AVALANCHE PRESSURE AT THE VALLÉE DE LA SIONNE TEST SITE: COMPARISON OF MAXIMUM MEASURED LOADS WITH DESIGN LOADS

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ABSTRACT: The assessment of the impact pressure exerted by avalanches on structures is an important task in avalanche engineering. Impact pressures of more than 50 avalanches were measured at the Vallée de la Sionne experimental site, in Switzerland, in the last 20 years. Measurements performed on a 20 m high and 0.6 m wide pylon show that the highest long-lasting bending moment is exerted by warm/wet avalanches, characterized by velocity of around $10\,\mathrm{m\,s^{-1}}$, which however can develop very high flow depths, up to 7 m in one of our data sets. In spite of the relatively low absolute value of pressures these avalanches exert a constant load for tens of seconds, over large depths. Conversely, the intermittency region, coupled with a dense basal layer, which characterized the front of large powder avalanches exerts the highest short-lasting bending moment. Mesoscale coherent structures which are present in this region can move with velocities up to $60\,\mathrm{m\,s^{-1}}$ and produce peak loads of 800–1000 kPa, which however, only last for a fraction of a second. The dense basal layer of large powder snow avalanches can also exerts a very large long-lasting pressure (up to 1000 kPa), which, however is concentrated in a thin layer close to the base of the flow, and thus contributes marginally to the overall bending moment. Finally, heavy objects transported into the flow, such as rocks, can exert large local pressure peaks that can be larger than 1000 kPa. We compare these measurements to standard calculation procedures and discuss their relevance in term of structure design.

Keywords: maximum impact pressure, maximum bending moment, snow avalanches.

1. INTRODUCTION

To improve our knowledge of the interaction between avalanches and structures, impact pressures and other dynamical variables have been measured at the Vallée de la Sionne experimental site (VdlS) in Switzerland since 1998. In these years of operation we have measured events with an approximate return period of 10–20 years, as well as more frequent events, which may have a return period of one year or less. We collected pressure data of around 50 avalanches featuring a large variety of flow regimes and snow conditions.

Indeed, recent high-resolution radar measurements performed at VdlS (Köhler et al., 2018), have shown that avalanches can be classified into several different flow regimes, illustrating behaviors much richer than the conventional dichotomy between dense and powder snow avalanches, which is used today as a basic criteria for avalanche dynamics calculations (Faug et al., 2018). Specifically, the new measurements show that there are three different dense flow regimes, and one dilute regime that may be relevant in term of impact pressure and thus important for the design of structures. These flow regimes are:

- The warm plug regime occurring when the snow cover temperature is mostly isothermal, T = 0°C. These avalanches are characterized by relatively low velocity, but cohesion between granules is large so that snow granules can easily stick together and give rise to large flow depths and flow units which behave like gliding solid-like blocks.

- The warm shear regime occurring at snow temperatures slightly below 0°C. The matrix of the flow is still granular as in the case of the warm plug regime, but the relatively high velocities reached by these flows suggest that the cohesive forces acting between granules are not sufficient to glue particles together into larger units.

- The cold dense regime occurring at snow temperatures below -2°C. Their behavior is similar to the warm shear regime but the snow temperature is lower and the velocity can be higher.

- The intermittency flow regime occurring at snow temperature below -2°C. This is typical for the frontal zone of powder snow avalanches and it is characterized by large fluctuations in impact pressure, air pressure, velocity and density. The intermittency is caused by mesoscale

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coherent structures, i.e. an organized motion of particles, which evolves into the turbulent flow.

Our aim is to understand which of these regimes is more destructive in term of impact pressure on obstacles, more specifically which regime produces the largest bending moment and the highest punctual pressures on the pylon of VdlS.

In order to have a reference pressure to compare with, the nominal 30 and 300 year design avalanches are calculated with standard technical procedures.

2. EXPERIMENTAL SITE, METHODS AND DATA

The full-scale avalanche experimental test site Vallée de la Sionne is located in the western part of Switzerland, in the community of Arbaz. Avalanches start from three main release areas and follow a partially channeled track. The deposition zone starts immediately below the channelled area, where a debris cone may extend to the valley bottom.

