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Federal University of Technology, Minna, Nigeria

Reliability Assessment of Civil Engineering Structures: A Review

*Akuto T. T.; Alhaji, M. M. & Alhassan, M
Department of Civil Engineering Federal University of Technology, Minna
* tersooakuto@hotmail.com

ABSTRACT
The use of new materials in civil engineering calls for a concerted effort to get precise and accurate solutions. It is obvious that deterministic values are not reliable and its use to design civil engineering structures can cause instant failure. The use of the theory of probability to determine the most reliable value for a parameter for design of civil engineering structures is very pertinent. This work set out to review the literatures on the application of the theory of probability and its related uses in civil engineering.

Keywords: *PUncertainty, Reliability, Probability, Failure, Deterministic, Probabilistic*

INTRODUCTION

The trend in civil engineering today more than ever before is to provide; economical or robust design at certain levels of safety, use new materials in construction. (When newer materials are being used in civil engineering design, there is a need to understand to what extent the structure is safe). that is to consider uncertainties in design.

Design of many facilities such as: buildings, foundations, bridges, dams, highways, airports, seaports, offshore structures, tunnels, sanitary landfills, excavation etc. need to address the design issues (data collection, analysis and design) rationally.

The loading in civil engineering systems are completely unknown, except for some of the features of the loading which are known; such as frequency and occurrence of earthquakes, movement of ground water, rainfall pattern, wind and ice loadings etc. All these loading are random in nature, and at times they create overloading situation. An illustration of the afore-going discussion is shown in the chart below.

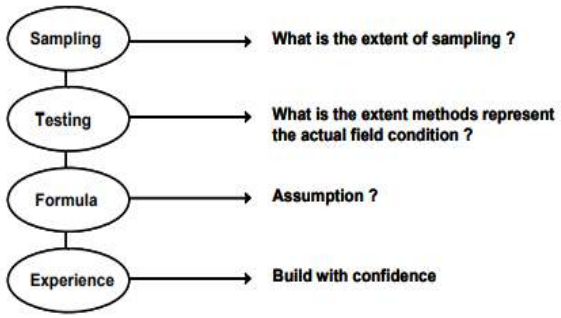

Figure 1: design and experimental processes

At all stages indicated above, there is an element of uncertainty with regard to the suitability of the site in terms of soils, construction materials, which we transfer to a different level using a set of expressions to obtain the desired quantities such as the floor capacity, allowable loads in buildings etc. Sayed et al. (2010).

1.1 PROBABILITY OF FAILURE AND RELIABILITY

The failure of civil engineering systems is a consequence of decisions making under uncertain conditions and different type of failures such as temporary failures, maintenance failures, failures in design, failure due to natural hazards need to be addressed. Thus definition of failure is important. It is expressed in terms of probability of failure and is assessed by its inability to perform its intended function adequately on demand for a period of time under specific conditions.

The converse of probability of failure is called reliability and is defined in terms of the success of a system or reliability of a system is the probability of a system performing its required function adequately for specified period of time under stated conditions.

1. Reliability is expressed as a probability
2. A quality of performance is expected
3. It is expected over a period of time
4. It is expected to perform under specified conditions

1.2 UNCERTAINTIES IN CIVIL ENGINEERING

In dealing with design, uncertainties are unavoidable. Uncertainties are classified into two broad types. Those

associated with natural randomness and those associated with inaccuracies in our prediction (aleatory) and estimation of reality (epistemic). Irrespective of the classification, understanding the nature of randomness is necessary. The nature of the first type arising out of nature (for example, earthquake and rainfall effects) needs to be handled rationally in design as it cannot altered and the second one needs to be reduced using appropriate prediction models and sampling techniques (Schweiger *et al.*, 2001)

The response of materials such as concrete, soil and rock to loading and unloading is of primary concern to the civil engineer. In all types of problems, the engineer is often dealing with incomplete information or uncertain conditions. It is necessary for the engineer to be aware of many assumptions and idealizations on which methods of analysis and design are based. The use of analytical tools must be combined with sound engineering judgment based on experience and observation (Sayed *et al.*, 2010). In the last two decades the need for solving complex problems has led to the development and use of advanced quantitative methods of modeling and analysis. For example, the versatile finite element method has proved to be valuable in problems of stability, deformation, earthquake response analysis etc. The rapid development of computers and computing methods has facilitated the use of such methods. However, it is well known that the information derived from sophisticated methods of analysis will be useful only if comprehensive inputs data are available and only if the data are reliable. Thus, the question of uncertainty and randomness of data is central to design and analysis in civil engineering.

