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Probability-Based Assessment of Electric Power Distribution Concrete Poles in Southwest of Nigeria

Quadri Ajibola Ibrahim[1] and Afolayan Joseph Olasehinde[2]

[1] Civil and Environmental Engineering Department, Federal University of Technology, P.M.B. 704, Akure, Ondo State, Nigeria

[2] Civil and Environmental Engineering Department, Federal University of Technology, P.M.B. 704, Akure, Ondo State, Nigeria

Abstract

A numerical study has been carried out to determine the safety level of electric power distribution concrete poles under uncertain loading conditions in the Southwestern part of Nigeria. Typical tapered electric power distribution concrete poles of 9 m high were considered and analyzed using probabilistic method. The determination of the response of the poles to the environmental loading was accomplished by the aid of SAP2000 Advanced 14.0.0 finite element analysis software program. The ultimate and the serviceability limit state equations were generated based on the provisions of the British Standard (BS 8110-1:1997). The probability of failure was estimated using the First-Order Reliability Method (FORM) coded in CalREL, a multipurpose structural reliability analysis software. Since every natural phenomenon is accomplished by uncertainties, the interaction between the capacity of a pole and the demand on it was considered uncertain. Critical positions/areas along the length of any concrete pole that require amelioration have been identified based on the implied levels of reliability when factors affecting material properties, geometry and loading are considered random in nature.

***Keywords:* Concrete poles, Reliability analysis, CalREL, SAP 2000, Overturning Moment, Deflection**

1. Introduction

Development of sources of energy to achieve useful work is the key to the industrial advancement which is vital to the continual improvement in the standard of living of people. The discovery of new source of energy, making energy ready everywhere needed, and the conversion of energy from one form to another and utilizing it without creating pollution to the environment are among the greatest problems facing the world today (Oritola, 2006). Hence, the electric power system is one of the instruments for converting and transporting energy which plays an essential function in meeting these challenges. An electric power system comprises three principal divisions: the generating station, the transmission lines, and the distribution system (William, 2005). Transmission lines are the links between the generating station and the distribution system and extend to other power system over interconnection. The distribution systems connect all the individual loads to the transmission lines at substations for the voltage transformation and functions.

An electric pole which is part of transmission lines or distribution system acts as cantilevered structure, which is designed and analyzed as a tapered member with combined axial and bending loads. The forces acting on a pole are from: the vertical loading (comprising dead weight of conductors, cross arms, insulators) and the horizontal loading due to wind pressure on conductors and pole (Oritola, 2006). The design of poles is mainly based on the principle of loading (Ilochi *et al.*, 1996). Tension calculation is quite involved due to the loading effect on conductors and the characteristic of conductor materials used. In recent years, utility companies have been exploring cost-effective alternatives to timber poles due to environmental concerns, durability, high cost of maintenance, and need for improved aesthetics (Lacoursiere, 1999). Thus, concrete poles have ability to withstand wind, ice, heavy snow, persistently wet or swampy areas where the soil greatly shorten the life expectancy, chemical contamination and pollution area where rate of decay of other pole types may be erratic, and other harsh conditions, and could potentially help to enhance system reliability. The tensile strength of concrete is only about 10% of the compressive strength (Blake *et al.*, 2013). As a result of this, nearly all reinforced concretes are designed on the assumption that concrete does not resist tensile stress. Reinforcement is designed to carry this tensile stress, which is transferred by bonds between the interface of the two materials. Reinforced concrete is a strong and durable building material that can be given various shapes and sizes. Its usage is achieved by combining the best features of concrete and other materials. In Nigeria, electricity is transmitted by conductors carried overhead by concrete and wooden poles. Concrete pole design is dependent on the power and voltage that is to be transmitted (Ilochi *et al.*, 1996). In Nigeria, 33/11/0.415KV is usually transmitted by overhead conductors; hence the concrete poles are more suitable for use.

