ABSTRACT: This paper shows that a precise mechanical analysis of destructive events can improve the knowledge of the avalanche action against structures in real situation. In fact, measuring avalanche’s impact on site is not common. In that way, the destruction of two deflective walls in Taconnaz site by February 11th 1999 exceptional avalanche was a favourable situation to undertake such a study. It consisted in two main parts: firstly, a large on site investigation program was conducted to complete observations and to analyse failure mechanism, including material specimen tests. Then, numerical simulations were performed with a rigorous three-dimensional finite elements model using a realistic representation of the concrete behaviour, in both quasi-static and dynamic approaches. Finally, two different scenarios are exhibited and confirmed: one of the walls was effectively destroyed under bending mode due mainly to a distributed pressure generated by the flow whereas the second was directly influenced by a localized impact.

Keywords: avalanche pathologies, back analysis, reinforced concrete, protection structure.

1. INTRODUCTION

The analyses of damages generated by snow avalanches can be very valuable to improve the knowledge of the avalanche pressure against a structure (Margreth & Ammann, 2003). Moreover, considering a real situation is particularly useful for taking into account the mutual influence of flow and obstacle and to treat with large structures. On the basis of a real event in Taconnaz site near Chamonix, the main objective is also here to better understand avalanche effects and to finally improve protection design.

This study includes several parts: after description of the site and of the event, it presents documentations and on site investigations before numerical simulations.

2. TACONNAZ SITE

In the French Alps, in the vicinity of the “Mont-Blanc” peak, Taconnaz avalanche path is situated in the middle part of Chamonix Valley under Taconnaz glacier. Avalanches that can be rated as the most important in France regularly sweep it.

Different cottages (Taconnaz, Vers-le-Nant, La Côte-du-Mont) are built on the alluvial fane at approximately 1050 m. At these locations the slope angle is still pronounced (17% = 9,6°) and positive.

In the upper lengthwise profile of the path, there is a serac wall in the middle of two large potential starting zones. A large part of the track is also over the glacier. The down part of the track (down to the beginning of the deposition area at 1250 m) is confined by a high moraine.

After several destructions until the 80s due to insufficiency of previous dams, a large avalanche protection system was built at the beginning of the 90s. Closing the run-out zone,
this stopping system stretches from 1250 m to 1180 m and includes 11 deflective walls, 14 braking mounds, 3 platforms and 5 different big dams. The main catching dam rises up to 14 m high.

The deflective walls are massive structures made of reinforced concrete. They are laid out in two lines with range disposition whose main function is to spread the flow when it arrives in the protection system and to break its energy. These deflective walls are also directly subjected to coming avalanches. Initially, they were dimensioned for a linear pressure profile representative of a dense flow defined by experts (between 180 kPa at the top and 300 kPa at the bottom) under an average direction of 30° with the plane of the main wall. Geometry and main dimensions of these deflective walls are given on figure 3.

Two foundation plates to take care of the slope of the site support the main wall. The reinforcement is very strong in particular for the uphill face of the wall. It is to be noted that the downhill belt and the uphill belt are not linked together by transverse reinforcement. To make these structures heavier, a rock block masonry mass is added behind the wall with a profiled shape to be hidden from the avalanche direction. It constitutes a several-tons ballast.

3. JANUARY 11TH 1999 AVALANCHE

At the beginning of January 1999, the snow cover in the northern Alps was shallow scarcely reaching 50 cm in north facing slope at 2000 m of altitude. At the end of January, 150 cm of fresh snow within four days were measured at the extremity of Chamonix Valley (altitude 1470 m). After several sunny windy and cold days, a new stream struck the Alps on 6th February. The temperature was particularly cold. In the Chamonix town centre (altitude 1050 m), the snowfall reached 140 cm of fresh snow. In these conditions, the avalanche risk was announced by the local meteorological forecast service as very extreme.

