J Fail. Anal. and Preven. (2021) 21:160–171
https://doi.org/10.1007/s11668-020-01040-3

TECHNICAL ARTICLE—PEER-REVIEWED

Failure Analysis of a Partially Collapsed Building using Analytical Hierarchical Process

George U. Alaneme · Gregory C. Ezeokpube · Elvis M. Mbadike

Submitted: 12 July 2020 / in revised form: 27 September 2020 / Accepted: 1 October 2020 / Published online: 27 October 2020

Abstract Building failure usually results in collapse if not discovered and properly addressed. Building collapse/failure most times causes loss of properties and lives. A case study of a partially collapsed one-story building is presented for emphasis with technical assessment of the partial-collapse cause so as to proffer remedy of the structure. This is achieved through detailed engineering analysis of the building's structural elements and identification of remedial options. Field inspection is carried out through soil excavation to assess the foundation condition, taking soil samples from the collapsed building for laboratory study and nondestructive test. From inspection, it was observed that the building construction was inadequately supervised and as a result was under-reinforced, which led to excessive cracks and deflection. The soil is classified by AASHTO A-2-4: maximum dry density 2.15 mg/m^3 and optimum moisture content 9%. The compressive strength of the structural elements was measured using the rebound hammer, and a mean compressive strength of 13 N/mm^2 was obtained which indicates a low-compressive-strength concrete. Analytical hierarchical process is utilized as the multi-criteria decision-making method to derive the actual partial-collapse cause; from the priority vector 6, 56, 26 and 12% were obtained for soil/foundation, under-reinforcement, low-compressive-strength and overloading alternatives, respectively. The consistency ratio computed was 0.065 which shows the decision maker's subjective assessment was consistent. The summary of the failure investigation underscored the importance of ensuring proper supervision and quality control for framed-structures construction.

G. U. Alaneme (✉) · G. C. Ezeokpube · E. M. Mbadike
Civil Engineering Department, Michael Okpara University of Agriculture, P. M. B. 7267, Umudike, Umuahia 440109, Abia State, Nigeria
e-mail: tinz2020@gmail.com

Keywords Building collapse/failure · Nondestructive test · Compressive strength · Construction management

Abbreviations

PCM	Pairwise comparison matrix
AHP	Analytical hierarchical process
PV	Priority vector
RI	Random Consistency Index
CI	Consistency Index
CR	Consistency ratio
AASHTO	American Association of State Highway and Transportation Officials

Introduction

Building failure can be described as the deficiency or dysfunction of any of the building components and results in various levels of severity with the worst of it, leading to the eventual building collapse. Building failure leads to collapse if not discovered and properly addressed; it does take time, but during this time, measures for remediation of the building are applied and executed to ensure restoration of the building to avoid collapse [1]. Collapse and failure of buildings result in loss of properties and lives in most cases, and its incidence has become a major development concern of any nation to reduce the frequency of its occurrence due to the magnitude of losses experienced. Building collapse can be simply described as when the whole structure or as a result of dysfunctional part, and the failure makes the building unable to serve its initial intended purpose. Buildings are structures which provide shelter and comfort for humans, his activities and properties. It is expected to give humans the desired satisfactions if properly designed, planned and executed. The building styles and aesthetics are frequently evolving with the emergence of new techniques and materials for construction. This makes it essential for the right components, structure and materials that meet the expected building standards to be selected to avert failure [2]. Research and investigation into the cause of building collapse have been carried out by civil engineers and professionals so as to find systemic measures which will help to ameliorate this menace. Mansur et al. [3] in their work performed the evaluation of building collapse via system thinking approach. Only secondary data were used to find out the main cause using a system thinking approach where casual loop diagram is developed showing relationships and interdependencies among critical factors identified. Vensim which is a system thinking application was utilized to develop the casual loop model which aided in finding out critical points namely, structural issues, structural failures and differential settlement which are all associated discipline in civil engineering. Recommendation based on findings is to ensure provision of quality of materials for the construction of building's structural elements becomes responsibility of structural engineers. Adetunji et al. [4] in their research study the building collapse assessment in Lagos Nigeria. Both primary and secondary data were utilized for the investigation program to add its quota to the existing literatures on critical steps to be taken to curb collapse of building in Lagos Island Nigeria.

For technical emphasis, a case study of a partially collapsed one-story building in Ikwuano Local Government Area of Abia State, Nigeria, is presented to thoroughly examine the cause of the building collapse using multi-decision-making technique known as analytical hierarchical process (AHP); the material properties were examined, and the building skeletal elements were assessed to obtain the engineering behavior and classification of the soil. AHP is a multi-criteria decision-making tool essentially suitable for the evaluation of complex and multi-attribute decisions involving the correlation of decision elements which are not easy to quantify. It consists of formation of a ranking of decision elements. The AHP enables the decision maker to work out the major sections and subsections of a given problem into a hierarchical structure (family tree) that is based on expert's judgments by pairwise comparisons. Then, to the pairs of homogenous criteria, experts' interviews and pairwise comparison judgments are applied to obtain the general priorities which are utilized for the ranking of the alternatives. AHP which is an advanced decision-making tool is utilized here to evaluate and prioritize the criteria and alternatives responsible for the collapse of the building. Site investigation and nondestructive tests will be used for the assessment process, and the soil engineering properties would be determined and classified [5, 6].

Building Collapse

Collapse of building usually occurs as an outcome of consistent breakdown or deterioration of the various constituting skeletal components of the building. Failure is an unacceptable difference between observed performance and expected performance. It occurs in a system making it incapable to fulfill its principal functions. Some projects in Nigeria are planned to fail because competent project managers, engineers and builders were not recruited to do the job. Inability of the client to recruit the expert team of professionals appropriate for the project is clear invitation of failure in the project deliverable [7]. It is very essential to carryout reconnaissance survey to explore infrastructures availability and condition of site in order to determine the appropriate type and depth of foundation which will carry the superstructure. Expert judgment from site investigation data is used to ascertain the type of foundation for buildings, the intended use, the number of stories and load analysis before project execution. Building failure can also result from defective construction, integrated by other factors related to the structural, functional, material and environmental deficiency resulting in a poor performance that occurs at any time in the product's economic life. Examples of failure in building include defects as deflection and overturning of column or beam, cracks in walls and differential settlement. Building collapse may occur because of failure in building's structural elements be either a progressive, partial and sudden or total collapse. The effect of any building collapse can be so detrimental as to cause loss of live, properties and wealth [8, 9].

