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A contribution to the design of flexible wire mesh facing

J.-M. Jailloux
Profractal Engineering & Consulting, Clichy, France

N. Freitag & P. Segrestin
Freyssinet International, Vélizy, France

ABSTRACT: The current mesh facing technology for MSE structures is validated mainly by observation of actual structures, but the structural design of the mesh remains unsolved so far. Classical approach gives deformations that are much larger than the ones observed on site. This paper presents a new methodology that leads to realistic results due to a better understanding of the actual interaction between the soil and the flexible facing. The communication includes: - the observations on actual structures - the principle of the modeling of the soil, with a behavioral law (stress vs. deformation of the backfill material) which constitutes an innovative feature in the design of such structures - the description of the algorithm which is used to calculate the stresses and deflections of the wire mesh facing units. Other applications that use a mesh facing, noticeably soil nailing, can take advantage of the method.

1 INTRODUCTION

Facing panels constituted of steel mesh have been widely used in Mechanically Stabilized Earth structures under various versions.

Sometimes bent or flat, with or without hooks, connected to reinforcements made of steel or synthetic strip or mesh, or geotextile, the different facing elements have been justified only by observation on actual structures and occasionally by experimentation.

So far no comprehensive approach of the mechanisms that govern the deformation and the stress in the steel wires has been presented.

The subject of this project was to analyze the situation and to derive some guidance as regard the justification of the facing technology.

A new methodology is now proposed. It introduces an innovative feature by taking account of a behavioral law stress vs. deformation for the backfill material combined with the non-linear calculation of the deformation of the mesh.

2 PRESENTATION OF THE TECHNOLOGY

For the purpose of this study we have considered one type of facing currently used for green MSE slopes. Its different components are presented in Figure 1. A flat steel mesh is supported at the proper angle of inclination of the facing by means of pre-bent hooks at the bottom. The reinforcing strip is connected to this main hook with a flat tie-strip. A secondary hook further maintains the facing and

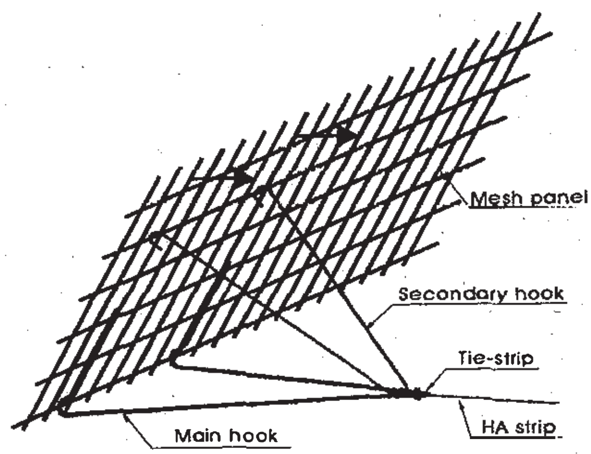

Figure 1. Components of a steel mesh facing panel.

helps to support the earth pressure during backfilling operation. So that it is possible to backfill a course of panel up to its top, and to compact the soil properly before installing the next course.

We observe that for each reinforcement, four bearings are created on the flexible facing panel, plus two bearings due to the overlapping of the next row of panels. In this resides the principle of this type of mesh facing: transferring the earth pressure applied on a flexible panel to the localized reinforcing strip by means of several separated connections so that the deformation of the facing is limited.

Several versions have already appeared on this principle: diameter of wires (ϕ) 8 or 10 mm) and openings in the mesh (100 or 150 mm). Also the overall length (2.4 to 6 m) and height may vary. Stone filling or topsoil for vegetation is currently used to back the mesh. These different versions finally are answers to different local manufacturing constraints and marketing requirements.

3 THE DESIGN PROBLEM

Anyone who built a MSE wall with a mesh facing knows that the deformation of the facing is very dependent on the way the workers place and compact the soil behind the facing. When the pressure of a foot behind the mesh is released, a permanent localized deformation is possible; it does not however question the stability of the wall.

Our concern is to assess the theoretical deformation and the normal tensile stress in the wires as if the wall was perfectly built (as it could be done in a laboratory under controlled conditions), without taking account of construction defects or damages to the facing. The problem is complex because the large number of elements brought into play and also the unknown response of the soil to deformation. However we can anticipate the benefit of a suitable method to justify and improve the existing technique, or test new solutions.

