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STABILITY IMPROVEMENT OF GRAVITY RETAINING WALL AFTER PLACING BURIED UTILITY RIGID PIPE IN THE BACKFILL

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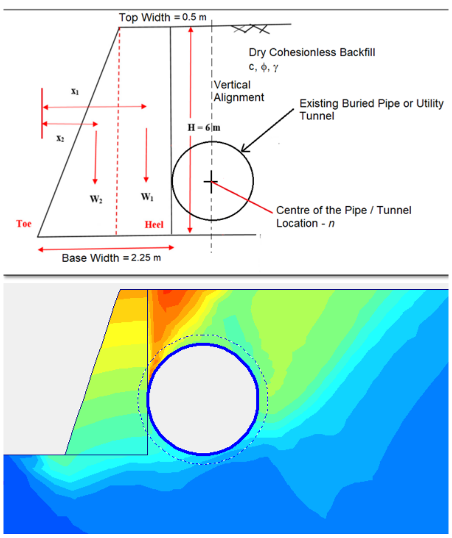


Abstract

Present study considers a practical possibility where retaining wall construction may take place close to the existing rigid buried utility pipe. Such practical scenario is analyzed numerically using PLAXIS 2D which is a finite element based tool commercially available. Stability trends are captured through a parametric study in which utility buried pipe or tunnel of different diameters i.e. 1.0 m, 1.5m, 2.0m, 2.5m, 3.0m and 3.5m that are placed at different locations in the vertical alignment close to the backside of the retaining wall. Results of the numerical analysis, i.e., estimation of factor of safety through "strength reduction technique" indicate that keeping other factors constant, such as, backfill geotechnical properties and geometry of the problem statement, the factor of safety (FoS) value is greatly influence by the location and diameter of the Rigid buried utility pipe. Similar trend was captured when the Factor of safety with respect to overturning was estimated with the help of proposed pressure distribution (earth) diagram in active mode behind the gravity retaining wall after placing rigid buried utility pipe on the backside. Further, issue of uncertainty in the geotechnical parameters is considered to estimate the reliability index to estimate the performance in probabilistic framework as well. Combination of numerical analysis, response surface method and first order reliability method eased the calculation with less demand for the computational time.

Keywords: Gravity Retaining Wall, Stability Analysis, Numerical Analysis, Strength Reduction Technique, Rigid buried utility pipe, reliability analysis, Response surface method

1.0 INTRODUCTION

Buried utility pipes are considered as the life line of a city or urban setting that are used for the purpose of water supply, sewage disposal, gas, electricity and power supply including development of transport infrastructure. On the other hand scarcity of land prompts developers to go vertical either above or below ground. Construction of basement with retaining structure is a common feature in urban construction. Apart from that requirement for the railway as well as road infrastructure and their widening requires earth retaining structures for supporting the natural steep slopes or backfill material. Hence, there is a high possibility that retaining structures are constructed where a Rigid buried utility pipe already exist. This practical scenario requires an assessment of stability of the retaining structure existing buried utility pipe close to the back of the wall.

Considering the case of a gravity retaining wall, the stability is assessed either using finite element or finite difference based numerical approach or analytically by computing Safety Factor (FoS) with respect to overturning by estimating active earth pressure (force) induced on the retaining wall. Conventionally, the most popular approach i.e. Rankine's earth pressure theory [1] which is still in practice is used to estimate the earth pressure (force) acting on the wall and then calculating the Safety Factor with respect to overturning of the retaining structure. Several researchers extended the theory to present the case of practical scenario, such as, presence of overburden, layers of backfill, inclined backfill, cohesive-frictional backfill, presence of water table etc. A detailed discussion is presented in several published books and literature [2,3]. Similarly, extensive work is presented on the buried pipe that can either by rigid or flexible in nature [4,5].

