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Case Studies on Failure Investigations in Structural and Geotechnical Engineering

Editors
Fabrizio Palmisano
Laurent Rus

International Association for Bridge and Structural Engineering (IABSE)

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Case Studies
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Preface

This monograph presents case studies *on failure investigations in structural and geotechnical engineering* in three sections: building collapses, bridge collapses, and structural failures leading to the loss of serviceability of the structure (failures without collapse).

This bulletin is the result of the work lead by the Task Group 5.1 (TG5.1) 'Forensic Structural Engineering' as part of Commission 5 'Existing Structures' of IABSE. The work of TG5.1 is not limited to any building material or type of structure and focuses on the exchange of knowledge on causes (technical, human, and/or organizational) of structural failures and on forensic investigation methods and techniques.

These case studies are selected from a wide range of reported and investigated structural failures. While this is an 'incomplete' set of case studies, the selection has been made based on well documented structural failures, either from direct contact to forensic engineering experts who worked in the technical investigation process, or from highly detailed investigation material that has been summarized by the relevant chapter author(s). As a result, this bulletin covers a wide range of causes, technical and legal investigation processes, and finally highlights the lessons learnt for each of the described structural failures.

The aim of the bulletin is not only to describe case studies but, mainly, to use emblematic case studies to show procedures that can be used when dealing with structural failures. In addition to obtaining a deeper insight into the technical causes for structural failure, the reader would be duly informed about the different countries' legal issues related to the investigation process.

It is interesting to note that some of the structural failures (loss of serviceability/performance) described in this bulletin have led the local authorities and the society to 'take advantage' of their structural non-compliance and to develop a 'landmark' environment for local/international tourism.

The Editors would like to thank each of the individual authors that have graciously accepted the invitation for writing a chapter for this bulletin and for the excellence in the content of these chapters. Special thanks go to TG 5.1 from where this bulletin originated and to Harshavardhan Subbarao (Chief Reviewer, member of the Editorial Board), Alastair Soane (external reviewer), Zhi Zhang (external reviewer), and Joseph Jiménez Elizondo (external reviewer) for their in-depth and rigorous reviews. Thanks also to the members of IABSE Bulletin Editorial Board for their support and commitment to this edition, and a special thanks to Brindarica Bose from IABSE Headquarters for her endless coordination effort across the different parties.

Finally, we would like to dedicate this monograph to the memory of Dr. Robert Ratay, with whom we started this journey of Forensic Structural Engineering dissemination in 2011. His deep and thorough knowledge and expertise in Forensic Structural Engineering will be always a benchmark for us.

Fabrizio Palmisano & Laurent Rus (Editors)
June 2023

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Chapter 1

Introduction

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This chapter gives a brief overview on forensic structural engineering.

1.1 Structural Failure

The failure of a structure is defined as either the non-conformity of the structure to withstand the design expectations leading to loss of structural integrity (Ultimate Limit State ULS failure), i.e., the loss of load-carrying capacity, or the inadequate difference between the intended behaviour and actual performance of the structure (Serviceability Limit State SLS failure). Thus, it ranges from hardly visible minor defects to catastrophic collapses. It can extend from total or partial collapse of the structure (ULS) to extensive or serious damage without collapse (ULS), to signs of distress (SLS), to excessive deformation (SLS), deterioration (SLS), to unacceptable aesthetic appearance (SLS), to unreasonable maintenance need (ULS or SLS), or to excessive soil settlement (ULS or SLS), to name a few structural failures.

There also are cases with no readily visible signs. These can be suspected design errors, construction defects, and hidden deterioration that present risks of potential failures but may not be recognized without structural analysis or testing.

Causes of structural failures can be related to any stage of a construction:

- Planning: system concept.
- Design: approach, calculations, drafting.
- Design-construction interface: shop drawing detailing, drafting, review and approval.
- Construction/renovation: erection, inspection, accident.
- Use, misuse, abuse, alteration, overload in service.
- Lack of maintenance.

Structural failures are often the result of human failings such as:

- Negligence: deliberate failure to properly analyse or detail the design and deliberate disregard of codes and standards.

