Quality Improvement in the Construction Industry: Three Systematic Approaches

by
Ilías Ortega and Søren Bisgaard
Institute for Technology Management
University of St. Gallen
Switzerland

Abstract

A major difference between construction and manufacturing is that most constructed facilities are unique, while manufactured goods usually are mass-produced. Therefore, to attain learning effects comparable to those achieved in mass-production, learning from failures in construction needs to take place at an industry-wide level. Further, methods of Quality Management adapted to the special circumstances of construction need to be developed. In this report, we discuss three systematic approaches to prevent construction failures. First, we discuss the statistical analysis of large samples of construction failures (macroscopic analysis) to identify primary failure modes and derive preventive measures. Next, we propose to select typical cases from the most frequently occurring construction failure modes. A detailed analysis (microscopic analysis) of the selected cases can then also lead to preventive measures. Finally, we review the transfer of safety management methods from risk-conscious industrial sectors, such as aviation, to construction (methodological analysis).

Introduction

Despite sophisticated computer based methods, such as finite element models, computer-aided-design technology, and advanced scientific theories, construction failures continue to occur at an alarming rate. *Table 1* shows estimates of the annual risk of construction casualties for the U.S. construction industry (Eldukair and Ayyub, 1991) based on samples from the years 1975-1986.

Description	Values
Annual number of deaths (failures)	456
Annual number of deaths (accidents)	1,569
Annual number of injuries (failures)	2,515
Annual number of injuries (accidents)	968
Total number of deaths	1,985
Total number of injuries	3,483
Annual cost of failures in dollars (direct and indirect costs)	\$ 14.4 x 10^{9}
Annual U.S. construction volume in dollars	\$ 300 x 10^{9}
Annual financial risk of structural failures	48 x 10^{-3} (approx. 5%)
Size of construction work force in U.S.	6,000,000

Table 1. Estimates of annual risk of construction casualties for the U.S. construction industry (Eldukair and Ayyub, 1991).

The annual figures for deaths, injuries, and financial losses due to construction failures shown in *Table 1*, underscore the need to reduce the number of construction failures.

The Technical Council on Forensic Engineering of the American Society of Civil Engineers has defined a construction failure as “an unacceptable difference between expected and observed performance” (Feld and Carper, 1997). Therefore, construction failures not only include major, catastrophic events such as bridge collapses, but also damages to building facades, foundation settlements, and other minor failures with a large industry-wide cumulative effect. Construction failures further comprise human deaths and injuries caused by the failures themselves. Failures occur during the construction and the operational phase of facilities.

Some of the reasons for studying construction failures are:

1. Each failure provides information that may be used to prevent similar failures.
2. The systematic investigation of construction failure patterns provides feedback for advancing construction science, improving construction practice and enhancing building regulations.
3. Detailed construction failure studies help identify errors to be avoided.

Differences between Construction and Manufacturing

One of the purposes of this report is to outline how methods traditionally used for Quality Improvement in manufacturing can be adapted for construction. However, to do that, it will be necessary to first clarify how construction differs from manufacturing:

1. Constructed facilities are unique, and seldom mass-produced.
2. The members of the construction team (architect, engineer and contractor) usually change with each project.
3. In contrast to manufacturing, the product of construction (i.e. the built facility) is stationary, while the production facilities are mobile.
4. The vast majority of individual construction firms is small and designs or builds a limited amount of facilities.

Because the individual construction firm designs or builds a limited number of facilities, learning from failures seldom takes place at the level of the individual construction firm. Further, lessons learned from individual construction failures are usually not exchanged between construction firms, and therefore, many failures are repeated. To be effective, learning from failures in construction should ideally take place at the industrial level. Construction requires not only creatively adapted traditional methods of Quality Management (Box and Bisgaard, 1987), but also new methods of Quality Management.

Some of the currently used managerial methods to prevent construction failures are checkpoints, standardized documentation, communication procedures, safety plans and hazard scenarios (Matousek, 1982; Matousek and Schneider, 1983; Schneider, 1997).

