LROBUSTNESS AND CONSEQUENCE BASED ASSESSMENT OF AN EXISTING DAM

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ABSTRACT

Robustness plays a relevant role in the capacity of a structure to sustain abnormal loads or to deal with unexpected events with large effects, such as explosions and terroristic attacks. Such situations on dams may have extremely large consequences. For buildings, the design approach that best implements robustness concepts is represented by the so called "Consequence Based Design": even if nothing is known about the cause, selective element removals and extreme load on the structure are modeled, and their effects are determined with respect to progressive collapse and damage arrest.

In the paper we try to set-up a "Consequence Based Assessment" of a typical example of a gravity dam built between the '30s and '40s of the last century in the northwestern Italian Alps. A simplified model of the structure is adopted. Removal of parts of the dam cross-section is assumed to occur: the effects of the extent of damage is discussed on the bases of the tension generated within the body of the dam.

INTRODUCTION

Usual structures, like buildings, may suffer large collapses if the actions acting on them are larger than their design values. As the recent fatal episodes remind to the engineering community, there is the possibility that the structure experiences a kind of unexpected situations, which cannot be taken into account in the design phase. That is why, there is the need of establishing a framework based on consequences, more than on reliability. In this sense, some approaches have already been tested on "regular" structures, e.g., bridges or constructions. In this paper, the "consequence-based" design approach is presented and tested on a dam structure.

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WHAT IS STRUCTURAL ROBUSTNESS?

A system is defined robust if damage acting on it has no disproportionate effects, say the global failure of the system. This idea is well documented in the modern design codes, like the Eurocode, which consider robust the structure that is “able to withstand events like fire, explosion, impact or consequences of human error without being damaged to an extent disproportionate to the original cause”. Obviously, a different kind of actions acts on a dam. That is why it is more suitable to speak about design situation, more than design action.

Chain events

The idea of design situation may help in evaluating the effects of multiple events and, in particular, the “chain-events”. Since the former can be predicted through the observation and the measurement in the environment in which the system is set, the latter are not so straightforward to predict. Consider, as an example, the nuclear disaster of Fukushima (Japan). On March 11, 2011 a violent trembler shake the Pacific Coast of Sendai, the main island of Japan. The M9.0 megathrust earthquake with epicenter 70 km off the coast and hypocenter at an underwater depth of approximately 30 km, generated a tsunami that struck the coast of Honshu with 13 to 15 m tall sea waves. When the seismic acceleration threshold was reached the nuclear power plant sliding control rods got down into the three running reactor cores. The fission of the enriched uranium fuel that allows a nuclear reactor to produce the steam that spins a turbine to make electricity was instantly stopped. Anyway, in general, even with fission stopped, nuclear fuel rods must be kept cool, as by-products of the nuclear reaction continue to break down and produce heat for years. The key to cooling the rods is simple: a flow of fresh water. But, because of the earthquake, no electricity could be delivered to the nuclear power plant to run the cooling pumps. The back-up diesel generators that should have kicked in when power was lost did not survive the tsunami (13 m high sea waves), which easily overtopped the seawall protecting the plant (10 m tall). Only batteries were available to run all the systems. At the same time, the tsunami flooded the critical electrical equipment. After eight hours, the batteries went dead, meaning the nuclear power plant had no electricity, and no way to cool itself. In essence, the now-still water inside the reactors began to boil off, exposing the fuel rods and threatening a meltdown of the uranium fuel pellets inside the core (Biello, 2011). What resulted were the explosion of four nuclear reactors and an extended contamination of air and water, which still continues.

Risk equation and robustness strategies

This situation is a perfect example of what a “chain” of events is. Sometimes, this kind of situation takes the name of Black Swan event (Nafday, 2008), after the book by N.N Taleb (2007). Designing a construction in order to prevent extended damages from “chain” events is, probably, one of the trickiest issues in structural engineering. In the majority of cases, the knowledge of the set of actions acting on a structure is limited. In parallel, the behavior of the construction under high magnitude loads cannot be forecasted (neither with numerical modeling) since, globally, the response to local damage is non-linear even if the hypothesis of linear elasticity is made (De Biagi, 2013).