Thus in three days, seventeen major avalanches reached down the bottom of the Chamonix Valley. Among them, the avalanche of Montroc occurred on February 9th (12 people killed, 17 houses destroyed) and on the 11th, approximately at 4 a.m., a big avalanche arrived at Taconnaz and concluded this terrible avalanches series.
This Taconnaz avalanche could not be directly observed but French experts tried then to exhibit a realistic scenario interpreting all available indicators (Rapin and Ancey, 2000). In particular, very big volumes of snow formed deposits outside of the protection system: 80 000 m$^3$ including ice blocks from the glacier as large as one cubic meter had flowed over the lateral dam and 220 000 m$^3$ jumped over the last catching dam (to be compared with the 530 000 m$^3$ measured inside the protection system).

Their conclusion is that this avalanche was very quick including a thick powder part and a flowing dense part with ice blocks. The main illustrations of the violence of this event are the damages generated on two of the deflective walls. These two deflective walls are those situated at the right (in the direction of propagation) extremity of each range, wall n°9 for the upper one and n°11 for the lower one. Their situation and the eventual original trajectory of this destructive avalanche perhaps led to a quasi-orthogonal avalanche impact.

The interpretation of these damages is the main aspect of this study, beginning with on site observations and investigations.

4. ON SITE INVESTIGATIONS

Firstly just after avalanche, it seemed roughly that these two walls were destroyed by the same way with the identical final state: their upper corner was like cut and stood on the ground some ten meters downstream, carried by the flow. Concerning rebars, some were cut but many of them were found free in the air like combed by the flow. An important part of coating concrete was also pulled out.

Figure 4. Deflective wall n°9 and its pulled out corner

Figure 5. Combed rebars and coating concrete

After a documentation step to gather all available information, precise on-site investigations were performed by the CETE of Lyon, service of the French Public Works ministry, specialized in pathologies analysis. This survey showed that two different scenarios happened (CETE, 2002).

These investigations began with materials specimens’ extraction. Then, laboratory tests confirmed the very good quality of concrete (about 58 MPa of maximum compression stress). Verification about rebars confirmed also that the reinforcement was correctly placed during the building period. This first step showed at least that the deflective walls were correctly constructed according to design documents.

But laboratory rebar tests began to make a difference between wall n°9 (upper range) and n°11: all the reinforcement specimens came from free rebars found in the air outside of the rupture zones. For wall n°9, tests showed that specimens had kept their original mechanical characteristics whereas for wall n°11, rebars had completely lost their elasticity as if they had been subjected to a general elongation during avalanche (See table 1).

<table>
<thead>
<tr>
<th>Test N°</th>
<th>Wall n°</th>
<th>σ elast 0.2% (MPa)</th>
<th>σ max (MPa)</th>
<th>Elongation (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>11</td>
<td>Rupture</td>
<td>738</td>
<td>0,4</td>
</tr>
<tr>
<td>2</td>
<td>11</td>
<td>Rupture</td>
<td>761</td>
<td>0,6</td>
</tr>
<tr>
<td>3</td>
<td>11</td>
<td>Rupture</td>
<td>748</td>
<td>0,6</td>
</tr>
<tr>
<td>4</td>
<td>11</td>
<td>Rupture</td>
<td>762</td>
<td>0,5</td>
</tr>
<tr>
<td>5</td>
<td>9</td>
<td>591</td>
<td>621</td>
<td>7,5</td>
</tr>
<tr>
<td>6</td>
<td>9</td>
<td>535</td>
<td>617</td>
<td>10,5</td>
</tr>
</tbody>
</table>

Table 1. Rebars laboratory tests results
The second important difference between walls n°9 and 11 was that the entire structure n°11 had also moved during avalanche of about 2 meters downhill creating a deep trough uphill and causing a general 7° inclination of the wall. Then, fracture investigations confirmed the necessity of two different scenarios to explain walls destruction.

Indeed, if the two still standing part of the walls showed bow cracks parallel to the main fracture, wall n°11 was much more damaged also with an horizontal cracks network on the upstream face and typical compression fracture at extremity on the back side. If the main fracture form is clearly explained by the rock ballast, the horizontal cracks network shows that the two walls do not behave in the same way. That means in particular that they were not subjected exactly to the same action.

The same differences were found on the pulled out corners: for structure n°9, this part is obviously more damaged on the two sides whereas for structure n°11, the corner is still quite in good state.

