Risk in Civil Engineering : from natural to man-made hazards

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Introduction

The Human Society is installed in structures and buildings constructed by Civil Engineers and she constantly uses these structures to live, work, exchange, communicate. The significant feeling of safety of our Western societies is probably partially based on the fact that a given number of risks affecting the structures in which we live and work has been correctly anticipated and tackled by engineers who provided satisfactory designs against most probable risks.

Historically, civil engineering is the first engineering activity. Beside houses and buildings, impressive symbolic and religious buildings such as the Egyptian pyramids (4540 BP) constitute significant engineered structures. Old engineered structures include roads and bridges and fortifications as the China Great Wall (started 2700 BP). Other less known civil engineering structures include old masonry dams, such as the Saad El Kafara 12 m high dam built on the Nile River in Egypt in 4600 BP and known as the more ancient dam, as reported by Herodote**.** As shown in Figure 1, it was a hybrid masonry-earth dam with no spillway because the constructors probably did not anticipated the risk of flood. It was destroyed by the first flood that occurred after construction. Apparently, the population was so shocked by the disaster that no further dam was built on the Nile river in the following 1000 years.

War fortifications made up earth, earth-wood structures or masonry also early developed in European countries. In France, fortification engineers learnt a lot from the medieval "Châteaux forts" and the contribution of Vauban (born in 1633) was particularly significant.

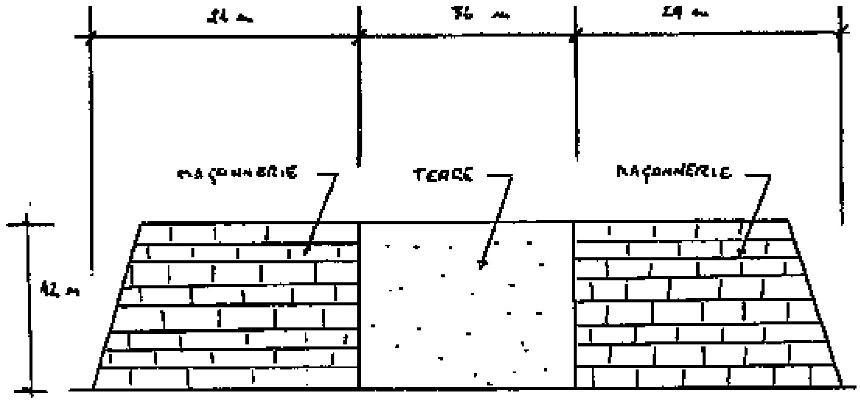


Figure 1 : the Saad el Kafara dam (Egypt, 4600 BP, hand-drawing by Pierre Londe).

Massive structures for religion or defence were built to be stable under the action of gravity and to resist to war attack. Their safety was guaranteed by very conservative empirical measures. The example of Saad El Kafara shows however that unexpected natural hazard may threaten even massive constructions that appeared to be initially safe. Later on, due to technological developments and to the corresponding invented structures, other potentially dangerous natural hazards had to be accounted for : earthquakes, stormy waves for port facilities, flood for river dikes and dams, wind for high buildings, suspension bridges and footbridges and, more recently, snow and stone avalanches and debris flows to protect structures in mountainous areas.

In this regard, some catastrophic events involving lost of lives periodically remind people that the notion of zero risk and of completely guaranteed safety does not exist. In most cases, technical catastrophes occurring in engineered structures (civil and industrial) are not accepted by the Society. The reaction of the Society, that is largely supported and amplified by the media for obvious economic reasons is to try to find and punish the persons (generally engineers) considered as responsible. This position is of course acceptable when the catastrophe is due to human deficiency, negligence or loss of adapted survey and maintenance. In the other cases, the idea that a catastrophe may occur due to unknown and unpredictable new phenomenon of either a natural or a technical nature is not admitted. The considerable scientific and technical progresses that have been accomplished since the industrial revolution (including in Medicine) provide an artificial feeling of safety in our Western societies. This is somewhat contradictory in the sense that any new scientific and technical progress involve facing new situations and hence new risks.

The serious concerns that presently affect the international geopolitical situation is related to an extremely dramatic event that affected two very large buildings that were destroyed in a way that had never been imagined before by anybody, including civil engineers and military strategists. As in many countries, impressive engineering challenges had been faced when building these buildings that symbolised economic prosperity and powerfulness. The admiration of people looking at such impressive structure is unconsciously based on the fact that the significant risks of failure of such high buildings, when built for first time ("World record of height"), was high and had been properly technically tackled by "their" engineers. For people, the fact that such buildings exist involve that all related risks have been "dissolved" by technology and no longer exist. This is not true.