That is why the philosophy in designing a structure able to survive such situations has to shift from reliability assessment to the evaluation of the consequences. A fundamental topic is represented by risk analysis. In its most simplest form, simple steps are required: identification of the hazard scenarios, evaluation of risk, and analysis of countermeasures for reducing the impact of the scenario. The general expression of risk is (Gulvanessian and Vrouwenvelder, 2006):

$$R = \sum_{i=1}^{N_H} \sum_{j=1}^{N_D} \sum_{k=1}^{N_S} p(H_i) p(D_j|H_i) p(S_k|D_j) C(S_k) \tag{1}$$

where N_H is the number of hazards H_i , N_D the number of direct (local) damages D_j , N_S the number of types of indirect behavior S_k, $p(H_i)$ the probability of occurrence of hazard H_i (first term), $p(D_j|H_i)$ the probability of the occurrence of direct damage D_j due to hazard H_i (second term), $p(S_k|D_j)$ the probability of the occurrence of structural behaviour S_k due to direct damage D_j (third term) and $C(S_k)$ the (monetarized) consequences of structural behaviour S_k (fourth term).

The common strategies for ensuring structural robustness act on the addends of risk expression. For example, the idea of controlling the event at its origin permits to reduce the first term of equation (1). This approach does not increase the inherent resistance of a structure, as reported by Starossek and Haberland (2010), but it limits the possibility of occurrence of the event. In case of extreme situations on dams, examples of event control measures can be (i) the planning of the geographical location of the building, (ii) provision for surveillance systems, (iii) maintenance monitoring and continuous evaluation of dam displacements. In parallel, if sufficient strength is provided to structural elements, they are able to resist overloads. This is the principle at the base of the Specific Load Resistance strategy for robustness, implying a reduction of the probability of local damage due to the occurrence of the event, i.e., the second term of equation (1). In building engineering, Sorensen and Christensen (2006) proposed to identify and to increase the capacity of key elements in order to account for the overload required in case of local damage.

A problem arises in case of unexpected events: the implementation of the strategies previously introduced requires, in a certain sense, the knowledge of the set of actions acting on the construction. That is why they can be employed when the “common” loads are considered. With the term “common”, the authors refer to the actions for which a statistics, or a prevision model, exists. In order to overcome this design problem, other solutions have to be considered. First, the idea of reducing the impact of local damage on the global behavior is possible. In this case, the term $p(S_k|D_j)$ may be reduced. The strategy consists in providing alternatives for a load to be transferred from the point of application to a point of resistance, namely the foundations. The alternative paths being sufficiently strong, the redistribution of forces originally carried by failed components prevents a failure from spreading. In order to achieve this requirement, the remaining structural elements must be strong enough, collectively, to resist the loads corresponding to the situation after the event. The resistance of the elements must be associated with a proper capacity in deformation without loss of resistance and without brittle failures (Knoll and Vogel, 2009). Alternate Load Path strategy is effective in case of both hazard-specific and non-hazard-specific situations because the notional damage to be considered in the application of the alternative-paths method is non-threat-specific (Diamantidis and Vogel, 2011). Obviously, it is possible to reduce the consequences of damage, and reducing the $C(S_k)$ component of equation (1). Since the computed value of risk refers to the population, in order to ensure the safety, other measures can be implemented. These are not necessarily linked directly to structural aspects of the construction. Technological equipment (like permanent sensors with predetermined thresholds) can be installed in order to activate emergency procedures that may interest areas far away from the effective place in which the dam is built. In buildings, structurally speaking, an effective way for reducing the consequences of events are the isolation of parts of the structure in order to prevent the spreading of the damages.

CONSEQUENCE BASED DESIGN

As illustrated in the previous section, the complete knowledge of the set of actions acting on a structure cannot be known with exactitude, or at least by means of a statistics. Events with severe consequences occur extremely rarely. Since common events can be dealt without problem, as much as the annual probability of occurrence reduces, the impact on the system increases largely. In parallel, as soon as the probability of occurrence goes below a lower threshold (say 10^{-6}), design codes do not consider such event. The problem now turns into the correct estimation of the probability of occurrence.

The common structural design starts analyzing the potential actions acting on a system, combining them into design situations and, then, dimensioning the single elements of the construction in order to fulfill the capacity demand. The approach has a probabilistic basis: for any element, one can compute the statistics of action, A, acting on it and the corresponding capacity, C. The reliability of the structural element, R, is computed as the difference between capacity and action, i.e.

$$R = C - A. \qquad (2)$$

The element is considered “safe” if the capacity is larger than the action, that is $R > 0$. Since action and resistance vary, the R can also be negative and, consequently, the corresponding situation is “unsafe”. The purpose of the probabilistic method is to limit the probability of having unsafe situations to a target value, p_r, which depends on many aspects

