IDEAS ON THE DESIGN OF EARTH MOUNDS AND DAMS TO PROTECT HIGHWAYS AGAINST SNOW AVALANCHES.

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ABSTRACT

The paper first presents the existing recommendations for snow avalanche protection of Norwegian roads by use of retaining structures as earth mounds and diverting dams. The major part of the paper presents the results of model experiments to investigate the retaining effects of such structures. The best effects of the structures are found when they are located high up in the run-out zone and with steep sides on the avalanche side. Finally, the transferring of the model results to nature is presented.

KEY WORDS
SNOW AVALANCHES, ROADS, PROTECTION, DAMS, EARTH MOUNDS

1. INTRODUCTION

A substantial part of the Norwegian roads are exposed to snow avalanches. The most exposed areas are found in Western and Northern Norway, where the traffic loads are generally low. Due to the low traffic, cheap avalanche protective measures made of earth have been introduced for the last 30 years. The most used of these measures are earth mounds, collecting dams and diverting dams.

The last years a comprehensive investigation has been carried out to investigate the efficiency of avalanche protective measures in use on the Norwegian road network, (Hammersland et al 2000). The investigations showed that the recorded numbers of road closures was almost similar for snow sheds and the cheaper earth structures. The reason is that the snow sheds are very expensive, and they are thus constructed with a minimum of length. The investigations also showed clearly that the retaining effects of the earth structures are sensible to the type of snow avalanches hitting them, the size and the velocity of the avalanches, and the steepness of the terrain in the run-out zone.

The last two years theoretical studies and model experiments have been carried out to improve our knowledge on the use and the design of such structures, (Brateng 2004 and 2005) and (Norem and Brateng 2005). The present paper presents an overview of these experiments and present ideas on how such structures may be used for avalanche protection of roads.

2. NORWEGIAN EXPERIENCES WITH RETAINING EARTH STRUCTURES

The methods used for snow avalanche protection of roads in Norway are presented in a textbook by Norem (1995), which gives recommendations for the design and use of the various protective measures, based on the experience assembled at that time. The existing recommendations for the use of collecting dams and earth mounds are:

2.1. Collecting dams

Collecting dams are usually located parallel and close to the road. The dams are in most cases made of soils excavated in the dam area, and the slopes of the dams are made as steep as possible depending on the stability of the dams. In some very few cases, where the space for locating a dam is limited, the slope angles are selected up to 60^0 by constructing the dams with geotextiles or with masonry walls.

The height of the dams for protecting roads varies between 4 m and 20 m. The height depends on the size and the velocity of the dimensioning avalanche, and to some extent on the area available for the dam and the required safety level for the road. Generally the height is selected relative to the kinetic energy of the avalanche, in front of the dam, Figure 1:

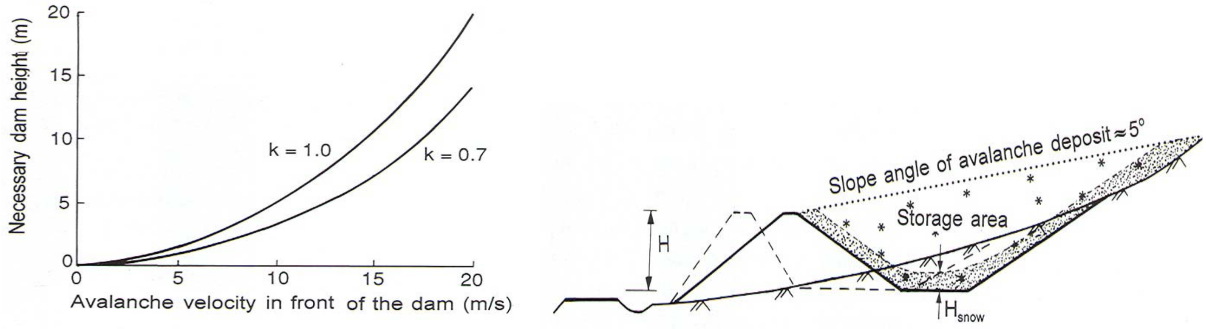

Figure 1 – Recommended height and storage area for the design of collecting dams. K=1 is usually selected for dry snow avalanches and k=0,7 for wet snow avalanches. (Norem 1995)