Measurements of the internal flow parameters are performed on an oval-shaped steel pylon that is $20\,\mathrm{m}$ tall, $0.59\,\mathrm{m}$ wide and $1.58\,\mathrm{m}$ long (Figure 1). Avalanche pressure is measured with six piezoelectric load cells. They are installed on the uphill face of the pylon from 0.5 to $5.5\,\mathrm{m}$ above the ground, with $1\,\mathrm{m}$ vertical spacing. The sampling frequency is $7.5\,\mathrm{kHz}$ and the sensors have a diameter of $0.10\,\mathrm{m}$ and an area of $0.008\,\mathrm{m}^{-2}$. The measurement range of the pressure is 0–25 MPa.

Assuming that each pressure cell is representative for an extended area around the sensor, the maximum bending moment at the pylon, $M_{max,}$ is calculated using the equation:

$$M_{max} = \sum_{h=0.5}^{5.5} hF_h \quad (1)$$

where h is the height of the pressure cell and F_h is the force. The force is obtained by multiplying the pressure measured by the small cells for the pylon impact surface between two consecutive cells. This method may produce an overestimation of the moment acting on the pylon in case a local impact, such the impact of a stone, is measured by the upper cells. In first approximation, we assume that this possible shortcoming compensates the lack of pressure measurements in the upper part of the pylon, i.e. the assumption that $q_a = 0$ for h $> 5.5\,\mathrm{m}$.

Further, optical sensors make it possible to reconstruct flow velocities up to $6\,\mathrm{m}$ above the ground, and height accelerometers monitor the pylon oscillation allowing the indirect evaluation of the avalanche impact force. Finally, density and flow depth sensors complete the setup.

The majority of the avalanches that reach the pylon in VdlS are large (Canadian avalanche-size classification (Jamieson, 2000)). In 20 years of operation, around 50 avalanches were measured at the pylon. The avalanches were both artificially and naturally released. Here we present pressures of two avalanches which exerted the largest bending moments and maximum pressures at the pylon.

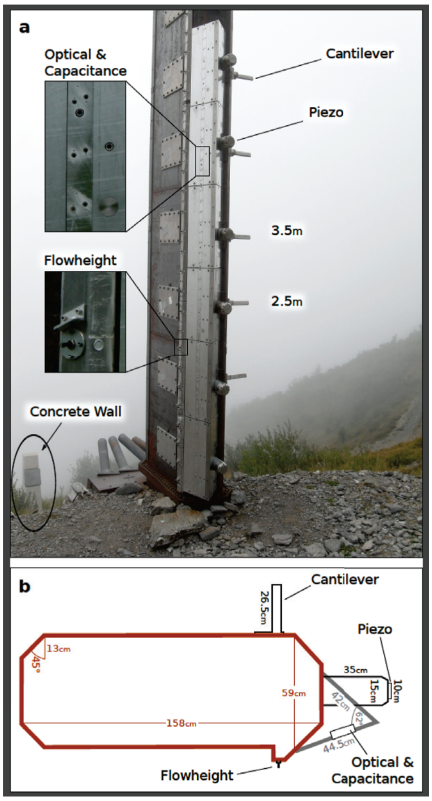

Figure 1: The 20 m high VdlS instrumented pylon. Panel a shows an overview with the impact sensors and close-up of optical sensors, capacitance probes and flow height sensors. Panel b shows a cross section of the pylon with the geometrical details of the sensor installation.

3. 30 AND 300 YEARS SCENARIOS

In order to have a reference to compare the measurements, we have calculated the theoretical load on the pylon using the practical approach described in Margreth et al. (2015). This method ensures a reproducible and standardized way to perform avalanche simulations and calculate avalanche impact pressure on towers by defining standard procedures to choose simulations parameters and boundary conditions.

At sites where little information about real avalanche activity exists, the results of such 'blind calculations' generally give reasonable results. However, as current avalanche models are far from perfect, the avalanche expert may recalibrate most parameters interactively whenever he has information about past avalanche activity for a specific site.

RAMMS, the avalanche dynamic program used by most Swiss practitioners, calculates dry snow avalanches as a Voellmy-Fluid. Main calculation results are the flow height d_a and flow velocity v_a for any point of the track (Christen et al., 2010).

