (1 - \tan\psi)^2 \quad (11)$$

Here, ψ is ground inclination angle. The key step is to compute Reliability Index, β and, as a result, the Probability of failure, Pf by determining the expected mean,μ_{qult}, standard deviation,σ_{qult} and variance,CFs of q_{ult}. To determine μ_{qult} and σ_{qult}, Taylor's series expansion is used and expressed as:

$$\sigma_{qult} = \left[V_c \left(\frac{\partial}{\partial c} q_{ult} \right)^2 + V_\phi \left(\frac{\partial}{\partial \phi} q_{ult} \right)^2 + V_\gamma \left(\frac{\partial}{\partial \gamma} q_{ult} \right)^2 \right]^{0.5} \quad (12)$$

Table 1: Characterization of Input Parameters

Descriptions	Unit	Quantity
Soil type	-	Cohesion less Sandy Soil
Drainage Condition	-	Drained
Angle of Internal Friction, ϕ	degree	37.645
Unit Weight, γ	kN/m^3	19.56
Unit Weight of Backfill, γ	kN/m^3	20
Coefficient of Variance of Frictional Angle, CVϕ	%	3.09
Coefficient of Variance of Unit Weight, CVγ	%	4.63
Ground Acceleration, Ah	g	0.18, 0.26, 0.34
Ground Slope, ψ	degree	30
Applied Load, qapp	kN/m^2	198.443
Length of Foundation, L	m	11
Depth of Foundation, D	m	3.6
width of Foundation, B	m	6.7

$$\mu_{qult} = q_{ult} + 0.5\left(V_c \frac{\partial^2}{\partial c^2} q_{ult} + V_\phi \frac{\partial^2}{\partial \phi^2} q_{ult} + V_\gamma \frac{\partial^2}{\partial \gamma^2} q_{ult}\right) \tag{13}$$

V = $(\mu.\text{CV})^2$ is the variance, which is the square of the standard deviation. The variation coefficient CV is the most common statistical parameter for a soil property. Thus, it is more practical and programming-friendly. For the definition of probability of failure, P(qult / qapp $<$1), reliability index can be expressed as:

$$\beta = \frac{CF_s - 1}{CV_{qult} CF_s} \tag{14}$$

This expression is used in study to evaluate the reliability index of bearing capacity, where CF_s is central factor of safety and CV_{qult} is coefficient of variance of q_{ult}.

3.2.3 Sensitivity Analysis

Sensitivity analysis investigates the effects of various input parameters on the output parameter. When output parameters are dependent on one or more input variables, this technique is used. Foundation depth, ground inclination, horizontal seismic acceleration, coefficient of variance of angle of friction, and unit weight were used as independent input parameters, with their values varied to see how they affected the output parameters; factor of safety and reliability index. The sensitivity analysis is carried out by adjusting each parameter by 30% above and below the original (normal) value by 10% in increment and decrement order, while leaving the other parameters constant. Sensitivity analysis is done for an average value of internal friction angle 37.645°and an average value of unit weight 19.56 kN/m^3 as per case study.

Table 2: Output results of reliability analysis

Descriptions	Unit	Quantity
PGA 0.18g		
Seismic Bearing Capacity, qult	kN/m^2	1360
Factor of Safety, FOS	-	6.854
Reliability Index, β	-	5.253
PGA 0.26g		
Seismic Bearing Capacity, qult	kN/m^2	896.972
Factor of Safety, FOS	-	4.458
Reliability Index, β	-	4.97
PGA 0.34g		
Seismic Bearing Capacity, qult	kN/m^2	580.754
Factor of Safety, FOS	-	2.927
Reliability Index, β	-	4.418

4. Results and Discussion

Shear parameters (c and ϕ) obtained from laboratory tests, unit weight derived from field tests, and geometric features of the site and foundation were used to analyze the reliability of shallow foundations using the Taylor series approximation. Thus obtained bearing capacity is used for reliability analysis. As per characterization of input parameters, analysis has been done for 3 values of horizontal seismic acceleration. Corresponding results including the seismic bearing capacity, factor of safety and reliability index, from analysis of Simaltar Bridge foundation are obtained which all are under acceptable values and shown in table 2.