The safety of structures

Resulting from a very long trial and error process that started with the first known historical structures that have been built many centuries ago, engineers found a way to guarantee the safety of structures through the progressive development of relevant mechanical models that are *supposed* to adequately reproduce their behaviour. Basically, the idea of the contemporary mechanical approach is that the materials that constitute the structure and on which the structure is founded have a maximum mechanical resistance above which they break. Engineers do their best to ensure that the forces induced in these materials once assembled within the structure are low enough to avoid breakage. The difficulties of the exercise are significant and many :

- Beside gravity, it is difficult to predict other mechanical forces that will affect structures. They come from natural hazards such as wind, earthquake, sea waves or river flood. Recent developments in statistical analysis obviously provide a method of predicting more precisely the hazards to be faced by the structures, but they need to be efficient a sufficiently rich data base gathered by rigorous observation along a significant period of time.
- It is difficult to completely identify the exact nature and properties of the ground on which structures are built. As other materials, soil and rocks have maximum admissible resistance and may fail if higher forces are applied. They are also variable in nature, and even slight changes in their properties between two points may have significant consequences on the stability of the structure (see Figure 2 on the Tower of Pisa)
- It is not always possible to completely identify and control the properties of the material used or concerned (steel, masonry, concrete, soil, rock). Hence, structure are founded (or excavated in the case of tunnels) on uncertainty
- Once probable dangerous mechanical actions are supposed to be known, it is difficult to know how forces distribute along the structures, because structures are complex in nature and because the models used are hence not completely adapted
- Once the structure is built, reasonably adequate maintenance dispositions may be altered by new aggressive mechanical, physical or chemical phenomenon (unexpected corrosion of steel, alkali-reaction in concrete) that threaten and sometimes may condemn the structure (the Chambon concrete dam in France does not work anymore due to fissures caused by alkali-reaction).

Other features that include financial and societal aspects also characterise the civil engineering structures and their safety (see also Londe 1990 and Verdel 1999) :

- There are most often unique
- They cost a lot of money and any trouble, defect or correction of unexpected behaviour is substantially expensive
- Their failure can be very dangerous for the human, natural or man-made environment
- They are constructed to be used for given periods of times (from 30 to 100 years) by communities of people that may change with time. This can result in a dangerous

neglected maintenance based on the fact that possible dangers are progressively forgotten by users of neighbours (in the case of abandoned structures)

- People are convinced that engineers are responsible of any failure and look for somebody to condemn
- It is extremely difficult to predict man induced risks resulting from war, terrorism or psychopathologic behaviour

Subsequent analysis of the September 11th disaster by civil engineers showed that, although it had never been suspected before, the collapse of the Twin Towers was finally not surprising when considering the mechanical capacity of the structure to resist to such an extremely powerful mechanical attack. As in other cases, such an example led to intense thinking in terms of risk analysis, structure behaviour, correcting measures and preventive dispositions. The Twin Towers example confirmed that, beside the consideration of natural hazards in relation with the resistance of structures, the human factor, including terrorists behaviour, is to be accounted for more and more seriously. However, it is a fact that all similar buildings are definitely unable to resist to such attack and that no correction measure exist. In such case, the only solution is preventive protection. Another conclusion drawn was that the effect of fire on structures and buildings materials had to be taken into account more deeply, leading to significant research programs in many developed countries. Various accidents recently occurred in European tunnels (Channel tunnel, Mont-Blanc tunnel with 39 deaths, Gothard tunnel with 11 deaths) showed that relatively few concern about fire hazards existed in civil engineering. Intense investigations are presently carried out in this topic, together with a reassessment of the safety of all tunnels presently in function.

and we can save 700 Lira by not taking soil tests

Figure 2 : On the foundations of the Tower of Pisa (and we can save 700 lira by not taking soil tests)

An illustration of some of the ideas presented above is given by the case of the Québec bridge, presented in Figure 3 and described in Shepherd & Frost 1995).