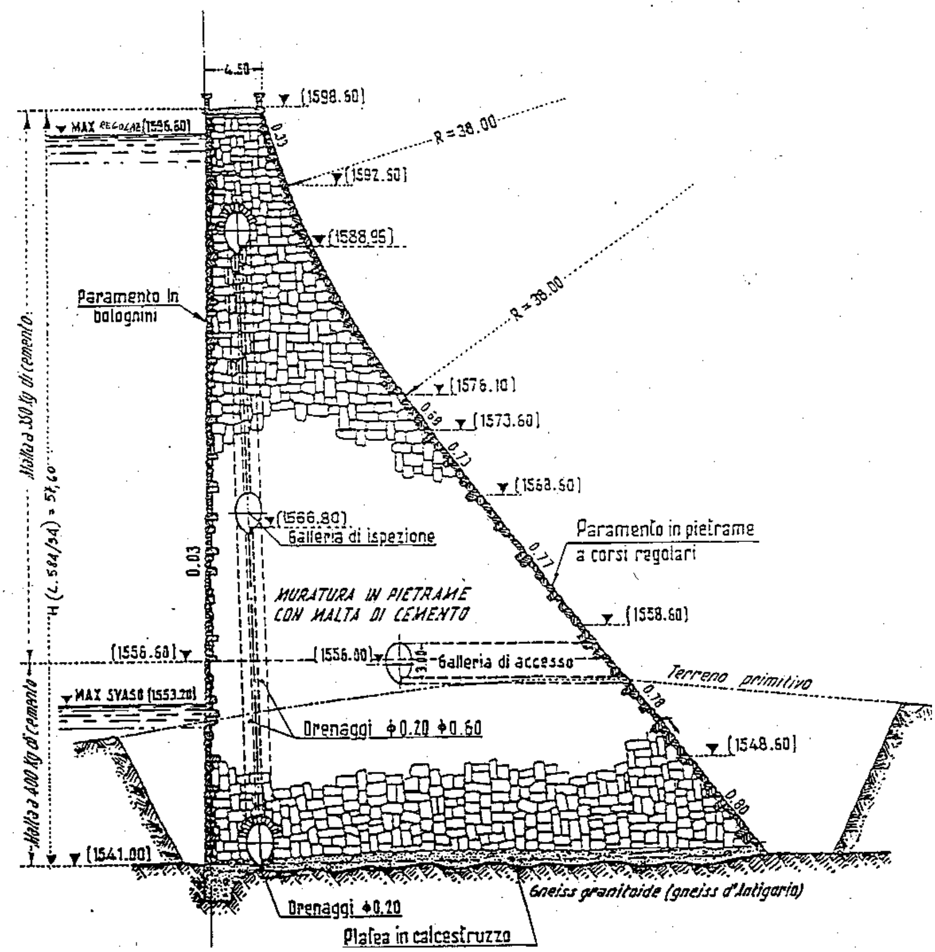


Figure 1. Cross-section of Agaro Dam, from the original drawing found at Enel S.p.A.

$$\Pr(R < 0) < p_r. \tag{3}$$

To overcome the problem of the unexpected events for which the statistics of A is not given, Abrams and colleagues (2002) proposed a new engineering approach for reducing the loss due to seismic hazard. This was based on the evaluation of the possible consequences of damage, but without knowing the origins of the damage.

The impacts on the system relate to different properties of it, say not only structural/construction considerations. Then, a four-step decision tree is used to determine if: (a) estimated consequences are acceptable, (b) if acceptable consequences should be redefined, (c) if modeling parameters should be refined and (d) if further system interventions should be considered. If anticipated consequences exceed tolerable ones, and no further redefinition of acceptability is feasible, parameters defining the hazard and built environment can be refined to reduce anticipated losses (assuming that the preliminary analysis were conservative), and/or system interventions can be prescribed for the same purpose. Iteratively, consequences can be estimated for a number of different system intervention strategies with various input parameters describing the hazard or the built environment. This approach has been used by Wen et al. (2004) in the set up of a framework for vulnerability assessment of building structures under seismic excitation, and further detailed by Kinali and Ellingwood (2007), who applied the previous concepts for the analysis of steel frames with different lateral load carrying systems and different connection strengths under ground motion. Nafday (2008) proposed a combined consequence + reliability approach for the design of structures. Key elements, identified by means of a parameter based on structure properties, are identified and properly designed.

All the approaches are based on the evaluations of the consequences after damage. This represents the framework into which a gravity dam is analyzed.