Chapter 2

‘Palazzo Edilizia’ in Salerno

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This chapter presents the forensic investigations relevant to the partial collapse of a historical masonry building in Salerno (the so called ‘Palazzo Edilizia’), which occurred in 2007 in Salerno (Italy). The investigations revealed that hidden structural defects were the main causes of this apparently unpredictable collapse.

2.1 Introduction

On the night of the 15th of June 2007, a corner of one of the most important historical buildings in Salerno, the so called ‘Palazzo Edilizia’, collapsed 80 years after its construction. Such a ruinous failure did not cause any casualties only because the collapsed side was that of the living rooms.

On the 29th of June 2007 the Judge for the preliminary criminal investigations nominated the authors as technical consultants (i.e., expert witnesses). After that, the authors carried out investigations, surveys, and tests in order to obtain useful information to understand the causes and dynamics of such a ruinous and apparently unexpected collapse [1].

The purpose of the investigations was not only to determine the causes of such a collapse but also to provide the Judge for the preliminary investigations with sufficient data to identify the parties responsible.

2.2 The investigation Process

In Italy the partial or total collapse of a construction (even if without injuries and/or fatalities) is always a crime. This means that the crime trial and the relevant investigations always start before the civil ones and, in general, their conclusions are adopted also in the civil trial.

The criminal proceeding is always initiated by the Public Prosecutor who starts to carry out the pretrial investigations. In the case of a collapse, the Public Prosecutor appoints experts (i.e., consultants) as expert witnesses to carry out the technical investigations. As,

Chapter 3

Building in 'Aggregate' in Barletta

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This chapter presents the forensic investigations relevant to the collapse of a building in 'aggregate' that occurred in Barletta (Puglia, South Italy) on the morning of the 3rd October 2011, causing five fatalities. According to the Italian technical standards, a building aggregate consists of a set of adjacent buildings that is the result of an articulated and not unitary genesis due to multiple factors. Some recent Italian collapses, such as that occurred in Barletta, have highlighted that the approach to be used in the relevant forensic investigations is not so obvious and simple. The aim of the article is to describe the different approaches used in the investigations by different consultants and their different conclusions on the trigger of the collapse.

3.1 Introduction

The Italian historical city centres are full of building aggregates that can be defined as a set of adjacent buildings, delimited by an open space, that is the result of an articulated and not unitary genesis due to multiple factors (e.g., different construction and modification ages, materials, uses, owners). When structural interventions are made on a building in an aggregate, specific investigations and analyses should be performed to evaluate possible interactions arising from the structural contiguity with adjacent buildings. The problem is that, when dealing with historical building aggregates, it is quite impossible to have a deep structural knowledge of the whole aggregate mainly because of the following reasons:

- difficulties in finding documents of the original project;
- difficulties in finding historical documents describing the construction sequence;
- difficulties in making surveys and tests in buildings of other owners;
- difficulties in the assessment of the mechanical characteristics of old construction materials (e.g., natural masonry blocks, 'poor' quality mortar);
- absence of national/international codes relevant to the vulnerability assessment of old existing constructions in building aggregates.

Chapter 4

Balconies in Maastricht

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This chapter focuses on human and organisational factors that are usually behind the technical cause of failure. This is illustrated by a case of the collapse of five balconies in 2003 in Maastricht (The Netherlands) resulting in two fatalities.

4.1 Introduction

In 2003 a residential building called Patio Sevilla was completed. In the evening of April 24th, 2003, five balconies of this apartment building collapsed, resulting in two fatalities. Several major investigations were started by insurance companies, police, and the criminal court.

To focus on learning points related to structural safety, it is worthwhile to investigate failure cases with a framework of set parameters.

A framework with possible influencing factors for structural safety has been set up [1, 2]. The framework is based on critical success factors derived from management literature and factors from safety science. In Section 4.3 the framework will be explained.

This chapter will first reveal the technical causes of the failure, and subsequently analyse to what extent human and organizational factors in the building process (as listed in the theoretical framework) might have played a role in the collapse of the balconies of Patio Sevilla in Maastricht. The focus is on the involved parties in the primary building process, like engineers and contractors.