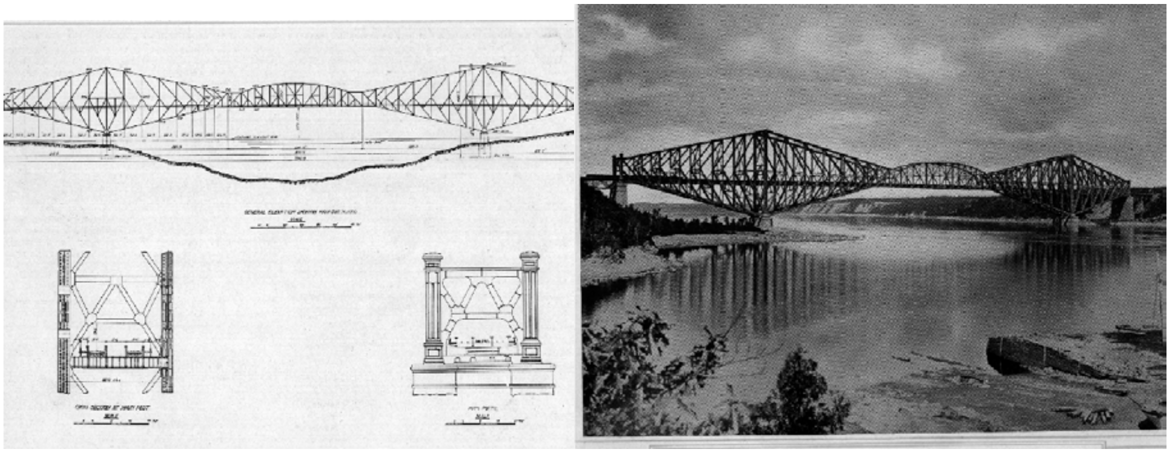
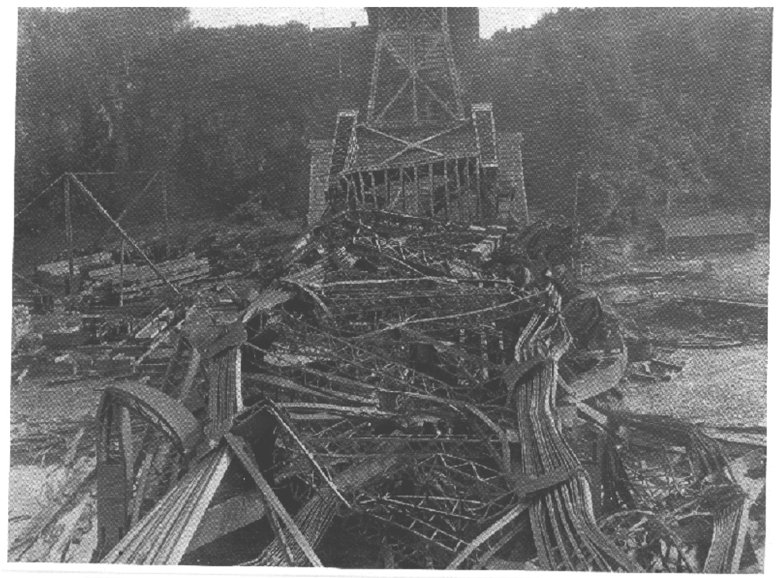
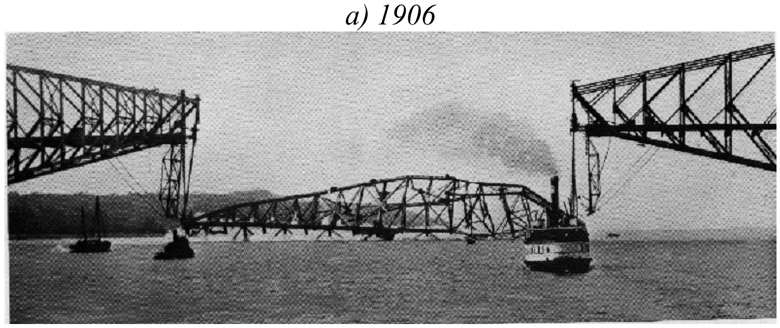


Figure 3 : The Québec bridge (1907-1919)