Decisions have to be made on the basis of information which is limited or incomplete. It is, therefore, desirable to use methods and concepts in engineering planning and design which facilitate the evaluation and analysis of uncertainty. Traditional deterministic methods of analysis must be supplemented by methods which use the principles of statistics and probability. These latter methods, often called probabilistic methods, enable a logical analysis of uncertainty to be made and provide a quantitative basis for assessing the reliability of foundations and structures. Consequently, these methods provide a sound basis for the development and exercise of engineering judgment. Practical experience is always important and the observational approach can prove to be valuable; yet, the capacity to benefit from these is greatly enhanced by rational analysis of uncertainty. Sayed et al. (2010).

1.3 TYPES OF UNCERTAINTIES

There are many uncertainties in civil geotechnical engineering and these may be classified into three main groups as follows:

a) The first group consists of uncertainties in material parameters such as modulus of concrete, steel stability of concrete and steel in different condition such as tension and flexure, soil unit weight, cohesion, angle of internal friction, pore water pressure, compressibility and permeability.
b) The second group consists of uncertainties in loads. Under static loading conditions, one is concerned with dead and live load and there are usually more uncertainties in relation to live loads. Structures and soil masses may also be subjected to dynamic loads from earthquakes, wind and waves. Significant uncertainties are associated with such random loads.
c) The third group consists of uncertainties in mathematical modeling and methods of analysis. Each model of soil behavior is based on some idealization of real situations.

Each method of analysis or design is based on simplifying assumptions and arbitrary factors of safeties are often used.

1.4 DETERMINISTIC AND PROBABILISTIC APPROACHES

An approach based on the premise that a given problem can be stated in the form of a question or a set of questions to which there is an explicit and unique answer is a deterministic approach. For example, the concept that unique mathematical relationships govern mechanical behavior of soil mass or a soil structure system. In this method of analysis or design one is concerned with relatively simple cause and effect relationship. For each situation it is assumed that there is a single outcome; for each problem a single and unique solution. Of course, one may not be able to arrive at the exact solution and also unique solution may not exist. In such circumstances a deterministic approach aims at obtaining approximate solution. Empirical and semi empirical methods have

always been used in civil engineering although with varying degrees of success. Finally, in deterministic method of analysis, uncertainty is not formally recognized or accounted for one is not concerned with the probabilistic outcome but with well-defined outcomes which may or may not occur, that is, either a 100% probability of occurrence or 0% without intermediate value.

For example, one may arrive at the conclusion that a foundation will be safe on the basis that the safety factor, F, has a magnitude greater than one. On the other hand, one may conclude that a foundation or a slope is not safe on the basis that the magnitude of the factor of safety F is less than one. A given magnitude of F. e.g. F = 2.5 represents a unique answer to a problem posed in specific terms with certain unique values of loads and of shear strength parameters. In conventional analysis one is not concerned with the reliability associated with this unique value.

1.5 PROBABILISTIC APPROACH

A probabilistic approach is based on the concept that several or varied outcomes of a situation are possible. To this approach uncertainty is recognized and yes/no type of answer to a question concerning geotechnical performance is considered to be simplistic.

Probabilistic modeling aims at study of a range of outcomes given input data. Accordingly the description of a physical situation or system includes randomness of data and other uncertainties. The selected data for a deterministic approach would, in general not be sufficient for a probabilistic study of the same problem. The raw data would have to be organized in a more logical way. Often additional data would be for meaningful probabilistic analysis.

A probabilistic approach aims determining the probability p, of an outcome, one of many that may occur, The probability would be any percentage between p = 0% and p=100% or any fraction between p = 0 and p=1. In a specific problem the number of likely outcomes may be limited and it may be possible to consider the probability of each outcome.

2.0 RISK AND RELIABILITY

In engineering practice, we routinely encounter situations that involve some event that might occur and that, if it did, would bring with it some adverse consequence. We might be able to assign probability to the occurrence of the event and some quantified magnitude or cost to the adversity associated with its occurrence. This combination of uncertain event and adverse consequence is the determinant of risk. In engineering practice to assess risk, three things need to be defined.

1. Scenario which answers what can happen.
2. Range of consequences which answers how likely is it to happen.
3. Probability of the event's leading to the consequences which considers outcomes.

Recently the feasibility of non-deterministic methods for solving civil engineering problems is highlighted in the literature. Although, still deterministic methods are implemented in practice, non-deterministic methods can be seen as a complement to deterministic methods. In fact, failures of several important projects with relatively high factor of safeties underlined the importance of reliability analysis in Civil Engineering projects. High factor of safety does not necessarily mean high reliability more specifically in Geotechnical Engineering where soil behavior is complex (Momeni *et. al*, , 2018). For example, in a deep excavation problem or slope stability problem, since soil behavior may vary from a place to another place within the soil mass, one cannot suggest the high reliability (or low probability of failure) based on a high factor of safety obtained from a deterministic analysis. There are several methods for performing reliability analysis, including random set (RS) method, random field method, Monte Carlo simulation, to name a few. Nevertheless, after obtaining the probability of failure, *Pf*, for a specific project using the aforementioned methods, the risk of a project can be estimated by multiplying the project *Pf* by the cost of the project failure (failure consequences of the project). Due to the increasing importance of the reliability analysis concept, this thematic issue is aimed to shed some light on the risk management and reliability analysis of Civil Engineering problems. The thematic issue comprises thirty four papers which are briefly summarized in the following paragraphs.