2.2. Earth mounds

The first earth mounds for protecting roads in Norway were constructed in 1975. The use of them was based on ideas and experiences from Switzerland and Rogers Pass in Canada. The design and location of the earth mounds up to now are partly based on trial and error, and partly on knowledge how to dissipate energy in water flumes. The Norwegian guidelines as expressed by Norem (1995) may be summarized to:

- Earth mounds should be avoided in slope angles above 15^o
- The height of the mounds varies between 4 m and 8 m. The highest mounds are used in areas with deep snow
- The earth mounds are usually made of soil excavated in the area. The slope angle of the sides is made as steep as possible, usually close to 34^o. The length of the mounds is recommended to be equal the height of the mound
- Earth mounds are always combined with a collecting dam parallel and close to the road.

- If possible, one to three earth mounds are located fairly high up in the avalanche path, Figure 2. Between the first 1-3 mounds and the dam, at least two rows of earth mounds should be constructed in the full with of the avalanche.

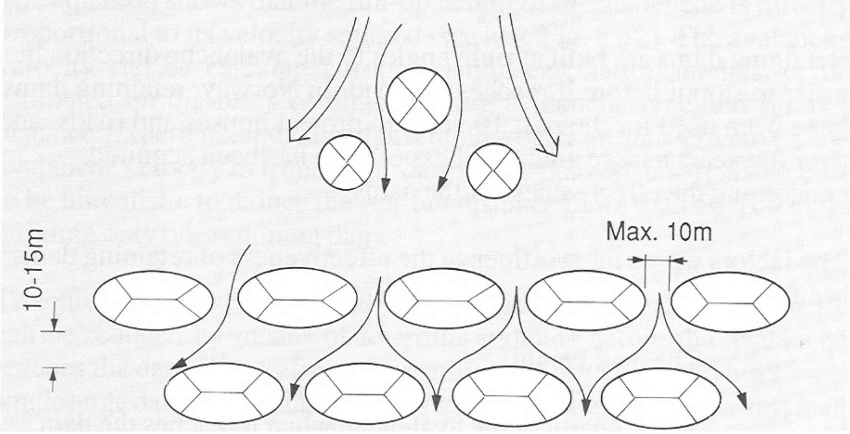

Figure 2. - Recommended design of earth mounds. (Norem 1995)

2.3. Main experiences with earth retaining structures

The effect of the existing protecting measures on the Norwegian road network was evaluated by Hammersland et al (2000). In addition there are more detailed evaluations of the avalanche protection for one road section in Western Norway, (Hustad 2000). The main experiences drawn from these investigations are:

- The retaining earth structures reduced the number of road closures with 75 % in average. The best result was found for structures having a considerable size, dams and combinations of mounds and dams costing more than 0,5 mill NOK (40 000 EUR)
- The earth structures have generally a very good effect on retarding wet snow avalanches, but have more limited effect to dry snow avalanches. Dams and mounds are thus less recommended to be used in the mountains than in the coastal areas, where a major part of the avalanches consist of damp or wet snow.
- The earth structures have shown to have a very limited effect on slush flows. Slush flows have in addition caused considerable erosion on the earth structures.

3. DESCRIPTION OF THE MODEL EXPERIMENTS

3.1 Scope of the experiments

The model experiments carried out at the Norwegian University of Science and Technology (NTNU) is a part of the master degree study, (Brateng 2004 and 2005) and (Norem and Brateng 2005). The experimental setups are relatively similar to the model experiments of Håkonardóttir et al (2001), but the scope of the experiments differed considerably. Håkonardóttir made experiments with the design of mounds and collecting dams located at a certain point in the run-out zone. The experiments of Brateng were made with different locations in the run-out zone of the protective structures, and they also included testing of diverting dams.

The main scopes of the present model experiments were to study the retaining effect of the most used protective measures due to:

- The height and the steepness of the structure on the avalanche side

- The location in the run-out zone
- The effect of different combinations of dams and mounds

In addition, analyses of how the results of the model experiments could be transferred to the field were an important task of the experiments.