a) 1906



b) 1916

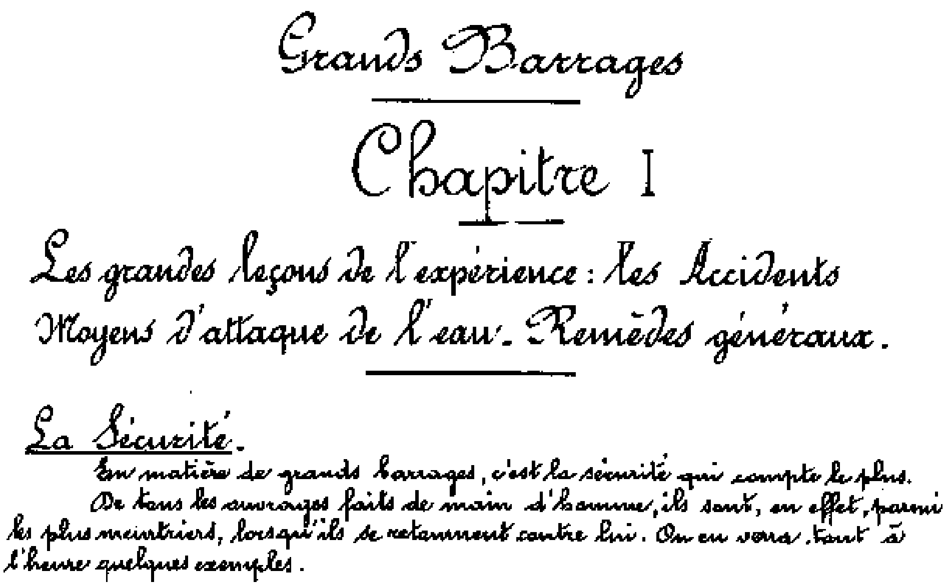
Figure 4: The two failures of the Québec bridge (1907 and 1916)

The bridge shown in Figure 3 was opened to traffic (railways) in 1919. Obviously, it is an impressive structure having a clear span of 1,800 ft (approx. 540 m). It was at the time the longest span ever attempted anywhere. Of course, the challenge faced here was not only symbolic. There was clearly a significant economic interest in providing a way to cross the Saint-Laurent river in that place to allow for easier exchanges between the City of Québec and the rest of the country, including Montréal. However, the economic and financial cost of this technological exploit was much higher than initially suspected, as observed in Figure 4.

The 1907 failure was due to improper design of the compression member of the south anchor arm. The mechanical model used by engineers apparently underestimated some compression forces, that appeared to be too high to be supported by the steel, somewhere in the structure. They was warning two days prior to failure (significant distortion in a panel) that was not properly interpreted. Seventy four workers were killed. As shown by the Figure, the 1916 failure occurred because of the failure of an element of the central simple span (5000 tons) when it was being lifted in place. Another eleven deaths occurred in this accident.

The failure of civil engineering structures

The failure of civil engineering structures has still been examined with utmost attention by engineers. Probably because they were the source of major accidents involving significantly high numbers of victims (2040 deaths in and around the small city of Longarone, Italy, due to the failure of the Vaiont dam, 1963), dams have been examined in terms of safety with particular attention. In France, the engineer André Coyne (see Figure 6), a pioneer in arch concrete dams, started in the Forties to teach at ENPC a course named "*Leçons sur les Grands Barrages*" (Coyne 1943).


Grands Barrages

Chapitre I

Les grandes leçons de l'expérience : les Accidents
Moyens d'attaque de l'eau. Remèdes généraux.

La Sécurité.

En matière de grands barrages, c'est la sécurité qui compte le plus. De tous les ouvrages faits de main d'homme, ils sont, en effet, parmi les plus meurtriers, lorsqu'ils se retournent contre lui. On en verra tout à l'heure quelques exemples.

Figure 5 : The importance of experience : the course on Great Dams by André Coyne (ENPC, 1943)

As seen in Figure 5, the first Chapter of the course was dedicated to the lessons taken from experience and it was stated that : " *In dams engineering, the security is of utmost importance. Among all structures built by Man, they indeed are the most murderous , when they turn back against him. Some examples will be commented later on.*"

This course showed the necessity to deeply analyse previous failures to improve the design of structures in order to ensure a better safety, based, among other cases, on the example of the failure of the South Fork dam in 1889 in Pennsylvania.

This case showed that :

- the failure occurred in an abandoned dam, due to human ignorance, negligence and lack of maintenance
- the 2000 deaths could have been avoided if people had listened to the alert given by an engineer who rode around on his horse to alert people.

Coyne concluded that the following aspects were significantly instructive : "*The apparent insignificance of the causes of the failure, the dreadful series of effects, the repeated warnings from Nature and the crazy blindness of people, the habit considered as safety, the suddenness of the attack and, when the catastrophe occurs, the unconsciousness of people, all these features are almost always met in dam failures*".

This statement emphasises the well known multiplying effect of human behaviour before, during and after catastrophes. The course on Dams was afterwards given until 1999 by Pierre Londe (Londe 1990) who also put in France a lot of emphasis on the necessity of accounting with utmost attention for the safety of dams and structures in civil engineering.

