Why are front elements on mechanical stabilized earth overdesigned but still failing?

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ABSTRACT: Mechanically stabilized earth (MSE) by using geosynthetic tension members is a well-known technique for retaining structures. The design and its execution is state of the art. The increasing number of executed structures worldwide is followed by an increasing number of reported failures. Surprisingly the number of front element failures takes a high percentage in these reports. Theoretically the forces taken into consideration in the design are significantly higher compared to real measured ones – so why do front elements fail and how can it be avoided?

Keywords: mechanical stabilized earth, front elements, failures

1 INTRODUCTION

Prof.em. Robert M. Koerner from the Geosynthetic Research Institute (GRI) at Drexel University/US administrates a database on all reported failures on MSE's. By using a catalogue of failure relevant criteria, all cases are analyzed and assessed. Based on a total number of more than 50.000 single mechanical stabilized earth structures, the database incorporates 236 failure cases. The statistics of the causes present following picture related to the defined criteria:

97% of the failed constructions are privately owned.
70% of the cases failed between the years 2000 and 2010.
81% of the reported locations are in North America.
76% of the constructions had a hard facing (concrete block facings).
71% of the constructions had a height between 4 and 12m.
93% of the structures had a geogrid reinforcement, the others were reinforced with other geosynthetic layers like geo-wovens or geo-composites.
78% of the failures occurred within the first 4 years of service
70% were constructed with cohesive fills
72% of the structures have been compacted with moderate to poor compaction
In 99% of all cases an inadequate design respectively execution could be investigated; in none of all failure cases the geosynthetic material was causing the failure.
In 62% of all cases water had a relevant influence; in the other 38% soil had a significance.

What now is the relevance of Prof. Koerner's database on this paper?
Also in Central Europe the increased use of MSE constructions lead to an increase of reported damages. As MSE walls and slopes are seen as very save in their design and uncritical in its execution, it might be assumed, that the accuracy in designing and executing these structures has to be questioned.
Contrary to the US, Europe is working mainly with flexible and semi-flexible facing systems. Those are seen as simple in their construction. Pachomov et.al. investigated the resulting earth pressure on flexible facings and found out along with various long term measurement campaigns, that the stability demand on flexible facings in reality is smaller compared to the theoretical design values under use. Therefore, it is even more surprising to see a bulk of all complains on MSE's coming from this side.
This work will investigate the source of failures on flexible facing systems, as well by checking the theoretical approaches used in the design and the possible mistakes and difficulties in the execution.

2 DESIGN VERIFICATION

2.1 *State of the Art in Facing Designs*

In the German speaking countries, the EBGEO – recommendations for design and analysis of earth structures using geosynthetic reinforcements – from 2010 is the guideline representing the state of the art. The given recommendations are based on Eurocode 7 and the national annex DIN 1054.

In terms of the deformability of facing systems the EBGEO defines, similar to the EN 14475 three cases:

Non-deformable facing systems; like full height panels, partial height panels and block elements, moulded bricks (connected to each other).

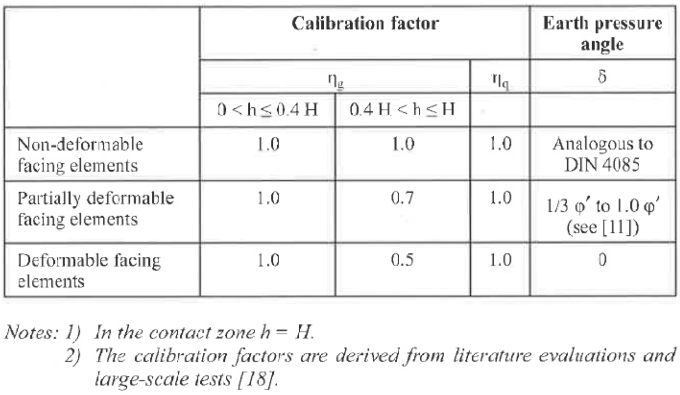
Partially deformable facing elements; like welded steel wire mesh, gabions, block elements or moulded bricks

Deformable facing elements; most popular is the wrap-around construction.

