0.1 STRUCTURAL INVESTIGATIONS

1. According to the work programme that the Structures team set for itself, one of their main tasks was to explore all the possible causes of the collapse:

I. Evidence of no structural design of the steel props

II. Evidence of inadequate steel props for the casting of the particular slab

III. Totally different steel props were delivered to site, and the required number was not adequately delivered to site

IV. Evidence of poor installation of the steel props

V. Evidence of installers of the props, who are not professional installers, but carpenters.

2. After the work of the Structures Team, the following results were obtained.

- On the basis of the first point raised – no structural design of the steel props – after the interview with the Contractor's project manager, he mentioned that there is a steel props design. However, after several requests for design documents, it could not be delivered. Moreover, several construction personnel interviewed, for example, the Site Engineer, the mason foreman, the carpenter foreman, and the Resident engineer, attested to the fact that they have never sighted any design report for the steel props. This therefore concludes that, there is no design report for the steel props.
- On the basis of the second and third points raised – inadequate steel props of very different size and types were delivered to the site for the casting of the slab - the team's investigation showed that there was the request made for further steel props, about one thousand extra props, however only 200 steel props were delivered to the site prior to the casting of the collapsed slab. The delivered steel props were of the smaller cross sectional diameter of about 36mm , with pipe thickness of less than 2mm thick.
- On the basis of the fourth and fifth points raised – poor installation of the steel props by non-professionals – the team realised after interview with the carpenter foreman that, the props dealer was contacted to come and install the props after the delivery. However, he delayed. The project manager therefore verbally instructed the carpenter foreman and his team of carpenters to install the props. The carpentry team were therefore those who did the installation of the steel props for the part of the slab that collapsed. The carpenter foreman who gave his

testimony as being responsible for the installation of the props, claimed they installed the props at minimum 600mm centers. He claimed, that due to the inadequacy of the props, some of the props were placed at 1000mm centers. The height of the props were between 3.7m long to 4.5m long

3. In the absence of any design calculations for the steel props used in the Address Project, the investigators decided to estimate the possible design capacities of the used props. Using Euler's Column Formula (Equation 1) for the buckling of columns under axial loads, the critical buckling loads for the steel props were calculated for various heights of props.

Equation 1: Euler's Column Formula

$$f_b = \frac{n\pi^2 EI}{l^2}, l = length\ of\ the\ prop\ (m);$$

$f_b = buckling\ load\ (kN);\ n = end\ conditions\ factor;$

$E = modulus\ of\ elasticity (kN);\ and\ I = moment\ of\ inertia;$

4. Since the support or end conditions of the pipes, the section properties (sectional area, radius of gyration, moment of inertia), and the Young's modulus of elasticity remain constant, a simple relation between the buckling load and the height of prop was established.