The implemented methods in the following papers can be used in other civil engineering problems (or other case studies) for further research.

The first paper entitled "Risk-based Decision Making Method for Selecting Slope Stabilization System in an

Abandoned Open-pit Mine" by Gharehdaghi et al. (2020) suggests the implementation of RS-based Finite element method (FEM) for reliability analysis of a real case study, a 50-meter-deep abandoned open-pit mine. In essence, as mentioned by authors, the paper is focused on determining the most appropriate method of stabilization using RS-FEM as well as risk-based decision making approach. The authors used PLAXIS 2D software for their reliability analysis. The RS-FEM suggests two upper and lower bounds for probability of failure or excessive displacement. The obtained probabilities of failures or excessive displacements (lower and upper bounds) can then be checked against the acceptable probability of failure or acceptable probability of excessive displacement Momeni *et. al, ,* (2017). The paper is an interesting study and readers are encouraged to get more into details regarding the reliability analysis and risk assessment of a real case study.

The second paper entitled "ARMA models to measure the scale of fluctuation from CPT data" by Brijid and Sina. (2020) suggests implementation of Auto-Regressive Moving Average (ARMA) model for estimating scale of fluctuation. As mentioned earlier, the variability of soil behavior is the reason behind shifting from deterministic analysis to non-deterministic analysis. As illustrated by authors, "this variability is primarily characterized by the scale of fluctuation which describes the distance over which the parameters of a soil or rock are similar or correlated; soil properties sampled from adjacent locations in the soil profile tend to have similar values and as the sampling distance increases the correlation decreases". Nevertheless, the authors compared the fluctuation values from the ARMA model with two other methods and concluded that the ARMA model outperforms other considered methods. However, the authors highlighted that a considerable amount of research is required before the model can become established in the geotechnical sphere.

The third paper entitled "An Overview of the Reliability Analysis Methods of Tunneling Equipment" by Ahmadi *et al* (2020) provides a detailed overview of the reliability analyses methods used for tunneling machines and equipment including excavator, shovel, LHD machines, conveyor transport system, mechanized tunneling machine, network ventilation equipment in tunnels and underground mines. The reviewed methods in their study include statistical analysis, failure mode and effects analysis, Markov and fault tree methods.

The fourth paper entitled "A Reliable PSO-based ANN Approach for Predicting Unconfined Compressive Strength of Sandstones" by Abdi et al. (2020) suggests the implementation of an artificial intelligence technique for predicting the unconfined compressive strength (UCS) of sandstones. In this paper, an artificial neural network-based predictive model of UCS is enhanced by particle swarm optimization (PSO) algorithm. The authors highlighted the feasibility and reliability of the aforementioned techniques including PSO-based ANN in solving Geotechnical Engineering problems.

The fifth paper entitled "Reliability assessment of progressive failure of a low rise framed building on weak soil-foundation interaction" by Onundi *et. al, ,* (2019). In this research a 4-storey reinforced concrete framed buildings was modelled in 3-dimensional analysis with the same sections and loadings for both rigid and weak foundations respectively using ETABS and FORM5 Software in accordance with Euro code provisions. The weak foundation was initially analyzed and designed as a fixed column-foundation joint and later re-analyzed and redesigned as a hinged column foundation joint. The ETABS software was used to obtain the most critical component member forces and bending moments while FORM5 software was used to obtain the reliability indexes. The results revealed that due to the effect of weak soil safe bearing capacities, allowable maximum displacement was exceeded resulting in lower predicted reliability indexes and higher probability of failures that enhanced progressive failure. It is observed that the reliability index recommended by Euro code was not achieved due to the effect of weak soil-structure interactions which showed that it will be very disastrous if rigid soil structure interactions were assumed for a weak soil safe bearing capacities. The report pointed out that the use of a hinge column foundation joint for structural analysis will produce increased sections and reinforcement areas in reinforced-concrete frames. These would consequently improve the reliability indices of structures built on weak soils and reduces its probability to fail. The authors concluded that, a hinged joint should be adopted as column-foundation connection when the soil is generally weak. The findings in this study would be a useful guide and reference materials for structural safety and reliability analysis with regards to variation of soil type.