Analytical Hierarchical Process (AHP)

AHP essentially assists the decision maker to prescribe priorities and proffer solutions to estimation and decision problems [10]. The complex decisions are reduced to set of pairwise comparison using scale of relative importance and by synthesizing of the results, it enables AHP to offer solutions to subjective and objective aspect of the decision; it also incorporates the consistency test of the decision maker's assessment in order to reduce bias in the process of decision making. AHP system of processes considers set of assessment criteria, sub-criteria and alternatives through which the optimal decision is to be executed [11]. For each assessment criterion, AHP generates weight function as prescribed by the decision-makers pairwise comparisons of the alternatives, sub-criteria and criteria. The higher weights indicate more importance of that criterion. AHP generates for fixed criterion, values of each options which is derive from the pairwise comparisons of options based on that criterion. The more values obtained, the better the performance for the considered criterion. Lastly, there is a combination of weights of the criteria into the global value for each option to enable the ranking of the options. The global weight value represents the score's weighted sum obtained with respect to all criteria [12].

AHP Assumptions

AHP is also a very important tool which enables the translation of quantitative and qualitative assessments performed by the decision maker into a multi-criterion ranking. It may require large volume of assessments, especially when the problem to be solved possesses many options and criteria. It requires the decision maker to decide by relative scale of importance how two criteria compare to each other. The following assumptions are considered in the processing of AHP, and there are as follows [13]:

Reciprocal Axiom

If element x by scale of relative importance is n times better than element y, then element y will be the inverse of n $\left(\frac{1}{n}\right)$ times better than x.

Homogeneity Axiom

When the elements possess equal scale of relative importance or when a criterion compares itself presented in Eq 1, i.e.,

$$b_{ii} = 1,\ \text{for all } i = 1, 2, 3, \ldots n \quad \text{(Eq 1)}$$

Axiom of Dependence

This allows the comparison of elements' group from level one with criteria in level 2 and level 3 of the hierarchical structure. The scores obtained for the various alternatives depend on the values obtained for the constituting criteria through which the alternatives would be judged. And any alteration in the hierarchical structure or adjustments in the weight functions would alter the ranking computation and require new priorities calculation for the new structure [13].

Mathematical Model

If n elements are compared through pairwise comparison to form a pairwise comparison matrix (PCM) which possesses m x n dimension matrix shown Eq 2.

$$\text{PCM} = \begin{bmatrix} a_{11} & a_{12} & a_{13} & \ldots & a_{1n} \\ a_{21} & a_{22} & a_{23} & \ldots & a_{2n} \\ \ldots & \ldots & \ldots & \ldots & \ldots \\ a_{n1} & a_{n2} & a_{n3} & \ldots & a_{\text{nm}} \end{bmatrix} \quad \text{(Eq 2)}$$

The element of the PCM which is the comparison ratio between the criteria is expressed by the formula in Eq 3.

$$a_{ij} = \frac{W_i}{W_J} \quad \text{(Eq 3)}$$

And considering the reciprocal axioms presented in Eq 4, we have

$$a_{ij} = \frac{1}{a_{ji}} \quad \text{(Eq 4)}$$

Then, we normalize the PCM with constituting elements represented as $\left[b_{ij}\right]$ computed as shown in Eq 5.

$$b_{ij} = \frac{a_{ij}}{\sum_{i=1}^{n} a_{ij}} \quad \text{(Eq 5)}$$

The weights computation is done through the eigenvector analysis $(w = [w_i])$ from the obtained normalized PCM $\left[b_{ij}\right]$. This computation is done by taking the average of each row of the normalized matrix using the formula in Eq 6:

$$w_i = \frac{\sum_{j=1}^{n} b_{ij}}{n} \quad \text{(Eq 6)}$$

Consistency Test

The test of consistency shows or indicates that the decision maker's judgment is coherent concerning the pairwise comparisons. If the PCM is consistent if $a_{ij} = a_{ik}/a_{jk}$, for all, i, j,... n, then it must possess a unit diagonal entries since $a_{ii} = a_{il}$, for all,$i, l = 1, \ldots n$. To check for consistency, the principal eigenvalue $(\lambda_{\max})$ is obtained by addition of the products of each eigenvector element and that of the reciprocal of the diagonals of the normalized PCM, and one of the conditions for consistency of PCM is that the ranking has to be transitive, i.e., if $a > b$ and $b > c$, then $a > c$ [14]. Because of the involvement of human judgment as the basis for the PCM formulation, it allows some degree of inconsistency termed reasonable level. For this, we have to work out a quantitative measure for the PCM and for it to be consistent, then the normalized matrix PCM_{norm} could be generated with identical columns of the form expressed in Eq 7:

$$\mathrm{PCM_{norm}} = \begin{bmatrix} \frac{w_1}{w_1} & \frac{w_1}{w_2} & \frac{w_1}{w_3} & \cdots & \frac{w_1}{w_n} \\ \frac{w_2}{w_1} & \frac{w_2}{w_2} & \frac{w_2}{w_3} & \cdots & \frac{w_2}{w_n} \\ \frac{w_3}{w_1} & \frac{w_3}{w_2} & \frac{w_3}{w_3} & \cdots & \frac{w_3}{w_n} \\ \cdots & \cdots & \cdots & \cdots & \cdots \\ \frac{w_n}{w_1} & \frac{w_n}{w_2} & \frac{w_n}{w_3} & \cdots & \frac{w_n}{w_n} \end{bmatrix} \quad \text{(Eq 7)}$$

The PCM is related to $\mathrm{PCM_{norm}}$ by division of the column elements i by w_i. The result of the division is expressed in Eq 8 in matrix notation:

$$\mathrm{PCM} = \begin{bmatrix} 1 & \frac{w_1}{w_2} & \frac{w_1}{w_3} & \cdots & \frac{w_1}{w_n} \\ \frac{w_2}{w_1} & 1 & \frac{w_2}{w_3} & \cdots & \frac{w_2}{w_n} \\ \frac{w_3}{w_1} & \frac{w_3}{w_2} & 1 & \cdots & \frac{w_3}{w_n} \\ \cdots & \cdots & \cdots & \cdots & \cdots \\ \frac{w_n}{w_1} & \frac{w_n}{w_2} & \frac{w_n}{w_3} & \cdots & 1 \end{bmatrix} \quad \text{(Eq 8)}$$