5. Equation 2: Simple relation between the buckling load and the height of prop

$$f_b = \frac{139}{l^2}, l\ is\ the\ length\ of\ the\ prop\ in\ metres\ and$$

f_b *is the buckling load in KiloNewton.*

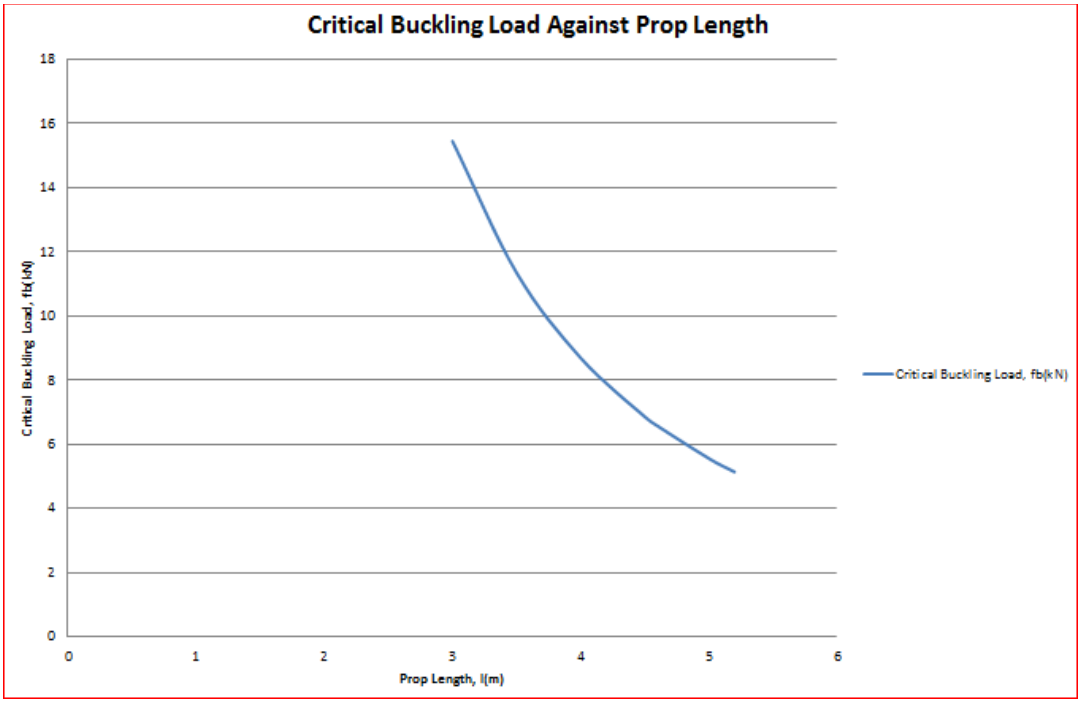
Table Error! No text of specified style in document.**-1: Critical Buckling Load against Prop Length**

Prop Length, l(m)	5.2	5.0	4.6	4.5	4.0	3.5	3.0
Critical Buckling Load, f_b(kN)	5.14	5.56	6.57	6.86	8.69	11.34	15.44

6. Figure 3-1 is a graph showing the relationship between the critical buckling load and the length of the steel prop. The graph is based on data from **Error!**

Reference source not found.. The relationship is an inversely proportional one and as such, the load carrying capability of the prop reduced rapidly from the 1.5tonnes once the height of the prop increased. For normal construction where the floor-to-floor heights rarely exceed 3.5m, 3m lengths of props can easily be used to carry the quoted load of the prop.

Figure Error! No text of specified style in document.**.1: Critical Buckling Load against Prop Length**



The Structures team also noted that the props were not properly fixed in place: non-verticality, inadequate to no bracing and irregular spacing. It was instructive to note that in most of the steel props, there was no fixation at the top of the prop nor at the bottom of the prop. And all these offered very little resistance the collapse of falsework. Indeed, certain props were supported on bare ground, which the contractor claimed to be compacted earth. For such supports, one may want to apply a timber plank as the base of the prop support. But there was no evidence of such support at the site, during the site visit by the investigators.