The analysis of the technical, human, and organizational factors of this case is based on: court judgement [3-5], a report from an expert witness [6], various other investigation reports [7, 8], newspaper articles [9, 10], and a book chapter on this incident [11]. This chapter is an adaption of an IABSE conference paper [12].

4.2 Structure and Technical Cause of Failure Resulting from the Investigation Process

4.2.1 Layout of the Structure

The balcony structure was made of prefabricated concrete. On two positions per balcony, a hinged, thermally isolated connection between balcony slab and floor was designed.

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Chapter 5

Kansas City Hyatt Regency Walkways

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The collapse of the walkways in the Kansas City Hyatt Regency Hotel remains the deadliest structural collapse in US history if terrorist attacks are excluded. After providing the relevant background, this chapter describes the site investigation and structural testing that determined that the collapse occurred for two reasons: 1) the design of the hanger rod-to-box beam connection was severely deficient, and 2) the hanger rod arrangement was changed such that the connection forces acting at the fourth level were doubled. The outcome of legal actions is described and lessons learnt are summarized.

5.1 Introduction

During a tea dance on 17 July 1981, the suspended walkways through the lobby of the Kansas City Hyatt Regency hotel collapsed (Figure 5.1), killing 114 people and injuring 216 others. First responders worked feverishly to rescue people who were trapped and injured, and to recover the bodies of the deceased. The US government, as well as engineers representing the owners and other parties, carried out intensive investigations into the cause of the collapse.

This chapter is written from the perspective of the author who led the investigation on behalf of the hotel owner, the Crown Center Redevelopment Corporation.

5.2 The Investigation Process

On 20 July 1981, Senator Thomas F. Eagleton's office contacted the National Bureau of Standards (NBS) and requested that technical assistance be provided to the city of Kansas City. This was followed later that day by a request to NBS from Mayor Richard L. Berkley for technical advice regarding the tragedy and its cause. On 22 July, Mayor Berkley formally requested that the NBS independently ascertain the most probable cause of the collapse of the Hyatt Regency walkways.

Chapter 6

Partial Collapse of Parking Garage at the Tropicana Hotel in Atlantic City

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In 2003, a major collapse occurred during the construction of a parking garage at the Tropicana Hotel in Atlantic City, New Jersey. It resulted in four fatalities, dozens of injured workers, and significant delays to the construction project. This chapter describes the engineering investigation that was conducted, the findings of the investigation, and recommendations to avoid future failures of similar structures.

6.1 Introduction

The structure being constructed was a ten-story, 2400-car parking garage located over a four-story retail complex. Figure 6.1 shows the overall plan and the location of the collapse.

6.1.1 Description of the Structure

A proprietary structural system for the slabs and beams, called the Filigree Beam and Slab System, was selected early in the design phase. The key feature of this system was that the formwork for the slabs and beams consisted of precast planks and shallow precast "tubs", both of which would become composite with the cast-in-place concrete. This avoided the expense of removing formwork and provided a more efficient structural design. The precast planks for the slabs were typically 2 ¼ inches (5.7 cm) thick. The precast tubs for the beams were typically 8 feet (243.8 cm) wide and 16 inches (40.6 cm) high. Figure 6.2 shows the typical construction along an interior beam line for this system.

6.1.2 Project Organization

The project organization, shown in Figure 6.3, played a role in the collapse.

Initially, the project organization was similar to many design-bid-build projects. The owner hired a design team who prepared a design that met the owner's objectives.

Chapter 7

2E Terminal at Roissy-Charles de Gaulle Airport

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This chapter presents the forensic investigations conducted after the partial collapse of the jetty of the 2E terminal at Roissy-Charles de Gaulle Airport near Paris that occurred in May 2004. The primary failure mechanism decided upon by the experts is the punching of the shell caused by steel struts in conjunction with the bending rupture of one of the solid arch elements of the shell. This mechanism was then followed by a shift of the shell from its supports and its fall on the tarmac.