When one tries to calculate the deformation by means of classical formulas of a beam on supports, the deformation is large and much larger than what is actually observed on sites. In fact the wires act as cables as well and carry a load that reduces the deformation.

A better approach is to use a more sophisticated calculation tool: a computer program for structural design with a non-linear method. The entire mesh is modeled with elementary bars connected to nodes (the cross welds). In that case the neutral axis in one element can elongate and generate a normal tensile load, which better represents the actual behavior of a wire in the facing. For purpose of simplification, the earth pressure is applied like a local force at each node proportionally to the surface area it represents (usually one mesh opening). A connection to one hook is modeled as a simple support, fixed in space. The program increases the load by small steps (method P-Delta for example).

For the real wall described below, under the most probable earth pressure (without any load factor), the result provides a too high deformation (84 mm) instead of some 20 mm observed on the wall.

Although rather sophisticated, the approach is not enough adapted to the reality. We need something else. Before going into details, let's review how was measured the deformation on a real structure.

4 MEASUREMENTS ON SITE

The structure is a Reinforced Earth wall in Italy. The facing about 5 m high is at an angle of 80°. The mesh panel used is the one described in Figure 1. The overall length of one panel is 3 m. The mesh is constituted by wires ϕ 8 mm, spacing 100x100 mm. Three steel reinforcing strips per panel are connected to hooks, which create 18 bearings per panel.

Figure 2 presents the technique to measure the deformation: a frame made of steel square tubes is placed more or less parallel to the facing. A T-shaped rule slides on the upper side of the frame. The distance between the vertical sliding rule and each node of the mesh is measured and recorded (300 nodes per panel). The exact position of hooks and surrounding panels were also noted. Three similar panels with small apparent deformation were measured on that particular project.

A Reinforced Earth design program for sloping wall was used to estimate the loads. The total force applied by the earth on that panel is 30 kN (10 kN per reinforcing strip).

The raw results (readings of the distance between a node and the frame) are transferred in a spreadsheet. The position of the reference plane is modi-

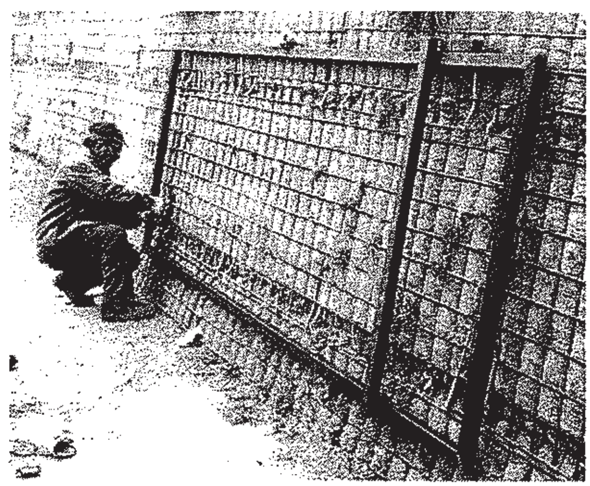

Figure 2. Measurement of facing deformation.

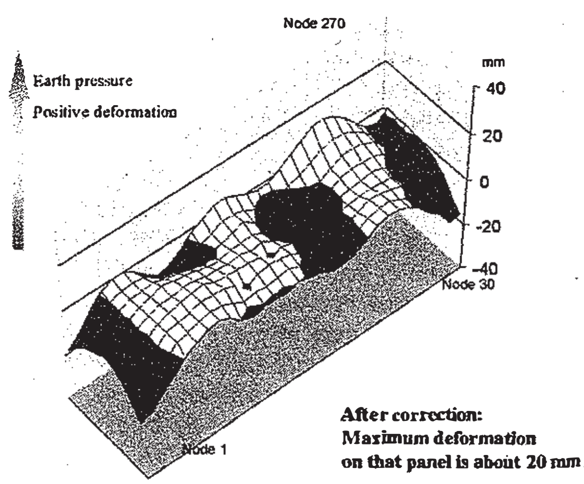

Figure 3. Analyze of actual deformation.

fied by calculation to find the best adjustment i.e. the plane that gives the minimum standard deviation. This is shown in Figure 3. Of course it is diffcult to have on a construction site all connection points in the same plane within a millimeter and there is no need to be so accurate. An ideal geometry after construction could be approached only in a laboratory where all parameters could be better controlled.