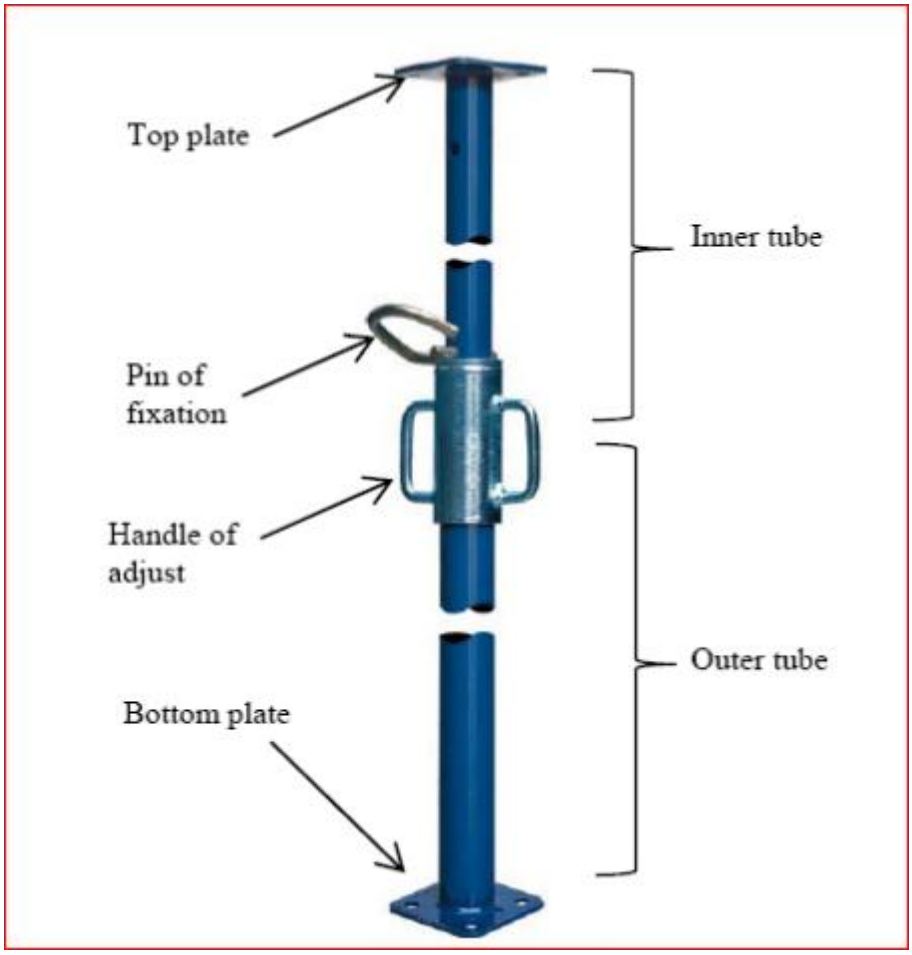
The original arrangement of the props resulted in some of the bases being considered fixed and the top being free. In many other cases, both the top and the bottom are all free, not fixed.

After relating the critical buckling load to the length of prop, the team went on to calculate the applied load that the supported concrete imposes on each prop assuming

certain prop spacing. The parameters used to calculate this applied load on the props assumed the unit weight of cured reinforced concrete instead of the unit weight of green concrete. No construction load was applied though in reality, a construction load of 0.75kN/m² plus 10% of the self-weight of the slab should have been added to account for the periodic short-term heaping of concrete during casting. It is clear from assumptions made by the Structures Team that loads obtained on each prop would be lower than the large construction load that in all likelihood exists during the construction. Nonetheless, the calculations of the Structures Team shows that a spacing of 900mm × 900mm imposes a load of 7.29kN which is in excess of the critical buckling load of 6.86kN which relates to a prop height of 4.5m. At props spacing of 1000mm x 1000m, the critical buckling load for a 4.5m long props is 9.0kN. This is even much excess of the 6.86kN mentioned above. In effect, the maximum spacing for the 4.5m long props for the normal props should be 870mm x 870mm . In reality, the load that would have been imposed on the prop would have been higher than stated here. Also, by the principles of limit state design, the critical buckling loads of the props should be reduced by the use of a suitable factor of safety to make for a safe design.

7. Figure 3-2 is a picture of a typical adjustable steel prop with the various parts well labelled. When fixing adjustable steel props, it was the expectation of the members of the Structures Team that the props would first be adjusted to a height reasonably close to the fixing height. The *pin of fixation* would then be slotted into the appropriate opening to lock the two parts of the prop together. The prop would then be positioned properly and steps taken to ensure that the prop is not out of plumb, i.e. truly vertical. Subsequently, the *handle of adjustment* would be turned to adjust the height of the prop till the top plate is at the correct level. In cases where the height of the props exceeds 3m, it is conventional to brace the props adequately to ensure safety.

Figure Error! No text of specified style in document..**2: Parts of a Steel Prop (Credit: IACSIT International Journal of Engineering and Technology)**



In the case of the ADDRESS project, it was noted that the inner tube (with the smaller cross sectional area) was placed on the ground, and the outer tune (with the larger cross sectional area) was placed above. Several of props were out of plumb by more than 1.5° (Fig. 3.4). The prop spacing was also not uniform, up to 1000mm centers.

