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Innovative design for repairing Gondo mudslide by 20 m high geogrid wall

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ABSTRACT: A mudslide destroyed ten houses and extinguished many lives caused by heavy rains and a subsequent pond forming behind a gravity concrete wall. An hour later, the pond pushed the wall over and washed the wall downhill through the village. The wall had to be rebuilt for protecting the village from dangerous rock falls from the cliffs directly above. A concrete wall was out too dangerous for pushing through the village again and unsafe when hit by a large boulder, since concrete shutters into pieces.

Innovative design principles were needed for properly conceiving a geogrid reinforced fill 20 m high against extreme rock fall. The paper describes methods and results of impact forces, risk, and deformation considerations for realistic geogrid reinforcing design for that extreme, yet rare loading condition. Finally, the paper mentions and features special impact features for minimizing deformations. Another task was to build a soil-nailing wall 12 m high in a steep cut slope for preparing the level base for the geogrids. Now the villagers enjoy a high grass slope behind the houses, which enhances the quality of life for persons living beneath: Here it is safer than anywhere in the village.

1 INTRODUCTION

A one-week continuous rain on the Southern Alps initiated a mudslide crushing through the border village of Gondo, destroying ten houses and killing 13 people. Gondo is a historical smuggler village sitting on the border between Switzerland and Italy. This was the only natural disaster hitting Switzerland within decades. The rain was a 10,000 year event and thus extremely rare. The granite mountains above the village collected and diverted runoff water into the slope directly beneath the 200 m high cliffs. This saturated glacial till layers directly above the village of Gondo and created a sudden mudflow. Groundwater on this slope was a surprise since drill holes recently made for a detour tunnel showed no groundwater whatsoever.

At first, the mudslide formed a pond behind a 10 m high concrete wall, made about ten years earlier for protecting the village from rock falls. The pond created intense water seepage through the wall foundation area, which then destabilized the subsoil. Within less than one hour the pond pushed the wall over and then widened the sides like opening large doors, unleashing the muddy water with boulders and transporting large pieces of the retaining wall, about $10 \times 10 \times 2$ m some 300 m downward through ten houses of the historical village of Gondo, blocking the important Simplon Alpine pass road. Many persons disappeared with it.

The Cantonal Highway Department and the Ministry for the Swiss National Highways called the author for designing the repair work. At first, they planned for a similar cast in place concrete wall, yet inhabitants and professionals asked for a reinforced earth wall for better protection against mudslides and rock fall. Detailed studies directed by the chief geologist of the Canton of Wallis resulted in a much bigger than originally expected rock fall potential. The new wall had to withstand the impact of boulders of 5 m^3 or 13.5 tons, falling from the 200 m high cliffs, with a design impact energy of 30,000 kJ.

The engineering tasks: (1) Prevent future mudslides, (2) Protect the Gondo village from high-energy impact rock falls. (3) Concrete a wide-open channel directly beneath the vertical cliffs to collect any rainwater running down the rock surfaces all the way along the slope above the village. This removes future percolation and positively prevents any future mudslide.

  

Figure 1. Historical photograph. Figure 2. Gondo after the failure. Figure 3. Gondo after repair.
Note historical building with short tower in all three pictures (Stockalper warehouse, built ~1600). Figure 2. see 3 large concrete blocks (top, middle, bottom) along the mudflow: concrete floated on it!

2 EXTREME LOADING CONDITION

The impact energy is transformed into an equivalent static surcharge strip load by theories based on Lang [1], Montani [2], and Descoedres [3]. The Lang and the Montani formula both resulted in similar magnitudes. Thus they are comparable in this case.