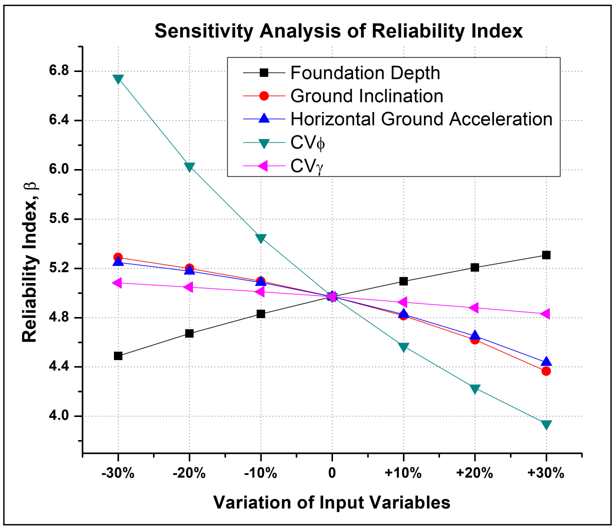

Figure 1: Sensitivity Analysis: Reliability Index vs Input Variables

Sensitivity analysis shows that reliability index is sensitive to all input variables such as foundation depth, ground inclination, horizontal seismic acceleration, coefficient of variance of angle of friction, and unit weight. As per the case study, sensitivity analysis is performed for an average value of internal friction angle of 37.645°and an average value of unit weight of 19.56 kN/m^3. In case of factor of safety, coefficient of variance of angle of friction and that of unit weight, representing the uncertainties and variability of soil properties are excluded during its calculation.

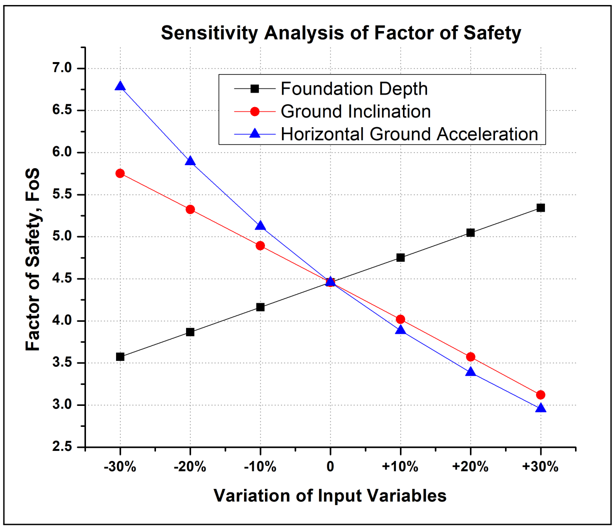

Figure 2: Sensitivity Analysis: Factor of Safety vs Input Variables

5. Conclusions and Recommendations

The conclusions drawn from the reliability analysis of seismic bearing capacity of bridge foundation on slope and sensitivity analysis are as follows:

• The seismic bearing capacity, reliability index and factor of safety of bridge foundation are found to be 580.754 kN/m^2, 4.418 and 2.927 respectively for horizontal ground acceleration 0.34g, which all are under acceptable values.so it can conclude that foundation design of Simaltar Khola is safe and reliable.So it can conclude that foundation design of Simaltar Khola is safe and reliable.

• The coefficient of variance of soil internal frictional angle, COVϕ has the greatest impact on the reliability index, followed by foundation depth, ground inclination, horizontal ground acceleration, and coefficient of variance of unit weight of foundation soil, COVγ.

• Factor of safety is most sensitive to horizontal ground acceleration and then to ground inclination and to foundation depth. Factor of safety is found to be unaffected on variation of value of COVϕ and COVγ during analysis.

• With increase in value of horizontal ground acceleration and ground slope, the value of reliability index and factor of safety are found to be decreased, while with increase in depth of foundation, the value of reliability index and factor of safety are found to be increased.

• It is observed that the reliability index has inverse relationship with the COV of both angle of friction and unit weight.

• Reliability index is most sensitive to coefficient of variance of internal friction angle while factory of safety is most sensitive to horizontal ground acceleration. Therefore, for reliable and safe design, reliability analysis should be incorporated with deterministic analysis.

As a recommendation for future research, it is better to perform the application of well-known reliability based design methods to other geotechnical problems like for slope stability, retaining walls and others. Spatial variation of soil properties is highly recommended to consider in further study. Effect of liquefaction, shrinkage and temperature load are recommended to include in future study.

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