We have performed RAMMS calculations for a 30-year and a 300-year avalanche scenario. At the pylon, the calculated avalanche velocities for the 30 and the 300-year scenarios where $v_a = 40\,\mathrm{ms}^{-1}$ and $50\,\mathrm{ms}^{-1}$, respectively. The corresponding flow heights where $d_a = 3.5\,\mathrm{m}$ and $5\,\mathrm{m}$. The snow cover height d_s which forms the gliding surface of the avalanche has to be estimated by the avalanche expert. It may consist of snow deposited by precipitation, wind and possibly avalanches. We have assumed a snow cover height of $d_s = 2\,\mathrm{m}$ and $4\,\mathrm{m}$, respectively.

A three layer model was used to calculate the avalanche pressure on the pylon: the first layer is the snow cover height d_s. For this layer, the assumption is made that no avalanche forces are transmitted to the pylon.

The second layer is the flowing avalanche itself. The height of this layer equals the calculated flow height d_a. Within this layer, $q_a = c\rho v_a^2/2$ acts on the pylon, with ρ the avalanche snow density. We have assumed a standard density of $\rho = 300\,\mathrm{kg/m^3}$. The factor c is a drag coefficient that is equal to 1 for a circular section, 1.5 for a triangular section and 2 for a rectangular section. The cross section of the VdlS has a rectangular shape with angled edges (Figure 1). Varying the c factor between 1.25 and 1.75, the calculated avalanche pressure varies for the 30- and the 300-year scenarios between $q_a = 250 - 420\,\mathrm{kPa}$ and $391 - 656\,\mathrm{kPa}$, respectively.

The third layer describes the avalanche run-up. The standard approach to calculate this run-up height $d_{\text{run-up}}$ is given in Salm et al. (1990) where it is calculated as kinetic energy height. This procedure often gives unrealistically large values. Indeed, with an energy dissipation factor $\lambda = 1.5$ the run-up height at the pylon is for the 30- and 300 years scenario of 8.5 and 9.2 m, respectively. Thus, we have decided to use the alternative approach suggested by Margreth et al. (2015) and defined the run-up height as the 10% of the calculated avalanche velocity. We estimate $d_{\text{run-up}} = 4\,\mathrm{m}$ and $5\,\mathrm{m}$ for the two scenarios. Within the run-up height, the avalanche pressure is assumed to change linearly from q_a at the bottom of the layer to 0 at the top.

Although the applied procedure tries to define the input parameters for the avalanche dynamics and pressure calculation as objectively as possible, many subjective decisions have to be made by the avalanche expert. Maybe the most important and most critical of these choices is defining the avalanche release zone. An avalanche catchment zone may extend over a large area with no obvious topological barriers for crack propagation, neither in flow, nor in transverse direction. When avalanche dynamic calculations are performed with a release area that contains the whole catchment zone, an unrealistically long run-out might result. To obtain a realistic result, a smaller release area has to be used for the calculations. In the case of calculations without the possibility to calibrate with observed events, the results of different experts may thus vary widely. If several experts were asked to perform a 'blind' calculation for the VdlS pylon, we estimate that the resulting moments could vary by a factor of 2 to 4.

4. MEASURED PRESSURES AND BENDING MOMENTS

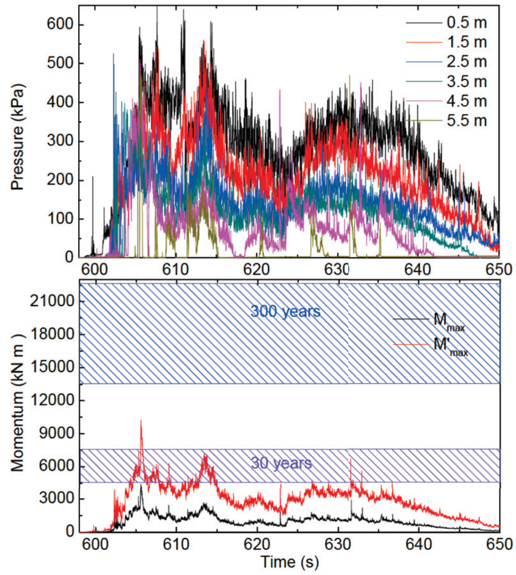

Figure 2: Avalanche #20103003. The upper panel shows the avalanche pressure measured at different heights above the ground. The lower panel shows the corresponding maximum bending moment (black line), and the maximum bending moment that could have happened if the avalanche had slid over a snow deposit of $d_s = 4\,\mathrm{m}$ as assumed by our expert. Horizontal blue and violet dashed bands show the maximum bending moment corresponding to the 300- and 30-years scenarios ($1.25 \le c \le 1.75$), respectively.