The generated comparison ratio is presented in the form $n \times w$ eigenvalue problem where w is the relative weights of the column vector w_i, for $i = 1, 2, 3 \ldots n$. Therefore, PCM is consistent if $(\mathrm{PCM})w = nw$. It is expressed in matrix notation in Eq 9

$$\begin{bmatrix} \frac{w_1}{w_1} & \frac{w_1}{w_2} & \frac{w_1}{w_3} & \cdots & \frac{w_1}{w_n} \\ \frac{w_2}{w_1} & \frac{w_2}{w_2} & \frac{w_2}{w_3} & \cdots & \frac{w_2}{w_n} \\ \frac{w_3}{w_1} & \frac{w_3}{w_2} & \frac{w_3}{w_3} & \cdots & \frac{w_3}{w_n} \\ \cdots & \cdots & \cdots & \cdots & \cdots \\ \frac{w_n}{w_1} & \frac{w_n}{w_2} & \frac{w_n}{w_3} & \cdots & \frac{w_n}{w_n} \end{bmatrix} \begin{bmatrix} w_1 \\ w_2 \\ w_3 \\ \cdots \\ w_n \end{bmatrix} = n \begin{bmatrix} w_1 \\ w_2 \\ w_3 \\ \cdots \\ w_n \end{bmatrix} \quad \text{(Eq 9)}$$

Criteria and Alternatives responsible for Building Collapse

A good building design must possess strength property capable of carrying intended dead and live load of the structure, failure to meet this basic requirement normally results to overloading of the building which will cause its collapse. The load due to serviceability requirements such as fire resistance, vibrational loads, deflection, durability, fatigue and the building is expected to withstand these series of stresses to satisfy the owner. Finally, the building ought to be eco-efficient and eco-friendly with respect to wind loads and soil conditions and maximize strength parameters using minimum costs following standard specifications [15].

Inadequate Preliminary Site Investigation

These are activities and operations which are performed to find out how the building would suit in the proposed site. It involves the examination of soil strata, topography of the site, flooding propensity, load bearing capacity of the soil and important information from a previously built site in the same location. Adequate investigation of site helps to forestall the problem of foundation failure because after thorough investigation of the soil, the most appropriate foundation for the structure is prescribed based on soil characteristics and the load analysis. The water level, tree existence, waste dumps, streams and discharge units and underlying soil strata are various pieces of information obtained from history of the site and are used for major reference points. The buildings resilience against collapse is dependent on the soil which bears the building weight and the soundness of the skeletal elements of the structure [16].

Non-Conformance to Standard

The quantity and quality of specified construction material are required to be adequate to meet the building demands, and good quality material is very essential as specified by the standard specification makes a very durable building. The utilization of sub-standard quality materials for construction activities has been the root cause of building collapse and failure. The specification for the quality of materials must satisfy the intended purpose of the project and is very standard and adequate enough to prevent collapse of the building.

Inadequate Technical Supervision

Accuracy and efficiency in design and execution of construction work depend strictly on effective monitoring and control (supervising) of the project's activities. When the civil engineer has delivered a good design, it could be easily misinterpreted by casual workers (masonry) in terms of concrete target strength and reinforcement placement; for this, it is important that every activities of the construction work to be supervised by a specialist (professional) primarily saddled with the responsibility of the attainment of the clients' demands and expectations as stated in the contract document are efficiently implemented and executed [9].

Soil and Foundation

It is a major part of the skeletal framework of a building system, and it plays an essential role of transmission and distribution of the structural loads (dead and live loads) to the underlying soil structure. Several building foundations are constructed without thorough load and soil analysis; for this, it is essential for thorough soil and site investigation to be conducted, so a suitable design that suits the specified geology of the area is obtained. The geotechnical assessment of the terrain and building type would enable the engineer to decide the type of foundation whether its shallow or deep foundation. Some of the major factors that influence the type of foundations are site condition, soil type, load bearing capacity of the soil, other constructional and economic considerations, evaluated load and weight of the proposed building superstructure [8].

Abuse of Intended use of the Building

When there exists the scenario where there is sudden alteration in the intended use of the building, it can come in several sorts, renovations or remodeling, expansions or conversion scheme. For the renovations and expansion scheme, before and after demolition of the unsuitable, it is imperative that the building's structural integrity is not jeopardized and this must be carried out by a specialist (structural engineer), especially when the conversion is from residential to industrial or commercial purposes. They stand in the best position to state and evaluate the building's structural integrity, especially as it concerns change of intended use. Failure to do that will lead to faulty constructions and overload of the building which can cause building collapse [17].

Overloading

It is one of the major factors that is responsible for building collapse, and it occurs in structures when live and dead loads on the building exceed the estimated projected load the building was designed to withstand. Overloading easily causes building failure because of the foundation which is designed based on the projected estimated load. A common example is when there is a one-story building with foundation for one story, after some period of time, the owner decides to add more stories (floors) to the existing building. This practice is highly discouraged because it can cause collapse of the building due to overloading [18].

Methodology

The methodology involves a host of experimental and field works performed to investigate if the building collapse occurred because of poor engineering design or fault in project execution or both. The investigations were conducted according to the guidelines given in the General Specifications, Roads and Bridges, Volume Two where appropriate and the British code of practice CP2001 (for site investigations), BS 5930 and ASTM C805 for concrete nondestructive test. The fieldwork consists of the following: observing the physical conditions of the collapsed building, excavating the soil to observe the soil type and depth of foundation, beams and slabs chiseling to show spacing and type of reinforcing bars, and the sections of the beams and slabs were measured to assess its depth and span. Soil samples obtained during the field investigation study were taken to the laboratory for experimental assessments. It is important to note that both the structural and architectural drawings for the investigated building were not provided to the research team despite persistent request [19].