The sixth paper entitled "Reliability analysis on civil engineering project based on integrated adaptive simulation annealing and gray correlation method" by Xiao-ping and Ya-nan (2016) The author mainly focused on accessing the dynamic reliability analysis for methods

including mainly dynamic fault tree, extension of event sequence diagram and Monte Carlo simulation, and et al. The paper researched the dynamic reliability optimization. On the basis of analysis of the four quality influence factors in the construction engineering, a method based on gray correlation degree was employed to calculate the weights of factors affecting construction process quality. Then the weights were added into the reliability improvement feasible index (RIFI). Furthermore, the authors included a novel nonlinear programming mathematic optimization model. In the Insight software environment, the Adaptive Simulated Annealing (ASA) algorithm was used to get a more accurate construction subsystem optimal reliability under different RIFI conditions. In addition, the relationship between construction quality and construction system reliability was analyzed, the proposed methods and detailed processing can offer a useful reference for improving the construction system quality level.

The seventh paper entitled "Target reliability for railway civil engineering structures" by Sýkora *et. al,* (2017) The authors considered practical applications of the theoretical principles which were demonstrated by the examples of a railway bridge, railway tunnel and road bridge over an important railway line. The authors illustrated how probabilistic reliability analysis and risk optimization can support decisions about alternative strategies to achieve the optimal designs complying with the requirements on human safety. Their contribution reveals that target reliability levels for civil engineering structures recommended in various normative documents are inconsistent in terms of the values and the criteria according to which the appropriate values are to be specified. This is because the optimal target reliabilities from economic point of view primarily depend on failure consequences and costs of safety measures.

The eight paper entitled "The application of reliability analysis in Engineering practice, reinforced concrete foundation" by Skrzypczak *et. al,* (2017) performed reliability analysis concerning a reinforced concrete foundation, for which reliability index and probability of failure had been specified using the following methods: analytical method FORM, simulation methods FORM and SORM as well as Monte Carlo simulation. The concept of the planned period of use was considered and adopted in the project interval in which the structure was to be used for its intended purpose without the need for general repairs. Reliability of building structures depends on a number of correlated factors, the authors focused on the quality of materials, building precision and level of control, protection against environmental influences and maintenance level during exploitation, specific period of use, adopted solutions for the construction materials, design details and technologies, adopted loads (both their values and combinations), standard requirements regarding capacity, exploitation and durability, quality of computational models used in the design process and methods for assessing reliability of the structure.

The ninth paper entitled "A Study of Probabilistic FEMs for a Slope Reliability Analysis Using the Stress Fields" by Farah *et. al,* (2015) In this paper, the authors considered the applicability and the effectiveness of the probabilistic finite element methods (FEMs) such as the perturbation method, and the Spectral Stochastic Finite Element Method (SSFEM) applied to the reliability analysis of the slope stability. The results were checked by the Monte Carlo simulation and a direct coupling approach combining the deterministic finite elements code and First Order Reliability Method (FORM) algorithm. These methods were presented considering the spatial variation of soil strength parameters and Young modulus. Then random field used to describe the spatial variation. Also, the reliability analysis was conducted using a performance function formulated in terms of the stochastic stress mobilized along the sliding surface. The present study shows that the perturbation method and SSFEM can be considered as practical methods to conduct a second moment analysis of the slope stability taking into account the spatial variability of soil properties since good results were obtained with acceptable estimated relative errors. Finally, the authors used the perturbation method to delimit the location of the critical probabilistic sliding surfaces and to evaluate the effect of the correlation length of soil strength parameters on the safety factor. In addition, the two methods were used to estimate the probability density and the cumulative distribution function of the factor of safety.

The tenth paper entitled "Quality Control and Evaluation Methods of Concrete Engineering and Its Reliability Analysis" by Wang and Jiang (2015) In this paper, the authors used the two tests (Ultrasonic pulse velocity (UPV) and rebound hammer (RH) tests) to determine the concrete quality by applying regression analysis models between compressive strength of in situ concrete on existing structure and the nondestructive tests values. With the combined method, equations were derived using statistical analysis (simple and multiple regression) to

estimate compressive strength of concrete on site. To add to that, the authors presented the reliability analysis to nonlinear reinforced concrete beams. A First Order Reliability Method (FORM) was used, and the results were compared to the ones given by Monte Carlo simulation.

The eleventh paper entitled "Construction System Reliability Analysis Based on Improved Firefly Algorithm" by Yancang *et. al,* (2016) In this paper the construction system reliability was introduced to solve the problems of (multi-objective control, objective quantification difficulties and computational complexity) into the project management. The process of construction project was divided into several units of work based on system decomposition theory and the reliability of each unit of work was calculated. Then, the system reliability was optimized by the improved firefly algorithm. To avoid that the basic algorithm is highly depended on the initial solution and easy to fall into local optimum at later stage, the dynamic population firefly algorithm was proposed. Engineering practice shows that the improved algorithm has higher convergence speed and accuracy of optimization. The study provides a novel method for effective construction management.