4.1. Maximum long-lasting bending moment

The maximum long-lasting bending moment (static equivalent load) occurs at the base of the pylon upon the action of a continuous, quasi-steady load which stresses the structure for a duration of tens of seconds as in the case of an impact with a dense avalanche. Our investigation into the archive data of VdlS has showed that the maximum long-lasting bending moment was exerted by the avalanche #20103003, which released spontaneously on 30 December 2009. At the pylon the avalanche was characterized by a warm plug regime, a maximum

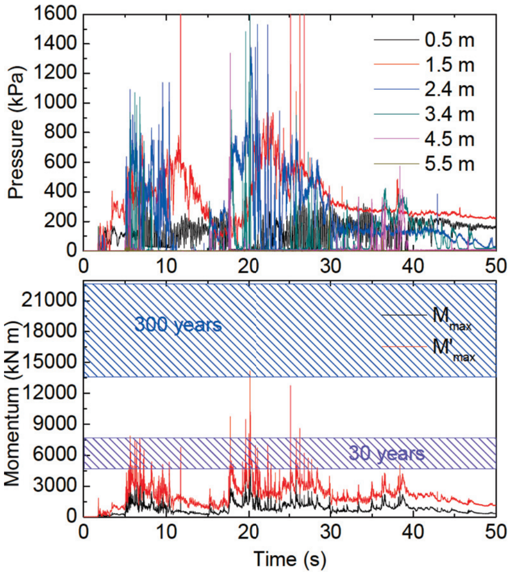

Figure 3: Avalanche #7226. The upper panel shows the avalanche pressure measured at different heights above the ground. The lower panel shows the corresponding maximum bending moment (black line), and the maximum bending moment that could have happened if the avalanche had slid over a snow deposit, $d_s = 4\,\mathrm{m}$, as assumed by our expert. Horizontal blue and violet bands show the maximum bending moment corresponding to the 300- and 30-years scenarios ($1.25 \leq c \leq 1.75$), respectively.

velocity of around $10\,\mathrm{m\,s^{-1}}$ and a maximum flow depth of around $7\,\mathrm{m}$.

The maximum pressure was reached close to the ground, just above the avalanche sliding surface (Figure 2). The maximum bending moment, M_{max}, was smaller than the 30-years scenario. However, assuming the avalanche could have slid over a snow deposit of $d_s = 4\,\mathrm{m}$ as defined in section 3, the maximum bending moment, M'_{max}, would have been locally larger than the 30-years scenario.

4.2. Maximum short-lasting bending moment

The maximum short-lasting bending moment (static equivalent load) occurs at the base of the pylon upon the action of an intermittent load. This load impacts on a large surface but stresses the structure for only a fraction of a second as in the case of an impact with mesoscale structures and surges characterizing the frontal zone of a fully developed powder snow avalanche (Sovilla et al., 2015). Köhler et al. (2018) defined this regime as intermittent.

The maximum short-lasting bending moment at the VdlS was exerted by the avalanche #7226, spontaneously released on 22 January 2005. At the pylon the avalanche was characterized by a frontal intermittent region, which was coupled with a thin basal cold dense layer. The cold dense flow had a velocity of around $30\,\mathrm{m\,s^{-1}}$ and a depth of $1–1.5\,\mathrm{m}$ while particles carried by the mesoscale structures had velocities up to $60\,\mathrm{m\,s^{-1}}$ and reached as high as $5.5\,\mathrm{m}$ above ground.

The avalanche slid around $1\,\mathrm{m}$ above the ground. Maximum pressures from the cold dense basal regime where exerted between 1-2.5 m (Figure 3). Very high local peak pressures were measured by all sensors, up to $5.5\,\mathrm{m}$ above ground. The maximum bending moment M_{max} was smaller than the 30-years scenario. However, assuming the avalanche could have slid over a large snow deposit, $d_s = 4\,\mathrm{m}$, as assumed by our expert scenario in section 3, the maximum bending moment, M'_{max}, would have locally reached to the 300-years scenario.