The distribution system transports and delivers power to the consumers after the voltage has been stepped down to the appropriate level. The distribution system uses wires that are carried by timber, steel or concrete poles that are 9 to 12 metres high and spaced 30 metres to 45metres in the suburbs and 90 metres to 120 metres in rural areas (Short, 2006). The voltage is usually between 4.16 KV to 34.5 KV in the primary distribution system (Brown, 2008). Considering failure due to natural hazards, the distribution system is the most vulnerable (Davidson *et al.*, 2003). This is because the generation stations are few and are usually designed to withstand high wind, floods, and earthquakes. The transmission system (towers and lines) is also designed to withstand natural hazards better than the distribution system. Another reason is that unlike the distribution system, there is always more than one way to transport the electricity from the generation plants. The distribution system has several subsystems that include distribution substations, the primary distribution system, and the secondary distribution system. Distribution substations are the first stage in the distribution process. Electricity from the transmission system enters into a substation through a single transmission line. The main function of the substation is to step down the voltage to the distribution level. This is achieved by utilizing a transformer. The primary distribution system is where the stepped-down power from the substation is carried to distribution transformers through feeders. The feeders exit the substation through underground feeder get-away which is routed to nearby poles. The cables then exit from the ground and become overhead three-phase main lines. Overhead feeder components include poles, overhead lines, and pole-mounted transformers. Poles support the overhead distribution equipment. Distribution poles and lines are critical in the reliability of a distribution system during natural hazards because they are exposed to falling trees and other debris, as well as direct wind forces. The secondary distribution system is the last stage where the stepped-down electricity from the pole-mounted transformers is transported to the consumers. This is done through simple overhead service drops or more complex secondary networks. Secondary systems are usually radial (only one path available) except for vital structures that are essential during disasters.

2. Reliability Consideration

Recent researches in the area of structural reliability and probabilistic analysis have centered on the development of probability based design procedures. These include loading modeling, ultimate and service load performance, and evaluation of current level of safety/reliability in design (Afolayan, 2014; Opeyemi 2012). In a reliability-based approach, uncertainty associated with material properties, loads, environmental conditions, models etc. are taken into account by treating the parameters as random variables, processes or field. The condition of a structure is assessed by probability of failure, P_f or related to the reliability indexβ, given by Val and Stewart (2009) as:

$$\beta = -\Phi^{-1}(P_f) \quad (1)$$

Where Φ denotes the standard normal distribution function. For the calculation of P_f, the failure of a structure needs to be formally defined and expressed as a function of relevant random variables, processes or fields. In this paper,

$$P_f = \int_{\Omega} f(\mathbf{x})d\mathbf{x} \quad (2)$$

Where **x** is a vector of random variables with joint probability density $f(\mathbf{x})$ and Ω is the failure domain defined as:

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$$\boldsymbol{\Omega} \equiv \{\mathbf{g}(\mathbf{x}) \leq \mathbf{0}\} \quad \textbf{(3)}$$

CalREL incorporates four techniques for computing probability of failure. The First-order reliability method (FORM),which is applicable to series system reliability, the Second-order reliability method (SORM), which is applicable to component reliability analysis, Directional simulation with exact or approximate surfaces, which is applicable to component or system reliability analysis, and Monte Carlo simulation which can be applied to all classes of problems. In this research, FORM was adopted.

3. Collection of Data for Concrete Pole Modelling

The design data of a typical tapered electric power distribution concrete pole of 9 m high as shown in Plate 1 were collected from one of the Electricity Distribution Companies in Nigeria. The tapered height of the concrete pole was divided into eight sections as shown in Table 1. The concrete pole carries electric cables made of aluminum spanning 45 m. The loads on the concrete pole include: the cross arms, the insulators, the street lamp, the self weight of the concrete and the effect of wind load.

3.1 Load Data

(i) Dead Load

(a) Weight of Concrete
Total volume of concrete = 3.98m^3
Unit Weight of Concrete = 24kN/m^3
Weight of Concrete = 3.98×24 = 95.5 kN
(b) Cross arms and Insulator = $0.15\ kN/m^2$
(c) Street Lamp = $0.005\ kN/m^2$
(d) The self-weight of aluminum = $0.86 kN/m^2$

(ii) Wind Load

BS 6399-2:1997 (Code of Practiced for wind loading), was used for the analysis of wind load
The dynamic pressure q_s is given as:

$$q_s = kV_e^2 \quad \textbf{(4)}$$

where;
$k = 0.613$
and

$$v_e = v_s \times k_1 \times k_2 \quad \textbf{(5)}$$

In which v_s is the wind speed taken as 3.6m/s according to local wind condition in Akure, Ondo State (Adaramola and Oyewola, 2011), k_1 is the risk coefficient taken as 1.0 and $k_2$is the terrain factor taken as 1.0 for flat terrain. Therefore,
$q_s = 0.613 \times (3.6^2) = 7.94\ N/m^2$