Site Investigation

The investigation program includes boring of two (2) hand auger holes of 150 mm diameter to the depths of 4 m and five points of nondestructive test of concrete. The hand auger boring was carried out with the possibility of continuous sampling at each lithological change of the strata, while the nondestructive test was done with Schmidt rebound hammer by sounding. The determination of depth of the foundation and the inspection of the soil's properties at that depth considering the building dead and live loads were also carried out as part of the assessment of the building's foundation (Fig. 1).

Soil Sampling

Soil samples from the study area were obtained in the following forms:

(a) Disturbed samples which are used for soil classification, consistency test and other index property test at specified depths. These samples are collected in bags suitable for preventing loss of moisture.
(b) Undisturbed samples for strength test were collected in samples tubes.

Fig. 1 Collection of soil sample with hand auger

Laboratory Tests

Representative soil samples were tightly sealed after being sourced from boreholes and are then taken to the laboratory where they were subjected to further visual inspection and classification using AASHTO method; the following tests will be carried out:

- Atterberg limits (liquid and plastic), the Plasticity Index (PI) was also determined.
- Specific gravity
- Natural moisture content
- Compaction test
- Sieve analysis
- California bearing ratio (CBR)
- Unconfined compressive strength (UCS)

All the laboratory tests were conducted in accordance with the guidelines provided in British standard BS 1377 [20–23].

Validation of Results

After the technical assessments and physical observation of the soil and skeletal framework of the collapsed building, weights are then assigned to the criteria, sub-criteria and alternatives in the hierarchical structure shown in Fig. 2. The problem's goal is the general objective which mainly influences the problem decision. It should be directly related to the challenge at hand. The goal has to be singular, i.e., the decision maker should avoid a case of satisfying multiple goals for one problem. The alternatives of the problem are the varying options which are being weighed in decision making, while the criteria are the factors used in the evaluation of alternatives with respect to an already defined goal. The alternatives would be picked depending on the criteria which are used to define how well they meet the problems goal [24].

The flowchart of this research study shows the required steps and the sequence of programs followed in this research study as presented in Fig. 3

Results and Discussion

The evaluation of the single-story building that was used for this case study showed that the foundation, though not properly proportioned, did not show any sign of distress, but the walls were partially distressed and prone to cracking and failure.

General behavior and classification of the soil

The preliminary test results of the soil presented in Table 1 have shown that the soil obtained from the site is silty (non-plastic) or clayey gravel and sand. The soil's strength properties also showed the values are of acceptable standards for materials to be used as foundation materials. The engineering properties of the soil were satisfactory. The failure would definitely be as a result of poor quality of materials and also engaging incompetent workers.

Particle Size Distribution of the Soil

The particle size distribution analysis shows the range of particle sizes present in the soil as presented in Fig. 4. The soil is well graded and contains silty (non-plastic) or clayey gravel and sand. The strength properties also showed the values are of acceptable standards for materials to be used as foundation materials.