3.2 Experimental setups

The experiments were carried out in a 3 m long chute, consisting of two parts with different slope angles. The upper part was 1.35 m and had a slope angle of 43^{o}, see photo in Figure 3. The length of the lower part was 1.65 m and the slope was either 11^{o} or 14^{0}. The width of the lower part for the 2004 experiments was 0.3 m, and for the 2005 experiments 1.6 m. In the later experiments the model deposits were thus allowed to be spread out sideways

The model snow used for the experiments was glass beads, 0.1 mm in diameter, with the product name Ballotini. The material is non-cohesive and has a friction angle of 23^{o}. Before the experiments, 3 kg of Ballotini (2 kg in the 2004 experiments) was located in a chamber on the top of the chute. The material was released and the material accelerated to a terminal velocity on the upper part. When leaving the upper part, the front velocity was 3,1 m/s and the flow height 65 mm.

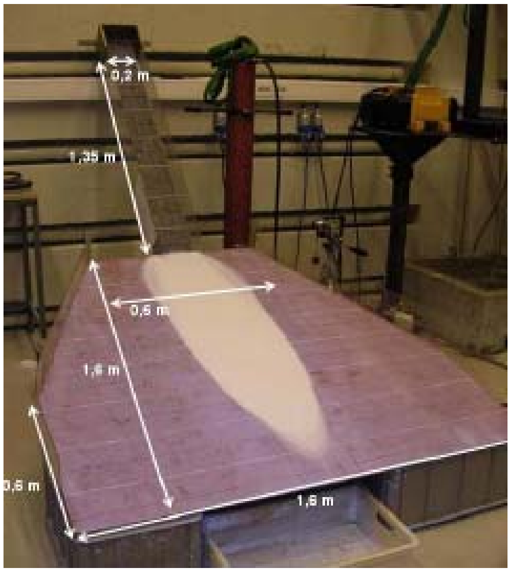

Figure 3 - View of the chute for the 2005 experiments. The angle of the upper part is 43^{o} and the lower part 11^{o} and 14^{o}.

The structures tested are:

- Earth mounds, with heights 1, 2 and 3 cm. The steepness on the avalanche side was selected to 30, 45 and 60^{o}. The earth mounds were located either in rows at different locations or in a plow-formed pattern at x=137 cm, close to the bend in the chute.
- Collecting dams, 2, 3 and 4 cm in height, located at x=150 and 180 cm. The steepness of the dams was 30, 45, 60 and 90^{o}.
- Diverting dams. The straight dams were tested as diverting dams with different angles relative to the avalanche direction and at two different locations, X=150 cm and 180 cm. Curved dams with a deflecting angle of 70^{o} were also tested as part of the experiments

In addition, a set of experiments were carried out to investigate the protection of a road passing the avalanche site, Nakkefonna; in Western Norway. These experiments included combinations of earth mounds and collecting dams. In the following, only a selected part of the experimental results will be presented.

3.3 Model laws

To be able to transfer the result of model experiments to the nature, the most important of the model laws have to be fulfilled. The most used model law for rapid mass movements is the Froude law, or the Froude number. The Froude number expresses the relationship between the gravitational forces and the inertia forces, and this number should be approximately the same in the nature and in the model. The Froude number is:

$$Fr = v / \sqrt{gh}$$

Where: v=velocity of the avalanche (m/s), g=acceleration due to gravity (9,81 m/s^2) and h=flow height (m)

In the nature, characteristic values for the velocity and flow height are 40-60 m/s and 1,0-2,0 m respectively. The respective numbers in the model was 3,1 m/s and 0,0065 m. These numbers give Fr=11-13 in the nature and Fr=12,3 in the model.

Another important requirement for transferring the model results to the nature is how fast the velocity is reduced with the distance in the run-out zone. The reduction depends mainly on the physical properties of the avalanching material and the roughness of the surface.