After a detailed description of this complex structure, the chapter relates the results of the investigations conducted by the administrative commission set up by the Transportation Ministry, the different courts of law, and SETEC engineering company. It then draws the lessons learnt from the collapse and presents the reconstruction of the new jetty opened in the spring of 2008.

7.1 Introduction

The construction of the 2E terminal was launched by Aéroports de Paris (ADP) in 1999 and the terminal was opened to the public in June 2003. It comprises 3 buildings (Figure 7.1):

- The main building, that has 8 levels, including 4 in the basement, which hosts the arrival and departure halls, the baggage sorting, and technical rooms.
- The boarding jetty that allows the docking of 18 planes, which is parallel to the main building and has a circular arc shape.
- An isthmus which ensures the junction between the two buildings and which houses the police checkpoints, shops, and offices.

The boarding jetty is a 650 m long nave and is made up of a succession of ten shells of a common length of 68 m: a central shell (n° 145), two shells adjacent to the isthmus (n° 144 to the west, and n° 146 to the east), five standard shells (2 to the west and 3 to the east) and two end shells (Figure 7.2).

Chapter 8

Roof of FC Twente Stadium

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This chapter focuses on human and organizational factors that are usually behind the technical cause of failure. In this chapter the focus is on the collapse of the extension of the roof of the Football Club Twente stadium in Enschede (The Netherlands) during construction, resulting in two fatalities.

8.1 Introduction

On July 7th, 2011, an extension of the roof of the FC Twente stadium collapsed during construction. This extension would increase the stadium's capacity with an additional 10.000 seats. Additional capacity was needed because of a successful period for the soccer club.

During the assembly of finishing structures for this new roof, a roof truss failed. This resulted in a progressive collapse. Two fatalities and nine injuries were recorded. A collaboration of the Public Prosecution, the Labour Inspectorate of the Ministry of Social Affairs and Employment, and the Dutch Safety Board [1] started an investigation. The Dutch Safety Board reported the outcomes of this investigation to the public [2].

At first, this chapter reveals the technical causes of the failure. Subsequently, it presents human and organizational factors in the building process that might have played a role in the collapse. This case was analysed with the same framework of human and organizational factors as was used in chapter 4. The analysis of the technical, human, and organizational factors of this case is based on a report of the Dutch Safety Board, an earlier paper on technical causes and various newspaper articles [1-5]. This chapter is an adaption of an IABSE conference paper [6].

8.2 Structural and Technical Cause of Failure Resulting From the Investigation Process

8.2.1 Layout of the Structure

The original FC Twente stadium was constructed in 1998 and extended in 2008. Because of sporting successes, a second similar extension was constructed in 2011.

Chapter 9

Roof of Paviljonki Congress and Trade Fair Centre in Jyväskylä, Finland

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This chapter describes the collapse mechanism that occurred on 1 February 2003, the undertaken investigation process, and lessons learnt from the roof collapse of Paviljonki, a congress and trade fair centre in Jyväskylä, Finland. Investigations were carried out and reported after the time of the collapse. However, this chapter also presents new findings and additional analyses of this case. Further discussion and other relevant viewpoints are also provided.

9.1 Introduction

The roof of Paviljonki, a congress and trade fair centre in Jyväskylä, Finland, collapsed on 1 February 2003 at 09:39. The collapsed area spanned 2,500 m^2, which constituted a major part of the main hall. The last exhibition had finished the day before and had attracted roughly 10,000 visitors over the course of the exhibition. There were 12 people in the hall when the collapse began. The collapse took approximately two minutes, and there were no casualties. The building was completed and taken into use on 17 January 2003. The weather was clear and sunny with an ambient temperature of -26 °C, Relative Humidity (RH) of 61%, and an indoor temperature of around 20 °C. The weather had not changed significantly before the time of the collapse. There was a relatively even layer of snow about 20–25 cm deep on the roof, and its weight was measured to be 50 kg/m2. The unfactored design load under snow conditions was 200 kg/m2. [1]

9.2 The Investigation Process

Half a minute before the collapse, one of the twelve people present in the hall called the emergency services. The first fire and rescue service units arrived at 09:47 [1].