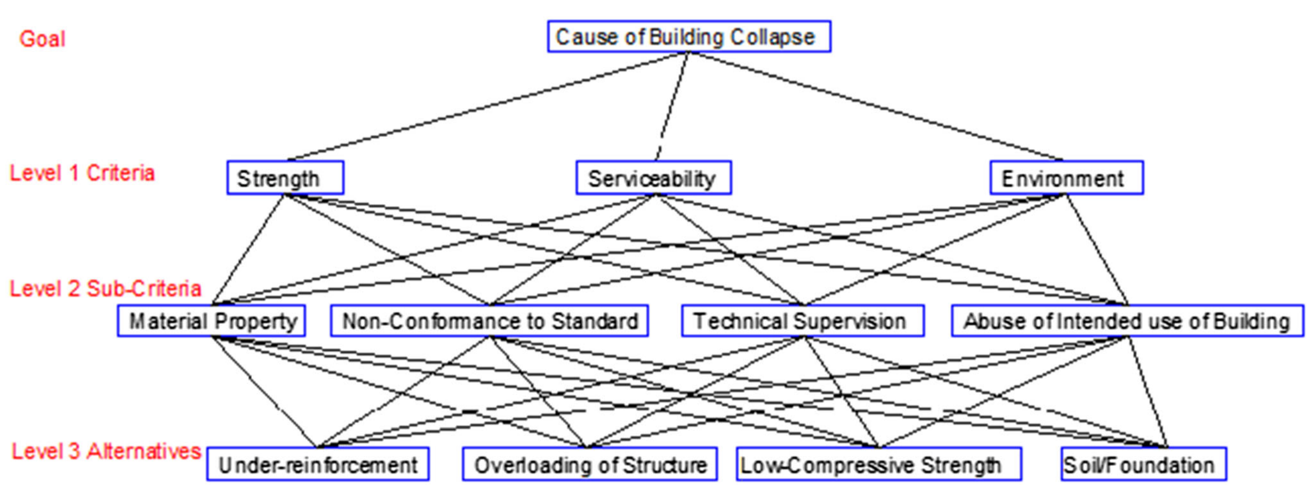

Fig. 2 Hierarchy of the problem decision factors

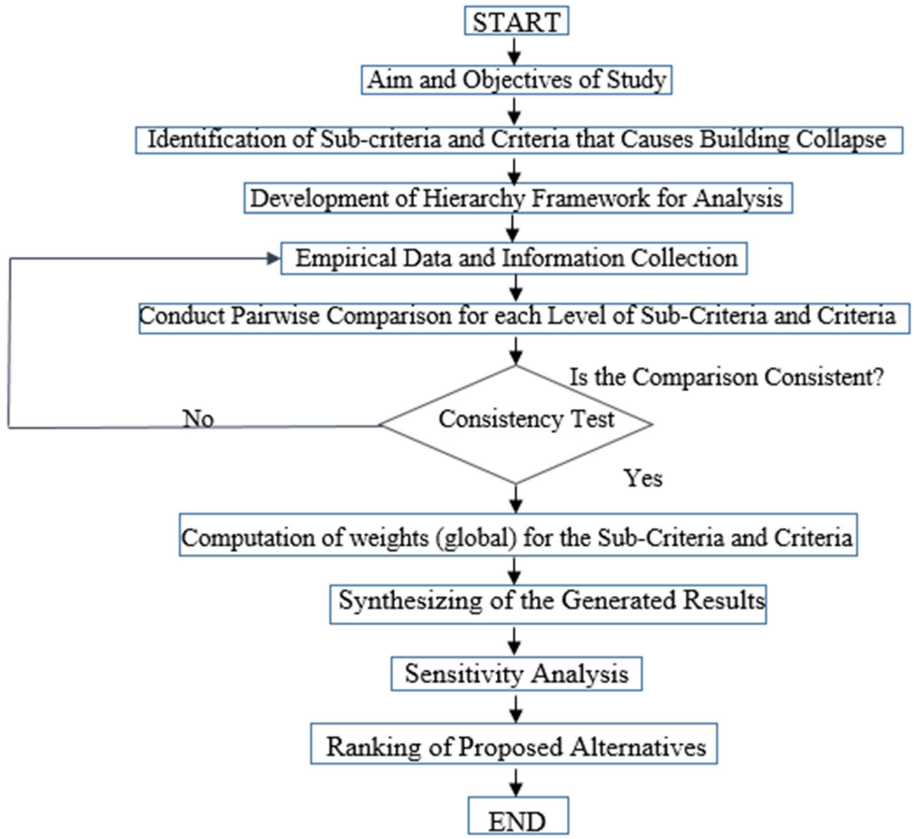

Fig. 3 AHP process flowchart

Table 1 Basic properties of the soil

Properties of test soil and units	Values
% passing sieve No 200	2
NMC (%)	12
PL (%)	16
LL (%)	24
PI (%)	8
Specific gravity	2.2
AASHTO classification	A-2-4
MDD (mg/m^3)	2.15
OMC (%)	9
Color	Reddish-brown
SL (%)	2.5
Unconfined compressive strength (UCS) (KN/m^2)	195
California bearing ratio (CBR) (%)	24

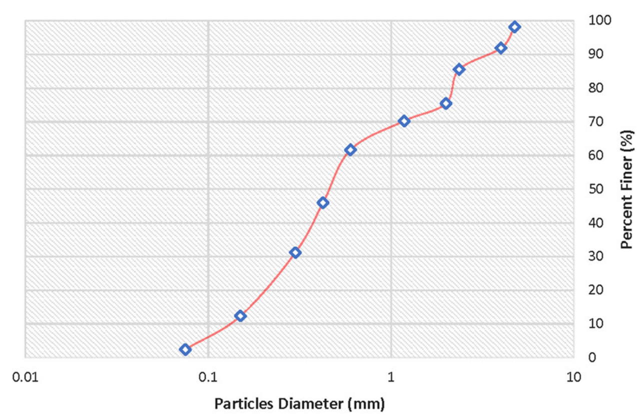

Fig. 4 Particle size distribution of soil

Causes of the Building Failure from technical Assessments

The investigative study of the engineering issues surrounding the collapse of a single-story building was carried out to discovering the actual cause of the building collapse. The source of the failure was objectively evaluated based on data obtained from field inspection survey, nondestructive test and laboratory methodology.

Field Inspection

From field inspection of the building, it was observed that the sub-structure and super-structure walls had cracked in several regions of the building. The building's general arrangement of the skeletal framework and, as a result, insufficient columns allowed the slab and connecting beams to span more than 6 m with inadequate depth; the

Fig. 5 Cracks at partition walls of the case study building

cracks are more pronounced in the side walls, the columns and beams. Figure 5 shows a partially collapsed portion of the partition walls of the building under study.

The long vertical cracks extend to the superstructure walls from the foundation as shown in Fig. 6. The cause of these cracks emanating from the lower region to the upper region of the building is as follows:

- The substructure block walls and mortar were too weak to withstand the lateral load due to the steepness of the land and applied load.
- Failure to introduce expansion joints at critical sections where the steepness of the land induces lateral pressure to the substructure.

Foundation Behavior

From the result of the tests carried out, a firm lateritic granular soil was obtained at the foundation depth. The topography of the land was observed to be hilly but with solid soil structure. Based on the soil test results obtained, it was observed that the results were in tandem with the values stipulated in the F.M.W & H Specification. However, the cause of the failure of the said one-story building was clearly not associated with the failure due to soil. The depth of the foundation was 1.2 meters, but the substructure blocks were poorly constructed with little care paid to fortifying the substructure blocks against the lateral earth pressure introduced due to the steepness of the land and no introduction of expansion joints where appropriate.

Nondestructive Test

The nondestructive test is carried out on five equally spaced points on the structural elements of the collapsed building which implies that the structural elements have a very low compressive strength and stiffness to carry the design load. The concrete works was not properly supervised as issues concerning mixing, water cement ratio, vibration and compaction were poorly handled, and as a result, the structural elements were made up of concrete with low compressive strength. With a mean compressive strength of 13 N/mm^2, the concrete is said to be substandard; falling below specification the detailed result is shown in Table 2. The rebound hammer test confirmed the obvious from site observation, and the concrete quality was poor due to inadequate cement. This can be the possible cause of the collapse since the construction work was poorly supervised and also design specifications poorly interpreted during project execution [25].

Fig. 6 Cracks drawing from the foundation of the building

Table 2 Nondestructive test of concrete results

Structural elements	*1*(N/mm^2)	*2*(N/mm^2)	*3*(N/mm^2)	*4*(N/mm^2)	*5*(N/mm^2)	Average(N/mm^2)
1. Column-A	14	12	13	11	13	12.6
2. Column-B	14	13	10	14	10	12.2
3. Beam-A	11	14	7	10	9	10.2
4. Slab	10	12	11	16	11	12
5. Beam-B	10	8	11	12	12	10.6

Structural Assessment of the investigated Building

The general arrangement of the building as obtained during the site investigation is presented in Fig. 7 showing the connections, arrangements and relative measurement of the structural skeletal framework which include beams, columns and slab of the building under study.