The design starts with the calculation of the earth pressure distribution by Coulomb. The earth pressure on adjacent construction elements on mechanical stabilized earth is statically indetermined and doesn't follow the used approach; but analogies based on reference figures can be used.
For the EBGEO approach research studies from Pachomov as well as experimental studies from field investigations from Herold et.al. have been used. Calibration factors are used to consider the deformability potential of deformable and partially deformable facing elements. Those calibration factors are valid for the lower 40% of the total construction height and allow to reduce the active earth pressure with a factor $\eta_{g.}$

Especially for flexible front systems the calibration factor allows a convergence to de facto measured stresses acting on the front and therefore avoids an over-dimensioning.

Table 1. Calibration factors for the reduction of the active earth pressure on the front according EBGEO (2010)



	Calibration factor			Earth pressure angle
	η_g		η_q	δ
	$0 < h \leq 0.4\,H$	$0.4\,H < h \leq H$		
Non-deformable facing elements	1.0	1.0	1.0	Analogous to DIN 4085
Partially deformable facing elements	1.0	0.7	1.0	1/3 φ′ to 1.0 φ′ (see [11])
Deformable facing elements	1.0	0.5	1.0	0

Notes: 1) In the contact zone $h = H$.
2) The calibration factors are derived from literature evaluations and large-scale tests [18].

2.2 *Sate in Research*

For gesynthetic reinforced soil bodies we do not have a homogeneous situation to determine the earth pressure distribution. It is more of a composite material with the construction materials geosynthetic and soil. Ruiken et.al. and Jacobs et.al. published various papers on their research work investigating the stress-strain-behavior of geogrid-reinforced soils.

Based on this research various approaches to calculate the deficit in forces and moments in a reinforced soil structure to achieve a stable situation were introduced by Jacobs et.al.. One approach is using an equal introduction of mobilized forces into the geosynthetic layers in the passive zone. To validate this approach in one to one models, a calculation of the connection forces from the front element to the geosynthetic layers was introduced. As well quantitative and qualitative the results of these research studies fit to the introduced theory.

3 theoretical options for the introduction of the forces into the geosynthetic layers were assembled and investigated by one to one model trials.

Option 1: Equal force introduced to each involved geosynthetic layer
Option 2: Constant introduction of forces; the designed stresses are proportional to the reinforcement length in the passive zone.
Option 3: Forces are dependent from the normal stress.

The required connection force to the front element is smaller compared to the decesive one required from the geosynthetic reinforcement in the failure plane, as just a small area on the front is leading to stresses. This corresponds to a failure mechanism with very steep failure bodies and correlates to a little length in the active failure body ($L_{A,akt,i}$). Jacobs recommends following formula (1) to evaluate the connection strength, which works with the maximum activation of friction $f_{sg,d}$ along the geogrid in the active zone.

$$E_{Front,\,id} = E_{i,d} - 2.\sigma_{vi}.L_{A,akt,i}.f_{sg,d}$$

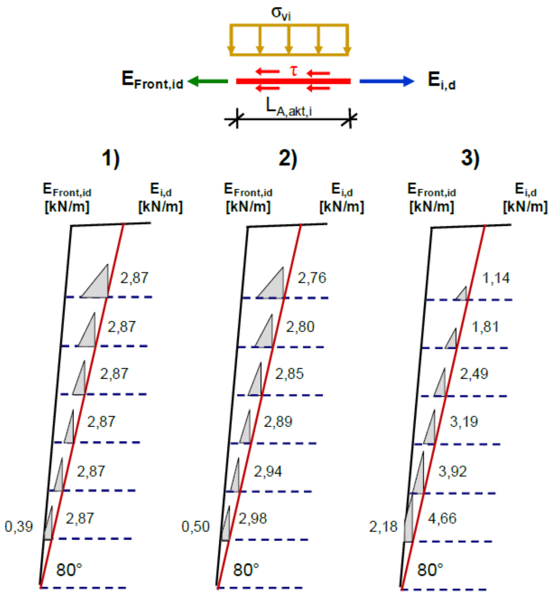


Table 2. Distribution of forces in the geosynthetic layers at the failure plane to the connection at the front for the three discussed options of force introduction according Jacobs et.al..