AGARO DAM

Agaro Dam is set in Lepontine Alps, in the municipality of Premia, in Piedmont region, Italy. The dam construction dates back to 1938 and the first hydroelectric exploitation were made by Edison S.p.A. The new impoundment submerged an ancient Walser settlement. Nowadays, Enel S.p.A is the owner of the natural exploitation and the concessionary of the water for the production of electrical power.

Agaro dam is a 57.6 m tall mortar-masonry gravity dam. The dam is 243 m long and its volume is about 149 500 m^3. The maximum pool level is +1596.60 m, while the crest is a +1598.60, i.e., the freeboard is about 2 meters. The impoundment capacity is 18.75 millions of cubic meters on a lake of about 0.65 km^2.

A cross-section of the dam is shown in Figure 1. Recent investigations on the blocks and the mortar composing the dam have shown that the average Young’s modulus is about 21.2 GPa (σ = 4.5 GPa) and the average compressive strength (on a cylindrical specimen) is 32.4 MPa (σ = 12.5 MPa).

A numerical analysis is performed in order to evaluate the response of the structure under loads. Gravity dams are known to resist through compressive mechanisms, i.e., a large part of the body of the dam is compressed. The hydrostatic load in the worst situation, i.e., water level at +1596.60 m, represents the external load. The triangular pressure distribution produces a top displacement of 45 mm, see Figure 2(a). The orientations of the principal stresses in the dam are sketched in Figure 2(b).

In a framework of consequence-based evaluation, damage is provoked on the body of the dam. As already stated, the origins of the damage are unknown, since the interest is on the possible consequences. Details on the two damage situations are shown in the following subsections.