In fluvial hydraulic analysis, the use of energy lines is common in evaluating the energy dissipation along streamlines. For shallow flows, the Bernoulli equation expresses that the sum of the potential energy and the kinetic energy is constant at any point if there are no energy dissipation. In real fluids, the difference between the sum of the potential and kinetic energy at section 1 and 2 represents the loss of energy between these two sections. The potential and the kinetic energy may be expressed in the dimension meter as:

Potential energy: z (elevation)
Kinetic energy: $v^2/2g$

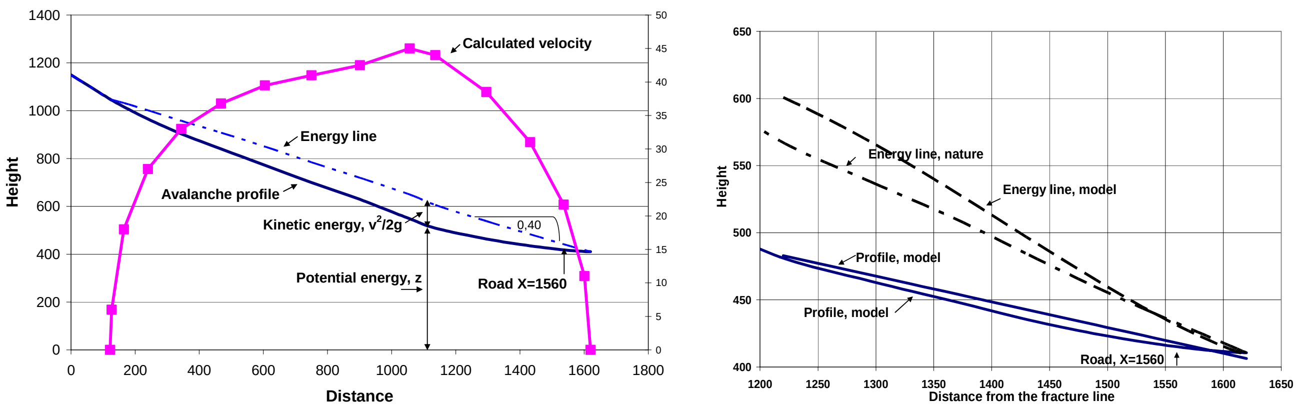

Figure 4. - Profile of Nakkefonna with calculated velocities and energy line (left) and and profile and energy line for both Nakkefonna and the model for the run-out zone (right). The lengths for the model are multiplied with the scale model, 273.

The Bernoulli equation may be presented graphically as shown in figure 4. The velocity in the figure is calculated by the NIS-model (Norem et al 1986 and 1988) for the avalanche site Nakkefonna in Western Norway, and the energy line is the sum of the potential and the kinetic energy for all x-values.

The slope of the energy line represents how fast the potential energy is dissipated and the slope angle of this line should be as close as possible in the nature and in the model. For the present experiments, the slope angle of Nakkefonna is calculated to be 0,44, and for the model experiments 0,53. Recorded avalanches in Norway and Switzerland indicates that the slope angle usually varies between 0,4 and 0,5. The right hand figure in figure 4 presents the profiles and the energy lines for the model and the nature in the run-out one. The lengths for the model are multiplied with 273, which is assumed to be the geometric scale. This is made to better compare the model and the field.

The slope angle of the energy line is dependent on the friction transferred from the ground to the avalanching snow. The numerical models in most use today all assume that the most important friction terms is a Coulomb friction and a term dependent on the velocity squared. In addition, there might be special terrain features in the avalanche path that may be represented as singular energy dissipaters. It can be shown that the slope angle can be expressed by:

$$\frac{dH}{dx} = -(\mu + \frac{f}{R}\frac{v^2}{2g}) - \left[(k_1 \frac{v_1^2}{2g})_{x=x_1} + (k_2 \frac{v_2^2}{2g})_{x=x_2} + + \right] \frac{1}{dx} \tag{1}$$

Where: μ=the Coulomb friction coefficient, f= a velocity dependent friction factor, R=hydraulic radius, v, v_1 and v_2 are avalanche velocities at x, x_1 and x_2 respectively, and k_1 and k_2 represents coefficients relative to the kinetic energy at $x=x_1$, x_2 respectively for singular energy losses.

Eq. 1 shows that if all energy losses are caused by Coulomb friction, the energy line will be straight and the slope angle is identical with the friction coefficient. If the velocity dependant friction is dominant the slope angle will have a maximum where the velocity is highest and a minimum in the first and last part of the avalanche movement. The energy line for both Nakkefonna and the model is fairly straight, and we may thus consider that the Coulomb friction is the dominant friction term in both nature and in the model. The last two terms represent abrupt changes in the avalanche path. This may be natural features like steep cliffs and river depressions, but may also be protective measures like earth mounds and collecting dams. In the following, we will assume the protective structures to be regarded as abrupt changes and the effect of them to be treated as singular losses. The effect of the measures, or the efficiency, is thus presented relative to the kinetic energy at the location of the measures.