The Montani formula applied is:

$$P = 1.35 * R^{0.2} * \exp(R/3e) * M^{0.4}{}_{E} * (\tan \phi)^{0.2} * E^{0.6} \quad (1)$$

for: $R = 1.06$ m radius of an equivalent block
$E = 3.50$ m thickness of impact layer
$\phi = 35°$ angle of internal friction
E = kinetic energy of block in this case:

$$P = 1.4 * M^{0.4}{}_{E} * E^{0.6} \quad (2)$$

The actually performed impact load calculations used detailed Excel tables with two sets of formulas. After evaluating, the pseudo static impact force found from this procedure is $q = 1466$ kN/m^2, based on the

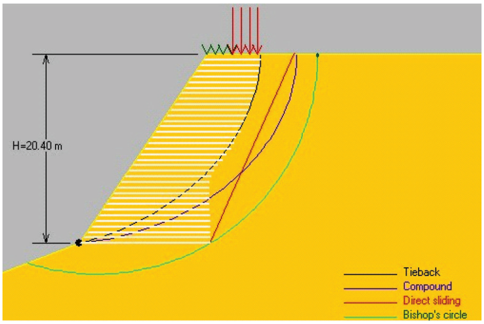

Figure 4. Global and combined failure planes.

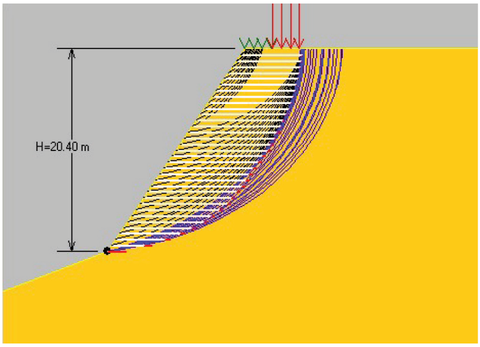

Figure 5. Failure planes for internal integrity. The strip load is equivalent to 1466/20 = 73 m of fill!.

Lang formula, with R =1.0 m, E = 30,000 kJ, loading an area of 3.0 m × 4.0 m. Visualize this extreme pressure: divide q by 20 kN/m^3, the average moist density of soil fill. The pressure is equivalent to vertical fill height of 73 m!

The expert F. Descoedres considers the size of the design rock fall mass an 'undisputable geologist assessment' based on local observations. The subsequent impact energy seems extreme. However unsafe factors counterbalance this:

– Non-vertical rock fall trajectories and the weaker geometry of the wall crest.
– Empty rock fall receiving channel.
– The impact energy formulas are not calibrated for deformable fill impact surfaces.

In conclusion and in view of the mix of positive as well as negative effects, the approach taken seems acceptable.

Compare this rock fall energy of 30,000 kJ with the commercially available rock fall nets for highways under cliffs: Their normal capacity ranges for 500 to 3,000 kJ, the newest and heaviest nets absorb 5,000 kJ. Thus, the capacity of normal impact energy for highway nets reaches a fraction of the design energy for the Gondo reinforced earth fill dam.

3 INNOVATIVE ENGINEERING CONCEPTS

Generally it seems that the impact energy was estimated on the high side, yet the calculations are made for vertical impact only and the thickness of the impact layer is a rough estimate. Thus the mathematics of the subject implies uncertainties:

(a) Statistics of size of rock fall,
(b) Statistics of failure trajectories,
(c) Accuracy of applied mathematics,
(d) Determining the pseudo static force,
(e) Assumptions on impact parameters such as modulus of deformation and penetration depth.

There are other engineering fields dealing with such uncertainties, such as flooding and accident loads, as well as military impact protection. Thus the most fascinating aspects was:

Develop reasonable design criteria for unusual engineering tasks:

3.1 *Deformation of reinforced earth fill*

The duration of the impact lasts for a fraction of a second only. Compare this with a traffic accident impact on highly deformable guard rails: The guard rail stops the impacting vehicle by deforming enormously. The purpose of the reinforced earth fill is the same: stop the block from continuing and rolling through the village below by deforming the fill. Thus considerable deformation of the reinforced fill is necessary. This requires acceptable repair work after impact.

3.2 *Design safety factors for impact loads*

Since the impact duration lasts for a fraction of a second only, the soil fill cannot move very far. Subsequent from the above definition of high repair potential in case of such a rare impact, special conditions allow for special requirements: Set safety factors at bare minimum of 1.00 for shear resistance of soil, for anchoring force of geogrids, and for sliding.