Finally we can estimate that the maximum deformation due to earth pressure is around 20 mm. No need to try to obtain a greater precision. We just want an order of magnitude.

5 MECHANISM OF DEFORMATION

Now, let's consider the nature of the mesh panel and the parameters that play a role in the mechanism of deformation:

- A very flexible beam, or more precisely a plate, constituted of wires, multi-supported; its inertia module is very small for such small witres,
- A network of cables in which a normal tension is developed as the deformation increases; it behaves somehow like a membrane,
- A soil for which we have little information particularly on the way it behaves behind such flexible facing.

The two first mechanical points could be dealt with, thanks to powerful calculation programs.

Taking account of the soil behavior is a new feature in the design of a MSE facing. Although it is obvious that the earth pressure decreases when the deformation increases, we must describe this behavior and quantify it.

Terrasol made a study (1988) on the subject of modeling the behavior of a facing constituted by rigid vertical posts or soldiers, between which are placed a thin concrete facing panel.

Since the facing panel can deform much more relatively to the soldiers, an arch of soil is built up that span over the panel and rest on the rigid components: the soldiers.

The Figure 4 shows the stress concentration effect on soldiers as well as the rotation of stress direction. The report concludes: "a small deformation of the facing (of some mm) is sufficient to activate the mechanism of arching effect". The earth pressure behind the facing is thus reduced drastically (for example to one tenth of the average pressure) depending mainly on the length between the supports, while the pressure increases behind the stiff elements.

Let's remind some basic concept in soil mechanics, noticeably as regards retaining sttuctures. The movement of a rigid screen toward or outward the soil from the position at rest gives a certain force F called respectively passive or active earth pressure. The result of that experimentation can be plotted as F in relationship with the deformation (see Figure 5).

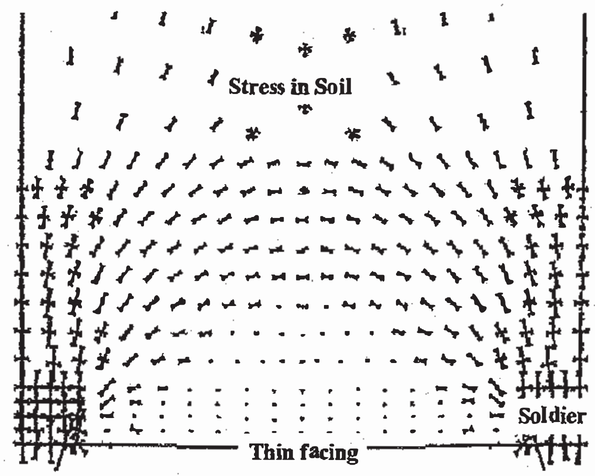

Figure 4. Arch effect on stiff elements (Terrasol).

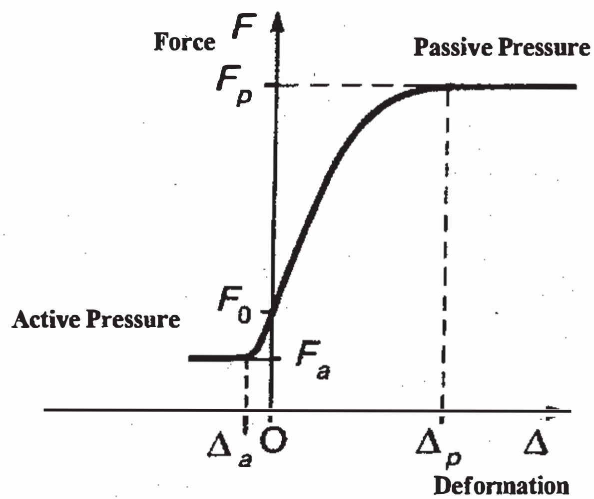

Figure 5. Force on a screen.

Also a more fundamental test, the triaxial test, allows drawing a similar curve for the intrinsic properties of the soil (Figure 6).

Under the earth pressure, the steel mesh deforms outward hence the earth pressure reduces considerably. For negative movement (like it can happen locally on the mesh) the pressure increases quickly.

Since the decrease of the earth pressure is due to the build up of arches, we must also consider the length of the span: we assume that the deformation is proportional to the span. Therefore, the general behavior law takes account of the relative deformation instead of the absolute deformation.