Several studies in the past suggest different approach that can be adopted to improve the stability of the retaining wall, such as, use of Geofoam [6, 7], soil reinforcement [8], utilizing geosynthetic materials, such as, Geogrids [9], Geocells [10], Geostrips [11], use of soldier pile [12], vertical plate anchors [13], tiered reinforcement [14, 15], provision of relief shelves [16] etc. Literature review also suggest that effect of tunneling on the potential impact on the performance of geotechnical system and works, such as, ground surface settlement, shallow and deep foundation have been studied extensively. For example, studying the impact of tunneling on existing pipelines [17], tunneling effect on shallow foundation [18, 19], influence of tunneling on pile foundation [20], arching effect and tunneling near the basement of the retaining wall [21, 22]. Although impact of presence of "existing buried pipe" on geotechnical system, such as, shallow foundation and pile foundation have been studied in a limited way that too on pile foundation or piling work.

Recently, existence of buried pipe close to the shallow and deep pile foundation have been extensively been studied by Srivastava et al [23], Malhotra et al [24 , 25], Malhotra and Srivastava [26], Srivastava et al [27], numerically as well as through model based studies. Finite element based Numerical tool, such as, PLAXIS have been extensively used to solve geotechnical engineering problems which is also used in the present study [28, 29, 30]. In all the studies, it was reported that buried pipe existence near the geotechnical system is critical and it greatly influence the stability and deformation behavior. No such work reported in the literature where stability of the earth retaining system is studied by placing the rigid buried utility pipe on the back of the retaining wall in the backfill. The objectives of the present work are defined as

- To perform the numerical analysis of gravity retaining wall with the existence of rigid buried utility pipe and estimate factor of safety through strength reduction technique;
- To perform parametric study of assessing factor of safety by placing buried pipe of different diameters, i.e., 3.5m, 3.0m, 2.5m, 2.0m and 1.5m near the back of the retaining wall at different locations in the vertical alignment
- To propose pressure distribution (earth) diagram in active mode for gravity retaining wall with buried pipe of different diameters placed at different locations in the vertical alignment in the vicinity of back of the wall and perform parametric study of estimating Safety Factor with respect to overturning
- To draw conclusion on the impact of existing rigid buried utility pipe on the stability based on parametric study with its placement having different diameters and locations in the vertical alignment
- Consideration of uncertainty in the geotechnical parameter and then assessment of stability of the wall in probabilistic framework through reliability index β utilizing numerical analysis results combined with response surface methodology and First Order Reliability Method (FORM).

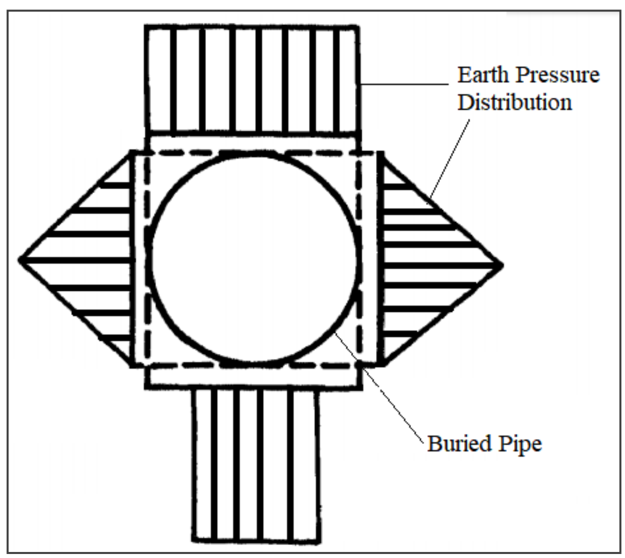
2.0 EARTH PRESSURE DISTRIBUTION

2.1 Retaining Wall

As per Rankine's earth pressure theory [2], pressure distribution (earth) in active mode is taken as $K_A\gamma H$; where K_A is the active earth pressure coefficient = (1-sinϕ)/1+sinϕ), γ = unit weight of the backfill material, H = height of the retaining wall. The pressure distribution (earth) is linear and the active earth pressure (force) is calculated as $1/2K_A\gamma H^2$, acting at a height of H/3 from the base of the wall. The theoretical assumptions involved are: backfill material is cohesionless, homogeneous and isotropic; backfill soil is in the state of plastic equilibrium; backfill surface is horizontal and back of the wall is smooth and vertical. With same assumptions, the calculation of earth pressure (Force) on the gravity retaining wall was carried out in the present study.