Learning from construction failures can take place at two logical levels: The *macroscopic* level of the overall construction sector, and the *microscopic* level of individual construction failures.

Macroscopic Analysis

Macroscopic analyses are statistical studies performed on large, industry-wide construction failure samples. Macroscopic studies can be used to determine the industry-wide impact of various types of construction failures and thus direct the main focus for preventive measures. They can also lead to the discovery of patterns in causes leading to construction failures. An example with potential application in construction are graphical methods such as *defect maps*, used in mass production to discover defect patterns (see e.g. Bisgaard, 1996; Ishikawa, 1983).

It is common in manufacturing to perform Pareto Analyses (Juran and Gryna, 1993) to determine the major, few causes contributing to the majority of the defects. Similar studies can be performed in construction using industry-wide samples.

An empirical, macroscopic study of 800 construction failures performed by Matousek and Schneider (1976) indicates that approximately 75% of construction failure cases is owed to human error. The remaining 25% of construction failures are caused by consciously (intentionally) accepted risks. According to the same study, 85% of the failures due to human error could have been avoided by the use of appropriate management principles and methods. The key inference that can be drawn from this study is that failure prevention is not so much a technical issue, but a managerial one.

The Pareto Chart in *Figure 1*, based on Matousek and Schneider's (1976) data, shows the causes underlying construction failures due to human errors of civil engineers. Specifically, about 35% of those construction failures are due to insufficient knowledge, 15% to underestimating influences (dead and live loads, wind loads, snow loads, etc.), and approximately 1% to unclear definition of responsibilities and communication errors. The Pareto Chart further shows that a small portion of those construction failures is due to low quality of materials.

The Pareto Chart in *Figure 1* implies that efforts to reduce the number of failures caused by human errors of engineers should be directed primarily towards filling educational gaps and providing knowledge and methods for properly assessing influences. Specifically, a 50% reduction of errors due to insufficient knowledge will result in approximately 17% fewer failures (due to human errors of engineers). On the other hand, a 50% reduction of errors due to unclear definition of responsibilities and communication errors will result in approximately 1% fewer failures.