After several attempts, we propose an exponential law, see Figure 7, where:

qi is the load (or earth pressure) at a given node i and relative deformation **di/LV**

q0 is the load at the supports (supposed to be fixed: no deformation)

a is the coefficient for the soil (no dimension); greater is **a**, stiffer is the soil.

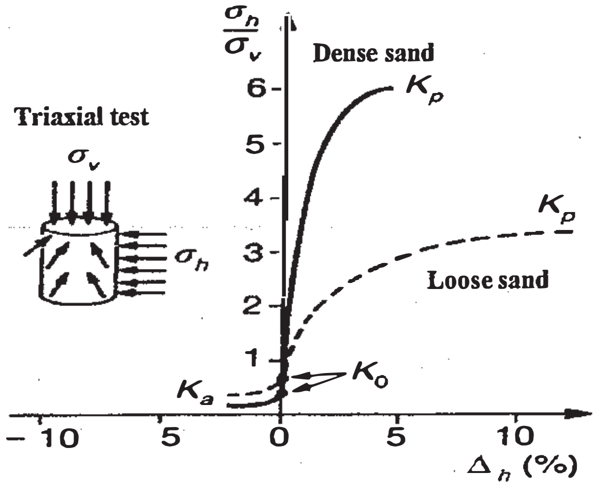

Figure 6. Triaxial response of a sand: K vs. deformation.

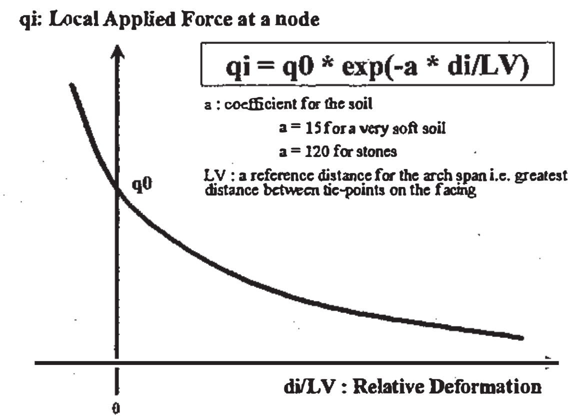

Figure 7. Earth pressure vs. facing deformation.

di is the deformation at node **i**

LV is the longest distance between two consecutive supports.

The advantages of this law is two fold:

- A quick convergence,
- A unique parameter for the soil: "a".

6 METHODOLOGY

The problem is now to implement the above behavioral law in the calculation.

The idea is to run first the calculation of a panel with a uniformly distributed load using a non-linear static calculation program. The method of analysis is P-Delta for geometrically non-linear beam element (Gachon and Galéa 1978). The best results were obtained by using the algorithm BFGS (Breydon-Fletcher-Goldfard-Shanno).

Then the deformation at each node is analyzed, input in the exponential law equation and the load is modified accordingly. Then again a new run will be

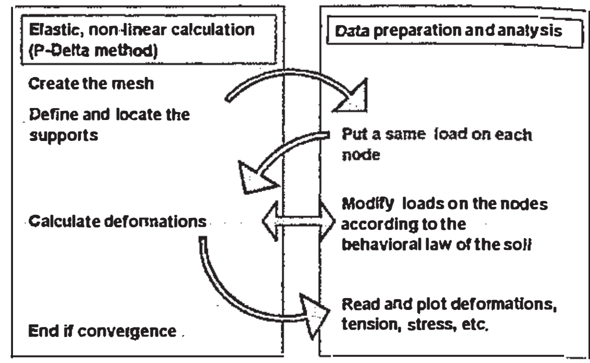

Figure 8. Flowchart of operations.

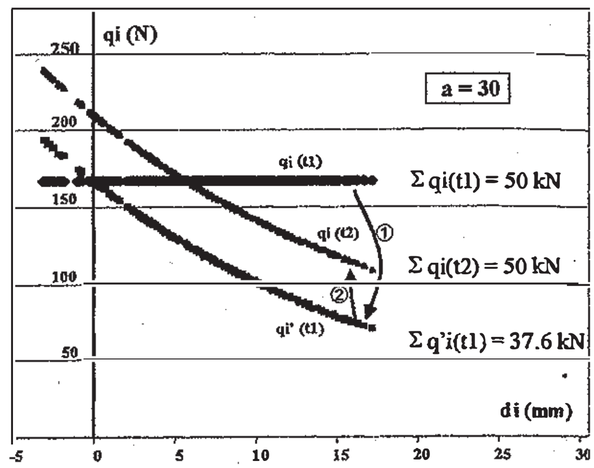

Figure 9. Modification of loads at the nodes.

done with a new distribution of load: higher load at the supports, lower load in span.