The twelfth paper entitled "Reliability-Based Structural Safety Evaluation of Concrete-Steel Composite Beams According to Euro Code 4" by Mamuda *et. al,* (2018) In this study, the authors considered the reliability analysis of Concrete-Steel Composite Beams According to Euro code using First Order Reliability Method (FORM) through a developed matlab programme, four failure mode considered are bending, shear, deflection and shear connectors capacity, by considering loads and resistances variables of the sections in the limit state equations to be random. The analysis was carried out by varying some parameters while keeping other parameters constant, and this is to study the effects of the parameters against one another. The safety index was found to be affected by parameters like steel yield strength concrete strength, effective width of the slab, web thickness, ultimate tensile strength, shank diameter of the shear connectors, Load ratio, live load and span of the beam. From the failure mode considered, Euro code 4 seems to be conservative with respect to shear, safe with respect to deflection, satisfactory to bending, while shear studs capacity was at critical. This study shows how FORM can be very useful in testing design parameters in structural engineering.

The thirteenth Paper entitled "Reliability based analysis of foundation settlement" by Salahudeen and Kaura (2017) This research study was aimed at the development of a method that will assist in the process of calibration of load and resistance factors for service limit state with focus on the soils of the South-East zone of Nigeria based on standard penetration test (SPT) results. Reliability analysis, expressed in the form of reliability index (β) and probability of failure (Pf) were performed for foundation settlement using First Order Reliability Method (FORM) in MATLAB. The footings were designed for a 25 mm allowable settlement value as recommended in Eurocode 7 for serviceability limit state (SLS) design which is a conventional approach. Reliability indices were calculated based on the Burland and Burbidge foundation settlement prediction method. Results of the reliability analysis show that, as the variability of geotechnical properties at a site increases, larger values of settlement were obtained with a higher probability of occurrence. Sensitivity study indicated that the applied foundation pressure and coefficient of variation (COV) of SPT N-value significantly affected the magnitude of foundation settlements. These comparative impacts could otherwise have not been known except some form of failure occurred after construction but for reliability analysis.

The fourteenth paper entitled "Reliability assessment of stringers spacing's in bridges as function of timber properties" by Owoeye (2016) This paper presentation accounts for established functions of stringer spacing of major Nigerian woods when used as bridge decks. It entailed stochastic evaluation of bridge wood decks with absolute regards to the spacing of supporting stringers. A timber bridge deck was modelled on timber stringers in accordance with current specifications as outline in AASHTO LRFD (2010), to represent real life experiment in order to depict the structural behavior of Nigerian timbers when used for bridge decks. This model was then subjected to some degree of entropy using Advance Second Moment Reliability Assessment (ASMRA) method, which is subsequently analyzed using JAVA library with the help of Flanagan polynomial. The concept of ASMRA with Flanagan polynomial returns optimum output values for any input array of data along the input normal distribution curve. Convincingly, the author established that, stringer spacing, strength classes, timber thicknesses and width are some of the major factors among others influencing the structural behavior of Nigerian timber species used for bridge decks. These data were treated as random variables to generate relative optimum values which, were used to predict the relationship between stringer spacing as a dependent variable on other variables using Analysis of Variance (ANOVA) and multiple Regression line analysis. For the considered timber species, it was observed that large percentages, ($R2 \cong 1$ that is 100% for the variation in the

dependent variable (stringer spacing) is explained by the independent variables (physical characteristics) which are all good fit. Also all the predicted regression lines were reliable and statistically significant as the significance F, (3.59709E-05 for EKKI, 5.58768E-05 for APA, 3.59709E-05 for IROKO and 8.55563E-05 for ABURA) are all less than 0.05. Thus, these established relationships were posed as a help in future forecast of stringer spacing for bridge deck design and analysis within acceptable structural reliability indices which are statistically significant (and are all within acceptable values ≤ 0.05).

The fifteenth paper entitled "Mechanics-based crack initiation prediction framework" by Zhang *et. al,* (2001) In this paper a mechanics-based top-down fatigue cracking initiation prediction framework for asphalt pavements was developed. This was achieved by undertaking further enhancement to HMA-FM (Zhang, Roque, Birgisson, & Sangpetngam, 2001). Asphalt mixture morphology-based sub-models were developed and incorporated into HMA-FM to consider age induced degradation in mixture fracture resistance and healing potential. Calibration and validation of the developed model was achieved using field pavement sections that have a well-documented performance history and high quality laboratory data The sixteenth paper entitled "Reliability based calibration for the mechanics based crack initiation framework" by Dinegdae (2015) in this study, the full probabilistic distribution approach was used to characterize design inputs variability. The parameters which were identified to be dominant and subsequently modeled as random variables are AC thickness, base modulus, traffic and DCSE_lim. Using these design inputs variability, a surrogate model is generated to represent DCSE_acum. A statistical analysis was performed on the fitted function to examine its adequacy and to ensure it provides a good approximation to the true system.