During the same day, the Safety Investigation Authority started an investigation because the incident was categorised as posing a major accident risk. The investigation

Chapter 10

Wilson Bridge in Tours

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This chapter presents the forensic investigations conducted after the partial collapse of the Wilson Bridge on the Loire River in the city of Tours in France. It reviews several papers published in French after the collapse, intending to share the main lessons with the international community. The collapse of five piers and six arches among the fifteen arches of this old masonry bridge occurred in 1978 during a strong flood of the Loire River. The main causes concluded by the experts are a general scour emphasised by a significant lowering of the river bed due to material excavations, a local scour of the alluvions, and a washout of the sand between the wooden piles through the protective rockfill, which seems to have remained in place. These causes led to the destabilisation of the foundations of the piers. This event triggered the publication of the Technical Instruction for the Surveillance and Maintenance of Bridges (ITSEOA) in 1979 and the necessity to limit the extraction of materials in French rivers.

10.1 Introduction

This bridge located in the city of Tours and dated from the 18th century, commonly called "the stone bridge" by the inhabitants of Tours, was renamed after American President Woodrow Wilson in 1918. It allows the national road n° 10, which goes from Paris to the Spanish border, to cross the Loire River. It has a total length of 440 m and comprises 15 masonry arches with a span of approximately 24.50 m, numbered from 1 to 15 going from the left bank to the right bank.

In the morning of Sunday, April 9, 1978, the pier 2 of the bridge suddenly tilted upstream, followed by a partial collapse of the upstream parts of the arches 2 and 3. Luckily, while this bridge is usually very busy, at that time only one car was present on the bridge and had just entered the left bank side; its driver, feeling the road was giving way, had the reflex to fully accelerate to cross the collapsing arches and to reach the part of the bridge that remained intact. There was, therefore, only a few material damages to the car and no people were injured.

In the hours that followed, the dislocated parts of arches 2 and 3 in turn collapsed, leading to the collapse of arches 4 to 6, and later arch 1 (Figure 10.1).

Chapter 11

Sully-sur-Loire Suspension Bridge

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This chapter presents the forensic investigations conducted after the collapse of the Sully-sur-Loire suspension bridge that occurred in 1985 in France. The failure mechanism concluded by the experts is the rupture of a cable-threaded tie in conjunction with a rupture of an element of the rigidity beam. The threaded ties had geometric defects, which were at the origin of the ruptures in service. These defects were either the threads themselves, or cracks due to fatigue, or corrosion phenomena. A decision-making process based on the determination of steel resilience was then launched to manage the other old suspension bridges in France during cold winters.

11.1 Introduction

With a total length of 376 m, the Sully-sur-Loire Bridge had 4 spans, three of which had a span of around 100 m and the fourth 76.25 m. It had a structure common to most of the old suspension bridges over the Loire River (Figure 11.1), with multiple suspended spans and head cables. The supporting cables (4 in number per side, with a parabolic shape) and the head cables (six in number, with a straight shape: three upstream and three downstream) were interrupted at each pier and hooked by ties on movable saddles located at the head of the pylon.

On January 16, 1985, at 7:40 a.m., the Sully-sur-Loire Suspension Bridge suddenly collapsed into the bed of the Loire River (Figure 11.2). The intense cold that reigned that morning, around -23°C, was immediately considered to be one of the determining factors of this disaster. At the time of the accident, only 2 cars, one semi-trailer loaded with logs, and a cyclist were on the left bank side span of the bridge, which collapsed on the bank, out of the water. This particularly fortunate circumstance led to the absence of deaths and serious injuries.

Indeed, the four occupants of the cars and the lorry driver escaped almost unharmed; only the cyclist was injured. They were lucky enough to be on the beach side and thus avoided falling into the icy waters of the Loire River.

The weather services then declared it “one of the coldest winters in French meteorological history”. Temperatures dropped below - 20 °C in the region where the bridge was located, and the Loire River carried pieces of ice at that time.