Plate 1: Electric Power Distribution Concrete Pole

Table 1: Section Properties of the Concrete Pole

Pole Sections	Height (mm)	Width (mm)	Depth (mm)
1	0	350	300
2	0-1500	320	260
3	1500-3000	300	240
4	3000-4500	270	220
5	4500-6000	220	210
6	6000-7000	200	185
7	7000-8000	160	157
8	8000-9000	140	140

3.2 Deterministic Analysis Using SAP2000

The SAP2000 advanced 14.0.0 application Programming Interface (API) is a commercially-available powerful and sophisticated finite analysis (FEA) and design software program. It allows users to automate many of the processes required to build, analyze and design models and to obtain customized analysis and design results. This program features sophisticated capacities, such as quick equation solvers, force and displacement loading, non-prismatic frame element, post tensioning multiple coordinate systems for skewed geometry. A typical electric power distribution concrete pole under consideration was first modeled on AutoCAD and then exported to SAP2000 software interface as shown in Fig. 1, for analysis to obtain the forces, moments and deflections at each section of the concrete pole due to the applied design dead and wind loads at uncertain loading conditions (1.4 Wind load + 1.4 Dead load) as specified by BS 8110-1:1997.

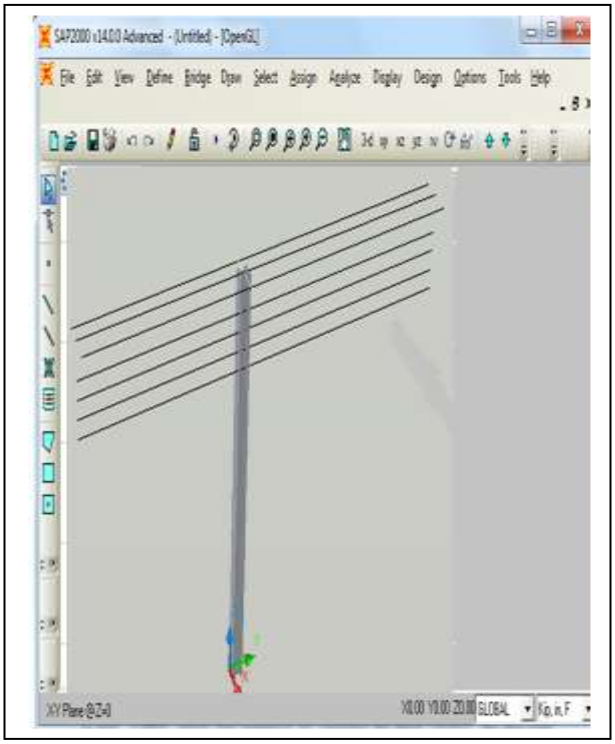

Fig. 1: Typical electric power distribution concrete pole modeled on SAP2000.

3.3 The Limit State Function

The difference between the resistance of the concrete pole and the applied load effect is the limit state function G(x), given as:

$$G(x) = M_U - M \quad \textbf{(6)}$$

where, M_u is the resistance of the pole, and M is the applied load effect.
The load combination for the ultimate limit state at adverse level from BS 8110-1: 1997 given as:

$$W = 1.4G_k + 1.4\,W_k \quad \textbf{(7)}$$

The moment capacity for the compression section is given as:

$$M_U = 0.156 f_{cu} bd^2 \quad \textbf{(8)}$$

While in the tensile section, the capacity is:

$$M_U = 0.87 f_y Z A_S \quad \textbf{(9)}$$

Let

$$\rho = 100\ {}^{A_S}/_{bd}$$

Thus,

$$M_U = 0.0083 f_y \rho bd^2 \quad \textbf{(10)}$$

The percentage reinforcement ratio (ρ) was varied from the minimum of 0.55% to maximum of 3.00% with an interval of 0.55. From equation (8) and (10), the moment of resistance is a function of the breath, effective depth, characteristics strength of concrete and steel, lever arm and the area of steel provided.
The deflection of the concrete pole designed as cantilever is given as:

$$\text{Maximum deflection } \delta_m = \frac{Wl^3}{3EI} \quad \textbf{(11)}$$

While

$$\text{Allowable deflection } \delta = \frac{span}{250} \quad \textbf{(12)}$$

The statistical data used for the analyses are as shown in Table 2.