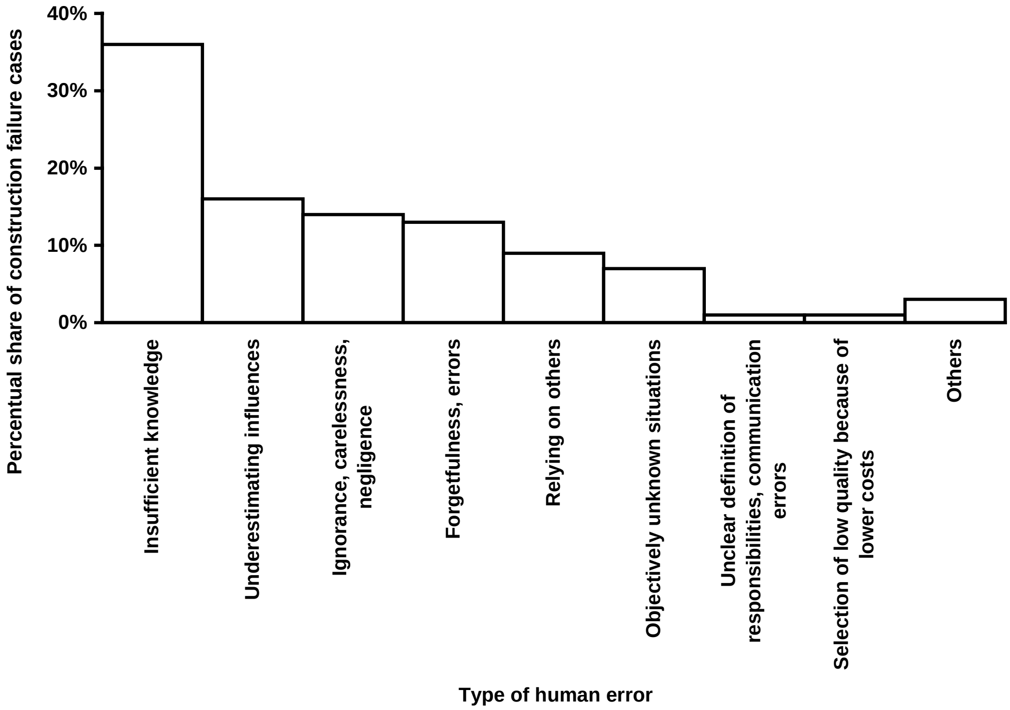


Figure 1. Pareto Chart of construction failures due to human errors of engineers based on data extracted from Matousek and Schneider (1976).

An additional Pareto Analysis (Juran and Gryna, 1993) performed on the failure cases due to insufficient knowledge has not been done, but could provide more precise information as to the kind of knowledge engineers are missing. Successive Pareto Analyses of this kind can be performed in a recursive manner until the desired degree of detail is reached. This idea is schematically illustrated in *Figure 2*.

Figure 3 shows the distribution of errors incurred during the planning phase of construction. The figure implies that about half of the damage sum is due to errors done while performing statical calculations. With the currently available data it would not be possible, but further Pareto Analyses could help discover more accurately the types of errors done while performing statical calculations.

As these examples indicate, macroscopic studies can help focus research in to those areas where the major pay-offs from efforts to prevent failures can be expected.

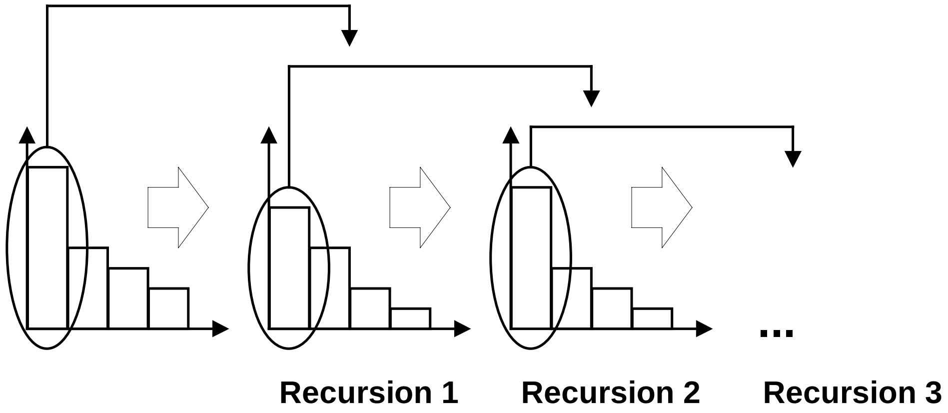


Figure 2. Recursive Pareto Analyses in order to reach the desired degree of detail.