In the US, the Committee of Education of the American Society of Civil Engineers (ASCE) created a Technical Council of *Forensic Engineering* that produced in 1995 an interesting publication on "*Failures in Civil Engineering : Structural, Foundation and Geoenvironmental Case Studies*" (Shepherd & Frost 1995). The title describes the nature of three possible failures in Civil Engineering. It also includes Geoenvironmental hazards that were not considered with so much emphasis in the past, probably because they are less apparent and can be easily hidden by ill-intentioned persons or entrepreneurs. Significant attention to this aspect started with the significant social impact of the environmental disaster of Love canal in the US in 1978.

The three previous failures could probably be completed by the hazards related to slope stability and mass movements, that also constitute a major concern of Engineering Geologists and Geotechnical Engineers, as shown by the recent dramatic consequences of a dramatic climatic event in Venezuela, that caused the loss of around 30 000 lives in 1999 along the seashore close to the Caracas airport.

The ASCE publication (Shepherd & Frost 1995) recalls some typical characteristics of civil engineering structures and failures. It is recalled that in most cases, a civil engineering structure is unique. Only one product is produced on each occasion. Also, these structures may be exposed to unpredictable natural hazards. Concerning failures, the following statements are made :

- They may "occur during the construction as well as during the service life of the facility, often when subjected to unusual or unanticipated load condition"
- "Failure may involve loss of serviceability as distinct of collapse"
- "Failure is an extreme form of damage which itself constitutes a material, non trivial change in the safety, serviceability, appearance or repairability of the constructed facility".

These definitions are purely technical and do not explicitly mention any human influence or societal impact in terms of vulnerability and loss of lives or properties. Also, man-made hazards, that in civil engineering have already been accounted for in nuclear plant safety analysis, are not mentioned. In the case of bridges or dams, the vulnerability of the structures to *war attack* are considered. Also, some disposition to allow for the rapid destruction of bridges for strategic purposes are also considered.

About the impacts of failures

The gravity of a failure is related to the possible occurrence of lost in human lives and properties, i.e. it is unconsciously analysed in terms of vulnerability. In a natural way, a failure that does not significantly and directly affect the social environment does not significantly interest the Society through the media. Logically, it is considered as a technical problem for specialists with no significant impact. Conversely, when dramatic failures with significant impact involving loss of lives occur, people attempt to elaborate some technical analyses of the failure. This phenomenon is amplified by the media that sometimes provide exaggerated or even false technical interpretations.

PARIS-PRESSE-L'INTRANSIGEANT

C'ÉTAIT LE BARRAGE LE PLUS MINCE DU MONDE

Nous avons retrouvé le bâtisseur du barrage : ANDRÉ COYNE

30 mois de travail, 580 millions de francs engloutis en quelques secondes

LA première pierre du barrage de Malpasset a été posée le 1er avril 1952. Il a été mis en eau en 1954, il était alors le plus mince barrage du monde (c'est aujourd'hui celui de Gage).

CONSEQUENCES MATÉRIELLES DE LA CATASTROPHE

ROUTES

Figure 6 : Press articles following the Malpasset dam failure, 1959.

This point is illustrated by the extract presented in Figure 6 from the newspaper "*Paris-Presse-l'Intransigeant*" shortly after the Malpasset dam failure (Londe 1987) in France in 1959 (more than 300 death in the city of Fréjus). The newspaper mentions that « *C'était le barrage le plus mince du monde* », which is not necessarily false. But the comparison made between the Génissiat and the Malpasset dam is unadequate because the two systems work in a different fashion : whereas the huge effort exerted by water (104 m !) is transmitted to the ground through friction in Genissiat (so-called gravity dam), arch dams like Malpasset report the load to the rocky edges of the valley where they are built. This system is only possible with rock foundations, and it appeared afterwards that the Malpasset failure was due to an unknown phenomenon that occurred in the rock, where an increase in water pressure due to the increase in water level behind the dam “exploded” some pre-existing fissures. In the case of Malpasset, it was finally concluded that no responsibility could be given neither to the conceiver nor to the building company. An unknown induced phenomenon had been identified. It induced considerable further research about the stability of rock masses and corresponding regulations were made to avoid any further similar trouble.

Of course, engineers can be wrong in their analyses. This may affect the initial design and also the relevant corrective measures that should be taken during construction when a problem appears. Post-failure expertise carried out by technical specialists to assess the mutual responsibilities of the failure are often very long due to both the nature of legal procedure and to the gravity of the problem to be solved.