Chapter 12

Point Pleasant 'Silver' Bridge

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This chapter presents the forensic investigations of the collapse of the Point Pleasant Bridge. The collapse of this bridge has left important lessons learnt about, among other issues, the importance of the choice of the appropriate fracture-toughness steel to be used in bridges, the concept of structural redundancy, and the correct and systematic need for inspection and maintenance of existing bridges.
Likewise, it was the beginning of important modifications in the analysis of fracture and fatigue of steel bridges in the standards and codes.

12.1 Introduction

The Point Pleasant Bridge, which carried U.S. 35 highway over the Ohio River, was located between Point Pleasant, West Virginia, and Kanauga, Ohio. The bridge was also known as the "Silver Bridge" because it was one of the major structures to be painted with aluminium paint. It was one of two nearly identical and unique eyebar chain suspension bridges in the U.S. The other bridge, also spanning the Ohio River, was at St. Mary's, West Virginia, until it was dismantled (Figure 12.1).

On December 15, 1967, Point Pleasant Bridge collapsed without warning, resulting in the loss of 46 lives (Figure 12.2) due to stress cracking corrosion of an eyebar.

12.2 Structural Characteristics of the Bridge

The Point Pleasant Bridge was an eyebar chain suspension bridge (top chord) with its axis in an east-west direction over the Ohio River. It had a 700 ft centre or main span and two 380 ft side spans, as shown in Figure 12.3. In addition, there were two approach spans on each side of the bridge, which were plate girder spans 75.25 ft and 71.50 ft in length supported on concrete piers. The two suspension bridge towers extended 130 ft 10.25 in. above the top of the two main piers. The total length of the bridge was 1,753 ft.

The roadway of the suspended span, as originally built in 1928, consisted of a timber deck and sidewalks. In 1941, the timber deck was replaced with a 3-inch-deep steel grid

Chapter 13

Thruway Bridge at Schoharie Creek

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Following the collapse of the Schoharie Creek Bridge on April 5, 1987, an extensive investigation was undertaken to determine the cause of the failure. The foundations and the bridge components recovered and laid out in their original positions, were closely examined, and soil borings were taken at the site, but it soon became clear that Pier 3 was the critical element. In addition to the site work, the investigation included a review of documents pertaining to the design, construction, inspection and maintenance of the bridge, and geological and hydrological reviews were made of historical and existing conditions. Structural analyses were made of the superstructure and substructure. A brief review of many of these investigative efforts is described in this chapter. The Schoharie Creek Bridge collapsed because of the extensive undermining under Pier 3 due to scour resulting from a flow rate of about 63,000 cubic feet per second at the bridge site.

13.1 Introduction

A major bridge failure occurred on Sunday morning, April 5, 1987, when two spans of the five-span Schoharie Creek Bridge on the New York State Thruway suddenly collapsed and fell into the flood-swollen creek. Five vehicles, in which ten persons were riding, all fell into the creek before traffic was stopped. All ten bodies were recovered. About 90 minutes later, a third span collapsed.

13.2 The Investigation Process

On Monday, April 6, 1987, the New York State Governor's office contacted Wiss, Janney, Elstner Associates, Inc. (WJE), prime, and Mueser Rutledge Consulting Engineers (MRCE), subcontractor, requesting the firms carry out a no-stone-unturned, independent investigation as to the cause of the collapse. The firms' engineers arrived on April 7, 1987, to begin their investigation. In addition, WJE and MRCE were responsible for planning and overseeing the removal and demolition of the structural components to

Chapter 14

The Leaning Tower of Pisa

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The Leaning Tower of Pisa was stabilised in the years 1999–2000 by an International Committee appointed by the Italian Government. An analysis of the history of the monument and the results of investigations and monitoring led to the conclusion that the tower was affected by a phenomenon of instability of the equilibrium. The stabilisation intervention, conceived to be totally respectful of the integrity of the monument, consisted of slightly decreasing the inclination of the Tower by removing a small volume of soil beneath the north side of the foundation.