Finally the two scenarios proposed by this study considered that the wall n°11 was simply destroyed by a distributed pressure as commonly considered for avalanche solicitation. All observations made for this wall are consistent with this conclusion and its destruction is supposed to be caused by a pressure level higher than its resistance capacity generating a bending collapse.

On the contrary for wall n°9, observations are finally quite different and the scenario explains them by the influence of a localized impact. This solution is not so astonishing considering that the ice part in the avalanche flow was estimated at 30% in volume and moreover, that big rock blocks are regularly carried by avalanches: several tons blocks have already been found in the protection system. Finally, all observations are also consistent with this scenario for wall n°9 and collapse is supposed to be mainly due to shear localized failure.
5. NUMERICAL SIMULATION

5.1 Numerical tools

Using a numerical approach can help us to quantify the avalanche effects more accurately. To be useful, tools used must be able to rigorously take into account the real geometry of the structure and moreover to model correctly the real behaviour of materials. In that way, we chose a finite element analysis with an explicit time integration scheme coupled with a stress strain relationship that allows a realistic representation of the concrete behaviour under dynamic loads and its corresponding damages. A long use of this numerical tool, in particular for falling rock on concrete slab or buildings under seismic conditions ensures the accuracy of the calculations (Berthet-Rambaud et al 2003).

In the present study, the finite elements code Abaqus is used. The explicit module of this code allows highly non-linear transient dynamic analysis of phenomena like impacts.

Abaqus offers also the possibility of managing several interactive entities (the wall and a block if necessary). The analysis can, therefore, introduce the impact in a way similar to real conditions, managing only the impact characteristic.

For an accurate simulation of the global structural response of these deflective walls, the behaviour properties for concrete must include some phenomena that are related to the damage under dynamic loads such as decrease in material stiffness due to cracking, stiffness recovery related to closure of cracks, and inelastic strains concomitant to damage.

The concrete behaviour is represented in the numerical analysis by the PRM damage model (Pontiroli 1995) that uses one scalar damage variable D, which is the damage indicator. The one-dimensional expression of the corresponding stress-strain relationship is the following:

\[(\sigma - \sigma_n) = E_0 (1 - D)(\varepsilon - \varepsilon_n)\]

where \(E_0\) is the Young modulus, \(\sigma_n\) is the crack closure stress in tension and \(\varepsilon_n\) is the irreversible strain corresponding to \(\sigma_n\). A similar expression is used with tensors to describe the three-dimensional state.

In fact, D is the combination of two damage contributions: \(D_c\) for compression phenomena and \(D_t\) for tension.

\[D = \alpha^c D_c + (1 - \alpha^c) D_c\]

Its value varies from 0 (for initial material) to 1 (for macro-cracked material). The variation of \(D_c\) or \(D_t\) is governed by the equivalent strain \(\bar{\varepsilon}\) (Mazars 1984):

\[\bar{\varepsilon} = \sqrt{\sum \langle \varepsilon_i \rangle^2}\]

where \(\langle \rangle\) denotes the positive part and \(\varepsilon_i\) are the principal strains.

The damage evolution is given by:

\[D_a = 1 - (1 - A_a) \frac{E_a}{\bar{E}} - A_a e^{-B_a (\bar{\varepsilon} - \varepsilon_a)}\]

with \(\alpha = c, t\); \(\sigma_n\) and \(\varepsilon_n\) are calculated with:

\[\sigma_\beta = \frac{E_\alpha}{(1 - D_c)(\varepsilon_\beta - \varepsilon_\beta)} + E_\varepsilon\varepsilon_\varepsilon\]

\[\varepsilon_\beta = \varepsilon_\beta(1 - D_c) - \frac{D_c}{1 - D_c} \varepsilon_\varepsilon\]

\(\sigma_{c0}\) and \(\varepsilon_{c0}\) are considered as material parameter data.

In order to model the strain rate effect under dynamical loading for concrete, the damage threshold depends on the strain rate assuming that its evolution is similar to the usual ratio on resistance (Malvar and Crawford, 1998) (Bischoff and Perry, 1991).