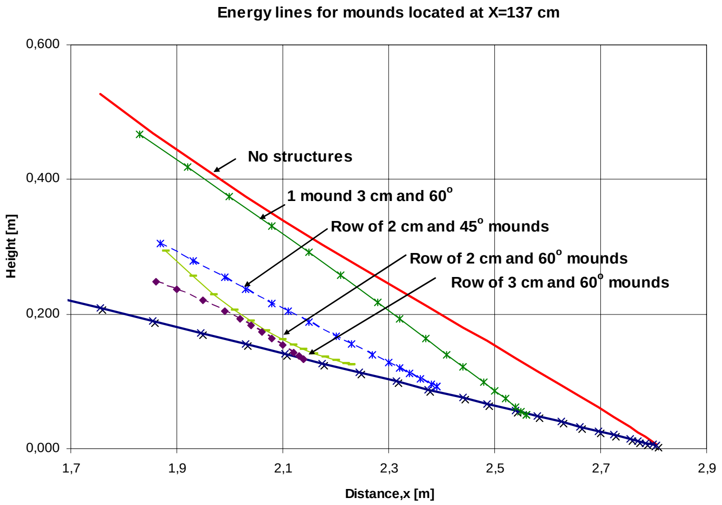

Figure 5 - Recorded energy lines for the model experiments with configurations and shapes of earth mounds and dams located at X=137 cm.

Figure 5 presents recorded energy lines from the model experiments with no structures and for different configurations with mounds. The figure shows that the energy line is to some degree parallel to the energy line for no structure installed. This means that the effect of the retaining structures may be regarded to be a singular energy dissipation introduced at the point where they are located. Simple geometric analyses thus tells us that the relative energy dissipation caused by the retaining structure is the same as the relative reduction of the run-out distance, measured from the site of the retaining structure, and equal to the parameter k in eq. 1.

4. RESULTS OF THE EXPERIMENTS

4.1. Earth mounds located in plow-shape pattern

The main idea behind the test series with location of the mounds in a plow shaped pattern was to investigate the effect of using earth mounds both to dissipate energy and to spread the deposits of the avalanches. The latter effect would probably reduce the flowing height of the avalanche and thus have the avalanche to stop earlier.

The experiments were carried out by testing one, three and five earth mounds in a plow-shaped pattern. In addition, the effect of one row of mounds was also tested, Figure 6. Two types of mounds were tested, one with length of the top equal the height, and one having length/height ratio equal to two In Figure 6 the results of only the first type are presented.

One single mound had a limited effect, while both the tests with 3 and 5 mounds showed to have a substantial effect, with run-out distances 242 and 236 cm respectively, compared to 283 cm without structures. The reduction of the run-out distance with 47 cm represents a reduction of the kinetic energy at X=137 cm with 35 %. k_1 in eq 1 is thus in this case 0,35. The effect of the mounds in a row was very close to the results with 5 mounds in a plow.shape pattern.