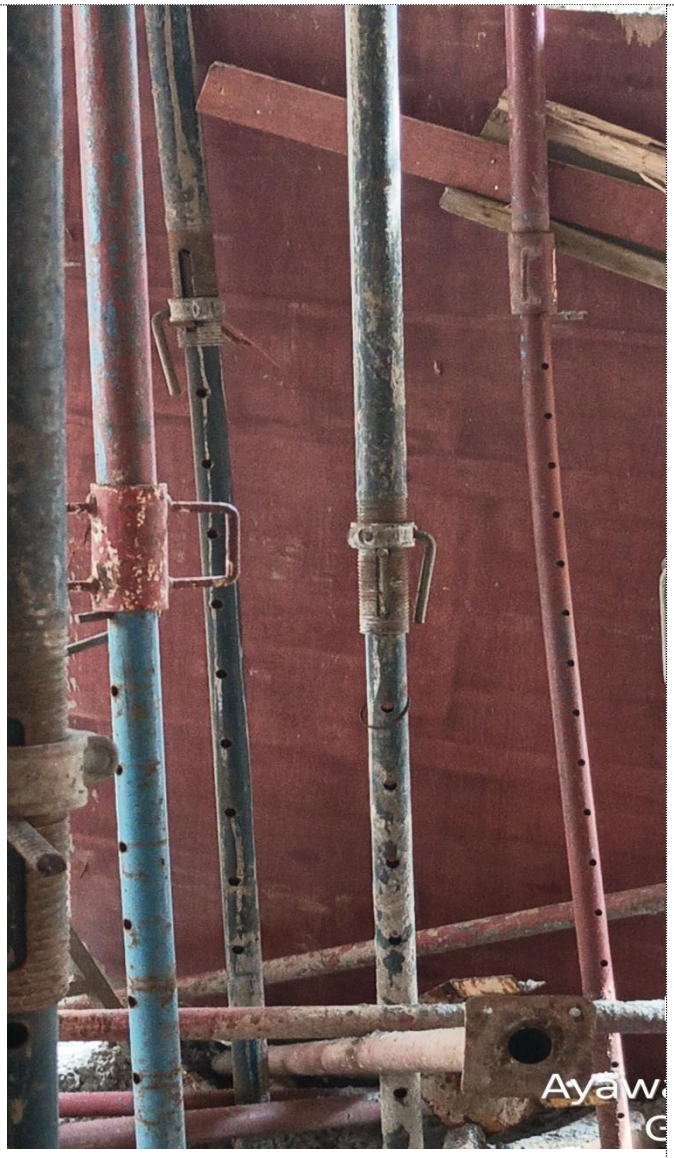
8. 

Figure Error! No text of specified style in document.**..3: Props severely out of plumb**

Different props sizes placed haphazardly together

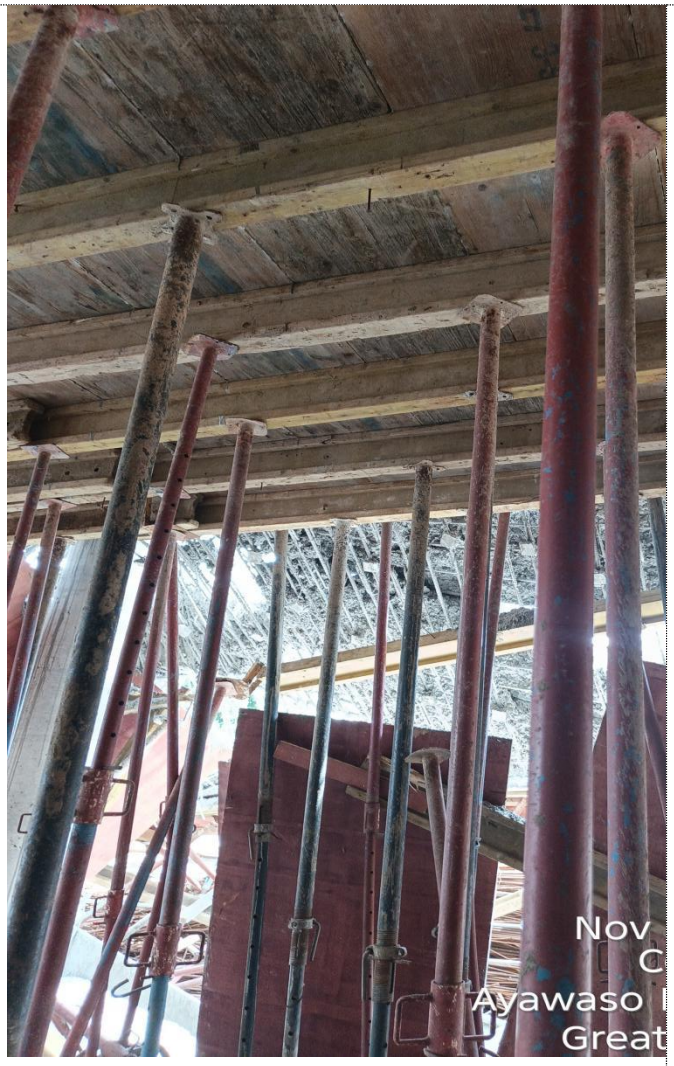
9. 