The seventeenth paper entitled "Case Study on the Typical Failure Modes and Reliability of Reinforced-Earth Retaining Wall" by Jingyu *et. al, ,* (2016) In this work Limit state equations were established based on Monte Carlo and point Method, combined with engineering calculations. The results showed that the internal stability of reinforced retaining wall (tensile and anti-uplift of reinforced materials) is the key index in reliability analysis; in a large range, the anti-uplift reliability index and the vertical distance from the reinforcement strip to the wall top are basically inverse proportion; the anti-uplift reliability index of the reinforcement strip in wall toe was minimum, so that it was the key index; it was noticed in calculation that the tensile reliability index of the reinforcement strip present to the middle range of the retaining wall. The smaller the vertical interval, the greater the reliability index of geotextile tensile and anti-uplift; but the greater the vertical density, the worse the economy. This procedure helps to seek the balance of safety and economy.

The eighteenth paper entitled "Reliability of steel frame systems with semi-rigid connections" by Hung and Wang (2003) This study focused on evaluating the reliability of steel frame systems with rigid connections and with semirigid connections. The system reliability of frames was assessed using simulation technique. The limit state function for the system reliability analysis established based on the collapse load factor which is obtained using the second-order refined plastic-hinge analysis method. The uncertainty considered were the loads and material yield strength. The results indicated that although the reliability of frame systems with rigid connections is always higher than that of frame systems with semirigid connections, however, from reliability point of view, in most cases their differences are not very significant. Therefore, it was concluded that if the quality control of the construction of the connections is adequate, the consideration of whether the connections are rigid or semirigid does not significantly impact the system reliability, although it could affect the estimated expected cost of the system which includes the initial cost and cost of collapse.

The nineteenth paper entitled "Time-dependent reliability analysis of reinforced-concrete bridges under the combined effect of corrosion, creep and shrinkage" by Chehade *et. al,* (2018) This paper proposes a methodology for the time-dependent reliability assessment of reinforced-concrete bridges, taking into account the combined effect of steel corrosion due to the aggressive environment, creep and shrinkage under realistic traffic. For this purpose, traffic was simulated over time according to weight in motion, data recorded in Europe, then time-dependent deflection calculated by

considering the cyclic creep effect due to traffic load in addition to shrinkage and tension stiffening. So, the time-dependent bending moment would be deduced using the finite element method; this moment was then introduced into the limit state function with the nominal resistance (flexure) which decreased over time due to the reduction of steel section under corrosion, the reliability index and the probability of failure was then calculated using the first-order reliability method. The twentieth paper entitled "Reliability analysis of soil liquefaction based on standard penetration: a case study in Babol city" by Choobbasti *et. al*, (2015) This paper has obtained information from Standard Penetration Test (SPT) and some empirical approaches such as: Seed et al, Highway bridge of Japan approach to soil liquefaction, The Overseas Coastal Area Development Institute of Japan (OCDI) and reliability method to studying potential of liquefaction in soil of Babol city in the north of Iran are compared. Evaluation potential of liquefaction in soil of Babol city is an important issue since the soil of some area contains sand, seismic area, increasing level of underground waters and consequently saturation of soil. The authors were able to gain suitable recognition of liquefaction potential and find the most appropriate procedure of evaluation liquefaction potential to decrease related damages.

The twenty-first paper entitled "*Reliability of shallow foundation design using the standard penetration test*" by Zekkos *et. al, ,* (2004) The sources of uncertainty, variability and bias in the performance of the Standard Penetration Test were identified and classified in a manner that should assist the practice in recognizing and reducing them. These uncertainties and additional uncertainties introduced in the design process were then incorporated in a reliability-based evaluation of the design of shallow foundations. The results of the reliability analyses showed that the factor of safety approach can provide an impression of degree of conservatism that is often unrealistic. At times, foundations with smaller factors of safety have smaller probabilities of failure than foundations with higher factors of safety. The reliability based approach provides rational design criteria, accounting for all key sources of uncertainty in the foundation engineering process, and thus should be the basis of design.

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The twenty- fourth paper entitled "Reliability-based design applied to retaining walls" by Low (2005) this paper illustrates practical reliability-based design procedures for retaining walls based on the Hasofer-Lind index and FORM. Correlated normal and non-normal random variables are considered. The efficient spreadsheet-based probabilistic approach, based on the work of Low & Tang, achieves the same result as the Hasofer-Lind method and FORM, but uses an intuitive

expanding dispersion ellipsoid perspective that greatly simplifies the computations and interpretations. The differences between a reliability-based design and one based on partial factors will be discussed. Sensitivity information as conveyed in a reliability analysis will be studied. The probabilities of failure inferred from reliability indices will be compared with Monte Carlo simulations. This paper deals only with certain aspects of reliability, namely methodology and concepts, and not reliability in its widest sense.