A typical stress-strain response produced by the PRM model for a uniaxial alternate loading in multi traction-compression steps is given in figure 10.
The three dimensional version of this model (used in the numerical analysis) was implemented in Abaqus-Explicit using an external Fortran subroutine.

The stress-strain relationship for the reinforcing bars is considered as simply elastic plastic with no hardening to better determine plasticization appearance.

The material parameters of the model are identified from laboratory materials tests performed in parallel with on site investigations. Finally, the Hillerborg regularization technique (Hillerborg & al., 1976) is used in order to avoid mesh dependency.

### 5.2 Numerical rupture definition

Using such tools, it is then necessary to quantitatively define the collapse of the structure from the numerical point of view. Indeed, it is quite easy on site to declare that the two deflective walls are destroyed but numerically, the question is rather to know quantitatively when the rupture happens. This problem is quite difficult to solve particularly for complex three-dimensional geometry and combination of non-linear materials (steel and concrete). A good indicator is also necessary. Using a damage model, this rupture could be linked to a certain damage level of concrete or to the displacement evolution of a particular point. The problem is then to detect correctly the right moment and to be able to have a consistent and quantitative approach. We finally chose to consider the “first” plasticization of a rebar in the structure.

This solution may not be perfect but it has at least a mechanical sense and this first plasticization often represents the beginning of irreversible damages that lead to the final collapse of the structure. Our objective was also here to model correctly the behaviour of the structure until the beginning of its collapse and to consider that the next phase is not but the destruction of the structure.

### 5.3 Numerical results

First simulations consist in determining the real resistance capacity of Taconnaz deflective walls for orthogonal distributed action. Indeed, the original dimensioning used French civil-engineering rules for concrete structures including safety factor. Finally, resistance capacity cannot be directly linked to initial hypothesis. Moreover, in the case of 1999 avalanche, it seems that the direction of the flow was closer to the orthogonal line of the wall than foreseen.

To determine this resistance capacity, the structure is modelled completely as in reality including its real geometry with foundation plates, real characteristics for materials and its complete reinforcement with the hypothesis of perfect bond between steel and concrete (keep in mind that the objective is to model the structure until the first plasticization of rebar).

For reinforcement, the model includes a sub-model of the rebars network with its self mesh and the corresponding elements are artificially embedded in the concrete part (HKS 6.4).

The boundary conditions with the ground consist simply in a perfect embedding for inferior nodes of foundation plates. It is to note that this calculation and next ones do not include for now possible interaction with the soil. Finally, pressure is uniformly and incrementally applied on the uphill face of the wall until the defined-rupture of the structure.

To ensure staticity of the simulation, solicitation rate was tested to verify that no dynamic influence happened. Finally, a solicitation rate of 400 kPa/s is used for like-static situation.

Without rock mass behind the wall, the normal static resistance capacity is also evaluated at 160 kPa and this capacity reaches 220 kPa including the rock mass. This rock mass is modelled has a quasi-rigid shell with the same shape as reality for the contact surface with the wall. The behaviour of this part of the structure is then basically modelled using four linear springs.
with a stiffness of $10^6$ N/m. This value was evaluated to obtain maximum horizontal displacements in the same range as separation distance between rock mass and wall observed on site.

These static calculations show first that the resistance capacity of the structure depends of course on the influence of the rock ballast but also that this capacity is quite greater than initial dimensioning hypothesis: in the orthogonal direction of the wall, this hypothesis was a linear pressure profile between 45 kPa at the top and 75 kPa at the bottom (including projection rules). In that way, our numerical tool can provide important information for risk management for example about the real capacity of protection system.

Next calculations concern the influence of the dynamics of the flow. The problem is that research has not yet fully apprehended the action of the snow avalanche and its effects. Pressure values have effectively been measured and published but these data have not been completely exploited for the specific purpose of civil-engineering design, especially in the particular context of real structures subjected to snow-avalanches: answers for real structures in the flow are missing. Then, certain phenomena such as the appearance of a stagnation zone upstream of the obstacle are rarely taken into account. Finally, even if new experiments are exploited in French experimental site of Lautaret also on the basis of back analysis of structures behaviour (Berthet-Rambaud 2004), the temporal evolution of avalanche pressure against an obstacle is not yet clearly known and realistic scenarios have to be proposed.