2.2 Buried Pipe

Marston and Spangler [5] suggested pressure distribution (earth) around buried pipe as depicted in Figureure 1. The distribution is based on placing the buried pipe in a trench and then back filling is done with cohesionless material. The concept of linearly varying pressure distribution (earth) on the sides of the buried pipe was employed to propose the type of pressure distribution (earth) around the rigid buried utility pipe when placed on the backside of the retaining wall in the backfill. The same was used to calculate the factor of safety of the gravity retaining wall against overturning and the same was critically analyzed with a limiting value of minimum 3.0 as per the suggestions in the literature [2].



Figureure 1 Pressure distribution (earth)s around buried pipe as suggested by Marston and Spangler

3.0 GEOTECHNICAL UNCERTAINTY

Conventionally, evaluation of factor of safety using Mohr-Coulomb failure hypothesis involves limit equilibrium based approach or strength reduction technique incorporated in finite element or finite difference tool in which the required input geotechnical parameters, such as, cohesion, friction angle, unit weight are assumed to be uniformly constant. Uncertainty in the estimation of these geotechnical parameters through field or laboratory test results performed on undisturbed or representative soil samples are taken care by factor of safety which is nothing but the ratio of Restoring Force (or moment) to the driving force (or moment). Choice of appropriate value of safety factor comes from experience, engineering judgment and confidence level which are qualitative. In case of safety of retaining wall against sliding, minimum safety factor of 1.5 is to be ensured and with respect to overturning, minimum safety factor of 3.0 is suggested [2]. It is assumed that factor of safety will take care of uncertainties involved in the estimation of geotechnical parameters due to inherent soil variability, testing error or model transformation.

A question that often arises "How much safe is actually safe?" or "what is the probability of failure or reliability associated with the safety value selected. Duncan [31] addressed the issue and suggested the way to choose safety factor depending on the extent of uncertainty, measured in terms of coefficient of variation (CoV%), i.e., ratio of standard deviation (σ) to mean (μ) expressed in percentage, involved in the input geotechnical parameters. Extensive work is done by researchers who advocated the application of probabilistic approach or reliability based approach in solving issues of uncertainty in the input parameters and its impact on the performance assessment of geotechnical systems [32, 33, 34, 35, 36, 37, 38, and 39]. Techniques like Monte Carlo Simulation (MCS) with Random Field Modeling, First Order Second Moment (FOSM), First Order Reliability Method (FORM), Point Estimate Method (PEM) etc are well employed to estimate the probability of failure (p_f) or reliability index (β) after considering input geotechnical parameters as continuous random variable with well defined parameters of distribution related with mean (μ) and variance (σ^2). For the estimation of probability of failure through conventional approach, an explicit functional relationship between input and output variables is required. Otherwise, available design charts, numerical analysis and implicit functional relationship are used for simulation and estimate the probability of failure or reliability index. Such techniques are highly computational and time consuming and warrant an alternative for the estimate of the assessment of safety in probabilistic framework through reliability index (β). USACE [40] suggest reliability index 3, 4, 5 for average, good and excellent performance of the geotechnical system and can be easily related to the selected value of safety factor.