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Table 2: The Limit State Function

Parameter	Assumed Distribution	Coefficient of Variation (%)
Breadth	Normal	10
Depth	Normal	10
Characteristic concrete strength (f_{cu})	Log Normal	30
Characteristic steel strength (f_y)	Log Normal	30
Reinforcement ratio (ρ)	Normal	10
Applied bending moment (M)	Log Normal	30

4. Determination and Discussion of the Probability of Failure

The failure of any structure can be measured in terms of the probability of failure P_f. On the other hand, the reliability of a structure is measured by the safety index, **β.** Reliability analyses were conducted for electric power distribution concrete poles based on the derived limit state equations. The results obtained from the probabilistic evaluation are discussed.

Figs. 2 to 7 show the plots of reliability indices against height of the electric power concrete pole of 9m high under flexural failure. There is a general trend of growing reliability index for the pole from its base to a height of 1.5m before it sharply drops. Increase in the reinforcement ratio also leads to increasing reliability, which of course, decreases with the height of the pole. For instance, with a reinforcement ratio of 0.55, the reliability index increases from 5.18 to 6.18 as the height of the concrete pole increases from the base to a height of 1.5m and then falls drastically to 0.65 at a height of 8m as can be seen in Fig. 3.

The comparison of reliability indices at varying reinforcement ratio (ρ) from 0.55 to 3.00 as the height increases from base to the top is shown in Fig. 8. Generally, reliability index initially is higher at the base of the pole, which grows with the height to about a point 1.5 m from the base. Although reliability increases with reinforcement ratio, the pattern of its sharp degeneration with increasing height is the same.

In Fig. 9 the reliability indices at different reinforcement ratio for the tapered concrete pole against the various cross-sections are compared. At the ground level the cross-section is rectangular while the next five sections are I-section, and the last two sections are also rectangular as shown in Plate 1. As the cross-section of a tapered electric concrete pole decreases with increasing height, so does the reliability decrease. On the basis of an assumed target reliability index, $\beta_{T,}$ of 3.0 proposed by the Joint Committee on structural Safety (JCSS, 2005), it implies that the cross-sections provided beyond $0.03m^2$ are not enough to carry the axial load on an electric concrete pole. At any given reinforcement ratio, the reliability index increases with the cross-section before a gradual fall as the cross-section increases towards the base of the pole. At lower cross-sections, a reinforcement ratio less than 1.1 will lead to a reliability level lower than the assumed target level. Under bending conditions, the tapered ends of electric concrete poles are extremely prone to failure.

In order to examine the dependence of the reliability of an electric concrete pole on its geometry and resistance property, Fig. 10 was plotted. It can be seen that as the height of the concrete pole increases at any given reinforcement ratio, reliability indices decrease. Similarly, an increase in the reinforcement ratio at any height of the pole leads to an increased reliability index. It is obvious that geometry plays a significant role in the performance of electric concrete poles.

Fig. 11 shows the reliability indices of deflection of concrete pole against the tapered cross section. It is noticed that the reliability level of the concrete pole decreases as the cross section decreases. Below a cross-sectional area of $0.03m^2$, the criterion for safety is violated as the reliability index is less than 2.0 being the target safety index as proposed by Elligwood (1987). The calculated safety index has negative values at lower cross-sections signifying that the probability of failure is high. A general comparison of the levels of reliability associated with overturning moment and deflection, under uncertain material properties, geometry and loading, shows that the key failure mode of electric power concrete poles is the violation of deflection serviceability limit state (see Figs. 9 and 11). Thus, sections above 4.5m from the base of electric power concrete poles are very critical to their performance.