In this regard, the failure of the Vaiont dam (1963) dramatically evidenced a new dangerous consequence induced by the first filling of the water level beyond the dam. This situation is known as being particularly risky and many dam accidents have occurred at this phase. The Vaiont failure showed that potential slopes instabilities around future retained lakes could be significantly activated by the increasing level of water. A huge mass movement involving a mountain slope of 2 km high (1.2 mile, Figure 7) went down in the water at an extremely high speed (25 m/s), causing a 240 m high wave that submerged the arch concrete dam and destroyed the city. Another conclusion was the incredible resistance of the arch dam who perfectly resisted this huge wave.

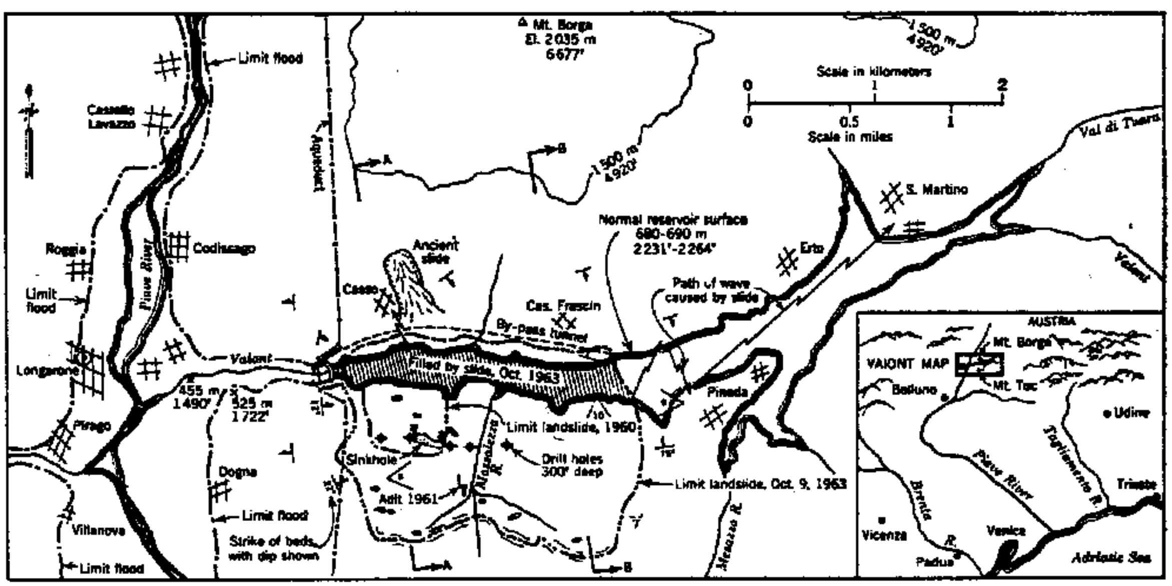


Figure 7 : A map of the Vaiont landslide (After Kiersch 1964, in Shepherd & Frost 1995)

The risk of slope instability and the magnitude of the mass movement were underestimated due to the lack of previous similar experience. Engineers instrumented the slope, monitored the movements of the unstable slope and observed that they were correlated to the increase in water level of the reservoir. Obviously, based on similar information, the filling would nowadays be stopped not to take the risk of destabilising the slope.

A movie recently produced on this subject (*Vajont : La diga del disonore*, Francia/Italia 2001) confirmed again the huge social impact of this catastrophe. Apparently, some of the engineers in charge of the project did not pay enough attention to the serious concerns expressed by some experts, some journalists and some local public associations. It is true that they were in charge of completing the project to deliver it in time to the user, which involved huge amounts of money, the prestige of the companies involved in he project (manufacturer and end users) and resulted in a huge social pressure at a national level (it was furthermore among the highest arch dams of the time). The consequences of this catastrophe illustrate the considerable challenges that engineers have to face when dealing with some hardly predictable risks that can affect the structure that they build, together with its social and natural environment. Note that this induced slope instability problem is presently being seriously considered in the future 650 km long retained lake of the Three Gorges project on the Yang-Tse river in China.

The importance of risk issues in dam engineering led to an interesting worldwide organisation to elaborate and disseminate technical knowledge, carried out by the International Commission on Large Dams (ICOLD). Beside the organisation of regular International Conferences, many Technical Bulletins dealing with all relevant engineering problems are regularly elaborated, based on the collaboration of internationally recognised experts from various countries. As an indication, the references of Bulletins dealing with various topics related to risk and responsibility (*Dams – Risks to third parties,* 1982. *Inspection of dams following earthquakes – Guidelines,* 1988. *Alkali-aggregate reaction in concrete dams,*1991. *Dam Failures – Statistical Analyses,* 1995) are given in the reference list.