Similarly set reduction factors to bare minimum of 1.0 for creep, for overstress of geogrids. Yet reduction factors for damages on geogrid during installation is 1.3 and for environmental damages (chemical, biological, UV etc) are 1.1 as normal. Obviously this combination of safety and reduction factors is unusual and reflects the special loading conditions of an extreme rock fall. This further means, that standard codes are not applicable for such a case and innovative risk analysis and engineering evaluation is required for rock fall energy absorbing structures.

3.3 *Rip-rap cover for absorbing energy*

Engineers active in military defence structures know the favourable absorption of explosive (or impact) energy by boulders and crushed stone beneath. The reason to easily dissipate large explosions in several meters of rock blocks or crushed rock lies in the capability to dissipate gas volumes in the void spaces and to dissipate energy by compacting and thus partly breaking angular blocks. This effect certainly applies to some extent for impact energy from rock fall. The wall crest was topped off with 3.0 m of rock fill (rip-rap) on crushed rock on top of geogrid reinforced soil. This strengthens the otherwise narrower and weaker wall crest portion.

3.4 *Precaution for slanted rock fall*

Standard design calculations use vertical impact forces. So it is not simple to evaluate the effect of slanted rock fall trajectories, which are likely to occur if the rock bumps onto the cliff before hitting the protection wall. Estimates of slanted forces indicate that this load can be substantial and difficult to absorb, since the crest of the wall is narrower and there is a lot less mass to activate. Thus stresses are much higher. The conclusion is: instead of down scaling the geogrid strength as the fill goes up, upscale the grid strength to maximum in the top layers. It is part of engineering evaluation to add extra strength where forces hit the most, whether it is defined by a formula or common sense. Again codes do not apply for such conditions and thus the engineer needs to analyze the risks and evaluate the means against.

3.5 *Comparison with a concrete structure*

Concrete is not capable for absorbing large impact energy, because boulders or missiles cannot penetrate into concrete and simply shutter concrete into pieces unless they are covered with deep rock fill. Heavily geosynthetic reinforced earth fill can absorb much larger impact energy, because of the much lower deformation modulus of compacted soil allows for more penetration depth and thus for a much longer lasting breaking depth with high energy absorption.

4 CONSTRUCT SOIL NAILING WALL

After clearing the mud and surveying of the new topography excavation started for a 12 m high soil nailing wall with 7 rows of nails 5 to 11 m long, made in short sections of 1.50 m depth, drill and grout soil nails, and then apply 0.1 to 0.2 m shotcrete (gunite) with mesh wire reinforcement. This deep excavation illustrates that a major soil reinforcement wall on a steep slope means tremendous preparation.

Figure 6. Soil nailing and shotcreting.

Figure 7. Place heal drain.

5 SOIL REINFORCING, SPECIAL FEATURES

Finally, the construction begins using soil reinforcement with heavy Huesker geogrids, designed by Reslope analysis as shown before. However, calculation results need adjustment for inclined trajectories impact: The heavy 200 kN/m bituminous-coated Polyester geogrids are located in the upper part, the lighter 110 kN/m to the bottom layers. This layout diverges from standard applications because the heavy geogrids must provide for slanted impact resistance.

Figure 8. Lowest geogrids placed.

Figure 9. Place back drains and fill.

The key for long-term performance is a meticulous drainage system with a bottom layer, the outlet pipe extending to both sides and added drains along the back, directly on the shotcrete to catch water

Figure 10. Completed Geogreen® wall with berme.

from hoses through the shotcrete for water pressure release.

Note the berme at half height of the outside slope for reducing the fall of any person and reducing hazards form falling objects.

Again, this is not a code requirement, yet a priority design feature.

A focal point consists of a thick layer of riprap at the crest to receive the rock fall impact and for absorbing energy by breaking big boulders and dissipating the impact effects into voids of riprap, like missiles hitting bunkers.