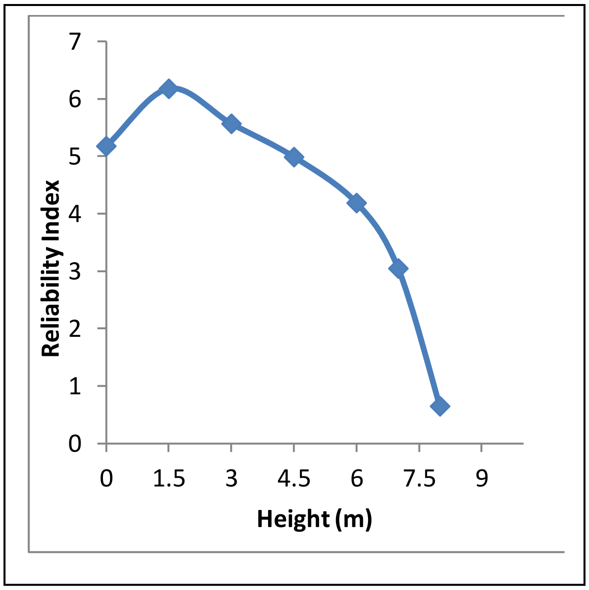

Fig. 2: Reliability Index for Overturning Moment at varying height for ρ= 0.55

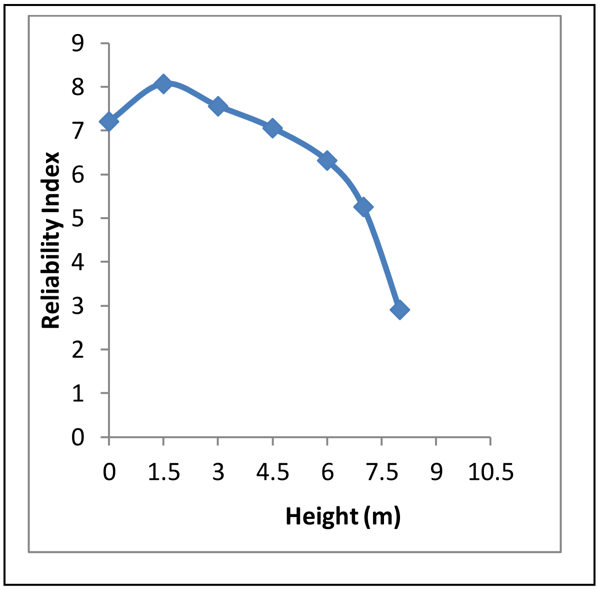

Fig. 4: Reliability Index for Overturning Moment at varying height for ρ= 1.65

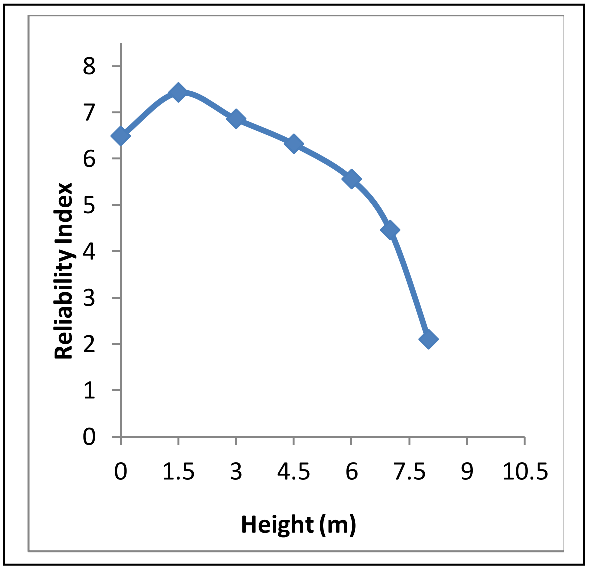

Fig. 3: Reliability Index for Overturning Moment at varying height for ρ= 1.10

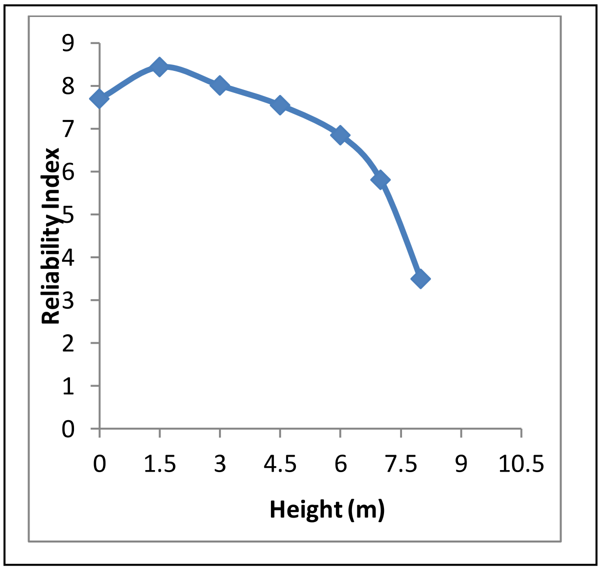