Figure Error! No text of specified style in document.**.4: Props with clear centers over 1000mm, free at the top**

10.

	Figure Error! No text of specified style in document..**5: Top of Steel Prop not fixed (free)**
	Figure Error! No text of specified style in document..**6: Bottom of Steel Props not fixed (free)**

Figure Error! No text of specified style in document..**7: Evidence of the buckled steel props with the small cross sectional area.**

The later to be delivered to site, there was inadequate in number, but was installed, even at 1000mm centers.

	Figure Error! No text of specified style in document..**8: Evidence of the inner tube at the bottom, and the outer tube on top of the support - as installed by the carpenters.**

ROOT CAUSES OF THE COLLAPSE

Introduction

After several investigation methods, namely: desk study, site investigations, personnel interviews, the following hypothesis were drawn for the root causes of the collapse:

Hypothesis 1:
This hypothesis was drawn after the Project manager, the site engineer and the Resident Engineer were interviewed.

The project manager's main assertion:

- **'There is steel props design and report.'** This assertion was later found to be untrue, since persistent request from him and the contractor's personnel, could not yield the report.
- **'the props at the collapsed section of the slab was placed on the bare ground. There had been rainfall and the ground was wet. And therefore the props sunk into the loose ground. That was the cause of the collapse'**. This assertion was also found to be partly untrue. As collaborated by several of the contractor's personnel, there was no rain on that day. Even where the props are supported on bare ground, the props will be supported on timber plank, to prevent props from sinking further into the soil.
- **'the resident engineer of the developer signed off the correctness of the props and formwork, before the go-ahead for pouring the concrete was issued.**' this assertion was found to be totally untrue

After the unfounded statements by the project manager, the Hypothesis 1 was discarded partially, but still kept in mind.

Hypothesis 2:
This hypothesis was drawn after further interviews were conducted with the various foremen of the project. These include the Safety officers, the Mechanical and Electrical engineers, the Carpenter and mason foremen. These were especially those who suffered casualties at the accident.

The Site engineer's main assertion:

- **'The specialists for the fittings for the swimming pool were not around, therefore he informed the project manager that they are not ready to cast the swimming pool slab. This slab should have been casted before the slab that collapsed. Due to this, he the site engineer, did not raise any Request For Inspection (RFI) for the Resident Engineer of the Developer. Moreover, there was no inspection of props under the collapsed slab, since it was not even the time to cast that slab.**' This assertion was found to be true.

The Resident Engineer's main assertion:

- **'There was no RFI presented to her on the inspection of the said collapsed slab. She therefore did not sign-off the go-ahead of pouring concrete for the casting of the said slab'.** This assertion was found to be true, as collaborated by the site engineer of the contractor, the mason and carpenter foremen of the contractor, and the safety officer.