Panel 5, beam B1, beam B3 and the partition walls were the most visibly failed portion of the building. The concrete

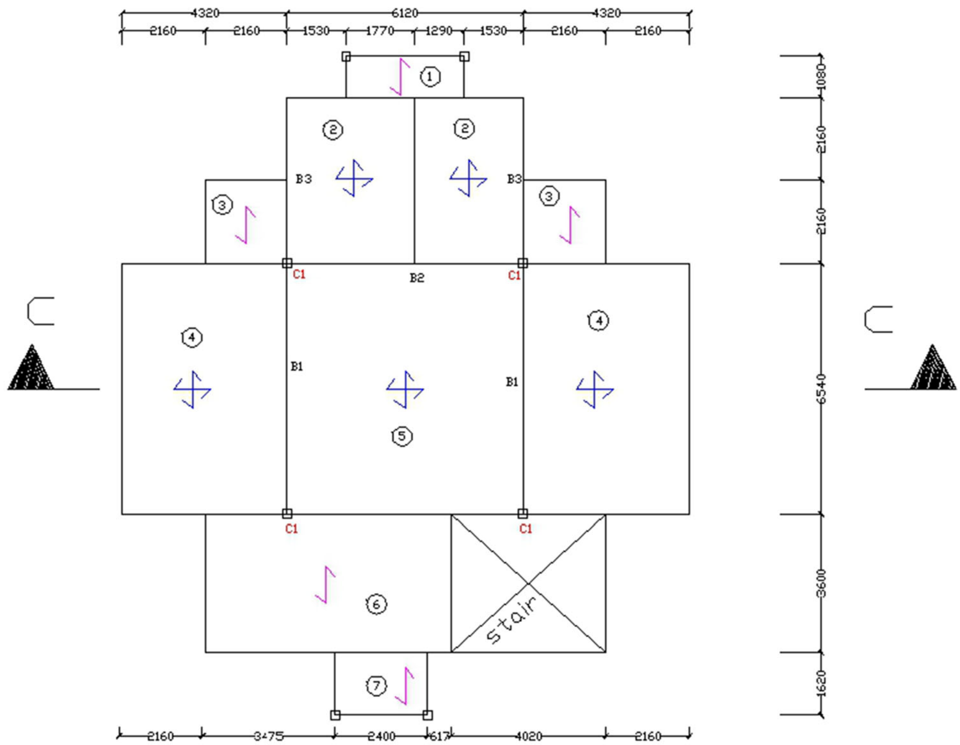

Fig. 7 General arrangement of the first floor plan of the building

works were observed to be sandy and seems not to bind properly due to inadequate quantity of cement and poor interpretation of concrete design mixture specification for the building. A section of the failed section of slab and beam of panel 5 showing the cracks, reinforcement arrangement and component thickness (depth) is presented in Fig. 8. This crack is caused by inadequate slab depth and support for the slab spanning more than 6 meters and the supporting beams poorly reinforced. This occurs due to poor technical supervision and quality control during the project execution.

The reinforcement placement for the slab section shown in Figs. 8 and 9 was assessed by chiseling some section of the slab. This indicates a poor and crocked alignment of the steel bars which will cause poor distribution of load and cracks due to inadequate top reinforcement.

Remedy to the Structural Failure

The building ought to be designed by a specialist following prescribed guidelines or design codes as the building partial collapse has caused economic loss to the client and it is unable to serve its economic life. A new structural design is expected to be conducted as one of the major tasks in the remedy program of partially collapsed building according to the provisions of Codes of Practice BS 8110 [26, 27], BS 6399 [28], Moseley et al, [29] and Kong et al, [30]: cracking, chiseling and re-construction of the building from foundation, then working on panels 4, 5 and all troubled regions of the skeletal framework. The lessons learnt from this setup show the need for experts to be engaged in construction activities from start till the finish of the project. Due to high patronage rate of non-professionals in carrying out engineering projects, engineering support and development is critically lacking while the need to engage them goes begging.

Multi-Criteria Decision Making to Determine the Cause of the Collapse

AHP is a multi-criteria decision-making method used to calculate scale ratios from pairwise comparisons while it also allows some inconsistency in judgment. This analytical technique will be adapted for determining the cause of the building failure by expert judgment in assigning weights to the criteria. From the building assessment and as shown in Fig. 2, three criteria are, namely strength, serviceability and environment. Four sub-criteria are, namely material property, non-conformance to standard, inadequate technical supervision and abuse of intended use of building. These factors will enable us to choose from four alternatives, namely under-reinforcement, overloading, low-compressive strength and soil/foundation. And the weights are assigned using ranking scale of relative importance to generate the pairwise comparison matrix (PCM). The length of the PCM is equal to the count of