4.0 RELIABILITY ANALYSIS

If the existing functional relationship is too complicated to perform the conventional probabilistic analysis or in scenario where such functional relationship does not exist at all and solution involves numerical analysis procedure through finite element or finite difference modeling, a simple linear explicit functional relationship can be established through response surface method (RSM) approach [41]. The approach involves estimating the output response through numerical analysis or complex design charts or equations, at the design points defined as combination of input parameters and then through regression analysis, an explicit linear relationship can be developed. Choice of Design points are based on 2^n full factorial design approach, where n is the number of input variables. For example, 3 input parameters will provide 8 design points as it can be indicated through the corners of a cube, mean value being at the center of the cube. The combinations of input parameters are taken from $\mu \pm m\sigma$, where m is taken as 1.65, i.e. to be in the range 1 to 3. Once a linear regression model is developed, with the known value of mean and variance in the input parameters i.e. Unit weight, cohesion, friction angle, the mean and variance in the output response (Factor of safety) is established and the reliability index value is calculated using FORM approach and compared with USACE [40] guide to assess the level of performance as average, good or excellent depending on the selected value of safety factor. Various researchers in the past employed the response surface methodology for the probabilistic analysis of the geotechnical system [42, 43, 44 and 45].

5.0 PROBLEM STATEMENT

Figure 2 defines the problem statement where it can be seen that a rigid buried utility pipe is present on the back of the gravity retaining wall of height 6m, top width 0.5 m and base width 2.25 m. For a parametric study, buried pipe is located with its centre at location defined as n, i.e., 0, 1, 2, 3, 4 and 5. Coordinates of these locations are taken at 1 meter interval in the vertical alignment as shown in the Figureure. The diameter of the Rigid buried utility pipe are taken as 3.5m, 3.0m, 2.5m, 2.0m, 1.5m and 1.0m, respectively. For reduced diameters, the vertical alignment shifts leftwards to make sure the rigid buried utility pipe touch the back of the retaining wall.

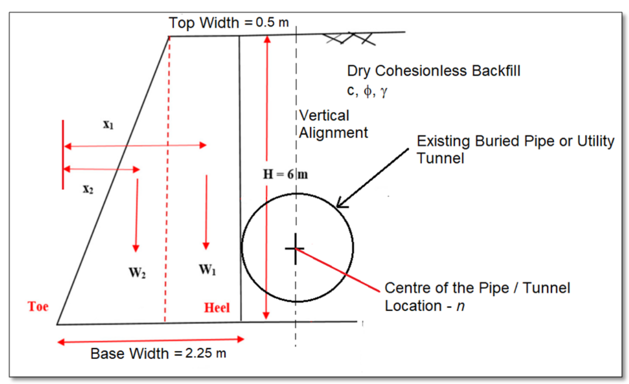


Figure 2 Gravity retaining wall with the presence of Rigid buried utility pipe in the vicinity

Retaining wall is assumed to be made of concrete having unit weight 25 kN/m^3 and accordingly the self weight W_1 and W_2 per meter length of wall are calculated as 131.25 kN/m and 75 kN/m length of wall, respectively. For the numerical analysis, it is assumed that constitutive behavior of backfill soil follows Mohr-Coulomb failure hypothesis with non-associated flow rule From Mohr-Coulomb failure hypothesis, input geotechnical properties of the backfill soil are taken as: cohesion (c) – shear parameter = 0 kPa, friction Angle – shear parameter (ϕ) = 35°, dry unit weight (γ) = 18 kN/m^3, Modulus of Elasticity (E) = 50 MPa and Poison's ratio (ν) = 0.35. The rigid buried utility pipe input properties are EI (Flexural stiffness) and EA (Axial stiffness) and numerical values are considered as 1.4×10^7 kN/m and 1.43×10^5 kN-m^2/m, respectively. For the reliability analysis, the coefficient of variation in the input geotechnical parameters, i.e. cohesion, friction angle and unit weight are taken from the published work by Duncan (2000) as indicated in Table [1].