Option 1 and 2 deliver similar results whilst option 3 shows higher needs in the lower parts due to the normal stress dependence. Compared to the calculation scheme given in the EBGEO (2010), following proportionality can be seen:

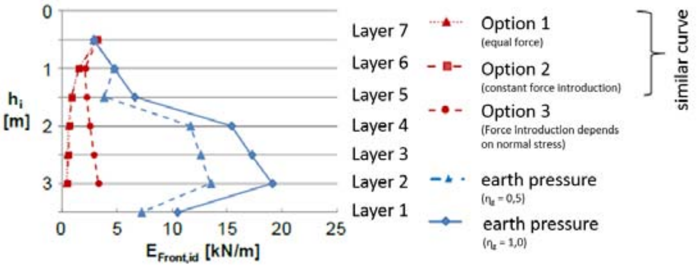


Table 3. Maximum connection strength for the three introduced options to calculate the geosymthetics and connection strength out of earth pressure design from EBGEO (2010).

Not considered in this comparison is the compaction pressure during installation, which has to be considered in the upper part of a construction according to EBGEO (2010).

The approach with the three options from Jacobs was simulated in a test box and showed following results:

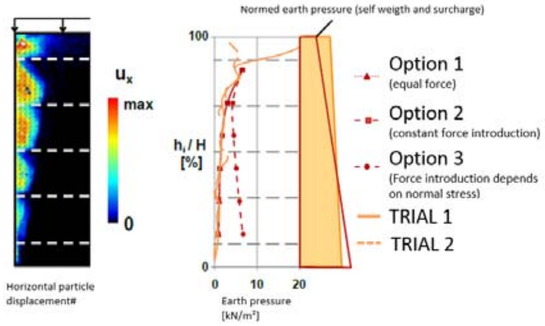


Table 4. Horizontal particle displacement and earth pressure of one to one trials in comparison to calculation results based on the three options (Jacobs et.al.)

2.3 *Conclusion on the state of the art*

The design of connection strength between geosynthetic reinforcement layers and front elements works by using the active earth pressure and distribute it over the height of the structure. This leads to results on the very save side, as the composite material behavior soil-geosynthetic is not taken into considerations. The lower the stiffness of the facing elements and the higher the deformability of the same, the lower is the in reality needed connection strength. The German guideline EBGEO for the design and analysis of reinforced soils is bearing that in mind by allowing a reduction of the earth pressure based on the flexibility of the used front by still keeping a certain reserve in safety.
Searching for answers, why front elements are in the spotlight of MSE failures, we don't find them in the state of the art design approach for connection strength.

3 EXECUTION OF MSE STRUCTURES

Following the criteria of Prof. Koerner for the causes of reported failures on MSE's many of those are directly linked to the execution of the structures. Quality of the used fills, its compaction and the active presence of water have a decisive influence to the stability.

But not just the influence on the overall stability, also the success of a functioning facing system depend on the execution quality and keeping general rules in earthworks.

The EN 14475 answers questions to the execution of reinforced fills, unfortunately it is not well known especially in road engineering. But also other standards and guidelines in our markets help to be informed about the specialties of reinforced soil structures. It is not so much the reinforcement, which needs information; it's more the basic rules for earthworks, which creates trouble. The right use of qualitative fill material; the compaction and its control, the correct drainage measures for earth structures – if we keep our knowledge from dams and embankments and bring it into reinforced fills would help avoiding lots of the problems we see today.

3.1 *Requirements for facing systems*

The front system represents the visible finishing of a MSE structure and has to fulfil various requirements. In our areas quite often the owners wish is to integrate the structure into the adjacent nature. Steep slopes therefore have to be finished with a permanent vegetated facing. Erosion and vandalism have to be avoided; the long term stability has to be supported. The minimum transfer of forces between facing and geosynthetic reinforcement layers was discussed already.

The given requirements lead to the development of well working facing systems, which are not just technically able to meet the owner's expectations but are also easy to install – a property which is of immense importance for the re-use and self-marketing of MSE's.

Table 5. System Polyslope S, a successfully used front system for vegetated facings

The front system Polyslope S for vegetated steep slopes supports the primary functions of aesthetics, fire resistance, UV-and erosion stability and resistance against vandalism and supports the growth phase during the initial vegetation phase. The mobilization of connection strength between the front elements and the geosynthetic reinforcement works via friction.

But in case of little to no idea on how a front system should work, here is an example of a missing concept behind the used elements.

Table 6. A protection bund against rock fall; designed for the eternity, executed for far less.

For the above illustrated protection bund, the used fill at the front doesn't allow a vegetation. The vegetation would be necessary to protect the geogrid, which is wrapped around to fulfil the connection strength. The used shuttering is black steel, which will corrode over the time.