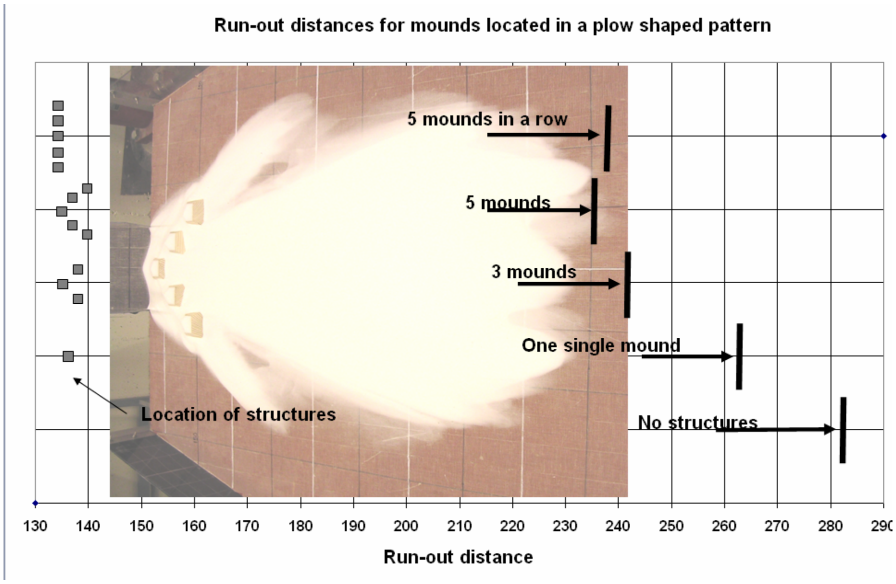

Figure 6 - Recorded run-out distances for earth mounds located in a plow-shaped pattern and in a row.

The recorded run-out distances for the mounds with a length/height ratio were slightly lower, 4 cm, for 5 mounds, but slightly higher when located in a row. To some surprise, the recorded spreading of the deposits was more effective for the mounds located in a row than for the plow-shaped location. Our conclusion so far is thus that the first mounds to be hit by the avalanche should be located in a row in full width of the avalanche. There are probably only small differences with length/height ratios between 1 and 2 as far as the aspect ratio or density in the front is within 70-80 %. However, the height of the mounds has considerable effect. There is a significant increase in the efficiency for heights up to 3 times the flowing height, but less increase for heights above that. This conclusion is also in accordance with the results of Håkonardóttir (2000).

3.2. The location of the structures in the avalanche path

The effect of the retaining structures, mounds and dams can be expressed in two ways, either as the reduction of the run-out distance or as the dissipation of the kinetic energy relative to the kinetic energy at the location of the structures. The first method is most descriptive and is easy to understand. The latter is more scientific and makes it easier to transfer the results of the model experiments to the nature.

The main results of the 2004 experiments with structures located at different distances may be summarized in the two diagrams in Figure 7. The left diagram presents the run-out distance versus the location of the structures. The diagram shows clearly that the run-out distances increase when the structures are located farther out in the run-out zone. The reduction is more pronounced for the mounds than for the dams.

The right hand diagram presents the efficiency of the structures relative to the kinetic energy. This diagram indicates that the efficiency is almost constant for all tested structures except for the very last part of the run-out zone. In this area the efficiency of the dams is increasing, and decreasing for the mounds. These results indicate that mounds should preferably be used in the higher part of the run-out zone and dams in the lower part.

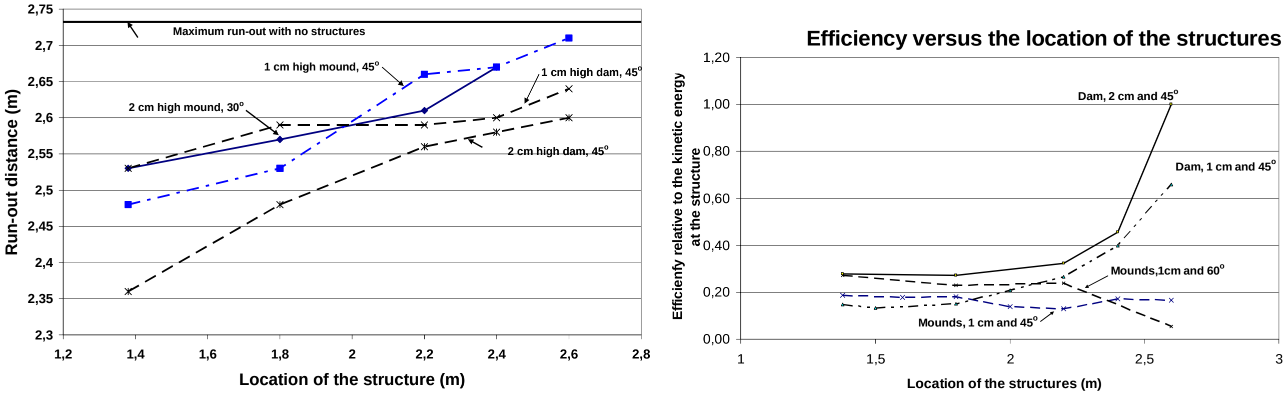

Figure 7 - Recorded run-out distances and efficiencies for dams and mounds located at different locations in the run-out zone.