The twenty – fifth paper entitled "Full probabilistic design of earth retaining structures using generalized subset simulation" by Hui Gao *et. al*, (2019) This paper develops an efficient MCS-based full probabilistic design approach, which directly makes use of Generalized Subset Simulation (GSS) to perform RBD of earth retaining structures. The method allows simultaneously approaching failure domains of different possible designs in a prescribed design space by a single GSS run and generating their corresponding failure samples in an efficient manner. As a result, a large number of failure samples can be generated for numerical representation of failure domains of possible designs. Then, the failure probabilities of possible designs are calculated for identifying feasible designs and the design point of each design can be approximately determined as the most probable failure sample of the design according to its probabilistic interpretation.

The twenty- sixth paper entitled "Reliability Analysis of Bored-pile Wall Stability Considering Parameter Uncertainties" by Alberto and Roberto (2020) In this study, an expanded reliability-based design approach, along with finite element analysis, was applied to conduct parametric analyses of bored-pile wall stability. In serviceability limit state design framework, the results indicate that cohesion and groundwater level are factors that significantly affect bored-pile wall stability. Moreover, high variability in the cohesion range causes great uncertainty to determine the embedment depth of bored-pile wall. The feasible embedment depth can reach 4 times the free height considering the maximum coefficient of variation (50 %) of the cohesion. In turn, when the groundwater level is located at the retained ground surface, the horizontal displacement of the upper end of the wall reaches 15.2 mm, i.e., 0.0038 times the free height of the wall, for which the soil mobilizes active earth pressures. It was also found that the resolution of probabilistic results is highly influenced by the number of iterations in Monte Carlo simulations.

The twenty – seventh paper entitled "Reliability Analysis on permanent displacement of earth slopes using simplified Bishop Method" by Jian Ji *et. al,* , (2020) This paper examines the seismic slope failure mechanism of rotational sliding mass. Permanent displacement is analyzed based on Newmark's sliding block theory, with extension to compute the rotational displacement in the presence of horizontal ground acceleration history. A simplified relationship between the rotational and horizontal motions of a circular failure mass is also obtained. By comparing case studies, the possible reasons whether and how the seismic slip surface differs from the static one are explained. In addition, the allowable displacement when a quantitative judgment of the slope performance is required was considered in the research. In this regard, the underlying uncertainties of the soil properties are introduced to probabilistically relate this threshold value to the reliability index, a substitute for the probability of failure or risk acceptance level. The results from the parametric studies indicated the reliability-based design of the allowable displacement is a promising approach for seismic slope analysis.

The twenty – eight paper entitled "Decoupled reliability-based geotechnical design of deep excavations of soil with spatial variability" by Wang- Sheng and Sai Hung (2020) This paper presents a general decoupled method for reliability-based geotechnical design that takes into account the spatial variability of soil properties. In this method, reliability analyses that require a lot of computational resources are decoupled from the optimization procedure by approximating the failure probability function globally. Failure samples are iteratively generated over the entire design space so that their global distribution information can be extracted to construct the failure probability function. The method is computationally efficient, is flexible to implement, and is well suited for geotechnical problems that may involve sophisticated models. A design example of two-dimensional deep excavation against basal heave is discussed for Singapore marine clay where the density and normalized undrained shear strength of soil mass are modeled as random fields. Results demonstrate that the proposed method works well in practice and is advantageous over the coupled or locally decoupled reliability-based geotechnical design methods.

The twenty – ninth paper entitled "Reliability-Based Design for External Stability of Mechanically Stabilized Earth Walls" by Chalermyanont and Benson (2005) A two-phase approach was used to develop a reliability-based design (RBD) method for external stability of mechanically stabilized earth (MSE) walls. In the first phase, a parametric study was conducted using Monte Carlo simulation to identify parameters that affect the probability of external failure of MSE walls. Three modes of failure were considered: sliding, overturning, and bearing capacity. External stability was assessed by treating the reinforced soil as a rigid mass using the same

procedures employed for conventional gravity-type wall systems. Results from the parametric study indicate that the mean and coefficient of variation of the backfill friction angle are significant for sliding, the mean and coefficient of variation of the friction angle of the backfill and coefficient of variation of the unit weight of the backfill are significant for overturning, and the mean and coefficient of variation of the friction angle of the foundation soil and the mean of the backfill friction angle are significant for bearing capacity. In the second phase, a series of additional simulations was conducted where the significant parameters identified in the parametric study were varied over a broad range. Results of these simulations were used to develop a set of RBD charts for external stability of MSE walls. A comparison indicates that similar reinforcement lengths are obtained using RBD and conventional methods and that the inherent probability of external failure in conventional deterministic design is ≤0.001. This probability of external failure is similar to inherent probability of failure reported by other investigators for similar geotechnical structures.