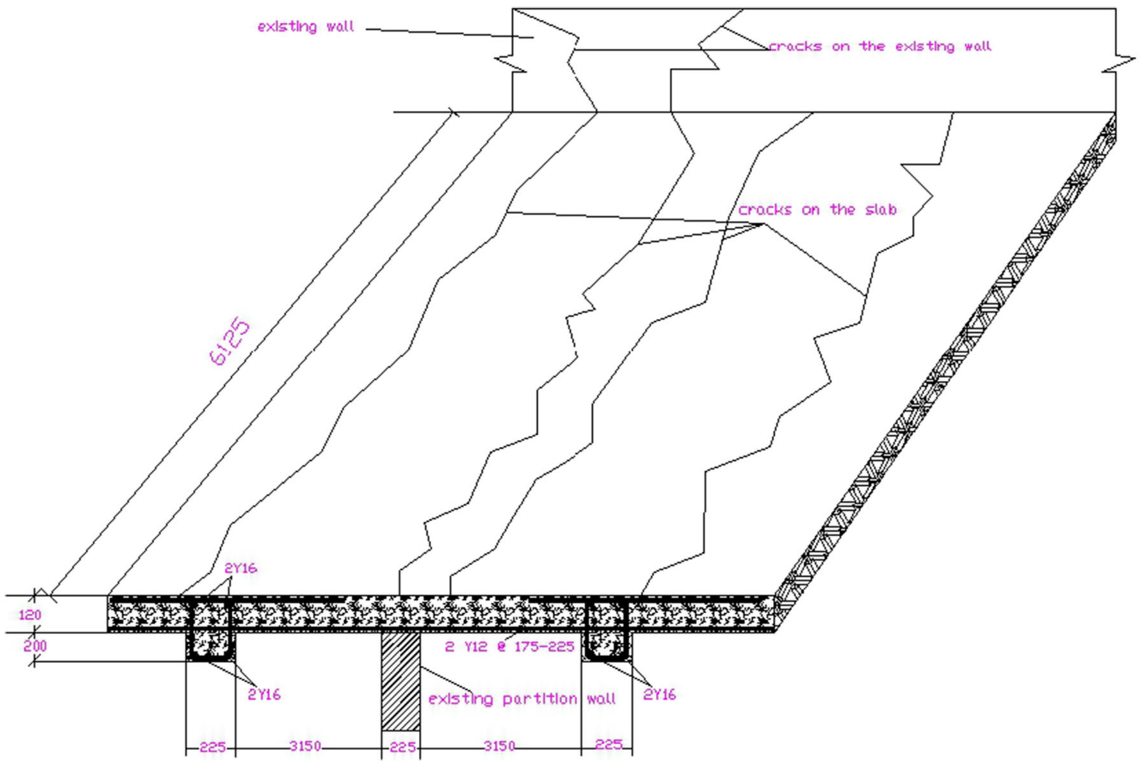

Fig. 8 Section through the failed portion

Fig. 9 Slab reinforcing bars placement

alternatives in the process of decision making. Here, we have a 4 × 4 matrix; the values in the PCM are dependent on the decision maker. For this research study, the criteria and rankings are based on the details obtained in the field inspection and laboratory investigation of the failed building. In Table 3, the PCM is constructed using scale of relative significance or importance.

From the assessment, it was observed generally that the material property of the skeletal framework of the collapsed building was below specified standard which is caused by misinterpretation of design information in terms of concrete mixture and the reinforcement used.

The PCM is 4 × 4 matrix shown in Table 4.

The PCM is then normalized by dividing each of the column entries by their respective sum, after which the row results would be averaged to obtain the priority vector (PV). Since PCM is normalized, the elements sum in the priority vector (PV) is unity. The priority vector (PV) presents the respective weights of the compared

Table 3 Relative importance

1	Equal significance
3	Moderate significance
5	Strong significance
7	Very strong significance
9	Extreme significance
1/3, 1/5, 1/7, 1/9	Values for inverse comparison

Table 4 Pairwise comparison matrix

	Soil/foundation	Under-reinforcement	Low compressive strength	Overloading
Soil/foundation	1	1/7	1/5	1/3
Under-reinforcement	7	1	3	5
Low compressive strength	5	1/3	1	3
Overloading	3	1/5	1/3	1

alternatives, and the computation is presented in matrix notation in Eq 10.

$$\begin{bmatrix} 1 & \frac{1}{7} & \frac{1}{5} & \frac{1}{3} \\ 7 & 1 & 3 & 5 \\ 5 & \frac{1}{3} & 1 & 3 \\ 3 & \frac{1}{5} & \frac{1}{3} & 1 \\ 16 & 1\frac{48}{71} & 4\frac{8}{15} & 9\frac{1}{3} \end{bmatrix} \begin{bmatrix} \frac{1}{16} & \frac{4}{47} & \frac{3}{68} & \frac{1}{28} \\ \frac{7}{16} & \frac{34}{57} & \frac{45}{68} & \frac{15}{28} \\ \frac{3}{16} & \frac{1}{5} & \frac{15}{68} & \frac{9}{28} \\ \frac{3}{16} & \frac{8}{67} & \frac{5}{68} & \frac{3}{28} \end{bmatrix} \begin{bmatrix} 0.06 \\ 0.56 \\ 0.26 \\ 0.12 \end{bmatrix} \text{(Priority vector)} \quad \text{(Eq 10)}$$

From the priority vector, we can observe that soil/foundation has 6%, under-reinforcement has 56%, low compressive strength 26% and overloading 12%.

Check for Consistency

To check for consistency, we need the principal eigenvalue which is obtained from the products summation of each eigenvector element and the reciprocal column matrix.

$$\lambda_{\max} = 16(0.06) + \frac{57}{34}(0.56) + \frac{68}{15}(0.26) + \frac{28}{3}(0.12) = 4.176$$

For consistent decision making according to Saaty [12], the maximum eigenvalue is equivalent to the number of alternatives of the problem, or $\lambda_{\max} = n$. Then, through a consistency measure called Consistency Index using Eq 11.

$$\mathrm{CI} = \frac{\lambda_{\max} - n}{n - 1} \quad \text{(Eq 11)}$$

$$\frac{4.176 - 4}{4 - 1} = 0.058$$

The Random Consistency Index (RI) is a very essential parameter for the computation of the consistency ratio of the decision maker. From Table 4, we have a consistency index of 0.9.

Then, we will work out the consistency ratio of the decision maker which is the quotient of the Consistency Index and Random Consistency Index, with the mathematical relationship expressed in Eq 12:

Table 5 Random Consistency Index (RI)

N	1	2	3	4	5	6	7
RI	0	0	0.58	0.9	1.12	1.24	1.32

$$\mathrm{CR} = \frac{\mathrm{CI}}{\mathrm{RI}} \quad \text{(Eq 12)}$$

$$\frac{0.058}{0.9} = 0.065$$

The value of consistency ratio is 6.5% which is satisfactory. If the consistency ratio is more than 10%, then we say the inconsistency level is unaccepted and we have to reorganize the subjective judgment because it is untrustworthy and too close for comfort to randomness. Thus, the decision maker's subjective evaluation is consistent (Table 5).

Conclusions

The following conclusions are drawn on the basis of this study:

- The building failure emanated from a series of cracks in the walls which extended from the sub-structure walls through to the super-structure walls and through deflection (sagging) of the slabs together with its over-spanned connecting beams.
- The building collapsed partially due to the presence of a long span slab (panel P5) which has series of cracks and shaking because of inadequate depth of slab and support at critical sections with under-reinforced beam. Further inspection reveals that the cracked slab sections had only bottom bars without top or tension bars and the reinforcing bars were poorly placed indicating poor technical supervision of the project.
- The AHP multi-choice decision-making method was adapted in this study to ascertain the cause of the failure, and from the priority vector, under-reinforcement of the structural members with 56% is the major cause of the failure followed by low compressive strength with 26%.

- Finally, it is clearly obvious from the information presented that the construction industry needs relevant professionals and engineers to forestall future occurrence of this hazard and strict attention ought to be paid to the quality of materials used in the execution of construction works.

Compliance with Ethical Standards

Conflict of interest In this research study, there are no recorded conflicts of interests. We also affirm that the content of this work is original and has followed the journal template. Compliance with Ethical Standards was strictly observed.