The carpenter foreman's main assertion:

- ' he was called by the project manager to come and fix the steel props with his team. He knew that more steel props had been requested for fixing. A quantity of about 1000 props were requested. But only 200 were delivered to the site. Moreover, he knew that on the normal circumstances, the props dealer sends in specialists from his outfit to install the steel props. This time, apart from the fact that the prop dealer's specialist did not come, the number of props were also not up to the quantity requested. Adding up to the above situation, the type of props were those with the smaller cross sections (the red type with the smaller cross section to be about 36mm , and the pipe thickness less than 2mm thick). He only obeyed his boss (the project manager) and together with his team, they installed the props, as they deem fit.
  When questioned further, they collaborated the investigated findings that:
  - The smaller tube was very small cross section - about 36mm
  - The props were installed free at the top and at the bottom (both not fixed)
  - Many were out of plumb - they lack verticality
  - The spacings were not uniform. Some were even 1000mm to about 600mm
  - Some were placed on the bare ground (a compacted soil) outside the concrete slab.
  - On several occasions, he was cautioned by one Mr. Rui to be careful of the props and formwork, and to finish casting the concrete carefully and quickly
  - The bare ground was under the cantilevered slab, and that ground was a little below the level of the concrete slab. It therefore meant that the height from the bare ground to the bottom of the formwork, needed a longer prop length than the normal.
  - When probed further, it was realised that the small cross sectional props (the red ones) were extended more out to make up the required height to the formwork.
  - He collaborated the findings of the investigators, that the smaller inner tube was placed on the ground, whiles the bigger outer tube was placed up under the top formwork.
  - Whiles on top of the formwork, he heard a strange noise, and therefore came down to check on the formwork. Without any visible shortfalls on the formwork, he went up again, just then the collapse occurred.

  These assertions by the carpenter foreman, was collaborated by Mr. Rui, the mason foreman, the safety officer, the site engineer and the Resident Engineer. The only one who did not collaborate this assertion was the project manager of the contractor.
  The hypothesis was then accepted as the main root cause of the collapse.

THE GENESIS AND ANALYSIS OF THE COLLAPSE: POINT BY POINT

1. **The said collapsed slab needed to be cast**
2. **Before casting that slab, there was the need to cast the swimming pool base slab**
3. **Before casting the swimming pool base slab, there is the need to put in fittings by swimming pool construction specialists**
4. **Project manager could not wait for the swimming pool specialists to execute point 3 above and gave the go-ahead for the point 2 to be executed**

5. **In order to cast the slabs in point 2, there is the need to get adequate steel props, for which order was placed by the contractor.**
6. **Some of the steel props were delivered to site, but they were not adequate.**
7. **The specialists needed to install the steel props, did not accompany the props to the site to do his work**
8. **The project manager could not wait for the props installation specialist, and therefore requested the carpenter foreman and his team of carpenters to install the steel props**
9. **The carpenter foreman and his team of carpenters obliged and installed the steel props as they deemed it fit.**
10. **The site engineer refused to raise an RFI for the installed formwork and its supporting system, because he did not feel the contractor is ready to cast the swimming pool base and even less ready to cast the said collapsed slab.**
11. **There was therefore no RFI issued out to the Resident Engineer of the Developer for the said formwork, its support system and the said collapsed slab. She therefore did not sign-off for the casting of the said collapsed slab.**
12. **The project manager gave the order for the casting of the slab, the concrete being supplied and poured apparently by a concrete supplier, apparently less used by the contractor.**
13. **The critically small sizes of the steel props (the red type), the relatively large spacing of the props (some around 1000mm), the fixation (free top and free bottom), the lack of bracings and verticality (being out of plumb), the height of the props (over 4.5m high) linked to the critical buckling load (about 6.86kN) and most probably the rate and nature of the concrete pouring (heaping at one point at high pouring speed), lead to one or more steel props buckling under the exceeded critical buckling load (up to about 9kN). There was then a domino effect after some steel props failed in buckling and that led to to the total physical collapse of the supporting system, the formwork and the slab being under construction.**