3.2 *Quality requirements to the fill material and its compaction*

The quality of the used fill material has a major influence for the front and its horizontal and vertical displacement. Although we have minimum quality requirements to allowed fill properties, like in the EN 14475, quite often cohesive soils with little shear resistance is under use. It is legitimate to use low quality fills; it is even one of the success aspects for MSE's to allow soils, which hardly can be used as backfill for gravity walls. MSE's are soft structures. The don't lose stability because of deformations. But minimum requirements to the shear properties and compaction ability have to be considered.

Table 7. Failure picture from a construction erected with soft clay under full dynamic compaction

The picture in table 7 shows a 70° steep reinforced slope, made of pure clay. Without moisture control the clay was compacted dynamically with full amplitude. The configuration of the clay particles got fully destroyed by this incorrect treatment. Beside the effects on the stability by destroying the shear resistance of the soil, the required inclination of the front went up to 90° by overturning of the front elements under the compaction pressure. Also the required green facing cannot be realized without the right soil material on the front.

Table 8. Examples for MSE constructions with high vertical settlements

The two constructions in table 8 show constructions with vertical settlements of up to 150 mm per layer (layer thickness 600 mm). Reason in both cases is an inadequate compaction at the front area.
The compaction of the fill in an earth retaining structure is of major importance. The compaction device and its passes have to match with the used soils. For MSE constructions also the distance to the facing and the provided stiffness of the facing elements have to be considered. In table 9 an example for the correct use of compaction devices for flexible facings is given.

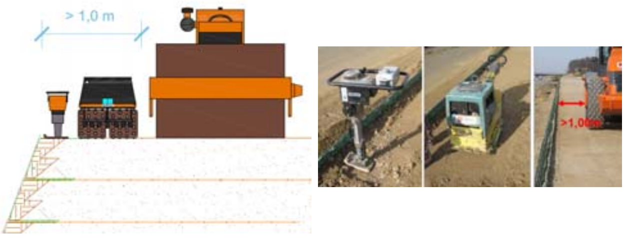


Table 9. Example for the right use of compacten machinery matching the stiffness of a flexible facing system

3.3 *Influence of missing drainage measures*

According to the study of Prof. Koerner 62% of all analysed failure cases are directly caused by water. Whilst a missing drainage concept may lead to a loss of global stability, also uncontrolled surface water may damage a MSE front system.

Table 10. Run off water washed out the facing of a MSE

Picture in table 10 shows a structure, where surface water flushed uncontrolled over the facing of a MSE and eroded the front. Secondary settlements where the result. A simple drainage measure at the slope shoulder could have avoided this failure as shown in table 11.

Table 11. Erosion-free drainage for surface water on top of a MSE (picture source: A. Herold)

4 SUMMARY

In line with the acceptance of MSE structures also the reported failures are increasing.

Prof.em. Robert Koerner from GRI is analysing the causes of the published failures and clusters them accordingly. His data base incorporates in the meanwhile 236 damaged structures.

It is remarkable that in none of all cases the geosynthetic reinforcement played a decisive role for the cause. But in almost all cases either the planning or the execution (and quite often both together) bared significant deficiencies.

Why is that the case? Are MSE structures seen as non-constructive retaining structures or is the reputation of MSE's generally seen as very, very safe and mistakes may be spoiled by the structure?

Is our low knowledge on the stress-strain-behaviour of reinforced fills, which is quite often sold as reserve in stability, overestimated and does it lead to the effect, that basic geotechnical principles are neglected?

With the rapid growth in the use of MSE's it can be identified on site, that the care needed during construction gets lost – and this leads to damages.

MSE structures are one of the very rare opportunities in geosynthetic applications, where a structure still can be seen even after completion and under use. What you see, is the facing! So, when damages are complained, it is quite often something on the facing which does not meet the expectations of the owner or user of the construction.

The given paper tries to find out, where the causes of these complains come from. Is it because of insufficient design knowledge and know-how or is the majority of complains linked to neglects during execution.

The design, analysis and execution of MSE-constructions is documented in a series of standards, codes of practice and guidelines. The way to plan with reinforced fills and execute them is relatively simple compared to substituting technologies, like cantilever retaining walls. But it has to be understood, that also with MSE walls and slopes we have an engineered construction to build and this requires a serious care during the whole process of planning and execution.

5 LITERATURE

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