References

1. M.A. Salau, Design, construction and maintenance measure for preventing the collapse of reinforced concrete structure. J. Niger. Inst. Struct. Eng. **I**(1), 1–13 (2005)
2. T.U. Onyemachi, Z.A. Uji, Building failures and it's implication on real estate investment in Nigeria. AARCHES J. **4**(1), 57–63 (2005)
3. Mansur Hamma-adama, Obinna Iheukwumere, Tahar Kouider, Analysis of causes of building collapse: system thinking approach. Jordan J. Civil Eng. **14**(2), 188–197 (2020)
4. M.A. Adetunji, O.I. Oyeleye, O.A. Akindele, Assessment of building collapse in Lagos Island. Nigeria. Am. J. Sustain. Cities Soc. **1**(7), 18–28 (2018). https://doi.org/10.26808/rs.aj.i7v1.04
5. W. Ho, X. Xu, K.P. Dey, Multi-criteria decision making approaches for supplier evaluation and selection: a literature review. Eur. J. Oper. Res. **202**, 16–24 (2010)
6. J.-Y. Do, D.-K. Kim, AHP-based evaluation model for optimal selection process of patching materials for concrete repair: focused on quantitative requirements. Int. J. Concrete Struct. Mater. **6**(2), 87–100 (2012)
7. I.G. Chendo, N.I. Obi, Building collapse in Nigeria: the causes, effects, consequences and remedies. Int. J. Civil Eng. Construct. Estate Manage. **3**(4), 41–49 (2015)
8. G.M. Ayininuola, O.O. Olalusi, Assessment of building failures in Nigeria: lagos and Ibadan as case study. Afr. J. Sci. Technol. **5**(1), 73–78 (2004)
9. R. Olagunju, S. Aremu, J. Ogundele, Incessant collapse of buildings in Nigeria: an architect's view. Civil Environ. Res. **3**(4), 49–54 (2013)
10. T.L. Saaty, An exposition of the AHP in reply to the paper "Remarks on the analytic hierarchy process". Manage. Sci. **36**(3), 259–268 (1990)
11. T.L. Saaty, L.G. Vargas, *Decision making with the analytic network process: economic, political, social and technological applications with benefits, opportunities, costs and risks* (Springer, New York, 2006)
12. T.L. Saaty, L.G. Vargas, *Models, methods, concepts and applications of the analytic hierarchy process* (Kluwer Academic Publishers, Boston, 2000)
13. T.L. Saaty, Axiomatic foundation of the analytic hierarchy process. Manage. Sci. **32**(7), 841–855 (1986)
14. T.L. Saaty, Decision-making with the AHP: why is the principal eigenvector necessary. Eur. J. Oper. Res. **145**(1), 85–91 (2003)
15. C.O. Olayinka, S.O. Abiodun, O. Ayodeji, J. Opeyemi, O.B. Daniel, Incessant building collapse in Nigeria: a framework for post-development management control. Develop. Country Stud. **7**(3), 114–127 (2017)
16. S.A. Oke, A.N. Amadi, A.E. Abalaka, R.T. Akerele, Result of subsoil investigation on a collapsed building site in Lagos. Nigerian J. Construct. Technol. Manage. **10**(1&2), 36–45 (2009)
17. A.F. Bosede, G.M. Sunday, An investigation on the causes of building collapse in Nigeria. J. Environ. Sci. Resour. Manage. **6**(1), 12–22 (2014)
18. A.M. Olajumoke, L.A. Oke, A.B. Fajobi, M.O. Ogedengbe, Engineering failure analysis of a failed building in Osun State, Nigeria. J. Failed Anal. Prevent. **9**, 8–15 (2009)
19. K.C. Onyelowe, G. Alaneme, C. Igboayaka, F. Orji, H. Ugwuanyi, D. Van Bui, M. Van Nguyen, Scheffe optimization of swelling California bearing ratio, compressive strength, and durability potentials of quarry dust stabilized soft clay soil. Mater. Sci. Energy Technol. **2**(1), 67–77 (2019). https://doi.org/10.1016/j.mset.2018.10.005
20. AASHTO (1995a) Determining the Liquid Limit of Soils. AASHTO Designation: T89-94, Standard Specifications for Transportation Materials and Methods of Sampling and Testing, American association of state highway and transportation officials, 17th Edition, Washington, DC
21. AASHTO (1995b) Determining the Plastic Limit and Plasticity Index of Soils. AASHTO Designation: T90-94, Standard Specifications for Transportation Materials and Methods of Sampling and Testing, American Association of State Highway and Transportation Officials, 17th Edition, Washington, DC
22. AASHTO (1993) Particle Size Analysis of Soils. AASHTO Designation: T88-93, Standard Specifications for Transportation Materials and Methods of Sampling and Testing, American Association of State Highway and Transportation Officials, 16th Edition, Washington, DC
23. AASHTO (1995c) The Moisture-Density Relations Using a 4.45-kg (10-lb) Rammer and a 457-mm (18-in.) Drop. AASHTO Designation: T180-93, Standard Specifications for Transportation Materials and Methods of Sampling and Testing, American Association of State Highway and Transportation Officials, 17th Edition, Washington, DC
24. M. Bernasconi, C. Choirat, R. Seri, Measurement by subjective estimation: testing for separable representations. J. Math. Psych. **52**(3), 184–201 (2008)
25. Nucera, F. & Pucinotti, R. (2009). Destructive and Non-destructive Testing on Reinforced Concrete Structure: The Case Study of the Museum of Magna Graecia in Reggio, Calabria
26. BS 8110: Structural use of concrete, Part 3. British Standards Institution, London (1985)
27. BS 8110: Structural use of concrete, Part 1. British Standards Institution, London (1997)
28. BS 6399: Loading for buildings, Part 1 (Code of practice for dead and imposed loads). British Standards Institution, London (1996)
29. W.H. Moseley, J.H. Bungey, *Reinforced Concrete Design, ELBS*, 3rd edn. (Chapman and Hall, Hong Kong, 1990)
30. F.K. Kong, R.H. Evans, *Reinforced and Prestressed Concrete, ELBS*, 3rd edn. (Chapman and Hall, Hong Kong, 1990)