Table1 Coefficient of Variation (CoV%) in input parameters

Sr. No	Input Geotechnical Parameter	CoV%
1	Unit Weight, γ	7
2	Cohesion, c	26
3	Friction Angle, $\phi°$	13

6.0 NUMERICAL ANALYSIS PROCEDURE

Numerical analysis procedure involves first creating problem geometry, then assigning boundary conditions, and material properties to the model. After discretization of the numerical model into 15 nodes finite element mesh having triangular elements, Initial effective stresses are developed and then calculation is proceeded. Figure 3 depicts the step by step procedure to perform the numerical analysis for the given problem statement. In the calculation mode, the plastic analysis is first performed for getting output related stress-strain and deformation pattern and then factor of safety is evaluated using c-ϕ reduction technique [46]. For detailed discussion on the numerical modeling and analysis procedure, reader may refer to scientific manual of the software

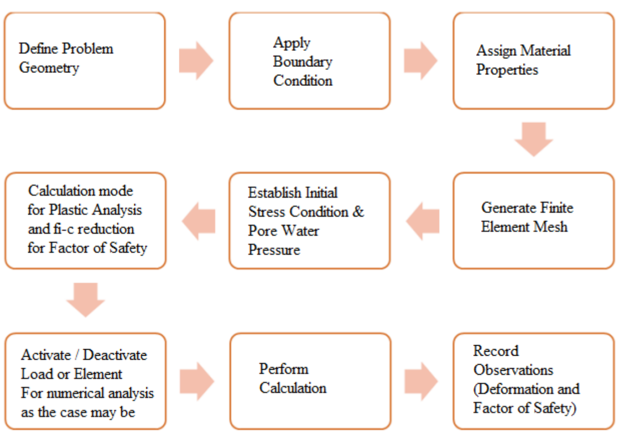


Figure 3 Finite Element Mesh using 15 node triangular element with standard fixities

7.0 PROPOSED PRESSURE DISTRIBUTION (EARTH)

To estimate the Safety Factor with respect to overturning, the following generalized pressure distribution (earth) is suggested as shown in Figure 4. The nomenclatures of different geometric features are as below:

- D_O = Depth of the soil over burden above the crown of the rigid buried utility pipe
- D = Diameter of the rigid buried utility pipe = 2R (Radius of the Rigid buried utility pipe)
- E = Depth of soil below the base till the base of the retaining wall
- $\Delta E_1F_1G_1$ = Pressure distribution (earth) in active mode due to overburden D_O
- $\Delta E_2F_2G_2$ = Pressure distribution (earth) in active mode due to soil portion of depth E
- ΔMF_1Q & ΔME_2N = Pressure distribution (earth) in active mode around the buried pipe

The line of action of active earth pressure (force) P_1, P_2, P_3, P_4 due to earth pressure diagram denoted with $\Delta E_1F_1G_1$, $\Delta E_2F_2G_2$, ΔMF_1Q & ΔME_2N are indicated in the diagram itself.

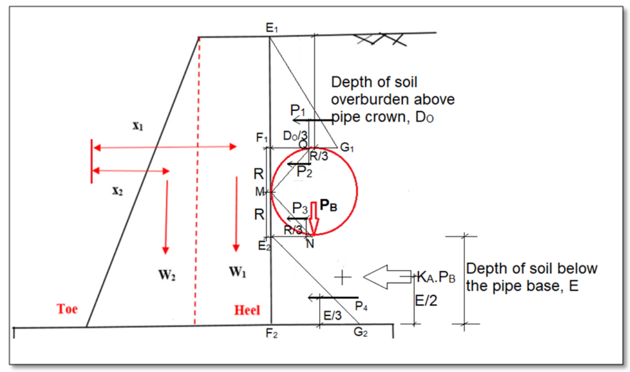


Figure 4 Generalized pressure distribution (earth) in active mode diagram with rigid buried utility pipe on the back of the wall

The values of P_1, P_2, P_3, P_4 is calculated using Rankine's active earth pressure theory. The weight of the Rigid buried utility pipe (P_B) will also exert horizontal pressure on the wall with a magnitude $K_A.P_B$ acting at a height of E/2 from the base of the retaining wall. The weight of the buried pipe or tunnel can be estimated as $(\pi Dt)L\gamma_p$; where D = diameter of the pipe , t = thickness of the pipe, L = length of the pipe which is unity in the present case and γ_p = unit weight of the pipe material. With this information, the driving moment about the Toe of the gravity retaining wall can easily be calculated. Also, knowing the values of W_1, W_2 , x_1 and x_2, the restoring moment about the toe of the gravity retaining wall can also be evaluated. The ratio of restoring moment to the driving moment will provide Safety Factor with respect to overturning, which is critical to the stability of a gravity retaining wall.