This kind of organisation exist in other technical fields, but perhaps in a less formal manner. It is essential to better face risk issues in engineering. A confrontation of analysis in various domains of civil engineering (including for instance other particularly risky structures like Offshore structures and Nuclear power plants) would be certainly fruitful. As a consequence of the elaboration and dissemination of technical knowledge, the elaboration of technical regulations for the design of structure constitutes the further step in the elaboration of a safe design of structures.

New technologies and new risks

In bridges, optimisation was achieved by increasing the span of the bridge, through i) an optimisation of a given technique and ii) the development of novel techniques (use of steel, reinforced concrete, prestressed concrete, high performance concrete). New techniques involve new risks. Whereas masonry bridges had a rather long lifespan, based on the use of natural geological material working in compression due to arching effect, with a negligible role of binding material (Pont du Gard, France), new technologies are associated with other physico-chemical actions that are not completely known at the beginning. Unexpected phenomenon may affect noticeably the lifespan of the structure. Among other examples, this was the case of strip corrosion for reinforced concrete, in a geotechnical innovation called Reinforced Earth, corrosion under stress for prestressed concrete and alkali-reaction in concrete. Obviously, adopting a new technology is still corresponding to a new risk due to unknown phenomena, with probably higher level of risk associated with more sophisticated techniques. In this regard, the case of the failure of the suspension bridge of Tacoma (1940) in the US is symbolic of these unexpected failures that help defining new related safe design rules. Failure was caused by excessive resonance induced by a strong wind, as represented in Figure 8 with humour in the Shepherd and Frost (1995) book cover.

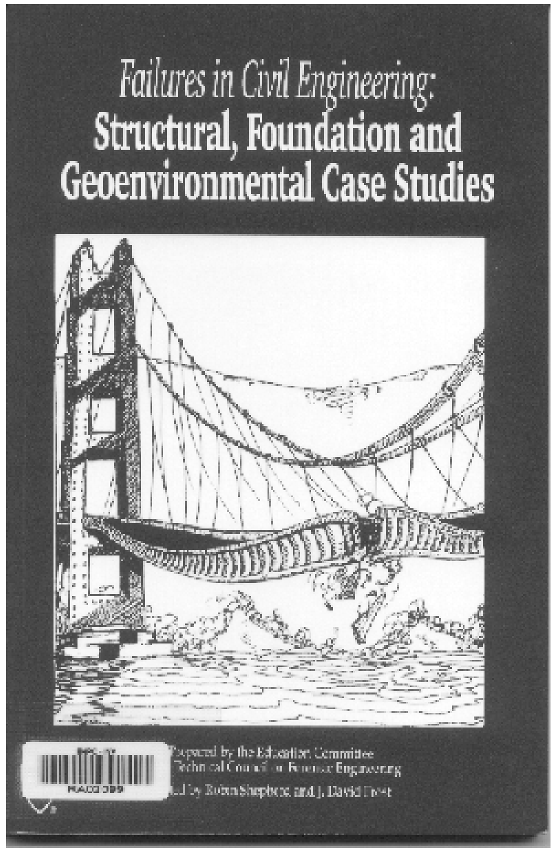


Figure 8 : the failure of the Tacoma bridge

In front of new technologies, administrative authorities have the responsibility to make a decision to whether or not they will accept it, considering that the level of risk that will be supported by the users is acceptable and safe. This is a high responsibility that explains that many administration have a conservative approach and are somewhat resistant to new technologies. In this regard, it seems that the French administration had not an excessively conservative position, allowing for various innovations such as, for example, prestressed concrete, reinforced earth, soil nailing. To allow for the current use of a new technique, the administration manages the definition of regulations and standards, based on the synthetic and convergent opinion of a group of selected experts.

Responsibility issues after failure : the case of Rue Raynouard in Paris

A recent case study concerning geotechnical risk is now briefly commented. Figure 9 (Lavisse & Mazaré 1999) corresponds to a recent serious litigation that occurred in a nice neighbourhood of Paris (Colline de Passy near the river Seine, 16^{e} arrondissement) where the pressure corresponding to real estate development is significant. Some trouble occurred in the building seen in the photo (8 levels, built in 1930) after a 6 m deep excavation was made below and close to the building, in order to construct a new building. Beside technical considerations, it should be mentioned that the new building would condemn the nice view on the river Seine of the existing building, that was also occupied by socially influent persons including various politicians, journalists and lawyers. Actually, the litigation is still going on and very few information is presently available.