The process is repeated till no significant change is observed. Practically we have created a small spreadsheet program to deal with the setting of the proper loads used by the calculation program. The flow chart of operations is shown in Figure 8.

Figure 9 presents the way the new set of loads is defined after the first run (tl).

The horizontal line represents the deformation caleulated by the program after all 300 nodes were loaded at qi(tl) = 167 N. The total load is 50 kN.

Now the qi'(tl) points represent the direct application of the behavioral law: the load increases for the negative deformation and decreases as the positive deformation increases. But the total is now down to 37.6 kN.

A "damping" coefficient p can be used to take a part only of the difference between the previous load value qi(tl) and the next one qi'(tl). This precaution was found to be useful to better control the convergence.

Once done, each value is multiplied by an overall factor to reach again the total load of 50 kN and thus obtain the final qi(t2) values ready for the next run.

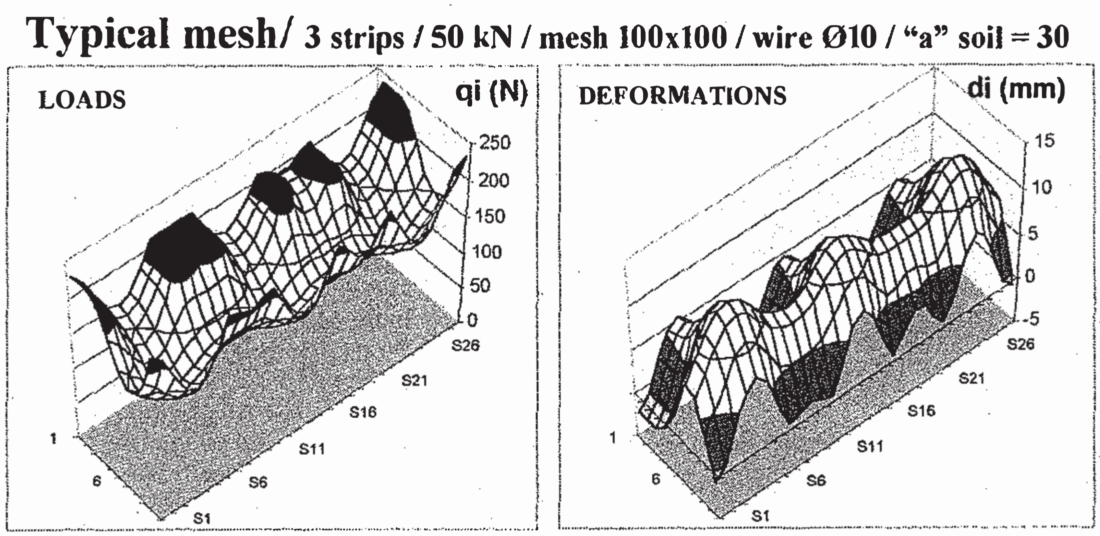

Figure 10. Presentation of results (loads and deformations) after convergence; the 18 tie-points are at di = 0.

7 RESULTS

7.1 *Soft soil*

A new set of results was obtained for a typical panel made of wires ϕ-10 mm, mesh size 100x100 mm. Three reinforcing strips are connected to one panel 3 m long; each strip provides four tie-points (the main and secondary double-hooks) plus two due to the overlapping of the next panel.

The Figure 10 presents the maximum deformation at 13.6 mm obtained after only 3 runs, under a total load of 50 kN with a soft soil (a = 30). On this view of the load distribution and mesh deformation, we see that the mesh is equally supported by the 18 tiepoints.

Tension in the wires is an information provided by the calculation program. It is thus possible to set a specification for the maximum stress in the steel wires. After scanning different wire diameters, mesh size and number of tie points, a graph was drawn, as shown in Figure 11, in which the field of application of the various mesh facing is clearly defined.

Note that the value of q0 is greater now: the load increases on the bearing points. This was expected.

The new set of loads is then sent to the calculation program and processed, and so on. Usually convergence is obtained after a few iterations only: 3 or 4 for a soft soil to 6 or 8 for a stiff soil.