4. TRANSFERRING THE MODEL EXPERIENCES TO NATURE

One of the main scopes of the experiments was to investigate proposals for the protection of the avalanche site, Nakkefonna, in Western Norway. Based on the experiences from the preliminary experiments and site investigations the following protective measures were proposed, Figure 8:

- At X=1250, which is in the upper part of the run-out zone, one row of earth mounds will be constructed. The mounds will have a special design. The base for the mounds will be a 4 m high dam to assure that the mounds are located above the snow deposited on the ground. On top of the base six mounds will be constructed. The height of each mound will be 4 m with a length/height ratio of 2. The mounds will be constructed with masonry wall with a steepness of 2:1 (63°), and the distance between the mounds at the base is selected to 4 m. This gives a density of 62%.
- At X=1340 a second row of mounds will be constructed almost similar as the first row. The only difference is the height of the base, which for this row is 3 m.
- At X=1520, just in front of the road, a 6 m high dam will be constructed. The slope angle of the dam is selected due to the stability of the soil in the area, 1:1,5 (34°)

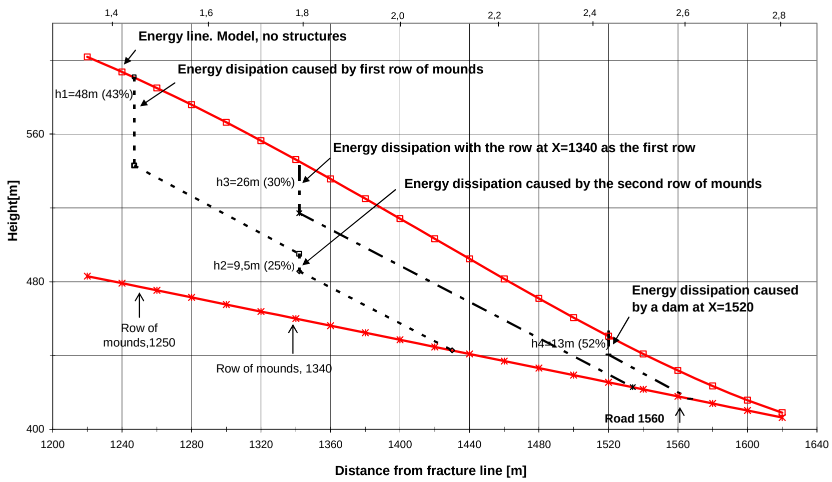

Figure 8. - Estimated effects of constructing one row of mounds at X=1250 and X=1340 and a dam at X=1520

The recommendations for the location and the design of the protective measures were based on the experiences gained from our experiments, and the main ideas behind the recommendations are:

1. To locate a row of mounds as high up in the run-out zone as practically possible. The experiments have clearly shown that especially the first row should have steep sides toward the avalanche, and a fairly high density. It is also important to have a considerable height to avoid the mounds to be buried during heavy snowfalls or by deposits from earlier avalanches. The experiments indicated that the energy loss caused by this row was up to 48 m or 43 % of the kinetic energy at the site.
2. The next row is located 90 m downstream from the first row. The experiments indicated that both the mounds and the dams caused the avalanche materials to be thrown into a jump. The length of the jumps was very close to standard equations for jumps, when using the velocity in front of the structures and the steepness of the structure as input data. The jumping length caused by the first row was estimated to 90 m. The recorded energy dissipation of the second row was found to be 9,5 m (25 %) causing the avalanche to stop at X=1430, which is 130 m ahead of the road. If the first row of mounds is covered by snow and thus has no effect, the second row will dissipate 26 m of kinetic energy (30 %). The stopping distance in this case is just in front of the dam. The recommended structures should thus be effective even if the first row of mounds is covered by snow deposits.
3. The dam in front of the road has two purposes. First the dam should stop any dense snow flowing toward the road in case the mounds have less effect than assumed. Secondly the dam has the effect to lift the pressure of the powder part of the avalanches. The retaining structures have only limited effect on this part of the avalanche, and the use of dams has shown to have significant effect to avoid cars to be blown off the road by the air blast of the powder part.

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