The thirtieth paper entitled "Optimal Maintenance Design-Oriented Non-probabilistic Reliability Methodology for Existing Structures Under Static and Dynamic Mixed Uncertainties" by Wang *et. al,* (2018) In this paper, a new time-varying non-probabilistic reliability-oriented optimal maintenance design method with the consideration of static and dynamic mixed uncertainties is proposed. The interval model is utilized to quantify the uncertain and time-varying characteristics and the structural reliability can be assessed combining the interval model and the first-passage theory. The authors tried to establish a more general maintenance cost model enlightened by Frangopol's work under the non-probabilistic system and the maintenance strategy including uncertainty assessment, reliability evaluation, and cost optimization is constructed.

The thirty – first paper entitled "Jointed distribution method reliability analysis of soil liquefaction based on triaxial test result" by Mohammad *et. al,* (2011) In this research the jointed distribution method is used for probabilistic analysis and reliability assessment of soil liquefaction. The stochastic selected parameters are dry and saturated unit weights which are modeled using a truncated normal probability distribution functions. The depth and earthquake acceleration ratio are regarded as constant parameters. The results are compared with the Monte Carlo method. Comparison of the results indicates superior performance of the proposed approach for assessment of reliability. The thirty –second paper entitled "Reliability analysis and sensitivity analysis of unsaturated soil slopes under rainfall infiltration" by Xiao- Hui Tan *et. al,* , (2014) Reliability analysis is very important for unsaturated soil slope under rainfall condition. To evaluate slope stability and its influencing factors, four rainfall and seepage conditions with three slope angles are studied. Sensitivity analysis presents that among the two strength parameters (c' and φ') and four hydraulic parameters (a, n, Sr and ks), c' affects slope stability strongly, φ' and n have medium influence on slope stability, a influences the slope stability weekly, while the influence of Sr and ks are very small and these two parameters can be considered as deterministic variables. Reliability analysis proves the results of sensitivity analysis, and shows that the 4p method, where basic variables X=[c' φ' a n]T, is accurate enough for a large value of coefficient of variation in the reliability analysis of unsaturated soil slope under rainfall. The same conclusions can be obtained from each rainfall condition with different slope angles. With the increase of rainfall intensity and saturated hydraulic conductivity, the influence of rainfall infiltration on slope stability becomes larger. And the influence of rainfall and hydraulic parameters on slope stability increase with the increase of slope angle.

The thirty – third paper entitled "Reliability analysis of earth dams using direct coupling" by Siacara *et. al,* (2020) Numerical methods are helpful for understanding the behaviors of geotechnical installations. However, the computational cost sometimes may become prohibitive when structural reliability analysis is performed, due to repetitive calls to the deterministic solver. In this paper, the authors show how accurate and efficient reliability analyses of geotechnical installations can be performed by directly coupling geotechnical software with a reliability solver. An earth dam is used as the study object under different operating conditions. The limit equilibrium method of Morgenstern-Price is used to calculate factors of safety and find the critical slip surface. The commercial software packages Seep/W and Slope/W are coupled with StRAnD structural reliability software. Reliability indices of critical probabilistic surfaces are evaluated by the first- and second-order structural reliability methods (FORM and SORM), as well as by importance sampling Monte Carlo (ISMC) simulation. By means of sensitivity analysis, the effective friction angle (ϕ') is found to be the most relevant uncertain geotechnical parameter for dam equilibrium. The correlations between different geotechnical properties are shown to be relevant in terms of equilibrium reliability indices. Finally, it is shown herein that a critical slip surface, identified in terms of the minimum factor of safety (FS), is not the critical surface in terms of the reliability index.

The thirty – fourth paper entitled "Reliability assessment of bearing capacity of layered soils using high dimensional model representation (HDMR)" by Suska

and Pula (2013) HDMR (High Dimensional Model Representation) is a relatively new method that is used to form response surface based on results obtained through laboratory experiments or through numerical calculations. So far the method has been used mainly in chemistry, although a few studies conducted in recent years show that it can be considered a useful tool in soil mechanics and foundation engineering. In this the application of HDMR method to reliability assessment of bearing capacity of layered soils. Madej's method, widely recognized and used by Polish engineers, is applied to conduct the calculations. In the analysed case bearing capacity is not expressed by means of an explicit formula. To fit the approximate functions of bearing capacity, its values are calculated on a grid of points equally spread on ranges of variables. Finding the relation between input and output data is conducted by means of assessing each variable's influence on response's mean value within a given scope. Approximate functions have been used to calculate reliability indices by means of FORM, SORM and Monte Carlo methods.

3 CONCLUSIONS

From the foregoing we will notice that the field of engineering has undergone many evolutionary progress and breakthroughs during the last few years. This paper provides a highlight of a somewhat recent historical perspectives of significant contributions in the field of reliability engineering since the beginning. The reason for the priority emphasis is that it is by far the most effective way of working, in terms of minimizing costs and generating reliable products. The primary skills that are required, therefore are the ability to understand and anticipate the possible causes of failure, and knowledge of how to prevent them. It is necessary to also have the knowledge of the methods as have been highlighted in the papers reviews in the preceding pages so as to be able to correctly analyze designs and design data.

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