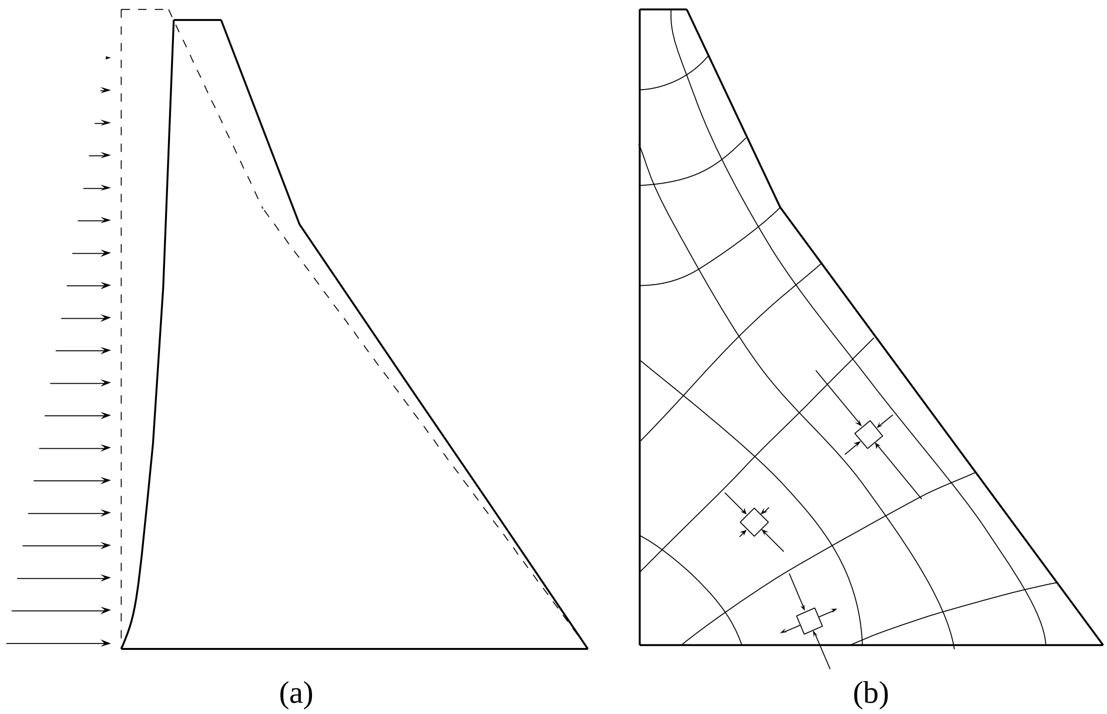


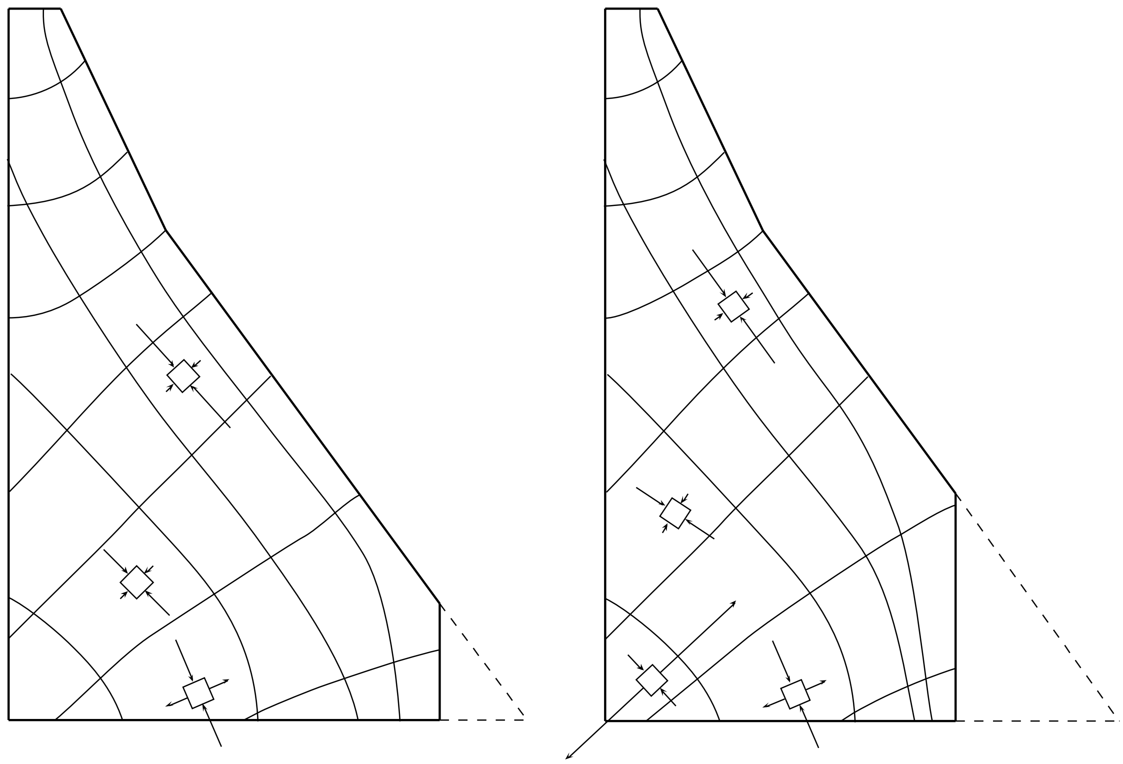
Figure 2. Numerical simulation on Agaro Dam in the undamaged situation. In subfigure (a) the displacements field is reported. In the operative situation, the top displacement is equal to 45 mm. In (b) the orientation of the principal stresses are shown.

<u>Damage situation A</u>

The first test on partial removal interests an edge at the toe of the dam of about 7.50 m of width. The numerical analysis is performed in order to evaluate the effects of element removal. As can be observed comparing Figure 3(a), showing the orientations of the principal stresses in damage situation A, and Figure 2(b), plotting the corresponding data in the undamaged situation, one notes that there is a change in the orientation of the principal stresses in the proximity of the damage interface, i.e., the right-hand side of the body of the dam. At the same time, no variations on stress sign and magnitude are shown. In other words, the small tensions that arise at the interface between dam and foundation surface are similar in both situations. The effects of element removal are, thus, negligible.

<u>Damage situation B</u>

The second test on partial removal interests a larger edge at the toe of the dam: 15.00 m of width. As before, the numerical analysis is performed in order to evaluate the effects of element removal. The comparison between Figure 3(b), showing the orientations of the principal stresses in damage situation B, and Figures 2(b) and 3(a), confirm that the damage situation has large effects on the body of the dam. As the reader can note, other



(a) (b)

Figure 3. Numerical simulation on Agaro Dam in the damaged situations. In subfigure (a), the orientation of the principal stresses reference system in damage situation A is reported. In subfigure (b), the orientation of the principal stresses reference system in damage situation B is reported.

than the different orientation of the principal stresses, a tension arises at the heel of the dam. Is the tensions are larger than the tensile strength, since the material is not reinforced, a crack opens and a collapse scenario can be supposed.

CONCLUSION

Extreme events with unknown origin and magnitude can interest hydraulic infrastructures, like the dams. The common design practices, essentially based on reliability approaches, cannot be used since the statistics of the design situations is not known. In substitution, a consequence-based design approach is suggested. This is based on the evaluation of the effects of damage on the structure, more than on the origins of the damage. An example related to an existing gravity dam is proposed.

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