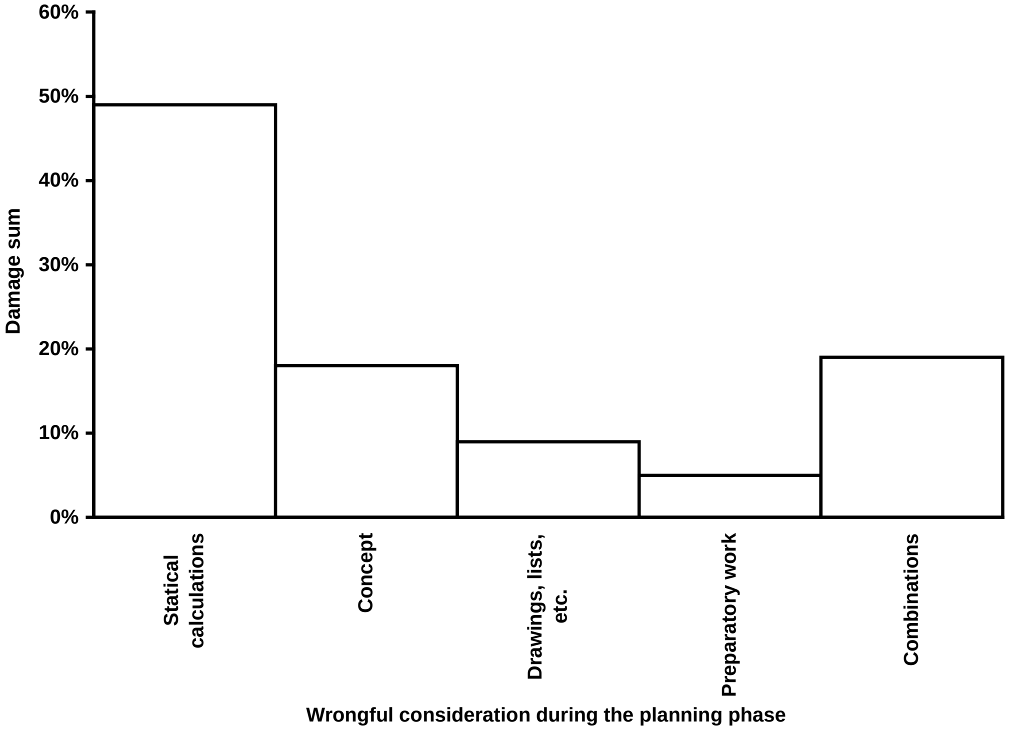


Figure 3. Pareto Chart of errors incurred during the planning stage of construction (data extracted from Matousek and Schneider, 1976).

For macroscopic studies to be useful, the following is required:

1. The data constitute a representative sample of construction failures.
2. The failure cases are systematically and consistently categorized along few variables.

Microscopic Analysis

Microscopic analyses of individual construction failure case studies (Boutellier and Ortega, 1998; Feld and Carper, 1997; Gnaedinger, 1987; Kaminetzky, 1991; Ortega, 1998; Petroski, 1994, 1993, and 1992) are performed after a macroscopic study has identified the major, few causes contributing to the majority of the failures. The lessons learned from microscopic analyses should be as general as possible, i.e. valid in many different contexts.

The main difficulties encountered while performing microscopic studies are:

1. The selection of representative construction failure cases identified from the major, few failure modes found in the macroscopic analysis.

2. The generalization of lessons learned from individual construction failure cases.

Now follows an example of a microscopic analysis of a major construction failure that illustrates the general lessons that can be learned.

Case Study: The Collapse of the Indoor Swimming Pool Ceiling in Uster, Switzerland

On May 9th, 1985 the ceiling of the Uster indoor swimming pool fell down, killing 12 persons and injuring another four (Peyer, 1987 and 1985; Peyer and Scherrer, 1985; TagesAnzeiger, 1985; Theiler, 1985). The swimming pool was inaugurated in 1972 with a ceiling designed as an eight-centimeter thick, reinforced concrete plate. The 166-tons heavy ceiling was suspended from the roof by 207 10-mm thick, chrome-nickel V2A steel bars. According to the responsible civil engineer, the ceiling's safety factor was 2.5. However, the ceiling was built 20% thicker and thus heavier than originally designed. Later, because of aesthetic and acoustic considerations, a wooden ceiling was suspended from the reinforced concrete plate.

Calculations performed after the accident by independent experts determined a safety factor of 1.3 for the ceiling structure before the suspension of the wooden ceiling and a safety factor of 1.2 when the wooden ceiling was considered.

Before the actual accident took place, several incidents came about that should have been cause for alarm. In 1979, after the ceiling had suddenly bent strongly, the steel bars were inspected for the first time. In the corresponding inspection report, the ceiling's deflection was judged harmless. In 1984, during the repair of rusty window frames, a second, coincidental inspection was performed. A broken chrome-nickel steel bar was found. Assuming that it was damaged during construction, it was repaired by welding a second bar to it. In the report to the City of Uster, in which the repair was not mentioned, the condition of the ceiling was described as flawless.