8.0 RESULTS AND DISCUSSION

8.1 Numerical Analysis and Factor of Safety

Without buried pipe, the factor of safety of the retaining wall system was evaluated as 1.39. Table 2 shows the results of the numerical analysis and factor of safety evaluated for Rigid buried utility pipe of diameter 3.5m, located at different co-ordinates in a vertical alignment.

Table 2 Factor of safety through numerical analysis results for buried pipe of different diameter placed at different locations in the vertical alignment

	Location of buried pipe / utility tunnel	Dia= 3.5 m	Dia= 3.0 m	Dia= 2.5 m	Dia= 2.0 m	Dia= 1.5 m
Y-axis	X-axis	22.0m	21.75m	21.5m	21.25m	21.0m
23m	L – 0	1.52	1.49	1.45	1.40	1.39
22m	L – 1	1.57	1.47	1.52	1.41	1.39
21m	L – 2	1.63	1.55	1.51	1.41	1.45
20m	L – 3	1.48	1.50	1.45	1.51	1.41
19m	L – 4	1.36	1.37	1.39	1.36	1.34
18m	L – 5	1.34	1.34	1.36	1.40	1.40

The vertical locations are selected in such a way that the values of D_O i.e. depth of overburden above the crown are obtained as 0 m (location-0), 1.0 m (Location-1), 1.5 m (location-2), 2.0 m (Location-3), 2.5 m(Location-4), 3.0 m (Location -5) and 3.5m (Location-6). Considering location 0 &1 as upper zone, 2&3 as middle zone and 4 &5 as lower zone, it can be noted that pipe placed in the upper and middle zone has greater influence on the factor of safety values with improved values. The highest factor of safety is obtained when the Rigid buried utility pipe is placed at location-2. Pipe in the upper and lower zones have comparatively lesser values of factor of safety. With decrease in the diameter of the Rigid buried utility pipe, the factor of safety value consistently reduces.

8.2 Factor of Safety against Over Turning

Without Rigid buried utility pipe, the Safety Factor with respect to overturning is evaluated as 1.94. Table 3 provides the results of the Safety Factor with respect to overturning evaluated through proposed pressure distribution (earth) diagram as per Figure 4. It can be noted that the factor of safety trend captured through numerical analysis is similar to the factor of safety evaluated for overturning. The Rigid buried utility pipe placed at location 2 has highest factor of safety compared to factor of safety values evaluated at other locations. Also, pipe located in the upper most and lower most zones has no significant influence on the Safety Factor with respect to overturning.

Table 3 Safety Factor with respect to overturning using proposed pressure distribution (earth) for buried pipe of different diameter placed at different locations in the vertical alignment

Location of buried pipe / utility tunnel	Dia= 3.5 m	Dia= 3.0 m	Dia= 2.5 m	Dia= 2.0 m	Dia= 1.5 m
Location – 0	1.91	1.93	1.96	2.01	2.03
Location – 1	2.71	2.66	2.67	2.73	2.82
Location – 2	3.41	3.13	3.01	3.00	3.07
Location – 3	3.20	3.26	2.94	2.79	2.77
Location – 4	2.55	2.46	2.50	2.54	2.57
Location – 5	2.06	2.06	2.07	2.07	2.08