14.1 Introduction

It was in the period of maximum splendour of the maritime republic of Pisa, in the 12^{th} and 13^{th} centuries, that the cathedral, the Leaning Tower, the baptistery, and the cemetery, were erected in the Piazza dei Miracoli (Figure 14.1). The square is the awesome manifestation of the ideal unity existing at that time among religious, spiritual, and political powers. From the very beginning, the history of art and civil history intertwine in its monuments, giving them an outstanding character of sign and symbol to the city.

The Leaning Tower is one of the world's best-known and most treasured monuments. Its extraordinary inclination turned it very early into a strong attraction.

The tower consists of a hollow cylinder surrounded by six loggias with columns and vaults, merging from the base cylinder and surmounted by a belfry (Figure 14.2). The external surfaces are faced by cut stone masonry. The annulus between the facings is filled by rubble and mortar with frequent voids, probably intended to lighten the structure.

After the collapse of the San Marco bell tower in Venice, in the early 20^{th} century, public opinion and the authorities turned their attention to the Tower of Pisa. The Italian government set up several commissions that carried out extensive investigations. A tender was called, but the contract was not assigned. Different stabilisation measures were proposed, but no significant action was taken.

At the end of the 20th century, the overhang of the tower had reached a value of almost 5 m and was increasing at a rate of 1.5 mm per year. The sudden and unexpected

Chapter 15

The Leaning Tower of St. Moritz

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This chapter explores the history of the Leaning Tower of St. Moritz and describes the stabilization attempts.

15.1 Introduction

The 13th-century Leaning Tower of St Moritz (Figure 15.1), is located in the historic centre of the famous Swiss ski resort town in the compression zone of the 10 million m^3 Brattas Landslide. Over hundreds of years, this slowly creeping landslide, which is blocked by a rock outcrop below the tower, had damaged the adjacent St. Mauritius church to such an extent that it had to be demolished already in 1893 due to dangerous differential settlements and cracks. The fact that the 33 m tall tower has survived its 5.40 degrees downslope inclination should not be taken for granted: this is an outcome of a century-long effort by several outstanding Swiss engineers who came up over the years with original stabilization solutions [1].

15.2 The Brattas Landslide

The Brattas-Fullun landslide, which constitutes the major factor for the special geotechnical conditions of the Leaning Tower, is located on the northern slope above the village of St. Moritz [2]. It is composed of a 600 m wide clastic flow bounded on both sides by almost parallel shear surfaces (Figure 15.2, top). The detachment zone is located on the southern edge of the terraced surfaces of the Val Saluver at an altitude of 2400 m a.s.l., and the area stretches over a horizontal distance of 1.5 km to a lower altitude of 600 m with the average inclination of about 20°. The clastic flow consists of two parts (Figure 15.2, bottom), with some geological evidence of a rock outcrop at the boundary between them.

The upper zone, which extends from the detachment zone between Sass Runzöl and Sass da Muottas to the crest at an altitude of approximately 2100 m, is composed of a rockfall with boulders reaching 2-3 m in diameter. The lower 600-700 m long zone, which

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Chapter 16

Excessive Deflections and Cracking in the Reinforced Concrete Floor Slabs of the Silverton Building in Canberra

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This chapter presents a case study of a multistorey reinforced concrete building, the Silverton Building, constructed in Canberra (Australia) in 1983, evacuated in 1989 due to concerns regarding its structural integrity, and demolished in 1994. The events, associated with the evacuation of the building, initiated court proceedings that ran between 1989 and 1997. In the description presented in this chapter of the structural issues affecting the integrity of the building, particular attention has been placed to avoid allocating blame to specific parties involved in the project and to utilise this case study as an opportunity to revisit the risks and responsibilities of engineers associated with structural engineering design and assessment. Personal remarks of the authors are also provided and clearly highlighted.

16.1 Overview of the Silverton Building

The case study deals with a seven-storey building designed in 1982 and built in 1983 in Canberra, Australia. This structure is widely known as the Silverton Building. A typical floor layout of the building is depicted in Figure 16.1 to highlight key dimensions and column arrangements based on the information provided in references [1-3]. The typical slab thickness specified for the floors was 210 mm.