Fig. 5: Reliability Index for Overturning Moment at varying height for ρ= 2.20

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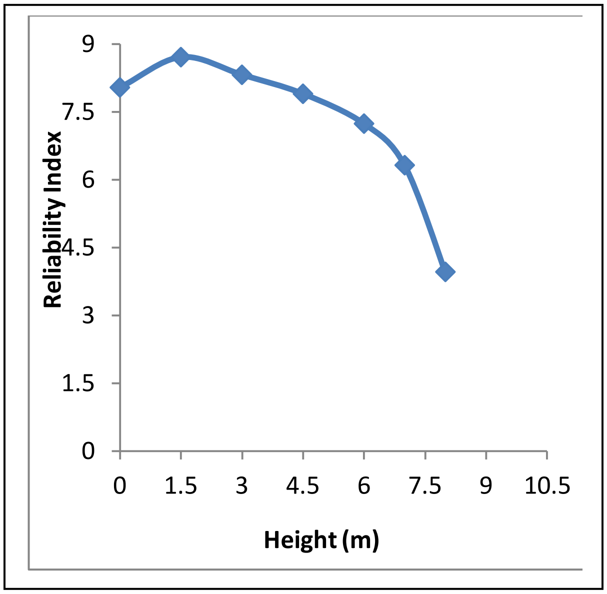

Fig. 6: Reliability Index for Overturning Moment at varying height for ρ= 2.75

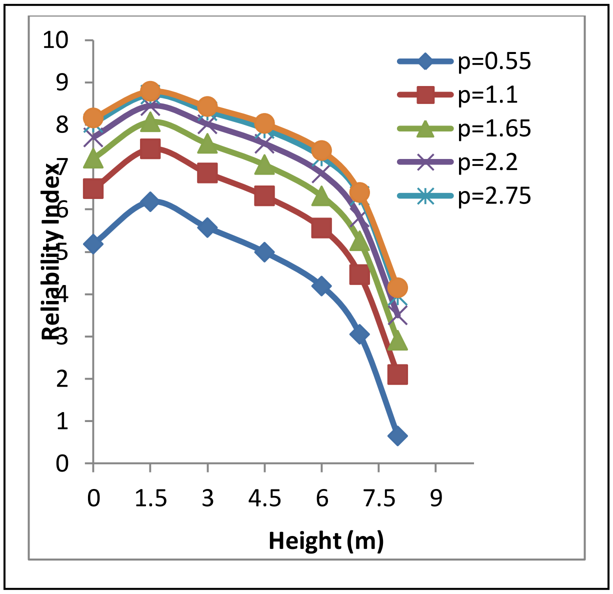

Fig. 8: Reliability Indices for the Concrete Pole at varying height under Overturning moment.