9.0 RELIABILITY ANALYSIS

To demonstrate the procedure for the reliability analysis through RSM approach combined with Numerical analysis and FORM, the mean value of input geotechnical parameters affecting the output i.e. Factor of Safety (FOS) is taken as indicated in Table 1. The choice of input parameters are deliberately taken in such ways that the combinations of ± input parameters are within the acceptable range and non-negative. The FOS value for the mean input geotechnical parameters is obtained as 1.60, which is acceptable as the minimum required value is 1.5. Hence, conventionally it can be assumed that the retaining wall is safe with the assumption that it will take care of the uncertainty in the input geotechnical parameter which is a kind of black box assumption. Although probabilistic approach is not a replacement to the conventional deterministic approach, but it can be complimentary to assess the stability of the retaining wall with the presence of buried pipe in probabilistic framework. It is assumed that all input geotechnical parameters are normally distributed continuous random variables.

As discussed, for the development of explicit functional relationship between input and output random variables using RSM approach, Table 4 provides that 8 combination of input geotechnical parameters chosen as $\mu \pm 1.65\sigma$, where μ is the mean value and σ is the standard deviation in the selected mean value of the input geotechnical parameter. For each combination of the input parameter, the corresponding output is obtained through numerical analysis and then the data is used for the regression analysis to establish an explicit relationship between input parameters and output response as below:

$$FS = 0.6625 + 0.0450c + 0.0498\phi - 0.0379\gamma \quad (1)$$

Table 4 Combination of input parameters for 2^n full factorial design points and corresponding output FOS from numerical analysis

Sr. No	Combination of inputs			c, kPa	$\phi°$	γ, kN/m^3	FS
Mean	0	0	0	25.0	10	18	1.60
1	+	+	+	35.7	12.1	20.1	2.08
2	+	+	-	35.7	12.1	15.9	2.31
3	+	-	+	35.7	7.9	20.1	1.87
4	+	-	-	35.7	7.9	15.9	2.09
5	-	+	+	14.3	12.1	20.1	1.18
6	-	+	-	14.3	12.1	15.9	1.27
7	-	-	+	14.3	7.9	20.1	0.97
8	-	-	-	14.3	7.9	15.9	1.07

Knowing the mean and variance of the input parameters, the mean and variance in FOS is obtained as 1.60 and 0.092, respectively. The reliability index is obtained as 2.0 using the equation β = [Mean (FOS)-1.0]/Standard Deviation (FoS). It can be noted that although the FoS from deterministic approach may be considered sufficient, but the reliability index value in given environment of uncertainty in the input geotechnical parameters is obtained as 2.0 which surely indicates below average performance as per USACE guidelines. This indicates working on improving the input geotechnical parameters in backfill to improve the geotechnical properties through ground improvement technique or redesigning the wall with different geometric details or extra provisions like reinforcement in the backfill or provision of different kind of retaining wall such as cantilever or buttress wall. Hence, reliability based approach helps in decision making through a rational approach with sound mathematical treatment of uncertainty in the input parameters. Accurate assessment of extent of uncertainty in the input parameter through sufficient data set is important aspect of probabilistic analysis. Engineering judgment, experience also plays a major role here while taking such an extra ordinary decision based on the outcome of the probabilistic analysis

10.0 CONCLUSION

- Keeping the geotechnical properties of backfill and input properties of retaining wall and lining of tunnel same, the stability of the retaining wall is influenced by the presence of the (rigid) Rigid buried utility pipe and its location and diameter matters a lot. Rigid buried utility pipe located in the middle zone improves the stability assessed in terms of factor of safety evaluated through numerical analysis using strength reduction technique as well as against overturning calculated using the proposed pressure distribution (earth) in active mode diagram.
- Reliability based approach can be useful in assessing the stability with proper mathematical treatment of uncertainty and to decide whether the evaluated factor of safety is sufficient to ensure the safety or requires additional measures such as redesigning, application of ground improvement in backfill or provision of different kind of retaining structure.

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Conflicts of Interest

The author(s) declare(s) that there is no conflict of interest regarding the publication of this paper

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