A slanted coarse gravel zone, directly behind the front facing, about 1.0 m wide strengthens very high soil reinforcement walls. Experience showed that this firm zone directly behind the facing minimizes deformations. This feature proved very successful for a 28 m high retaining wall in Ponferrada beneath the motorway Madrid-Coruña in the Northeast of Spain with clay backfill only. That way very high soil reinforcement walls can be built even with mediocre fill material, provided special precautions are met, such as drainage (above, behind, and beneath the wall), fill on the dry side with over-compaction and use a zone of firm, well compactable material behind the facing.

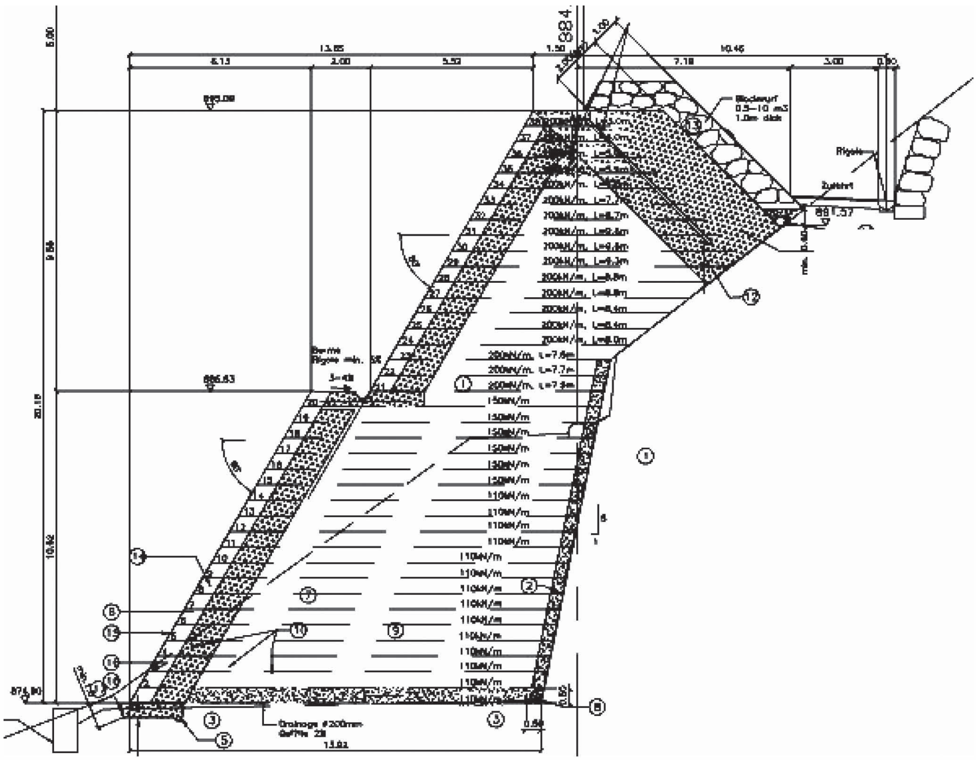

Figure 11. Section of reinforced soil fill using Huesker geogrids 110 to 200 kN/m resistance at 0.6 m vertical spacing. Note the heavy polyester geogrids are near the top of the wall to resist slanted rock-fall impact forces, which are not readily determined by current design procedures yet.

Further features are details regarding deep excavation on a steep hillside using soil nailing with special drainage precautions, new concept to prevent accumulation of groundwater in the hillside, special surface protection against high impact damages.

6 CONCLUSIONS

The rock-fall protection wall resulted in a 20 m high Geogreen® reinforced earth retaining wall with a berme at mid height for safety and fully planted surface. Thus the mudflow has now changed to a steep grass slope enhancing a better environment for persons living beneath safer than anywhere else in the village. A heavily reinforced earth fill is the only feasible way to absorb large energy impact from rock fall. The design method was adapted from accident impact deformations on traffic barriers for reasonably conveying to rock-fall impact. This meant a change of the standard set of safety and reduction factors. Then numerous special features were necessary to add resistance to the narrower crest part of the dam by using heavy geogrids near the top and adding a thick layer of rip-rap for high impact absorption as successfully used for military bunker protection against explosives. Developing geosynthetic technology requires a wide look for neighbouring engineering fields and creative thinking.

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