The collapse of the swimming pool ceiling was triggered by stress corrosion, i.e. corrosion and simultaneous mechanical stress. It is conjectured, that at the beginning of the ceiling's fall, some chrome nickel steel bars were so strongly damaged by stress corrosion, that they broke. The loads to be carried by the broken bars were then transferred to the neighboring bars. Some of them were already weakened by stress corrosion, and promptly broke. Further bars tore due to simple overloading. Because of lack of structural redundancy, this process repeated itself, until all bars had torn like a collapsing house of cards, and the ceiling fell down.

The accident's investigation arrived at the following conclusions:

1. The responsible engineers and architects lacked experience in the design of suspended ceilings.

2. The responsible engineers and architects held chrome-nickel steel for a "stainless" steel, although stress corrosion had been known for more than twenty years before the accident happened.

3. Inspections were not planned for this - for the responsible designers - unconventional structure. The inspections that were carried through took place coincidentally.

The collapse of the ceiling of the Uster swimming pool cannot be attributed to a single cause. Using the damage level classification scheme proposed by Brauner (1990), *Figure 4* shows the different events contributing to its failure.

The collapse of the ceiling of the Uster indoor swimming pool was caused by seven factors. None of them alone would have been sufficient to cause the accident. However, the unfortunate combination of all factors precipitated the tragedy. This case illustrates the common observation that many failures often cannot be assigned to a single fact or individual, but are frequently caused by an unfortunate chain of errors.

The general lessons learned from the failure of the ceiling of the Swimming Pool Uster that, if incorporated as managerial practice could prevent accidents, are as follows:

1. Inexperienced architects and engineers designing unconventional structures should seek the advice of independent consultants. An independent peer-review of the project may be also necessary (Bell, 1989; Zallen, 1990).

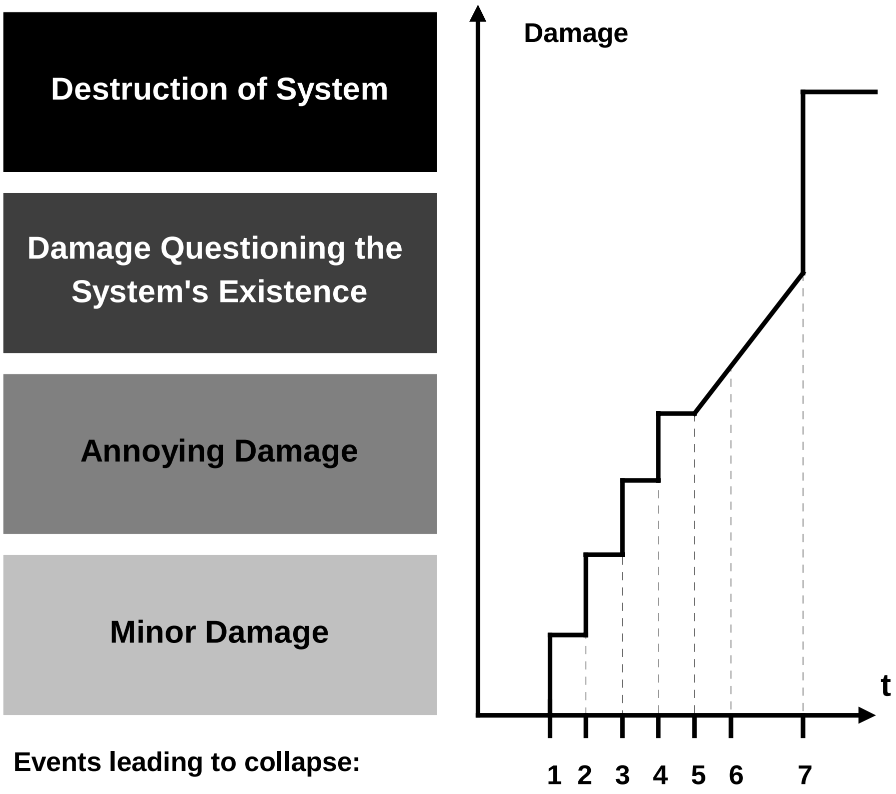
2. Independent experts should be consulted before using unconventional materials, and also before designing facilities in chemically aggressive environments.