Different values for "a" were tried to fit with the observations on the actual wall. For the wall described in §4 above (with an estimated total load on one facing panel of 30 kN), a calculated deformation of 23.7 mm was obtained (compared to 20 mm observed on site) with a coefficient a = 30, which can be considered typical for a soft soil as the one generally used as backfill for MSE structures.

A similar graph can be drawn for another criteria like the allowable deformation for example.

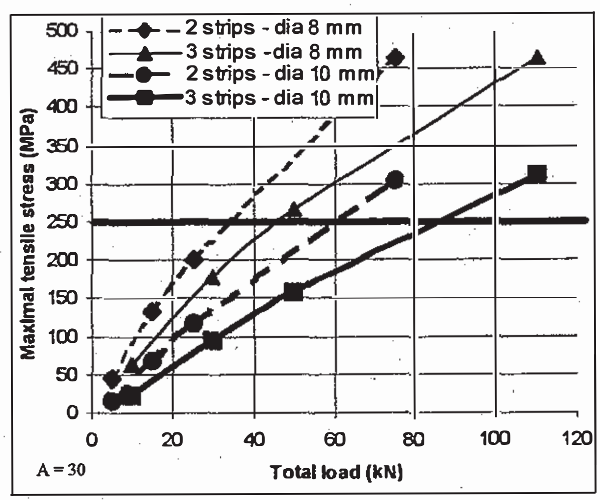

Figure 11. Tensile stress in the wires - Mesh 100 x 100 mm.

7.2 *Stiff soil*

In Figure 12 are presented the results obtained on exactly the same panel and load as described in figure 10, but the soil is now much stiffer with a "a" coefficient of 120. This case would correspond to a stone filling behind the panels. The loads are extremely concentrated at the tie-points. The ratio between the maximum and minimum value of the load at one node reaches 6.3. The calculation is a little longer and a damping ratio of 1.5 (it means that only 67% of the difference between qi (t1) and qi' (t1) was used to define the next qi (t2)) helps for convergence.

The deformation after the first run was 17 mm; it is the value we would have without considering the soil behavior. After 5 or 6 runs, the maximum deformation was stabilized at 9 mm, but it took some more runs to balance the distribution of loads.

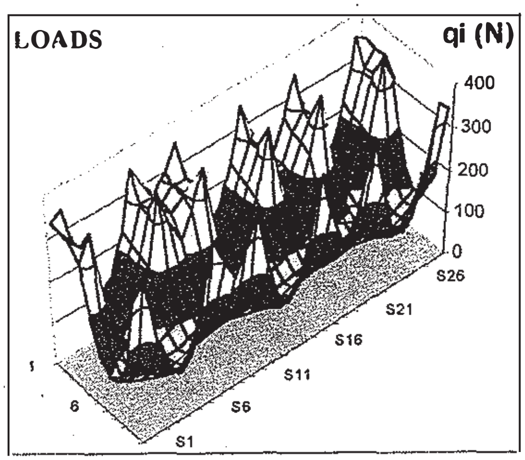

Figure 12. Same mesh and loading as above in Fig.11; a = 120. All 18 peaks correspond to tie-points.

7.3 *Limitations*

We have considered that the tie-points are fixed. If in the model we allowed them to slide in the plane of the panel, the tension in the wires due to the cable effect would be reduced and the deformation increased.

In fact, the stress decreases much quicker than the deformation increases due to this modification. Further work would be needed to refine the model, but we admit that the results obtained with this method are quite satisfactory and certainly conservative as regards the tensile stress in the wires. Finally this calculation tool is very useful to define new geometry of panels in accordance with the desired specifications on load, deformation and stress.

Similar technologies in which a flexible mesh receives the earth pressure can also take advantage of this calculation technique to estimate the behavior of the structure; this is noticeably the case for soil-nailed embankment where a steel mesh is used to retain the soil between the heads of the nails.

8 CONCLUSION

More and more Mechanically Stabilized Structures use light steel mesh panels as facing. So far no comprehensive approach of the mechanisms that govern the deformation and the stress in the steel wires has been presented.

The use of non-linear analysis combined with a behavioral law stress vs. deformation for the backfill material constitutes an innovative feature in the design of mesh facing technology. The deformation is now realistic and all tensile stress in the wires can be estimated.

Although used first for MSE facing technology, the methodology presented in this paper is valid for other kind of applications.

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