RECOMMENDATIONS

0.1.1 Recommendations

- For concrete cube strength test, confirmation by an independent laboratory is important.
- All concrete cube test should be on a standard template.
- The scope of work of monitoring or supervising consultants should include the approval of the design of formwork and associated false works.
- Authenticated Reports of the monitoring or supervising consultants should form part of the evaluation processes leading to the issuance of a certificate of occupancy for public buildings, school buildings, hospitals, places of worship and buildings where large crowds congregate.
- A traceability system should be established for all construction materials.
- Ghana Standards Authority should develop stringent standards for the certification of adjustable steel props manufacturers and approval of promotional literature.
- The site's policies are well documented but the legal department is advised to ensure that headings, wordings and addresses conform to legal entities' details as enshrined in the project management document and also the bill boards as displayed for the avoidance of doubt.
- It is recommended that a further investigation be conducted into how completed phases of work are signed off
- It also is recommended that health and safety issues should go beyond PPEs and include improvement in health messages and signage. Particular need is a designated area for smoking as per the health and safety policy document to stem passive smoking.
- It is recommended that storage of potential hazardous materials such as sharp edged materials (e.g. iron rods) around exits should have visible warning signs and where possible sealed to avoid falls and cuts
- Human Resource Manager –
    - It is recommended that the human resource manager should have a physical working presence with the site to answer worker/management issues, explain policy, raise morale albeit periodically and to formulate a site specific sub-policy driven by the expectations of all stakeholders,

- Adequate data of ALL persons who have at least a day's relationship with the site should be captured.
- Social Security and National Insurance contributions should be **Compulsory.** It should not be left to the discretion of the workers, especially the casual or contract workers.
- Consider post emergency rapid assessment on project site.
- Have at least two qualified HSE officers to take responsibilities of health & safety and environment issues.
- Have an Emergency Response Plan and Procedures to handle any possible emergencies that may arise on the site and beyond
- Have well stocked first aid medications available for emergencies
- Have Semi-Annual general trainings on Occupational Health and Safety Management for both permanent and contract staff.
- Have simulation exercises and drills to test the level of preparedness of workers on site
- Non-compliance must be criminal national issue
- We propose to strenghten the implementation agents, such as the metro/municipal/district assemblies with competent structural engineers, certified by the ghana institution of engineers, to ensure planning processes are strictly adhered to.
- Like the internal audit agents, engineering council is to send a representative of certified structural engineers to the assembly.
- The representative of cert structral engineer is to a member of the distrist planning authority in the assembly, responsible for issuance of permit, after technical scrutity, prior to permit issuance.
- Encourage the ppp in the permit-processes at the assembly
- Structural engineering companies with requisite competence and tech. Know-how are to be assigned to /registered at the assemblies, for sturctural analysis and design of high rising buildings. This is to encourage ppp for synergy
- All high-rising buildings must be peer-reviewed by the structural & geotechnical committee of the ghana institution of engineers, as part of permits issuance. This is to ensure double-checking.

- Finally, ghie should be given by law an oversight responsibility to monitor the implemenation of high rising building, and report directly to the minister of works, housing and water-resources, and to parliament, national security agents

5 REGULATION AND LAWS

The National Building Regulations, 1996 LI 1630 contains the arrangements of regulations guiding the process for application of building permits through to habitation permit. The regulation specifies codes of practice for foundations and the super structure.

A general overview of the regulation shows that it is still very relevant if proponents and the Issuing authority strictly adhere to it.

Between the available British codes and the BRRI Seismic Design Code there is adequate provision for safe design of statically designed buildings as well as wind loading when used in conjunction with wind loads produced by the Ghana Meteorological Dept. Various Engineers use different codes when they make allowance for earthquake loading - an Engineering choice based on their experience. The number of floors above which rigid earthquake design is required is also an engineering choice.

An oversight of the **NATIONAL BUILDING REGULATIONS 1996**

The following arrangement is lifted from the regulations. As it stands the regulations relevantly apply currently and when applied in the ideal situation should prevent such occurrence. It is conjectured that weakness lie in the enforcement of regulations. This is due largely to the following:

- Lack of adequate staffing (professional engineers, building inspectors)
- Lack of skilled staff
- A general system failure