3. Unconventional structures require a monitoring plan (e.g. of deformations) for the construction *and* the operational phase so that damage can be noticed before it is too late.

4. The effect of design changes (e.g. increased loads, modified geometrical dimensions, alterations to load-carrying mechanisms, etc.) on prior design assumptions should be

carefully analyzed and documented.

5. Structural redundancy may be necessary to prevent the progressive collapse of long-span or high-rise structures.



Events leading to collapse:

1 Lack of design experience
2 Low safety factor
3 Reinforced concrete ceiling, 20% heavier than planned
4 Additional wooden ceiling
5 Stress corrosion
6 Inadequate inspections
7 Lack of structural redundancy

Figure 4. Events leading to the failure of the ceiling of the Uster indoor swimming pool using the damage level classification scheme proposed by Brauner (1990).

The main concern while performing microscopic analyses is to obtain representative failure samples. Unfortunately, only major construction failures are made public. Information from minor, but likely cumulatively more relevant cases is often kept secret, mainly for legal reasons or fear for the reputation of the parties involved. Further, organizations involved in liability suits often do not provide access to information concerning failure cases. Prime sources for construction failure cases are laboratories for materials testing, insurance companies and forensic engineering offices. However, because of the pressures of their primary business activities, these organizations seldom take the time to perform the studies proposed in this report. Because of the sensitive, confidential nature of failure information, independent, impartial, state-run institutions, like universities, are well suited for the scientific investigation of construction failures.

Methodological Analysis

In this report, we first discussed macroscopic industry-wide, statistical studies. They have the purpose of identifying the major causes leading to construction failures and deriving preventive measures. Next, we reviewed subsequent microscopic case study-oriented analyses. Their objective is to illustrate the mechanisms leading to construction failures and also gain preventive methods. Now, we will discuss a third approach to prevent construction failures: methodological analyses.

Methodological analyses are concerned with the analysis of safety management practices used in risk-conscious industrial sectors such as aviation with the objective of transferring them to the construction industry. One such method are Incident (or Near Miss) Reporting Systems.

According to van der Schaaf (1991), an incident is “any situation in which an ongoing sequence of events was prevented from developing further and hence preventing the occurrence of potentially serious (safety related) consequences.”

Many different “iceberg” theoretical models describe qualitatively the fact that incidents occur more often than accidents. *Figure 5* shows van der Schaaf’s (1991) “iceberg” model.

Incident Reporting originated in aviation, where the safety standards are especially high. The Aviation Safety Reporting System (ASRS) was established by the Federal Aviation Administration’s Office, and is administered by NASA. It covers incidents reported by pilots, dispatchers, airport personnel, air traffic controllers, mechanics, and cabin crew. Further information concerning incidents is obtained directly from confidential telephone interviews with incident reporters. The reports are handled anonymously and standard report forms can be downloaded from the Internet. ASRS provides two regular publications, *Callback* and *ASRS Directline*[1]. They contain excerpts from ASRS reports and summaries of ASRS research studies. There is also an ASRS Database containing more than 50’000 recorded incidents, which cannot be accessed from the Internet. However, a selection of recent, relevant cases is made available in the Internet.

A further example of an Incident Reporting System is the Air Data Acquisition System (ADAS) used by Swissair (Rüegger, 1990). It records in-flight data and automatically triggers incident reports as soon as flight variables exceed predefined thresh-

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[1] http://olias.arc.nasa.gov/ASRS/ASRS.html

old values. Thus, pilots do not need to be aware of an incident for it to be reported. ADAS allows the analysis of dangerous yet unrecognized situations. Because ADAS guarantees confidentiality, personal interviews with the reporters are used to gain further insights into the incidents' causes.