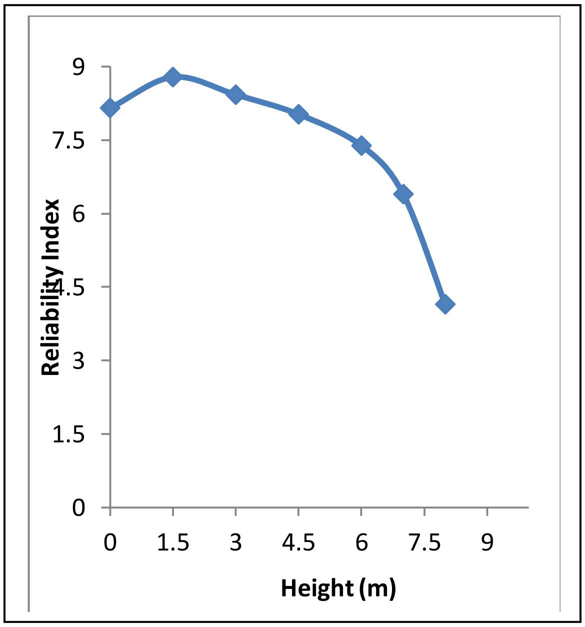

Fig. 7: Reliability Index for Overturning Moment at varying height for ρ= 3.00

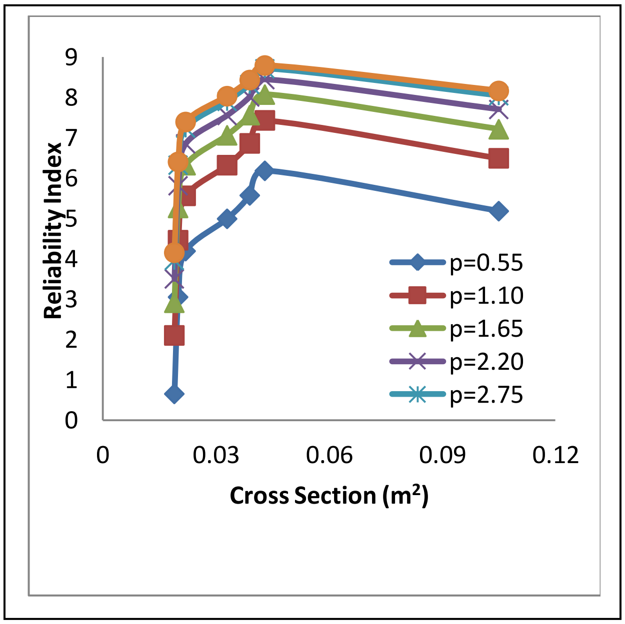

Fig. 9: Reliability Indices for the Concrete Pole at varying Cross-Section under overturning moment.

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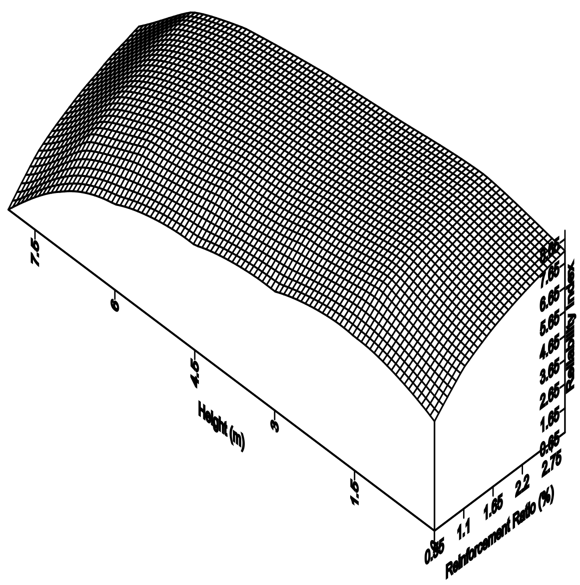

Fig.10: 3-dimensional plot of Reliability Index, Reinforcement Ratio and the Height of Concrete pole for Overturning Moments.

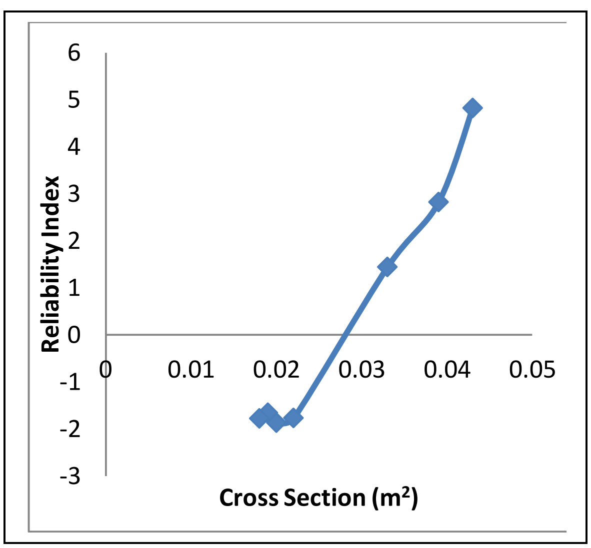

Fig. 11: Implied Reliability Indices for Deflection at Varying Cross-Section.

5. Conclusion

The results of probabilistic appraisal of tapered electric power distribution concrete poles using generated limit state functions and first order reliability method (FORM) under uncertain loading conditions, based on the provision of British Standard (BS 8110-1:1997) have been presented. A finite element analysis software SAP2000 14.0.0 was adopted for the static analysis of the poles. The reliability levels of tapered electric power distribution concrete poles have been found to be non-uniform over their height. The level of reliability increases as the reinforcement ratio increases but decreases as the height of the concrete pole increases. Comparing the levels of reliability associated with the effects of overturning moment and deflection, the most critical mode of failure for tapered electric power distribution concrete poles is deflection. Risk assessment is advocated for newly designed facilities before construction is carried out and adequate dimensions should be ensured by workmanship to increase the efficiency and life span of concrete poles.

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