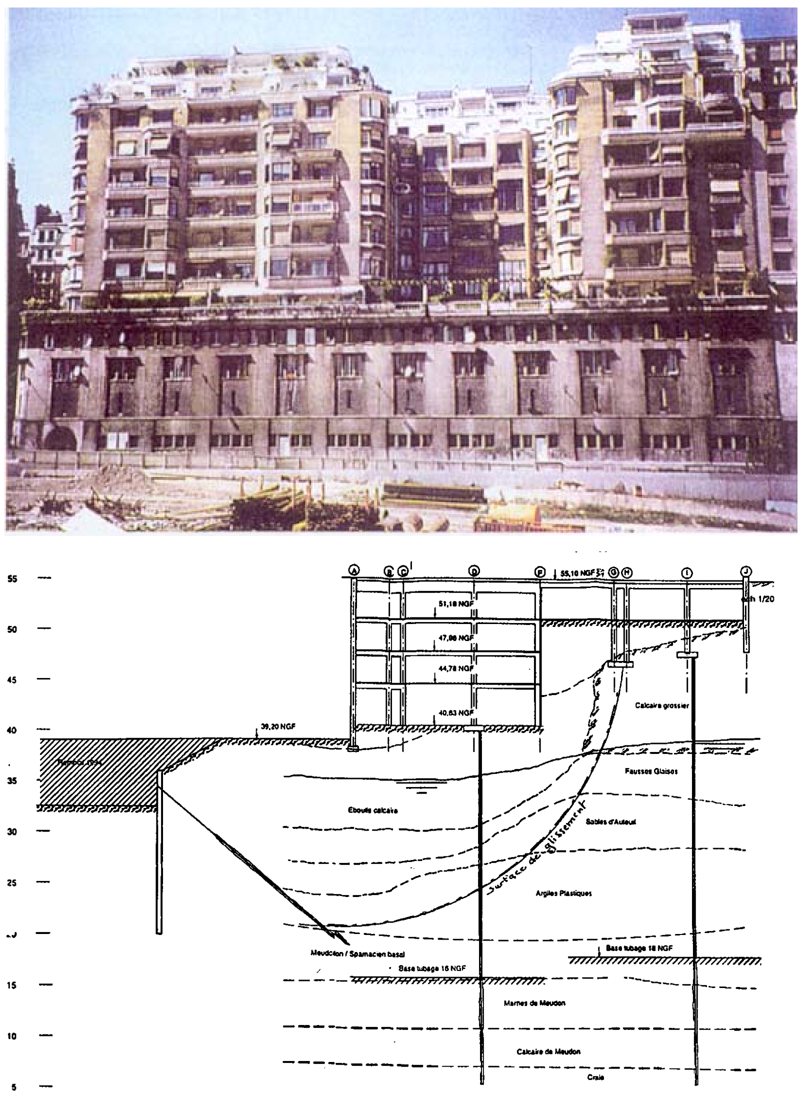


Figure 9 : a view of an unstable building in Paris (Lavisse & Mazaré 1999)

It was observed that the anchored retaining wall had a 10 cm horizontal front displacement, resulting in vertical and horizontal movements of 5-6 cm that severely fissured the existing building (various cm). Of course, construction was immediately stopped and some soil was backfilled against the wall to reduce displacement.

Extensive in-situ soil investigation conducted afterwards (too late !) showed that the foundation of the old building was not satisfactory at all. The building was based on shallow foundations on a very heterogeneous ground formed on one side by the remaining a calcareous cliff and on the other side on weak slope talus coming from the degradation of the calcareous cliff. The Figure shows one of the hypothesis proposed, i.e. the development of a circular instability that explain the trouble. Other possibilities have been proposed by experts. The total cost of the trouble was approximately 75 billion dollars, and Justice had to distribute the cost in proportion of the estimated responsibility to the various organisations involved : owner, construction company, geotechnical consulting firms. In spite of the obvious deficient nature of the foundation of the existing building, the responsibility of the construction company was engaged, resulting in a significant loss of money.

Conclusion

Some particularities of risk issues in civil engineering have been presented and illustrated. Obviously, their importance in terms of risk is probably not completely integrated in the Society. Natural hazards that may threaten civil engineering structures are difficult to predict, but engineers progressively managed in ensuring a satisfactory level of safety of the structure. For various reasons described in the text and that also include the effects of human behaviour, periodic catastrophes occur. The conclusions drawn from their detailed analysis allow to improve the safety of structure in an attempt to reduce the level of risk “as low as reasonably achievable”.

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