After completion, the building was sold to a large corporate fund at the end of 1983. Following the standard practice of the fund, consulting engineers were appointed to perform a pre-purchase inspection of the building in September 1983.

Soon after, the building was tenanted in 1984. Some defects were reported by the tenants in early 1984. It appears that these included excessive deflections of the floor slabs, some concrete cracking in the structure, and leakage of the curtain wall [1]. In this building, an aluminium frame was used to carry the aluminium panels and glass windows of the curtain wall that was then supported by the reinforced concrete frame. The reporting of these defects initiated an investigation that was performed in the same year.

Chapter 17

Agrigento Cathedral: Landslide Assessment and Mitigation of the "Girgenti Hill"

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This chapter illustrates the studies carried out to interpret the landslide phenomenon that affected the hill where the Cathedral of Agrigento (Girgenti) and the entire diocesan area stand, producing subsidence of the bearing soil and damage to the superstructures of the buildings. The interpretation of the landslide phenomenon made it possible to rationally address the design of landslide risk mitigation interventions and, consequently, the execution of structural consolidation works on the building.

17.1 Introduction

The city of Agrigento (Girgenti) is known worldwide for the presence of the Valley of the Greek Temples. The morphological configuration of the site and the cathedral's location on the slope, together with the geological characteristics of the subsoil, have caused numerous instabilities since its original construction, which, despite numerous interventions over the centuries that have been mostly of a structural nature, have not stopped the ongoing deformation process. The slope bordering the City of Agrigento on the north side contains numerous architectural assets belonging to the Diocese of Agrigento: from the left side of the picture in Figure 17.1, one can note the Church of St. Alphonsus, the Curia, the Bishopric, the Cathedral, the Diocesan Museum and the Seminary. The area is also characterised by the presence of underground *hypogea* (underground chambers) of Greek origin.

The cathedral, whose construction began in the 11th century, is located on a ridge that develops in the east-west direction. The instability of the area manifested along the ridge with a lesion starting from the Church of St. Alphonsus and extending westwards to the Diocesan Museum, also affecting the cathedral.

Case Studies

Objective:

To provide in-depth information to practicing structural engineers, in reports of high scientific and technical standards through case studies on design, rehabilitation, forensic engineering and other topics.

Topics:

Structural analysis and design, dynamic analysis, construction materials and methods, project management, structural monitoring, safety assessment, maintenance and repair, and computer applications.

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Case Studies on Failure Investigations in Structural and Geotechnical Engineering

Failures of structures occur in all parts of the world as the result of design errors, construction defects, abuse or misuse, ageing and deterioration of the structure, lack of maintenance, as well as environmental effects such as wind, flood, snow, earthquake and, of course, human errors. They can result in catastrophic human costs as well as heavy financial losses to all involved, including local economic growth deceleration, expensive delays and repairs, as well as other repercussions, such as legal actions to responsible parties.

'Welcome' effects of these unfortunate events include a better understanding of the origins and causes of structural failures, their corresponding lessons learnt, and a more effective mitigation of their occurrence through changes in codes, standards, guidelines, and practice.

In several countries the investigation process of the causes of failures, responsibilities, and resolution of the consequent claims have created an active, demanding, and specialised field of professional practice – often referred to as Forensic Structural Engineering – with well-defined technical and legal procedures.

This bulletin is the result of the work lead by the Task Group 5.1 'Forensic Structural Engineering'. It provides understanding of the origins, causes, and consequences of failures, their forensic investigations, and the lessons learnt from them.

The aim of the bulletin is not only to describe different examples but, mainly, to use emblematic case studies to show procedures that can be used when dealing with structural failures. In addition to obtaining a deeper insight into the technical causes for structural failure, the reader would be duly informed about the different countries' legal issues related to the investigation process.

The bulletin is aimed at young, mid-career and experienced structural engineers who want to acquire a better understanding of failure mechanisms towards improving their design, inspection, construction, administrative, and other project-related practices to avoid pitfalls that may lead to failures. It also aims at those wanting to acquire a working knowledge of the challenging professional practice of forensic structural engineering.

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