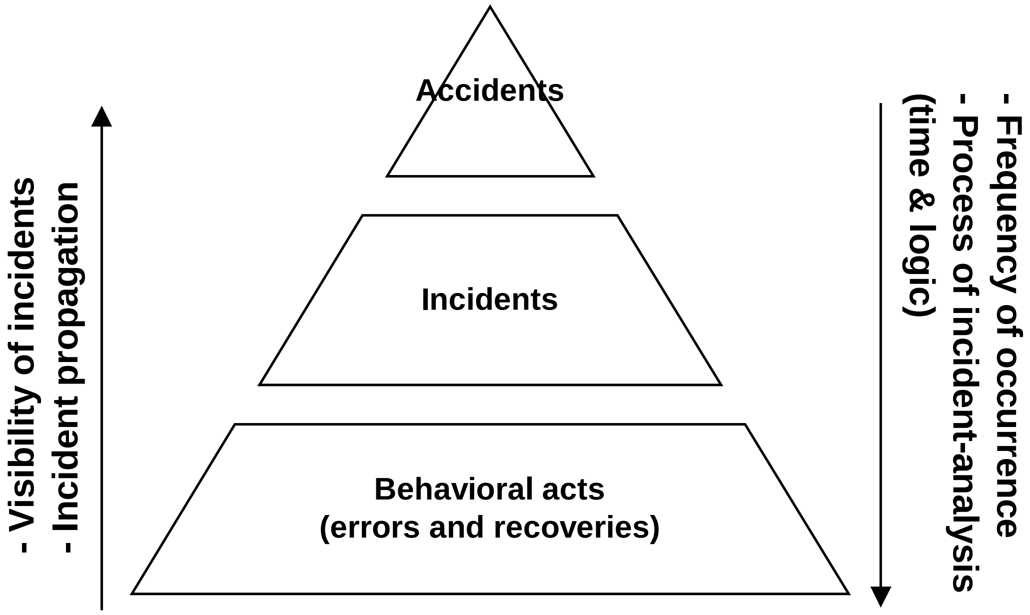

Figure 5. Qualitative "iceberg" model describing the interactions between accidents, incidents and behavioral acts (van der Schaaf, 1991).

The conceptual ideas behind ASRS and ADAS can be effectively transferred to the construction industry. The main advantages of Incident Reporting Systems are the following (see also Rüegger, 1990):

1. Incident reports provide larger samples than accident reports.
2. Individuals involved in incidents are more willing to report than individuals involved in accidents.
3. If confidentiality is guaranteed, follow-up personal interviews may lead to deeper insights than individual incident reports.
4. The analysis of incident reports is far more economical than that of accident reports.
5. Since incidents do not lead to adverse outcomes, they point to errors to be avoided and deliver recovery measures to surmount the incidents. Therefore, in many cases not only the problems are identified, but also the solutions are provided.

To be successful, three conditions need to be fulfilled by an Incident Reporting System (Lucas, 1991):

1. *Anonymity:* This will secure the individual's willingness to report incidents.

2. *Forgiveness:* Employees need a contractually guaranteed freedom from prosecution if they are expected to report incidents. This will also encourage them to provide unbiased reports.

3. *Feedback:* To motivate employees and to justify the use of an Incident Reporting System, employees should be regularly updated on improvements achieved by using the Incident Reporting System.

Incident Reporting Systems can be more advantageous if their data sample is broadened by collecting international data using the Internet. Using the Internet, data can be collected at a low cost and information can be effortlessly and widely disseminated.

Conclusion

In this report we discussed three different, complementary approaches to construction failure research in order to derive preventive measures. Macroscopic and microscopic analysis are most effective if performed sequentially, with the macroscopic analysis done first. They are based on the tenet of learning from the past. Methodological analysis is based on the principle of applying already successful methods. The largest improvement in construction safety will result if the three discussed methods are applied simultaneously.

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