4.3. Maximum pressures

The pressure distribution along the pylon varies according to the flow regime. Maximum long-lasting pressures are exerted in the frontal region of large powder snow avalanches by the dense basal layer. Figure 3 shows that the maximum long-lasting pressure for avalanche #7226 is of the order of 800-1000 kPa. The basal layer of this powder avalanche is characterized by a cold shear regime, which has an estimated depth of around $1–1.5\,\mathrm{m}$. Branches of trees, rock and ice granules transported into the flow can produce large local pressure peaks. Figure 3 shows that the maximum peak pressure for avalanche #7226 are of the order of 1600 kPa.

5. DISCUSSION

5.1. Flow regimes and pressure

The design of a narrow structure subjected to an avalanche impact requires the knowledge of the load distribution along the structure for both the calculation of the bending moment and the definition of maximum local loads. The analysis of the measurements performed at the VdlS in 20 years of operation shows that the maximum long-lasting bending moment at the pylon was exerted by a warm plug avalanche characterized by relatively low velocity (up to $10\,\mathrm{m\,s^{-1}}$) and large flow depths (up to $7\,\mathrm{m}$). Indeed, in spite of the low velocity, warm plug avalanches are able to produce force amplifications on narrow structures as a result of the jamming of the material around the pylon (Sovilla et al., 2016). Low-speed wet avalanches exert hydrostatic-like forces on structures that are flow-depth dependent, thus these avalanches can become decisive if the flow depth is as large as in the case of avalanche #20103003.

On the contrary, cold dense avalanches flow fast but normally the flow depth is thin in comparison to wet avalanches, so that their maximum bending moment is small. Nevertheless, cold avalanches are still important since they can exert very high local pressures, up to 1600 kPa in Figure 3, which may locally damage the structure and endanger its stability. Further, cold avalanches can have longer runout compared to wet avalanches and thus they are decisive for the design of infrastructure which are located outside the reach of the warmer flow.

In particular, a cold dense regime is particularly important if it is coupled with the intermittency flow regime, as normally happens in the frontal region of large powder snow avalanches. The intermittency regimes is caused by mesoscale coherent structures. These structures can have velocities as much as 60% larger than the avalanche front speed and they can directly transport denser snow clusters and single snow granules from the dense layer or the static snow cover to significant heights and thus it can cause very large forces at large heights above the basal dense layer (Sovilla et al., 2015). However, these forces are intermittent and last only for a fraction of a second.

5.2. Current design approach

According to the current design approach, load distribution and maximum local loads are calculated using avalanche dynamics models that reproduce the movement of a generic dense avalanche corresponding to return periods of 30- and 300-years. Our analysis shows that the idealized avalanche used as a basis for the calculation differs considerably in respect to the real process. It is important to note that a large part of the load defined by the technical procedures is due to the auxiliary definitions of a large run-up height and snow depth. Indeed, comparisons to field measurements show that, run-up on small structure is smaller than calculated and in some cases also negligible. Similarly, the effective snow depth around the pylon, which is theoretically setting the avalanche sliding surface, might be reduced due to entrainment. These two quantities somehow balance the pressure calculated with the numerical models and the current applied design approach, which in the cases examined in this work, is lower than the measured one.

It is also important to note that the pressure exerted by the intermittency flow regime is not taken into account by the procedures, and it is not considered in practice. Nevertheless, the pressure of the mesoscale structures can be considered indirectly included by the procedures, thanks to the definition of the run-up height, which covers approximately a similar vertical extension.

Finally, it is very important to consider that pressure peaks due to impact with stones or objects moving inside the avalanche can damage the structure and cause failure after local deformations reduce the section modulus of narrow profiles. The same applies to the dense basal layer that is often coupled with the mesoscale structures inside the front of the powder snow avalanche.

6. CONCLUSIONS

This simple analysis shows that the avalanche dynamics calculations based on the current design approach refer to an idealized avalanche that differs considerably from the observed physical processes. On the other end, the technical procedure currently used for the design of towers (Margreth et al., 2015) is a conservative approach which covers most of the situations observed at VdlS, if correctly applied. Thus, corrections to procedures based on actual observations can be very risky. This means that, for example, the run-up height of the avalanche cannot be reduced without otherwise adjusting the maximum pressure. It is important that in future avalanche dynamics models and methods to calculate avalanche impact pressure reproduce real processes more realistically so that the calculations can be optimized and adapted to the specific situations. Finally, we must not forget that it is also important that these results, valid for narrow objects, must be extended to structures with other shapes and sizes.

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