For this present study and without reliable available space-time profiles, we decided to use a simple time profile with two parameters: the time $t$ of the maximum pressure and the value $P_o$ corresponding to pressure stage. Spatially, the pressure is still uniformly distributed.

$P_o$ is chosen inferior to the static resistance capacity at 200 kPa and $t$ varies from $10^{-1}$ and $10^{-4}$ s (Figure 11). Dynamic calculations show finally that the rupture can happen prematurely due to dynamics influence in the range of avalanche impact characteristics. In particular, figure 12 shows that rebars can plasticize depending on pressure increasing rate even if the stabilised pressure is inferior to the static capacity of the wall. It underlines the necessity to take into account the dynamic of the phenomena for such structures subjected to snow avalanches or to other natural hazards like falling rock, to design and dimension them correctly.

The importance of the first avalanche impact is confirmed by on-site observations: concrete parts coming from deflective wall were found outside of the protection system, downhill from the last dam. The intuition is that the walls were damaged from the very beginning of the avalanche so that fragments can be transported so far.

Using damage model for concrete, it is then possible to determine weakest zones in the structure: applying a uniform pressure (scenario for wall n°11), we found such damage distribution on the wall, very close to real fracture. Numerical simulations also confirm the influence of the rock ballast for the main fracture form.
Similar calculations are also possible introducing a block impact (scenario for wall n°9) and it confirms that the upper corner of the wall is then much more destroyed (in particular with damages on the back face). In that case, rebar plasticizations happen locally directly during impact.

Finally, this numerical tool appears to be a very powerful way to model structure behaviour for a phenomena like snow-avalanches. It allows one to take into account complex geometry and dynamic loads and can be used to complete the back analysis approach. In a way it is even able to perform numerical experimentations or assessments, then provide new elements to improve protection design. In particular, in our case, it confirms the two scenarios for each deflective wall.

6. CONCLUSIONS

February 11th 1999 Taconnaz avalanche was a great chance to study in real conditions interaction between snow flow and structures. Without no direct observation or experimentation, this study is based on the back analysis of the final state of two destroyed deflective walls. This analysis used both on site investigations and numerical simulations to propose two collapse scenarios for wall 9 and 11. The consistency of observations is confirmed by numerical calculations and different conclusions can be drawn from this event to improve protection design and generally conception of protection structures subjected to snow avalanche:

Snow avalanche is a dynamic phenomenon and design needs to take into account this action aspect. Numerical mechanical tools are nowadays available to model such situation and development of adapted engineering tools will be necessary in this domain to let them be diffused until risk managers.

Next point is that knowledge about avalanche action against structures is still insufficient and it is necessary to continue with appropriate experimentations in order to obtain reliable space-time pressure profiles usable for civil-engineering design. This explains partly the development of new French experimentations on Lautaret site with an original approach also using an equivalent back-analysis principle.

Then, avalanche action cannot be limited spatially to a distributed pressure. In many cases, it is possible to found rock or ice blocks or trees in the flow that can be very prejudicial for structures. These localised impact must be introduced in the hypothesis and taken into account for dimensioning.

Concerning reinforced concrete structures, reinforcement design is very important and must not be neglected. For example, concerning Taconnaz deflective walls, the absence of transverse reinforcement was very prejudicial, particularly for shearing due to localised impact but also under bending mode. This aspect can be a first step to really improve structures.

Numerical tools can be very useful for risk management: they provide at least real resistant capacities and various conditions can be tested through realistic scenarios. Using a damage model for concrete, it is also possible to exhibit potential fractures and weakest zones of the structures, eventually to reinforce it.

In conclusion, back analysis of destructive events is very positive to improve avalanche action knowledge and protection design then to be able to refine dimensioning hypothesis and to make sure that future structures will resist for what they were planned. Of course, it will never prevent that one day, the avalanche is stronger than ever before …
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